Tactile illusory movement: Effects of spatio-temporal stimulus characteristics on the integrative processing of saltatory and successively activated stimulus patterns

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Preface

This dissertation emerged at the Spatial Orientation Systems Department at the Navel Aerospace Medical Research Laboratory (NAMRL), located at Navel Air Station in Pensacola, Florida, USA. Here, vibrotactile interfaces like the Tactile Situation Awareness System (TSAS) are developed and evaluated. Based on vibrotactile cues, TSAS provides information about an aircraft's attitude or threat to the pilot, and thus maintains an operator's situational awareness. As a member of the German Scientist Exchange Program of the German Armed Forces, I worked as a Research Assistant at NAMRL and was able to collect data for my thesis. Angus H. Rupert, Captain in the US Navy Medical Service Corps, and Head of the Spatial Orientation Systems Department and Roger W. Cholewiak, Ph.D., Director of the Cutaneous Communication Laboratory at Princeton University supervised the experiments at NAMRL and at Princeton. The experiments were supported by ONR Grant No #N0001401WX20204 to NAMRL and the Intergovernmental Personnel Agreement N6645200MD00012 to Princeton University and were approved by the Committee for the Protection of Human subjects.

In order to generate percepts of movement, two tactile illusions were examined: Successive activation to produce a phi-like motion and saltation. Tactile movement can be used for example as a directional vector in tactile displays.

But the experiments were not only conducted for practical purposes, sensory illusions are of particular interest as they expand our knowledge of human perception in that they help to clarify disparities between physical stimuli and the psychophysiologically measured sensations they evoke. Thus, the tactile illusions used in our experiment may aid in studying the integration of spatio-temporal stimuli into percepts of continuous motion.

At the University of Mannheim, the saltatory phenomenon is used to asses dynamic changes in somatosensory maps due to spatio-temporal repetitive stimulation. The results of these studies are discussed in connection with the investigation of chronic pain and other disorders possibly related to deranged "body maps". Professor Rupert Hölzl, Professor for Clinical Psychology and director of the Otto Selz Institute and the dedicated Laboratory of Clinical Psychophysiology agreed to supervise my dissertation at the University of Mannheim.

Part of this thesis has been published: The study to determine vibrotactile thresholds on the torso was published in Perception & Psychophysics 2004, a summary of the results of

Experiment 2 was presented as poster at the Psychonomic Society Meeting, Vancouver, Canada, in 2003.

I would like to thank all colleagues at the University of Mannheim and NAMRL, who supported my work: First of all Prof. Rupert Hölzl and Prof. Roger W. Cholewiak, for their patience, their ongoing encouragement, and the technical and scientific steering of my thesis. Also CAPT USN Angus Rupert, who made this research project possible at his department. Kristy Beede, not only assisted me in recruiting and testing subjects, she also became a friend outside the Research Laboratory. I would also like to thank the whole NAMRL staff and CAPT MC USN Anderson, Commanding Officer at NAMRL, who were very supportive and made my stay in Pensacola an interesting and very pleasant one. Sincere thanks are given to my subjects, who participated in my studies.

Dr. Annette Stolle, who also studied saltation at the University of Mannheim was a valuable dialog partner, and I would like to thank her for the time she spend with me, discussing the contents of my thesis. Additionally I would like to thank Dr. Dieter Kleinböhl and Dr. Andreas Möltner for their helpful statistical advice and Dipl.-Psych. Jörg Trojan for his helpful suggestions, as well as the Laboratory Stuff for their administrative support.

Last, but not least, I want to thank my husband, who was always understandingly, encouraged me and provided any practical and emotional support, he could.

Augsburg, January 08

Anja Schwab

Abstract

Saltation and apparent movement are related phenomena: Both generate illusory stimuli in-between the actually activated stimulus sites. This dissertation examines spatio-temporal stimulus parameters where both phenomena create equivalent percepts. In these cases it is assumed that cortical representations adapt identically to the properties of both stimulus patterns – saltation and apparent movement. Furthermore it is tested whether repetitive stimulation results in plastic changes of the cortical map and related perceptual changes. Another focus lies on the integration of the stimulus patterns over both body halves. We used varying numbers of vibrotactile point stimuli that were presented on a horizontal array around the trunk.

In two pilot studies and three main studies with a total of 139 subjects we reached the following conclusions: In accordance with neural network models stimuli presented close together in time are expected to belong together. Therefore both stimulus patterns generate indistinguishable percepts at short interstimulus intervals (<100 ms); the same applies for short stimulus durations (<50 ms). Increasing the number of tactors – and thus decreasing inter-tactor distance – tends to improve the integration of both stimulus patterns into a percept of continuous movement. Vibration frequency affects the quality of illusory movement as well as the similarity of both patterns. Further studies exploring the spatial resolution of low- and high-frequency vibrotactile stimulus patterns on hairy skin are needed to clearly explain this result. An effect of repetitive stimulation on the comparability of both stimulus patterns could not be found – presumably because plastic changes in the cortical map of body sites like the trunk – which are less innervated and rarely used to explore the environment compared to the fingers – might require more stimulus repetitions. Crossing the body midline impairs comparability of both stimulus patterns, however in the majority of cases saltation and apparent movement generate indiscriminable percepts when presented unilaterally or bilaterally indicating that integration of spatio-temporal stimuli occurred over the body midline – yet interstimulus intervals might differ due to interhemispheric transmission time.

The results of this dissertation shed further light on the processing of spatio-temporal stimuli and might also be used in the design of tactile torso displays.

Zusammenfassung

Saltation und takile Scheinbewegung sind verwandte Phänomene, da beide illusorische Reize zwischen physikalischen Reizpunkten generieren. Diese Dissertation untersucht die Ausprägungen der spatio-temporalen Reizmerkmale, bei denen beide Phänomene als identisch wahrgenommen werden. In diesen Fällen wird eine identische Anpassung der zerebralen Repräsentation an die beiden taktilen Reizmuster - Saltation und Scheinbewegung - angenommen. Darüber hinaus wird getestet ob eine wiederholte Reizdarbietung eine Veränderung der kortikalen Karte und damit perzeptiver Korrelate nach sich zieht. Die Integration der Reizmuster über beide Körperhälften ist ein weiterer Fokus dieser Arbeit. Stimuli waren punktuelle Vibrationsreize, die in unterschiedlicher Anzahl auf einer horizontal um den Rumpf verlaufenden Stimulus-Matrix vorgegeben wurden.

In zwei Pilot- und drei Hauptstudien mit insgesamt 139 Versuchspersonen wurden folgende Ergebnisse erhoben: Im Einklang mit neuronalen Netzwerk-Modellen werden Stimuli, die in engem zeitlichen Abstand präsentiert werden als zusammenhängend wahrgenommen, beide taktilen Reizmuster generieren daher nicht unterscheidbare Perzepte bei kurzen Interstimulus-Intervallen (<100ms); gleiches gilt für eine kurze Stimulusdauer (<50ms). Eine Erhöhung der Anzahl der Reizgeber – und damit eine Verkürzung der Reizdistanz - verbessert tendenziell ebenfalls die Integration der beiden Reizmuster zu einer glatten Scheinbewegung. Die Vibrationsfrequenz beeinflusst die Qualität der Scheinbewegung und damit auch die Vergleichbarkeit der Reizmuster. Weitere Studien zur räumlichen Auflösung hoch- und niedrigfrequenter taktiler Reizmuster auf haariger Haut sind nötig, um dieses Ergebnis eindeutig erklären zu können. Ein Effekt repetitiver Stimulation auf die Vergleichbarkeit der Reizmuster konnte nicht nachgewiesen werden – vermutlich weil plastische Veränderungen der kortikalen Karte bei Körperregionen wie dem Rumpf – die weniger sensibel innerviert und seltener im täglichen Gebrauch genutzt werden wie z.B. Finger - mehrere Reizwiederholungen erfordern. Das Überqueren der Köpermitte beeinträchtigt zwar die Vergleichbarkeit der Reizmuster, jedoch generieren Saltation und Scheinbewegung sowohl bei unilateraler wie bei bilateraler Darbietung überzufällig oft identische Perzepte, so dass von einer Integration spatio-temporaler Reizmuster auch über die Körpermitte hinweg ausgegangen werden kann – evtl. jedoch bei unterschiedlichen Interstimulus-Intervallen aufgrund der interhemisphärischen Übertragungszeit bei bilateralen Reizen.

Die Ergebnisse dieser Dissertation leisten einen Beitrag zur Erklärung der Verarbeitung von spatio-temporalen Reizmustern und tragen auch zur Entwicklung taktiler Displays bei.

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Index of Abbreviations

2-AFC	Two-alternatives forced-choice
AL	Alignment button
df	Degrees of freedom
e.g.	for example
FA	Fast adapting units
fMRI	Functional magnetic resonance imaging
i.e.	that is
ILD	Interaural level difference
ISI	Interstimulus interval
ISOI	Interstimulus onset interval
ITD	Interaural time difference
L1-3	Stimulus location 1-3
LED	Light-emitting diodes
M	Mean
Max.	Maximum
Min.	Minimum
MT	Middle temporal area
N	Sample size
n	Number of observations
n.s.	Not significant
NAMRL	Naval Aerospace Medical Research Laboratory
P	Significance
PC	Pacinian corpuscles
p.	Page
pp.	Pages
P1-P3	Pulse 1-3
RA	Rapidly adapting units (=fast adapting units)
SI	First (primary) somatosensory cortex
SII	Second (secondary) somatosensory cortex
SA	Slowly adapting units
SD	Stimulus duration
StdDev	Standard Deviation

Tac/tactor	Tactile vibrator
TSAS	Tactile Situation Awareness System

Units of Measurement

C	Celsius
cm	Centimeter
cm/s	Centimeter per second
dB SL	Decibel sensation level
gr	Gram
Hz	Herz
mm	Millimeter
mm/s	Millimeter per second
ms	Millisecond
s	Second
µm	Micrometer
°	Degree

1 Importance of spatio-temporal illusions

Von Békésy (1967) states: “In the complex system of neural and cortical processing with inhibitory, excitatory and feedback connections it is difficult to determine, which feature in the complex produces a sensation like illusory movement” (p. 162). Psychophysical measures provide a non-invasive technique to describe connections between stimulus characteristics and sensations, which in turn are supposed to correlate with network features.

With the help of tactile illusions the gap between psychophysics of perception and cortical representation might be closed and an answer found for the question: Do topographic representations in early somatosensory cortices map physical locations of peripheral stimuli or rather subjective perceptions (see Chen, Friedman, & Roe, 2003) and how are those representations correlated to spatio-temporal stimulus characteristics?

The research about tactile illusions has a long tradition: Almost a century ago, Gestalt psychologists like Wertheimer discovered that non-moving stimuli can elicit the perception of motion (see summary of Sarris, 1989). When two stimuli are presented successively with the appropriate time interval and distance between the stimuli we see the shift as movement. This compelling illusion known as apparent motion was studied first in the visual sense, but was also found in the auditory and tactile sense.

Another class of spatio-temporal illusions employing successively delivered stimuli found that depending on spatio-temporal stimulus characteristics, the perceived location of a stimulus can shift towards the location of a rapidly delivered subsequent stimulus (a phenomenon called saltation) or even merge to a single sensation (von Békésy effect). Furthermore, it was found that the apparent spatial distance between successively presented stimuli depends on the time interval between them (tau-effect). A parallel interaction, known as the kappa effect, occurs when apparent temporal intervals for successively-presented stimuli are affected by the physical distance between the sites that generated the tactile sensations (Cohen, Hansel, & Sylvester, 1955).

Cholewiak and Collins (2000) have shown that apparent motion and saltation can both elicit the same percepts of movement. Alike saltation, apparent movement obviously implies the mislocalization of stimuli, as in both illusions, stimuli are not perceived, where they physically are. To obtain the perception of smooth, uninterrupted movement, timely separated stimuli must be integrated into a unitary percept, where illusory stimuli are perceived at locations in-between the actually activated stimulus sites. Cholewiak and Collins (2000) conclude that “repetitive presentation of spatio-temporal stimuli … can lead to considerable changes in cortical spatial organization” (p. 1233).

Further exploration of spatio-temporal illusions might lead to a better understanding of these processes of cortical reorganization.

Tactile illusions help to study the connection between perception and somatotopic cortical processing The body map for somatosensory perceptions represents neurons in the somatosensory cortex (SI) that are activated by touching certain body parts. This map was presumed to be a topographic map of the physical body. But new research showed that “brain maps perception, not reality” (Chen et al., 2003) . The researchers used an illusion called tactile funneling: When adjacent fingers are stimulated, subjects perceive a single stimulus between the two stimulated sites. In this case only a single cortical location responded which was situated between the areas that were responding when both fingers were stimulated (see also Gardner & Constanzo, 1980b, 1980c). Chen et al. (2003) conclude that the pattern of cortical activation reflects our subjective perception rather than physical stimulation.

Blankenburg, Ruff, Deichmann, Rees, and Driver (2006) found the same result when they examined a tactile illusion called saltation (Chapter 3.1): An illusorily perceived stimulus during the saltation condition activates exactly the same sector of the brain that would respond if that (illusory) stimulus location had actually been touched.

Wiemer, Spengler, Joublin, Stagge, and Wacquant (1998, 2000) demonstrated that temporal distances between stimuli are transferred into spatial distances in cortical representation. The shorter the time interval between two stimuli, the closer the representational distances in somatosensory cortex. Apparently, activity of the somatosensory cortex adapts to spatio-temporal stimulus characteristics (see also Braun, Haug, Wiech, & Birbaumer, 2001; Wang, Merzenich, Sameshima, & Jenkins, 1995).

Clinical importance of tactile illusions Tactile illusions can support in detecting sensory impairments in neurologically damaged individuals and may aid in recognizing worsening or improvement of the sensory deficit. Clinical tests evaluating a patient's ability to discriminate the direction of tactile movement simulated by the successive delivery of stimuli might be helpful to detect sensory deficits after nerve injuries and accordingly measure recovery rates (Essick, Whitsel, Dolan, & Kelly, 1989; Johnson, Yoshioka, & Vega-Bermudez, 2000; Szaniszlo, Essick, Kelly, Joseph, & Bredehoeft, 1998).

Two examples for the clinical relevance of tactile illusions: Temporal stimulus parameters of visual saltation were found to differentiate between males diagnosed with chronic schizophrenia, mixed psychiatric patients and a normal control group (Brassel, 1993). The identification of numbers "drawn" on the skin with discrete tactile stimuli is enhanced in the affected body-half of cervical spinal cord-injured subjects with central pain, but deteriorated in most patients with supraspinal injuries and central pain (Gonzales, Lewis, & Weaver, 2001).

Technical implications: Vibrotactile displays Tactile displays convey information by presenting vibrotactile stimuli to the user's skin. Recently the interest in and the application of tactile displays is rapidly growing, partly because the development of more complex human-computer interfaces leads to an increasing overload of the visual and auditory information channels. Hence, the need for an additional or alternative information channel pushed researchers to use the sense of touch in multi-modal interfaces.

Tactile displays can either serve as Sensory Assistive devices, aiding blind or deaf people to perceive the world around them, by translating visual or auditory information into tactile stimuli (e.g. Tactaid II or Tactile VII for the deaf or OPTACON/TCD for the blind). Or they are employed as information displays that convey certain information about our environment: The skin can be used as a medium to communicate spatial information like the location or direction of moving objects. Thus, vibrotactile displays for spatial guidance have been developed. Examples for the successful application of relatively simple displays would be: The Tactor Locator System (TLS) by Rochlis and Newman (2000) that presented information about position and velocity by vibrating stimuli (called tactors) on the torso and neck and was tested onboard the International Space Station (ISS; see also van Erp, 2007); a haptic back display e.g. embedded in a driver's seat as a navigation guidance system (Tan, Gray, Young, & Traylor, 2003) or vibrotactile warning signals in automobiles to present spatial information to drivers (Ho, Tan, & Spence, 2005). Van Erp (2007) demonstrated that a tactile navigation system in a driving simulator is superior to a visual display, since the reaction time to navigation messages and subjects' mental effort ratings were lower for the tactile display. In addition, in a high workload condition, reaction time to visual stimuli in the periphery of the visual field increased when the visual display was used, but remained constant, when the tactile display was used, compared to a normal workload condition.

More complex displays consist of 60 or more tactors that cover the whole torso of the user. They do not only convey simple information like direction but also map spatial coordinates of a stimulus to a specific location on the torso. This enables for example pilots or divers who operate many times under poor visual conditions to maintain spatial orientation or help to navigate. An example would be the Tactile Situation Awareness System (TSAS), a tactile array applied on the torso and limbs to provide orientation cues to the operator (Rupert, 2000). Another application under development is a vibrotactile vest to support astronauts' orientation awareness (van Erp & van Veen, 2003).

Beyond navigation applications, tactile displays can be part of rich interaction scenarios like pervasive computer environments. The "Aura project" at the University of Carnegie is working on a wearable interaction device that is the user interface to any computer on campus and also contains an array of micro tactors that provide various notifications (e.g. notification of emails or incoming files) to the user (Gemperle, Ota, & Siewiorek, 2001).

The usefulness of tactile displays in teleoperation and virtual realities has been demonstrated amongst others by Kontarinis and Howe (1995), who used a teleoperated hand system that delivered vibratory stimuli to the operator's finger tips.

In all the studies reported above, tactile displays have turned out to be an effective component of multisensory human-machine-interfaces.

2 Perception of vibratory stimuli

2.1 Cutaneous Mechanoreceptors

The primary receptors for tactile stimuli are located in the skin and the mechanoreceptive units in glabrous (hairless) skin can be categorized by the size of their receptive fields and their response to static stimuli: Afferent fibres with small receptive fields are called type I, those with large receptive fields type II. Units adapt either fast (FA) or slow (SA) to static stimuli, i.e. they either respond just to the stimulus onset, and often at the termination (FA) or respond during the whole stimulus duration (SA). The end organs for FAI units are Meissner corpuscles, for FAII units Pacinian corpuscles (PC), for SAI units Merkel disks and for SAII units Ruffini cylinders (e.g. Cholewiak & Collins, 1991; Greenspan & Bolanowski, 1996; Martin & Jessell, 1993).

The size and form of the receptive fields may vary with indentation force of a static stimulus, the amount of variation in field size depending on unit type. Also the type of stimulation, e.g. lateral or vertical skin displacement changes the extent of the receptive fields (Johansson, 1978; Vallbo, Olausson, Wessberg, & Kakuda, 1995).

Each type of mechanoreceptor responds especially to a certain aspect of the stimulus: Pacinians are excited by vibratory high-frequency stimuli; they perceive vibrations transmitted through an object or tool held in the hand. Ruffini cylinders respond to skin stretch and consequently transmit information about forces acting on the hand. Merkel disks are sensitive to edges, corners and curvatures, and therefore responsible for form and texture perception. Meissner corpuscles have a lower spatial acuity than the SAI system; they are responsible for the detection of surface form and texture when surface variation is too small to activate the SAI system. They are also very sensitive to minute motion on the skin surface and sudden changes in load force and thus provide feedback signals for grip control (Johnson et al., 2000; Johnson, 2001; Johnson & Hsiao, 1992).

Psychophysical measures of vibrotactile sensation lead to the “four channel model of cutaneous mechanoreception”, showing that each of the four mechanoreceptive units have different frequency-response characteristics: The Pacinian channel (FAII) responds to frequencies between 35 and 500 Hz, the threshold-frequency function being U-shaped. The SAII units are operating at about the same frequency range (80-500 Hz), but at a much lower sensitivity. FAI and SAI units both are excited by frequencies between 3 and 100 Hz (SAI units even operate at frequencies as low as 0.4 Hz), their sensitivities are not affected by changes in frequency. As the sensitivities of the four channels overlap, suprathreshold stimuli can activate two or more mechanoreceptive units at the same time (Bolanowski, Gescheider, Verrillo, & Checkosky, 1988). In Figure 2.1 vibratory thresholds derived from the glabrous skin of the thenar eminence are presented as a function of frequency for each of the four channels.

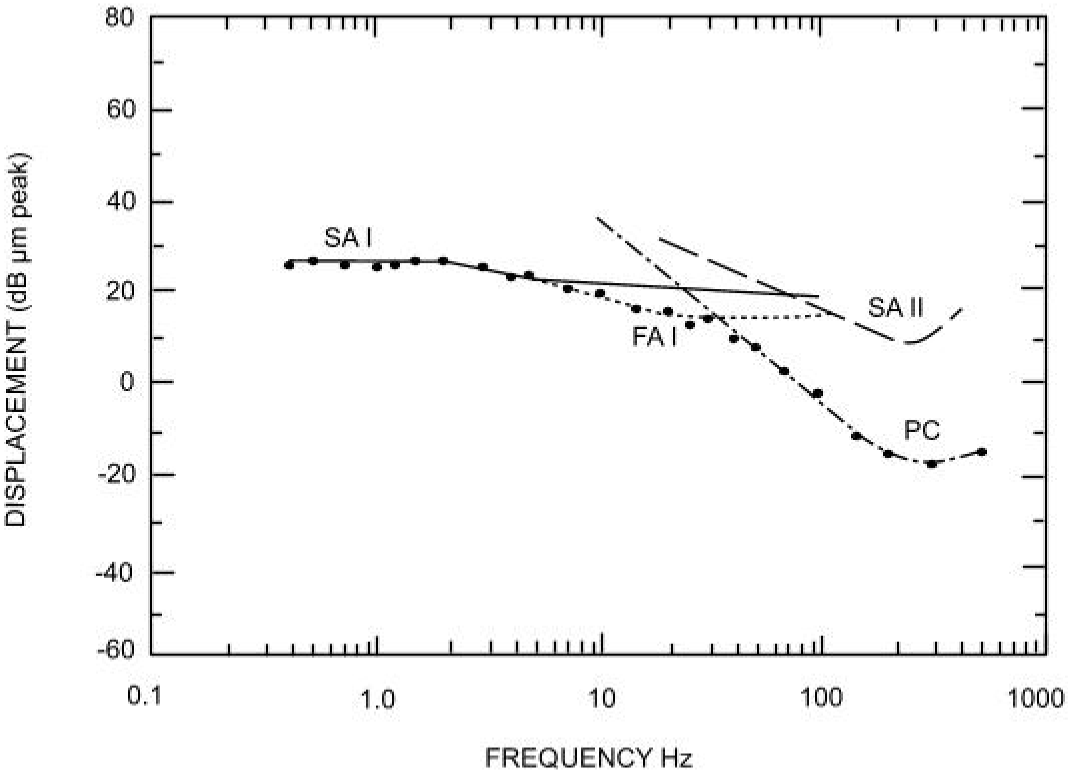


Figure 2.1: Vibration thresholds on the thenar eminence as a function of vibration frequency. Threshold values are expressed in decibels (dB) referred to 1-µm peak displacement. The diagram shows the threshold-frequency characteristics of the four mechanoreceptive units: The Pacinian (FAII) channel (— - —) , the SA II (−−−), the FAI (---) and the SA I (——) channel. The data points (••••) represent the average thresholds for frequencies ranging between 0.4 and 500 Hz for the whole receptor population.

From: Bolanowski SJ, Gescheider GA, Verrillo RT, Checkosky CM, 1988, p. 1691.

The density of sensory units innervating the skin varies considerably. In the glabrous skin of the hand for example, density of FAI and SAI units increases in proximo-distal direction, whereas type II units are nearly uniformly distributed over the glabrous skin, but in total there are less type II than type I units (Johansson & Vallbo, 1979).

In hairy skin, the structure of mechanoreceptors differs: Aside from slowly adapting units (SAI and SAII, however they can not be categorized as clearly as in glabrous skin), there are three rapidly adapting unit types: Hair units (responding to movements of individual hairs; larger receptive fields than type I units; end organs are almost evenly, but thinly distributed), field units (comparable to hair units, but unknown histological structure of the end organs and more diffuse receptive field borders; they are more sensitive to skin indentation) and Pacinian-type units (quite homologous to the Pacinian channel in glabrous skin, except they are not sensitive to temperature changes, probably because they are located deeper in the skin and less numerous than in glabrous skin). No rapidly adapting units with small receptive fields were found on the hairy forearm skin. (Bolanowski, Gescheider, & Verrillo, 1994; Greenspan & Bolanowski, 1996; Vallbo et al., 1995). In addition, there are unmyelinated mechanoreceptive afferents in the forearm skin that respond to light tactile stimuli (Vallbo, Olausson, Wessberg, & Norrsell, 1993). As there are only few psychophysical studies of human hairy skin afferent fibres, "the relationship between hairy skin afferent fibres and tactile perception is still largely unknown" (Greenspan & Bolanowski, 1996, p. 43). However, we know that in hairy skin hair follicle receptors are responsible for the detection of low-frequency vibratory stimuli (less than 80 Hz), and presumably the deeply located Pacinian receptors for the detection of high-frequency stimuli (Mahns, Perkins, Sahai, Robinson, & Rowe, 2006). Hairy skin is the type of skin that will be studied in all of the experiments in this dissertation.

Depending on the skin site tested and the type of skin (glabrous versus hairy skin), number and structure of receptors vary (e.g. Meissner corpuscles can only be found in glabrous skin; there are no Pacinian corpuscles in the skin of the cheek). Thus, the skin does not respond uniformly to tactile stimuli: Sensitivity to tactile stimuli depends on innervation density and appearance of mechanoreceptors (Cholewiak & Collins, 1991).

2.2 Spatio-temporal variables affecting vibration perception

Detection thresholds for vibratory stimuli depend on several spatio-temporal parameters like frequency, contactor size, stimulus duration and location, and skin type (glabrous or hairy).

Thresholds are low for vibration frequencies in the range 200-300 Hz, dependent on contactor size. For very small contactors (< 0.02 cm^2) threshold is independent of frequency. For larger contactors, low frequencies (< 40 Hz) have no effect on detection threshold, but as frequencies increase, threshold improves until it reaches maximum sensitivity and then sensitivity decreases rapidly. Subjective stimulus magnitude is also affected by vibration frequency: Higher frequencies must be presented at lower intensities (displacement in decibels) to be perceived at the same subjective magnitude as a low-frequency stimulus (Summers, 1992; Verrillo, 1965). Cholewiak and Collins (1991) first published a table that summarizes these parameters, later reproduced and expanded by Greenspan and Bolanowski (1996).

If contactor size is taken as independent variable, it appears that at the higher frequencies (80-320 Hz) sensitivity increases with the size if the vibrating element, indicating that spatial summation takes place. At low frequencies (<40 Hz) contactor size doesn't affect detection threshold, in this case, there is no spatial summation. In addition, for receptor systems showing spatial summation (Pacinian channels) applies: The larger the contactor size, the greater the apparent stimulus intensity, independent of stimulus frequency (Cholewiak & Collins, 1991).

Additionally stimulus waveform also influences the detection and perception of vibrotactile stimuli. While a sine wave is perceived as smooth, a square wave is more intense and "sharp", due to a square wave pulse's rapid on- and offset and the phase-locked responses of FAs to the periods of the stimulus waveform. Ide, Akimura, and Obata (1985) found lower vibratory thresholds for square waves than for sine waves.

Also, the duration of the stimulation is crucial, as temporal summation – which only works for stimuli > 40 Hz – facilitates the perception of vibrotactile stimuli (FAII and SAII). Here again, very small contactors (0.02 cm^2) are an exception (Summers, 1992; Verrillo, 1965).

Thresholds are low on fingers and hands compared to the limbs and the trunk. Figure 2.2 shows that thresholds decrease proximodistally. It seems that vibratory threshold is correlated with cortical representation of certain body sites. (Sherrick & Cholewiak, 1986). Body site not only influences detection thresholds, but also the perception of changes in the subjective magnitude ("loudness") of the stimulus. The subjective magnitude of stimulation increases more rapidly on lesser innervated body sites like the forearm (Summers, 1992) or the thigh (Cholewiak, 1979). Furthermore, body site and thus innervation density correlates with the skin's spatial resolution: Two-point thresholds and errors of localization are both higher for lesser innervated sites like the trunk.

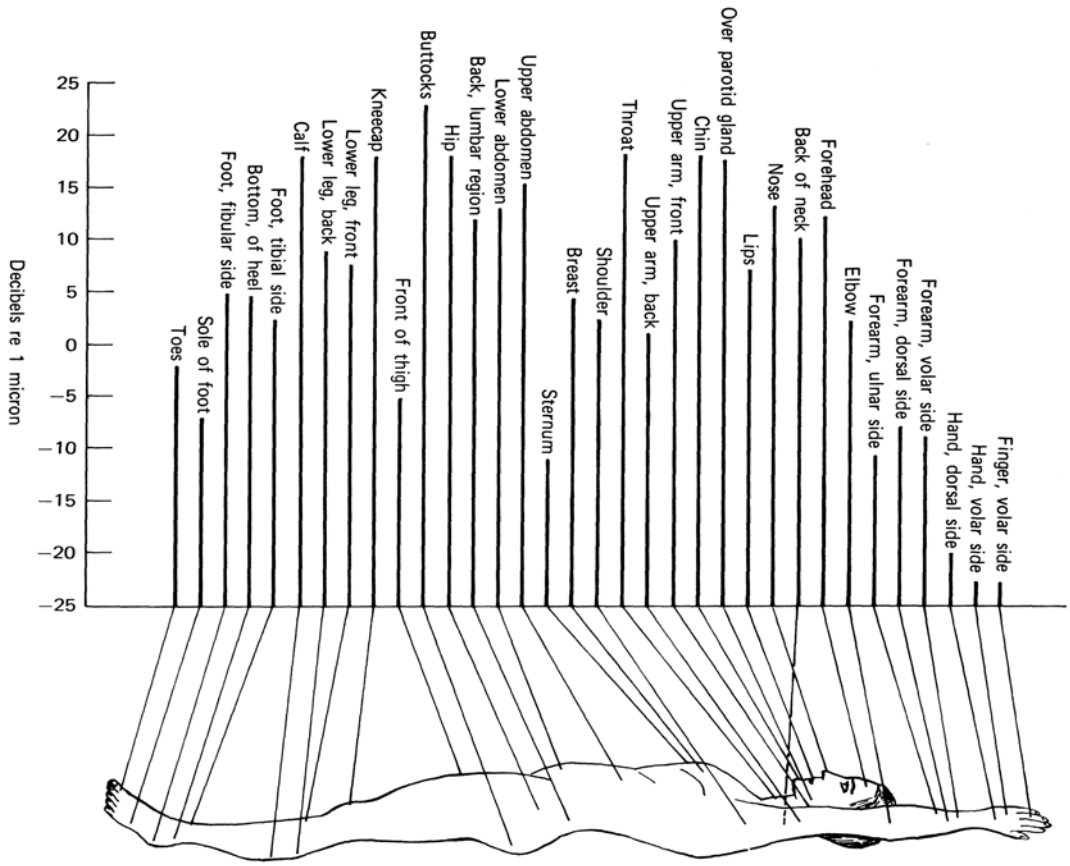


Figure 2.2: Vibratory thresholds on a number of body sites measured by Wilska (1954). Wilska used a 1cm^2 contactor that presented a 200 Hz sinusoidal stimulus. Threshold values are expressed in decibels (dB) referred to 1-µm peak displacement (adapted from data presented in Wilska, 1954).

Thresholds are low on glabrous skin compared to hairy skin, as Pacinian corpuscles are found in higher numbers in glabrous skin, compared to hairy skin (Cholewiak & Collins, 1991).

Sherrick (1953) tested the hypothesis that tissue relatively free of bone should have the same sensitivity curve for vibration as a function of frequency as would tissue overlying bone. Although bony tissue appears to conduct vibration better at nearly all frequencies tested (100-600 cycles per second), sensitivity curves for bony (finger) and boneless (tongue) tissues were quite similar. As early as 1935 Gilmer reported observations, when a contactor was placed over a bone or joint, the location of vibration was difficult to identify.

A fixed surround around the vibrating element of a tactor likewise lowers detection threshold (Summers, 1992). By placing a static surround around the vibrating contactor, travelling waves of energy across the surface of the skin are restricted, however, deeper waves may still continue to spread laterally. Thus, the use of a fixed surround can reduce the number of superficial receptors stimulated (Meissner's corpuscles, Merkel disks), but may not affect the stimulation of receptors lying deeper in the dermis (Ruffini endings, Pacinian corpuscles) (Cholewiak & Collins, 1991).

Skin-surface temperature can also affect threshold: FAII and SAII units show a clear reduction of their sensitivity as well as in the frequency at which they are most sensitive at lower temperatures (15-25°C). The other channels are only slightly affected by changes in temperature (Bolanowski et al., 1988; Cholewiak & Collins, 1991).

The processing of temporal information can be measured by the threshold of successiveness or by the perception of order. In the first case, two stimuli are presented close in time and subjects are asked, if they feel one or two stimuli. If the temporal separation of the two stimuli is greater than 5 ms, subjects are able to tell, that there were two stimuli. At a time interval of more than 20 ms, subjects can determine, which of the stimuli occurred first (perception of order; Sherrick & Cholewiak, 1986). Geffen, Mason, Butterworth, Mclean, and Clark (1996) showed that bimanual simultaneity thresholds (minimum interstimulus interval ISI at which the subjects can perceive that two stimuli have occurred separately) are higher than unimanual thresholds: The time needed to cross hemispheres increases the ISI required for subjects to perceive the two stimuli separately.

2.3 Processing of tactile stimuli and dynamic adaptation of somatosensory cortex to spatio-temporal characteristics of tactile stimulation

Individual nerve fibres innervating mechanoreceptors are bundled to a single nerve trunk, before they enter the spinal cord. A localized band of skin that is innervated by a single nerve root from the spinal cord is called dermatome. Along the abdomen, dermatomes look like a stack of disks, but there is considerable overlap between two adjacent dermatomes (Itomi, Kakigi, Meada, & Hoshiyama, 2000).

After entering the spinal cord, modality specific information is conveyed over the dorsal-column-medial-lemniscal pathway to the dorsal column nuclei, and from there to the thalamic nuclei which projects to primary somatosensory cortex (Hsiao, Johnson & Yoshioka, 2003). In the sensory cortex, there are two main areas where tactile information is represented: Primary and secondary somatosensory cortex (SI, SII). Whereas area SI receives afferents from the contralateral body site, both body halves are represented in area SII (Sherrick &

Cholewiak, 1986; Maeda, Kakigi, Hoshiyama, & Koyama, 1999; Ruben, Schwiemann, Deuchert, Meyer, Krause, Curio, et al., 2001). In SI of monkeys, area 3b and 1 respond to tactile stimuli. Both areas contain separate representations of the body surface (Kaas, 1983; Kaas, Nelson, Sur, Lin, & Merzenich, 1979). Receptive fields of SI neurons are small, they respond to specific spatial features of the stimuli. Neurons in SII have larger receptive fields and show more complex responses (Hsiao et al., 2003). Vibratory stimuli of different frequencies activate spatially distinct cortical domains in SI – both, in area 3b the first processing stage, and in area 1 the next hierarchical processing stage (Friedman, Chen & Roe, 2004). SI as well as SII show phase-locking to low- and high-frequency vibratory stimuli, whereupon the extent of phase-locking was greater for SII neurons. Attention not only affects neurons' firing rates, but also the degree of synchrony of firing. SII neurons are affected stronger by attention than SI neurons (Hsiao et al., 2003). Highly innervated areas of the body (e.g. fingertips, lips) with small receptive fields are represented in lager cortical areas than poorly innervated body sites (like the trunk, whose representational area is small), a principle which is called cortical magnification (Cholewiak & Collins, 1991; Sur, Merzenich, & Kaas, 1980). Receptive fields in the cortex are larger than those in the periphery. Some cortical cells have fields, that are sensitive to specific features (e.g. direction of moving stimuli) of the stimulus. Even illusory sensations, like saltation are represented in corresponding patterns of cortical activity (see Blankenburg et al., 2006).

As stated before, somatosensory topographic maps are not definite representations of the body surface, they adapt dynamically to afferent input. Recent research has shown that changes in the cortical representation of the body surface occur with structural changes of the body (e.g. amputations) or with experience (Cholewiak & Collins, 1991).

Merzenich, Kaas, Wall, Nelson, Sur, and Felleman (1983) found that after cutting the median nerve in monkeys, which provides afferent input from mechanoreceptors from the palm of the hand and the first three digits, the cortical sites formerly activated by input from the median nerve were now activated by stimulation of adjacent skin sites. The pioneer work of Yang, Gallen, Schwartz, Bloom, Ramachandran, and Cobbs (1994) demonstrated that shifts in the organization of somatosensory cortex occur also in humans. They showed that the somatosensory maps of amputees were altered such that representations of other body parts expanded into the cortical area once activated by the amputated body parts (see also Rauschecker`s, 1995 work on compensatory plasticity in visually deprived cats). The cortical reorganisation found in amputees can be reduced by sensory discrimination training, in doing so, phantom limb pain is also decreased (Flor, Denke, Scheafer, & Grüsser, 2001).

Long-term changes in cortical representation, i.e. adaptation to spatiotemporal stimulus characteristics, was found after excessive tactile stimulation as the following examples demonstrate: An enlargement of the cortical representation was found for the reading finger of blind Braille readers (see Noppeney, Waberski, Gobbelé, & Buchner, 1999). Long-term intensive synchronous tactile stimulation of adjacent fingers of owl monkeys resulted in integrated representations of these fingers in SI, whereas asynchronous stimulation (stimuli applied separately to each finger) lead to a segregation of their representations (Wang et al., 1995). When fingers are stimulated in a fixed order, the distance between the cortical representations of these fingers is decreased, compared to random order stimulation. These changes in the cortical map occur within minutes and are rapidly reversible (Braun et al., 2000; Hegner, Wiech, Preissl, & Braun, 2006). Increasing stimulus intensity increases the size of the representational areas in SI, as well as the amount of representational overlap, when two adjacent fingers are stimulated separately (Krause, Kurth, Ruben, Schwiemann, Villringer, Deuchert, et al., 2001).

The dependency on cortical topography of spatio-temporal stimulus characteristics was also researched by Wiemer et al. (1998, 2000). Not only the spatial but also the temporal relatedness of tactile stimuli were found to influence their cortical representation: Stimuli presented close together in time are associated and represented close to each other in somatosensory cortex. Thus, temporal distances between successive stimuli are transformed into representational distances. Synchronously applied stimuli are integrated (compare Wang et al., 1995), i.e. they are represented at a single cortical location, or their representational distance is reduced. When the interstimulus interval (ISI) exceeds 300 ms, stimuli are segregated, i.e. they are represented at several distant cortical locations, or their representational distance is increased. Wiemer explains these findings with wavelike shifts of cortical activation produced by successive stimuli, leading to either shortened or lengthened representational distances dependent on ISI . His model of cortical plasticity is able to explain the spatio-temporal illusion called saltation (see Chapter 3.1), but does require long-term repetitive stimulation.

However, long-term stimulation may not be necessary to induce changes in cortical representation. Stolle (2003) showed that also short-time repetitive stimulation (single-location or saltatory tactile stimuli) resulted in changes of the cortical topography of the stimulation area (forearm): The space of the stimulated area was contracted in perception after being stimulated less than 300 times (whereas in Wiemer's experiment a few thousands stimuli were applied).

In their literature review, Kohn and Whitsel (2002) presented evidence, that already within seconds, sensory stimuli can alter the response properties of neurons in SI, e.g. the degree of phase-locking to different frequencies of sinusoidal vibratory stimuli changed increasingly with ongoing stimulation (>0.5 s after stimulus onset).

That repetitive spatiotemporal stimulation causes representational changes in sensory cortices, which, in turn, are correlated with subjects' behaviour or perception was amongst others demonstrated by Recanzone, Schreiner, and Merzenich (1993). They have shown that changes in subjects' behaviour due to training–in this case monkeys' ability to discriminate different frequencies of tones–parallel changes in the auditory cortex: Monkeys were able to improve their difference limens by 50%, while an increase in the area of representation of the tested frequencies in primary auditory cortex could be observed. Another proof for the perceptual consequences of such plastic processes was found by Godde, Spengler, and Dinse (1996) and Joublin, Spengler, Wacquant, and Dinse (1996) in the tactile sense: After 2-6 hours of pair-wise, simultaneous presentation of tactile stimuli, spatial discrimination performance improved. Applying the same stimuli on a rat's hind paw lead to an enlargement of receptive fields and cortical representational areas. Similar results were found in humans, even when subjects were instructed not to attend the stimulation (Godde, Ehrhardt, & Braun, 2003; Pleger, Dinse, Ragert, Schwenkreis, Malin, & Tegenthoff, 2001). Directly stimulating the cortical representations of the index finger in SI *from outside the brain* using repetitive transcranial magnetic stimulation, lead to the same results: Improvement of tactile discrimination (via unattended stimulation) and enlargement of the index finger representation in SI (Tegenthoff, Ragert, Pleger, Schwenkreis, Förster, Nicolas, et al., 2005). Joublin et al. (1996) conclude that plastic changes "… enable higher [cortical] levels to perform a faster and more elaborate decoding and processing of information" (p. 285).

The relationship between perceptual learning and plasticity in the topographic map was recently demonstrated by Polley, Steinberg, and Merzenich (2006). Rats trained to attend selectively to either frequency or intensity of an auditory stimulus, showed a correlated expansion of the cortical areas–primary auditory cortex and higher auditory fields–that either represented the trained frequency range or the trained intensity range. So, they proved that 1) even in the same neural circuit, cortical maps can display plastic changes that appear to be independent and 2) not only the temporal proximity between a stimulus and reinforcement ("bottom-up" factors), but also by "top-down" factors that modulate the selective processing of stimulus features are important. (see also study of Blake, Strata, Kempter, & Merzenich, 2005: Receptive fields of owl monkey SI double in size after four weeks of training the animals to detect patterns of taps delivered to adjacent fingers.). In humans, Noppeney et al. (1999) showed that spatial attention can affect the representation of digits in SI in such a way that the area of cortical representation shifted medially or laterally towards the locus of attention (see also Braun, Haug, Wiech, & Birbaumer, 2001).

Detection or localization of tactile stimuli is facilitated when subjects direct their eyes to the stimulated body site, even when this site is not visible or when they are allowed to move the body part that had been touched (e.g. Halnan & Wright, 1960; Tipper, Lloyd, Shorland, Dancer, Howard, & McGlone, 1998; Tipper, Phillips, Dancer, Lloyd, Howard, & McGlone, 2001). A possible explanation might be the existence of excitatory links between spatiotopic maps of different sensory modalities (Lloyd, Bolanowski, Howard, & McGlone, 1999).

3 Tactile illusions: Saltation and apparent movement

3.1 Saltation

The saltatory phenomenon was detected in the early 70's in the Princeton Cutaneous Communication Laboratory by Geldard and his colleagues. Three contactors were placed equidistant along the forearm and five 2-ms square-wave mechanical pulses delivered to each contactor. With appropriate timing, the effect felt was that of a series of single taps running from the first contactor to the third–hopping like a little rabbit. Thus, the new phenomenon was called "the rabbit" or saltation (Latin: saltare, translated into English: to jump or leap).

To study the characteristics of saltation Geldard (1975, 1982) introduced the condition known as the "reduced rabbit": A series of three pulses presented by two spatially separated contactors - a first pulse (P1 which is the localizing pulse), to indicate the position of the first locus L1. After an interstimulus interval (ISI) of at least 300 ms (800 ms in most of Geldard's experiments), the second pulse P2 was presented, also at L1, followed by the third pulse P3 at the second locus L2 after an ISI of less than 300 ms. P3 was called the "attractant", because it appeared to attract the stimuli given at L1, causing displacement of P2, whereas P2 was called the "attractee", because it appeared to "jump" towards L2.

To determine the amount of mislocalization of P2 towards L2, subjects were asked to set the ISI between P2 and P3 to the point where the saltatory leap covered a certain distance between L1 and L2. This procedure, known as the psychophysical method of "fractionation", required that the observer set the ISI so that the apparent location of P2 subdivided the apparent distance between L1 and L2 into quarters.

3.1.1 Spatio-temporal characteristics of cutaneous saltation

Temporal limits The saltatory illusion depends on the interstimulus interval (ISI): At large ISIs (>300 ms for the original 5-5-5 series of pulses with three equidistant contactors), every pulse is felt where it was physically presented. When ISI is shortened, the pulses start to spread from under the contactors where they were generated (named point of "exodus"). Over a certain range of ISI the pulses are mislocalized in-between the active contactors. Further shortening of ISI (~ 20 ms) leads to a grouping of taps at the attracting contactors (which are the next contactors in the series), which Geldard called "coincidence".

The relationship between ISI and the amount of mislocalization was assumed to be linear (Geldard, 1982; Geldard & Sherrick, 1986). Individual differences alter the shape and gradient of the "fractionation lines" (relationship between ISI and amount of displacement).

To my knowledge only one study (Cholewiak & Collins, 2000) has ever systematically varied the stimulus duration (SD) to examine the effect of SD and the interaction between SD and ISI (as in studies of apparent motion) on saltatory movement. SD has presumably been considered to be of secondary importance.

Time course/stability of the saltatory phenomenon Based on Wiemer's neural network model Stolle (2003) hypothesized that repetitive spatiotemporal stimuli induce changes in the cortical and consequently the perceptual representation of the body. She used the reduced rabbit and utterly reduced rabbit (without localizing pulse) paradigms as stimulus patterns since variations of the amount of displacement of P1 and P2 in the temporal course of the experiment would result in shifts in the cortical topography. In fact, although subjects received fewer than 300 trials−whereas Wiemer applied thousands of stimuli−the perceived skin area on the forearm that was covered by the two saltatory patterns diminished, which was interpreted as evidence of the dynamic behaviour of somatosensory maps (Stolle, 2003).

Spatial limits With the original 5-5-5 rabbit sequence and ISIs between 50 and 100 ms, saltatory leaps of up to a distance of 150 cm were reported (Geldard, 1975), but these longer distances require special spatial conditions.

Direction of stimulation (distal to proximal or vice versa on the arm or leg) did not appear to be a significant variable in the production of the saltatory phenomenon. In an experiment where the reduced rabbit was either running up or down the arm, no differences in the fractionation data could be found (Geldard, 1975). Cholewiak and Collins (2000) compared two different vibrotactile patterns which were delivered to the back, forearm or finger: One pattern consisted of the successive activation of each of seven tactors on a linear array and the other one of multiple pulses at only three of the seven tactors, thus producing saltation. Direction (proximodistally or distoproximally) of activation had no effect on subjects' judgments of the quality of movement produced by the two stimulus patterns. Mrsic, Hölzl, Kleinböhl, Stolle, and Tan (2004) applied the reduced rabbit paradigm on the abdomen either upwards or downwards along the longitudinal body axis and asked their subjects to indicate the position of the displaced stimulus by pointing to it. The error of localization is influenced amongst others by the position of the limb in relation to the trunk and by anatomical anchor points like the joints such as the wrist or elbow (Cholewiak & Collins, 2003; Stolle, 2003). Mrsic et al. (2004) avoided those effects by using the trunk as test site and arranging the stimuli along the longitudinal body axis (so that the navel couldn't serve as anchor point – see Cholewiak, Brill, & Schwab, 2004). In this case, the amount of mislocalization of P2 did depend on the direction of the stimulus pattern–displacement of P2 was greater for the "downwards" direction, suggesting that the network in primary somatosensory cortex is anisotropic. The different findings reported above might be due to the different measurement methods used in these studies: Fractionation, quality judgments and localization.

Therefore, the question of the influence of direction on the saltatory effect can not be conclusively answered today–more studies involving other directions and different body areas are needed. One of our pilot studies therefore examined if direction of movement around the torso–either produced by saltatory or successively presented stimulus patterns–can be discriminated correctly and reliably. If so, we will drop direction of movement from further consideration.

Saltatory areas The paradigm of the reduced rabbit was used to explore the extent of saltatory jumping, the so-called saltatory area, i.e. the maximal physical distance between L1 and L2 where saltation still occurs.

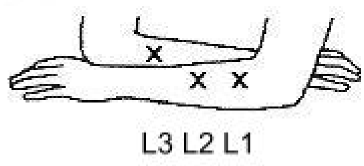
Size and shape of the saltatory area vary with the body site being tested: On the thigh and forearm, the saltatory area has an ovoid shape, the distance between L1 and L2 where saltatory jumping can be observed, is longer in the longitudinal direction than in the transverse direction (Geldard, 1982; Geldard & Sherrick, 1983). The palm and index finger show an almost round shape of the saltatory area. (Geldard & Sherrick, 1983, 1986).

According to Cholewiak (1999) the size of the saltatory area appears to be negatively correlated with its area of cortical representation: The larger the area of somatosensory cortex representing a skin site–and thus the higher the innervation of that site–the smaller the saltatory area (see also Geldard 1985; Geldard & Sherrick, 1983).

Furthermore, experiments on the forehead and thorax showed that the saltatory area is discontinuous at the body midline: When the two stimulators are placed on either side of the body-midline, no saltation occurs (Geldard, 1982). However, saltation can be observed in this condition if an additional stimulator is placed on the body-midline (Geldard, 1975, p. 79). Tan, Lim, and Traylor (2000) also speculate that in this case saltation might occur as the stimulator placed on the body-midline might “bridge the neurological gap” (p. 1111).

Experimental evidence that saltation is still vivid when the attractee and the attractant are placed on different body-halves is reported by Eimer, Forster, and Vibell (2005). They presented tactile stimuli to both arms when both arms were positioned in parallel and perpendicular to the body axis. Figure 3.1 demonstrates the stimulus locations in Eimer’s experiments.

(A)



(B)

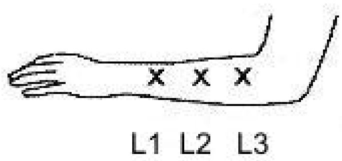


Figure 3.1: Stimulus locations (L1, L2, L3) on the arms in the experiments of Eimer et al. (2005). Stimuli were metal rods that touched the skin for 6 ms. The figure above (A) shows the both-arms condition where L1 and L2 were located on one arm, L3 on the other. The figure below (B) shows the single-arm condition where all stimuli were presented to the same arm. On saltatory trials the first and second stimulus were presented at L1 and the third stimulus on L3. On tap trials L1, L2, and L3 were successively activated. Two different control trials were used: On static control trials either L1 or L3 were stimulated three times, on motion control trials L1 was stimulated once and L3 was stimulated twice. Direction of stimulation was either from L1 to L3 or vice versa. Subjects had to report if they felt a stimulus on L2 in each type of trial.

From: Eimer M, Forster B & Vibell J, 2005, p. 460.

Stimulus locations L1, L2, L3 were either activated sequentially (one stimulus per location, referred to as tap trial) or two stimuli were presented at L1 and one stimulus at L3 (referred to as rabbit trial). Stimuli were delivered in both directions (L1→L3 or L3→L1). In "static control trials" either L1 or L3 were successively stimulated three times. In "motion control trials" one stimulus was delivered to L1 and two stimuli to L3 (or vice versa). The latter type of control trial was introduced to eliminate a response bias due to stationary (static control trial) versus moving (moving control trial) stimulus patterns. ISI was set to 100 or 300 ms, SD to 6 ms.

Subjects were instructed to focus on the middle location (L2) and report whether or not they had felt a stimulus at that location in the different types of trials. For trials starting at L1 illusory stimuli at L2 were reported more often on rabbit trials than on motion control trials. But when the rabbit trials started at L3 a mislocalized stimulus could not be perceived more frequently on the other arm compared to control trials.

Eimer et al. (2005) concluded that although the rabbit failed to jump across arms, a stimulus presented on one body-half can be attracted by a subsequent stimulus presented on the other body-half and thus produce the illusion of saltation. According to Eimer et al. (2005) this result suggests that saltation should be generated in higher order somatosensory areas, because in primary somatosensory cortex, SI, only the contralateral body-half is represented and only few connections to the opposite hemisphere exist. Indeed, Maldjian, Gottschalk, Patel, Pincus, Detre, and Alsop (1999) have shown that besides SI, SII seems to be the region processing some tactile patterns.

The size of the saltatory area depends also on the number of stimuli delivered to L1 in the reduced rabbit paradigm: When the single P2 pulse was replaced by several pulses, the extent of the saltatory area increased. The distance of saltatory jumping was found to be a parabolic function of the number of P2 pulses (Geldard, 1982).

Although Geldard and Sherrick (1986) argue that P1 and P3 are localized "within the normal error radius" (p. 91) there are indices, that P3 can also be mislocalized: When they created an experimental setting where the rabbit hopped in both directions at the same time (Geldard & Sherrick, 1972), there was the impression "that the taps extend beyond the terminal contactor" (p. 178). Thus when more than two stimulus sites are involved there seems to be an "overshoot" of saltatory jumping. In our experiments we will test whether length of saltatory movement varies dependent on spatio-temporal stimulus characteristics.

Cholewiak (1999) reanalyzed the data of various experiments involving spatio-temporal illusions like saltation to investigate spatio-temporal interactions. He showed that the smaller the time difference between P2 and P3, the smaller the extent of the sensation, i.e. the more the two stimulus locations L1 and L2 attract each other, so that one can assume, the attraction also involves P3.

Trojan, Kleinböhl, Stolle, Andersen, Hölzl, and Arendt-Nielsen (2006; using thermal stimuli) showed that the perceived length of a saltatory stimulus pattern (reduced rabbit paradigm) varies with the test site on the forearm: Length decreased from distal to proximal sites, which was explained by differences in the cortical magnification factor.

The experiments of Kilgard and Merzenich (1995; see paragraph "Attention") also indicate that, dependent on the subjects' focus of attention, the perceived location of P3 may vary.

Number of pulses Up to about 16 pulses per contactor can be delivered to produce saltation. But with increasing number of contactors, ISI must decrease to obtain evenly distributed taps (Geldard, 1982).

Waveform/frequency For his first experiments Geldard (1982) used square wave pulses that produce sharp and bright taps. However, the saltatory phenomenon also emerged when rounded waves were used–and thus the hypothesis that saltation only occurs when square wave pulses are used while phi movement is only produced by sine waves could be disproved.

To examine the effect of stimulus frequency, Cholewiak (reported by Geldard, 1982) used haversine waves for P3 of six different frequencies: 30, 60, 120, 250, 500, and 1000 Hz. The frequencies of P1 and P2 were kept constant at 500 Hz. Although the perception of low-frequency stimuli differs from high-frequency stimuli–low-frequent stimuli appear to be dull whereas high-frequent stimuli produce bright, sharp taps–saltatory leaping occurred with all frequencies as Figure 3.2 shows. Although it seems that low-frequency stimuli produce "fractionation lines" that are steeper than those of high-frequency stimuli. That means that low-frequency stimuli seem to need higher ISIs to produce evenly distributed saltatory jumps than high-frequency stimuli. Unfortunately Geldard doesn't provide any information about the statistical significance of the interaction between stimulus frequency and ISI, and didn't vary the stimulus frequencies for all three stimuli.

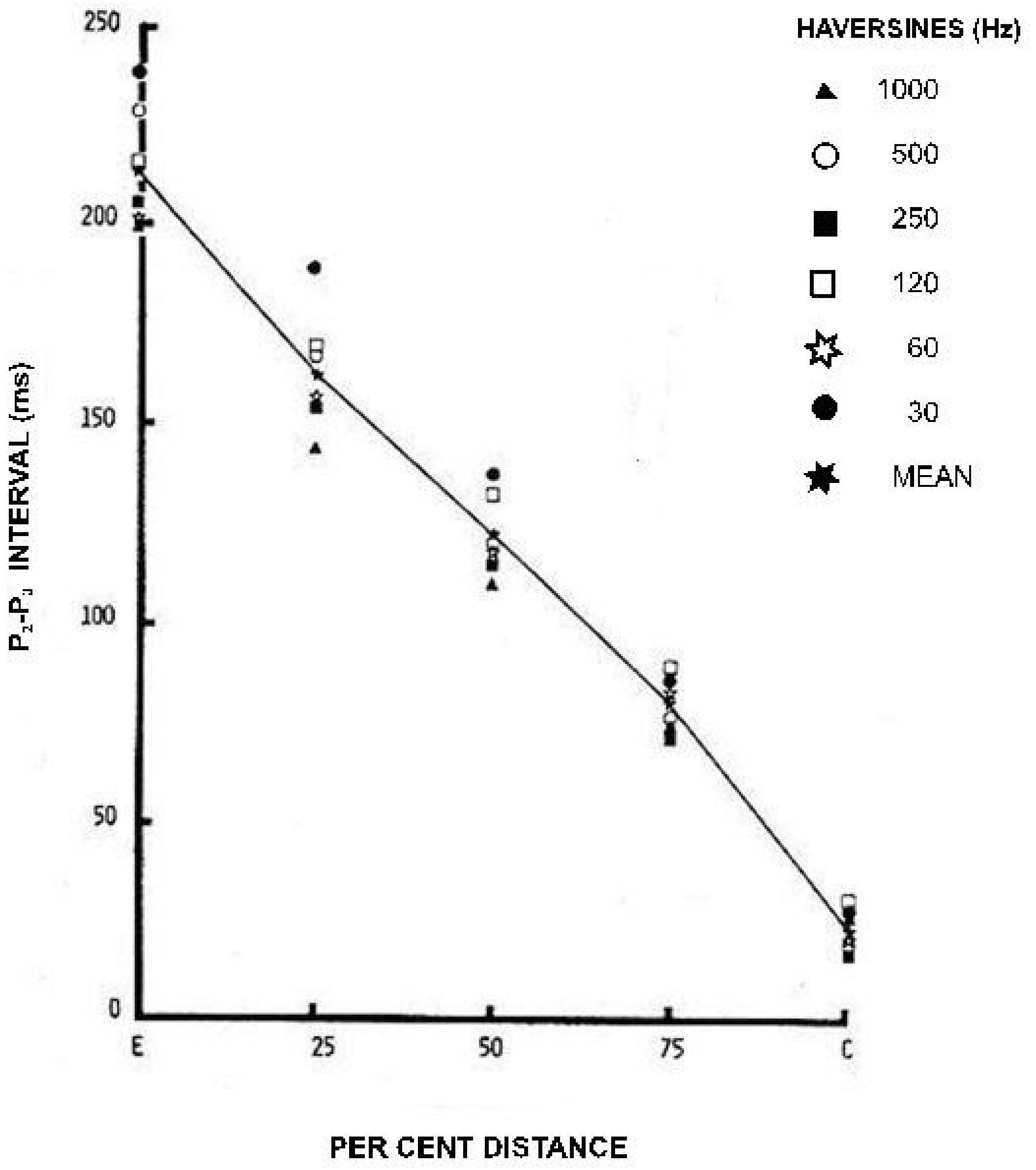


Figure 3.2: Fractionation data for the “reduced rabbit” (series of three pulses P1, P2, P3 presented on two spatially separated locations L1 and L2) with variation of the stimulus frequency of P3. For P1 and P2 stimulus frequency was 500 Hz, for P3 stimulus frequency ranged between 30 and 1000 Hz. There were 12 observations per point. Subjects had to set the ISI between P2 and P3 to the point where the amount of mislocalization between L1 and L2 reached a certain extent: Either “exodus”, 25%, 50%, 75% of the distance between L1 and L2, or coincidence. The different symbols mark the average ISIs per frequency where the saltatory leaps reach the specific distance between L1 and L2.
From: Geldard FA, 1982, p. 147

One question about saltation left unanswered is how varying stimulus frequency at all stimulus sites alters the perception of saltation. We will address this question in our experiments.

Attention Attention influences the perception of the mislocalized stimulus, but the extent to which saltation is biased by attention is not completely clear.

To study attentional contributions, Kilgard and Merzenich (1995) added a fourth stimulus to the reduced rabbit paradigm: A second localizing stimulus that was separated in time from the two saltation stimuli (P2 and P3). They found that P2 and P3 attracted each other, i.e. the perceived distance between the two stimuli decreased with decreasing ISI. As subjects were instructed to concentrate either on the proximal or distal region of the forearm, where the stimuli were applied, the perceived locations of P2 and P3 shifted towards the attended direction although the perceived distance between P2 and P3 remained unaltered. Kilgard and Merzenich (1995) conclude that the perceived distance between P2 and P3 depends on ISI whereas the perceived location of P2 and P3 is determined by attention.

However, Eimer et al. (2005) state that "saltation cannot be explained solely in terms of attentional bias" (p. 462). In their experiment–already described before (see also Figure 3.1)– they delivered tactile stimuli to three locations on either one or two arms and asked subjects to attend only to the middle location (L2).

If attention would have exerted a comparable spatial bias on rabbit and (static and motion) control trials, then similar response patterns should have been evoked. But, in fact, the perceptual reports differed considerably: In rabbit trials an illusory stimulus was reported significantly more often at L2 than in both types of control trials.

The difference between the two studies is that Kilgard and Merzenich (1995) focus on the effect of attention on the localization of the displaced stimuli, whereas Eimer et al. (2005) measure only the presence or absence of a mislocalized stimulus at a certain distance between L1 and L3. In Eimer's experiments attention might have had a different influence on saltation and the control stimulus patterns. Because they did not vary the attended region it remains unclear if the location of illusory stimuli in saltation and control patterns would have shifted in the same way towards the attended region.

Additional issues that have been studied in saltation, such as variation of stimulus intensity or mode of stimulation (electrocutaneous or thermal stimulation), are not discussed here, because they were not experimental variables in the following experiments.

3.1.2 Explanatory approaches for the saltatory phenomenon

There are a number of arguments for the hypothesis that central mechanisms are responsible for the saltatory effect. These can be listed as follows:

1. Experimental evidence was found that wave propagation in the skin or peripheral mechanisms (receptive fields, peripheral nerve branches) could not explain the saltatory effect (see Geldard, 1982).
2. When the area between L1 and L2 was anesthetized, a mislocalized stimulus could still be perceived in that area (Geldard, 1982; Geldard & Sherrick, 1986). This is a strong argument against a peripheral origin of the saltatory phenomenon.
3. Saltation also occurs in vision and audition (see Chapter 3.3).

According to Wiemer's (1998) neural network model, the topography of somatosensory maps adapt dynamically to the time course of stimulation (see also Chapter 1). He argues that temporal distances between successive stimuli are transformed into spatial distances in somatosensory cortex. These temporal distances may be used to alter cortical representations due to shifts of cortical activation: An incoming stimulus produces a wave-like activation in primary sensory cortex. A second stimulus generates a forward activation, that causes a shift in activation towards the prevailing wave front when the ISI between the two activated stimuli is small (<300 ms). In this case both stimuli are integrated, i.e. the spatial distance between cortical activities caused by the two stimuli decreases. This might in turn influence the perception of the location of P2: For short ISIs (<300 ms), integration of P2 and P3 takes place, the distance between P2 and P3 thus decreases.

Whereas Wiemer based his assumptions on experiments where a few thousand stimulus repetitions were applied to cause changes in the cortical representation of spatio-temporal stimuli, Stolle (2003) showed that a few hundred stimulus replications are sufficient. The perceived extent of the stimulated skin area on the forearm decreased over these repetitions. Stolle reasoned that these perceptual changes point to alterations in the cortical representation of the stimulated area in somatosensory cortex.

Blankenburg et al. (2006) used functional magnetic resonance imaging (fMRI) to test whether activities in somatosensory cortex (presumably area 1 of SI) represent the physical location of saltatory stimuli (multiple stimuli at each of three locations) or the perceived (illusory) location. He found that activation in contralateral SI was somatotopically corresponding to the illusory stimulus location and even the level of activation didn't differ from veridical stimulation.

3.1.3 Saltation in other senses

Systematic mislocalizations of stimuli dependent on ISI also take place in vision and audition.

Audition In one of the first experiments addressing auditory saltation Sherrick (cited in Geldard, 1975) required subjects to discriminate between sequentially presented clicks along an array of seven equally spaced loudspeakers on an arc that span 45 degree to the left to 45 degree to the right front side of the body with either one click to each or multiple clicks to some of the seven loudspeakers. The larger the number of clicks on one loudspeaker the more correct discriminations were obtained.

Bremer, Pittenger, Warren and Jenkins (1977) used the original rabbit paradigm–multiple pulses at three locations–and judgments of equal spatial distribution of the displaced stimuli to demonstrate the dependence of the saltatory phenomenon on ISI in the auditory sense. Fractionation data display a linear relationship between ISI and the amount of mislocalization, like in touch (Geldard, 1975, 1982).

When stimuli are delivered via headphones, they need to be presented binaurally with sub-millisecond interaural time difference (ITD; Shore, Hall & Klein, 1998) or with an interaural level difference (ILD; Phillips & Hall, 2001) to produce the saltatory illusion. (Note: Dichotic clicks, separated by short ITDs are perceived as being lateralized to the side of the first click. Shore et al. (1998) presented eight dichotic clicks, the first four having an ITD to favour the right ear and the last four having an ITD to favour the left ear and vice versa. When dichotic clicks are presented with a certain ILD, i.e. with different loudness, the click is localized towards the ear where the louder click is presented). For dichotic stimuli, saltation is vivid in the ISI range of 30-150 ms (Phillips & Hall 2001; Phillips, Hall, Boehnke, & Rutherford, 2002; Shore et al., 1998). A quite similar time interval (50-150 ms) was reported by Bremer et al. (1977) who used speakers arranged on a horizontal array (the middle speaker in the sagittal plane of the subject, the outer speakers 24° to either side of the sagittal plane) to present the clicks or by Hari (1995) who demonstrated saltation with binaural clicks (half left-ear, half right-ear leading) at ISIs between 30 and 120 ms. This time interval is much smaller than the corresponding interval in touch (20-300 ms) and vision (0-300 ms). It should be noted though, that Geldard (1975) reports a much larger range of ISI where saltation was observed: ~50-420 ms. The difference might derive from the fact that Sherrick (in Geldard, 1975) presented the auditory stimuli on the left body-halve only whereas in the other experiments trains of clicks were presented either on a horizontal array that span the body-midline (Bremer et al. 1977) or binaurally with certain ITDs or ILDs which resulted in clicks, moving from one body-side to the other (Phillips & Hall 2001; Shore et al. 1998; note that Sherrick also used a speaker array that extended across the front of the body, but in this experimental setting, the ISIs he used for creating saltation only ranged between 25 and 80 ms). Another difference between Sherrick's experiments and those performed by others is the response paradigm: While Sherrick used the method of fractionation other experimenters (Bremer et al., 1977; Phillips & Hall 2001; Shore et al., 1998) used ratings of evenness or continuity of motion produced by the displaced stimuli to verify the saltatory effect. Yet, it is noteworthy, that auditory saltation travels across the body-midline (however at lower ISIs), in touch and in vision, it does not. Phillips and Hall (2001) try to explain this finding with the existence of large populations of neurons in the forebrain auditory system that have spatial receptive fields that span the left and right sensory hemifields and thus span the complete area between the motion endpoints. But as long as the level of processing which is responsible for producing auditory saltation is not investigated further (e.g. saltatory areas have not been determined yet in the auditory sense) this explanation remains theoretical.

Another psychophysical measure of saltation that we modified slightly to use in one of our experiments, was introduced by Kidd and Hogben (2004): They elicited the saltatory illusion by trains of dichotic clicks with an ITD of 0.8 ms–four clicks favouring the left ear and four clicks favouring the right ear (but note that the temporal intervals are much shorter than those used in other studies of saltation). Subjects had to compare these saltatory stimuli against "real" motion stimuli that were generated by dichotic clicks with linear varying ITDs (-0.8 to 0.8 ms) and had to decide in a paired-comparison paradigm whether they perceived saltatory or "real" movement. Discrimination performance was found to depend on ISI, with the highest percentage of correct discriminations reached at the highest ISI (120 ms). Other studies, using quality ratings of motion confirmed that when ISI is small–less than 50 ms–the quality ratings for saltatory and continuous motion are nearly similar (Boehnke & Philips, 2005; Philips et al., 2002).

As in touch, the number of stimuli delivered to one location has an effect on the perception of saltation: The more stimuli (2-5 clicks produced by speakers) were delivered to each location, the less uniform was the distribution of clicks (Bremer et al., 1977). In addition, with increasing number of stimuli per location, the ISI needed to create the saltatory illusion decreases: Shore et al. (1998) report an ISI of about 105 ms as the largest number that can evoke saltation with 8-click trains, Phillips et al. (2002) report an ISI of about 120 ms for 6-click trains.

Direction of stimulation doesn't seem to be crucial for generating the saltatory illusion in audition: Saltation occurred in the horizontal plane (e.g. Phillips et al., 2002) as well as in the vertical midsagittal plane (Boehnke & Phillips, 2005). The range of ISI that was required to produce saltation was about the same for stimuli that moved up or down the vertical midsagittal plane or the horizontal plane. The fact that illusory saltatory motion can be produced in the vertical and azimuthal plane is important, because localization in the two cases is based on different processes: Stimuli in the azimuthal plane can be localized by differences in interaural time or interaural level differences. Stimuli in the midsagittal plane cannot be localized using those stimulus cues, a much more complicated process of analysing differences in the spectral content of the stimuli is involved here (see Boehnke & Phillips, 2005).

Summarizing these results, it seems that auditory saltation needs a spatial representation of stimuli either generated by binaural stimulus information (based on interaural time or interaural level differences) or monaural spatial information (Boehnke & Phillips, 2005; Phillips & Hall, 2001; Phillips et al., 2002).

But new research has shown that saltation even occurs in pitch perception, a non-spatial dimension, and follows the same regularities: The saltatory illusion was stronger for stimuli presented closely in time (short ISIs) and at small spectral distances, i.e. more similar frequencies, which can be seen as an analogue to smaller spatial distances (Getzmann, 2007).

The mechanisms underlying auditory saltation are still not completely clear. Both, low-level and central-level explanations, as well as cognitive approaches (perceptual grouping) have been discussed (e.g. Boehnke & Phillips, 2005; Getzmann, 2007; Phillips et al., 2002).

Vision Unfortunately there are very few publications about visual saltation (e.g. Brassel, 1993; Geldard, 1975, 1976; Lockhead, Johnson, & Gold, 1980). In early experiments LEDs (light-emitting diodes) that were arranged horizontally and emitted brief flashes of light were used as visual stimuli.

A precondition for the saltatory phenomenon in vision is that the visual stimuli do not fall at or near the fovea (Geldard, 1975, 1976). Only when they fall on the peripheral retina, saltation can be observed, presumably because of the high spatial resolution of the fovea.

The relationship between ISI and amount of mislocalization proved to be curvilinear. The gradient of the fractionation lines varies with the degree of eccentricity of fixation: The further away from the fovea the light spots are projected, the larger the range of ISI where saltation occurs. At ISIs close to 300 ms, when stimuli fall 40° from the fovea, stimuli are perceived at their veridical position–the same temporal limit for saltation as in touch (Geldard, 1976). SDs up to 100 ms were feasible to create the saltatory illusion.

Separation of stimuli is also an important variable: Saltatory leaping was observed for visual angles up to 25°. In this case, stimuli were horizontally disposed slits, arranged one upon the other. When size of jump and distance in-between stimuli were expressed in terms of visual angle, a bell-shaped curve described the relationship between those two variables (Geldard, 1976).

Limited saltatory areas could also be found in vision: Saltation did not cross the body midline, like in touch (Geldard, 1975, 1976): When both stimuli were presented on the vertical axis, one on one side of the body, the other one on the other side, saltatory leaping across the midline of the visual field could not be observed.

When the two visual stimuli (light spots) span the blind spot of the eye, a displaced stimuli can still be perceived in-between them (Geldard & Sherrick, 1986; Lockhead et al., 1980). This was analogous to the experiments in which saltatory leaps could be observed in an anesthetized skin area. Because these experiments provide evidence that receptors are not required at the site at which the illusory stimulus is perceived, a peripheral origin of the saltatory phenomenon can be excluded.

Another proof for the central seat of the saltatory phenomenon was seen in the fact that saltation could be observed when P2 fell on one retina and P3 on the corresponding field of the other (Geldard & Sherrick, 1983).

Brassel (1993) showed that the range of ISI in which visual saltation occurs is significantly higher for chronic male schizophrenics (350-500 ms) compared to mixed psychiatric patients (150-320 ms) and a normal control group (60-320 ms). Also, repetitive stimulation (rapid flickering) at L2 lead to an increase of ISI where saltation was perceived in the normal control group whereas in the mixed psychiatric group 46% and in the schizophrenics group 63% didn't to show a corresponding change. This difference was significantly related to memory impairments in the two psychiatric groups. Theses results not only support the assumption that central mechanisms are responsible for the saltatory phenomenon, but also recommend the use of saltation as a model to diagnose psychiatric disorders and study neuronal timing in humans.

A specific characteristic of saltation in vision is what Geldard (1976) calls the "dip": When saltatory stimulus patterns were observed over a longer period of time (10 minutes), after about a minute of repetitive exposure, the amount of displacement of P2 suddenly declined and afterwards increased again to approximately the initial level. To this day, the "dip" lacks an explanation and has not been found in cutaneous or auditory saltation. Experiments have been conducted to test the hypothesis that light or dark adaptation processes might account for the "dip", but without a definite outcome.

3.2 Apparent movement

Apparent movement is an illusion that can be found in the visual, auditory, and tactile sensory system. The illusion of continuous movement when two or more stimuli separated in space are activated sequentially was first described in vision and is known as the "phi phenomenon". At appropriate spatial and temporal intervals sequentially presented stimuli seem to merge to a continuous, uninterrupted sensation of apparent motion (e.g. Burtt, 1917b; Kirman, 1974a, 1974b; Sherrick & Rogers, 1966).

3.2.1 Spatio-temporal characteristics of tactile apparent movement

One of the first studies on apparent tactual movement was carried out by Benussi (1916; see Burtt, 1917b), who varied spatio-temporal stimulus parameters to obtain "pure" movement. But in contrast to the visual system, in the tactual system, early studies, using point stimuli, failed to produce continuous movement, only partial movement could be observed (see summary in Sherrick, 1968a). Later studies that used vibrotactile stimuli were successful in producing good haptic movement. The different stimuli–point stimuli versus vibrotactile stimuli–excite different mechanoreceptors which display different capabilities of spatial resolution: Whereas especially PC receptors respond to vibration, but do not provide useful spatial information, RA and SAI receptors are excited by dynamic skin deformation respectively sustained indentation and display a sharp isomorphic representation of tactile patterns (Johansson, 1978; Hsiao et al., 2003). It is likely that mechanoreceptors, activated by point stimuli, prevent single stimuli from melting together to a percept of uninterrupted movement, because of their ability to resolve fine spatial detail. In addition, vibration produces travelling waves deep in the dermis and epidermis, where PCs are located, that may activate distant receptors, and thus enable punctate stimuli to merge.

Temporal limits Sherrick (1966, 1968) found a linear relationship between stimulus duration (SD) and interstimulus onset interval[1] (ISOI, which is the time between the onset of the first and the onset of the second stimulus) when he asked subjects to adjust ISOI to a value where continuous, uninterrupted movement between two vibrating stimuli was perceived–at least for stimulus durations greater than 25 ms. For longer SDs (>100 ms) more temporal overlap in the activation of successive stimulators is required.[2]

Other studies with two stimulators–using a different response paradigm (categorization of movement from "movement was impressive and continuous" to "no movement at all"; Kirman, 1974a, 1974b)–showed that as ISOI was increased, movement judgments increased to a maximum value and then decreased (except for very short SDs <10 ms). However, this interaction between the number of stimuli and ISOI disappeared, when more than two stimuli were used (Kirman, 1974a).

When SD was increased, better movement judgments were obtained, the ISOI value for optimal apparent movement shifted to higher values (Kirman, 1974a, 1974b, 1975), and the ISOI range where uninterrupted movement was perceived became wider (Kirman, 1983; Szaniszlo et al., 1998). Thus, a significant interaction between SD and ISOI was found by Kirman (1974a, 1975). The impact of SD is stronger for two-stimulus patterns than for multiple-stimulus patterns (Szaniszlo et al., 1998). Sherrick and Rogers (1966) generated percepts of continuous movement with SDs up to 400 ms, but, according to Kirman (1974b) the impression of apparent movement reaches its maximum degree at SDs < 200 ms, which is the highest SD value used in most experiments.

[1] In contrast to saltation experiments, most researchers used ISOI instead of ISI as a temporal variable in studies on apparent movement, as temporal overlap was thought to affect apparent motion.
[2] ISOI (interval between stimulus onsets) is the addition of SD (stimulus duration) and ISI (interval between the end of the first and start of the second interval); if ISI instead of ISOI would be plotted against SD, a negative relationship would emerge: As SD increases, ISI that produces optimal apparent movement decreases.

Optimal ISOI values vary in the experiments reported above. These variations are presumably due to differences in the tactile stimuli used: Different contactor sizes, square wave or sinusoidal pulses and different test sites–although the latter variable only exerts a minor influence due to Sherrick (1968).

When only two vibrating probes were activated, percepts of good apparent motion decrease when the velocity of movement was increased (Szaniszlo et al., 1998). But when additional stimuli were applied–and thus the total path length was increased–velocity of movement didn't affect the quality of motion.

The velocity of movement also exerts an influence on the perception of straightness and length of a line that was produced by a moving stylus on the forearm (Langford, Hall & Monty, 1973): When the rate of movement was decreased, deviation from a straight line increased, i.e. the line felt more curvy and bent; in addition, reported length of the line decreased, as rate of movement increased. Langford et al. (1973) tried to explain this finding with inhibitory processes: Stimuli with a rapid onset might inhibit laterally spreading stimulation and thus feel more centralized, that is straighter and shorter.

Test site/direction The optimal ISOI for "best" apparent movement varied only marginally with the body site being tested: Thigh, forearm, back, stomach, fingertip or palm of the hand (Sherrick, 1968a).

Direction of apparent movement didn't have an effect on the quality or temporal parameters for good apparent movement (Sherrick, 1968a). There appears to be only one study, that examined, if tactile apparent movement crosses the body-midline without being degraded: Sherrick (1968b) found that movement qualitatively declined, when stimuli were presented bilaterally (on both forearms), but the relation between SD and ISOI remained constant, compared to unilateral stimulation. Sparks (1979) notes that when apparent movement crossed the abdominal midline, directional sensitivity decreased. However, he didn't vary systematically the positioning of the electrotactile array, this result was detected rather accidentally, when he varied inter-stimulus spacing.

Number of stimuli/distance between stimuli Percepts of motion can be generated with only two stimulators. When Sherrick (1968a) varied the distance in-between two vibrating stimuli from 12 to 40 cm, the ISOI value for continuous movement didn't change, although, the movement was faint in the middle of the trajectory when the distance increased. Szaniszlo et al. (1998) using vibrating probes on the face, spaced 0.4-2.5 cm apart found the same result:

The distance in-between two successively activated stimuli does not affect goodness of motion or the range of ISOI where good motion was obtained. In contrast, Burtt (1917b), using two point stimuli, found that the longer the temporal interval between stimuli, the greater the distance in-between stimuli must be to get the impression of uninterrupted movement. Maybe the type of stimuli used in these experiments, point stimuli (Burtt, 1917b) versus vibrating stimuli (Sherrick, 1968a; Szaniszlo et al., 1998) accounts for the different findings.

Increasing the number of stimuli resulted in better movement judgments (Kirman, 1974a, 1975). In addition, an interaction between the number of stimuli and ISOI was found: When more stimuli were used, then ISOI has to be decreased to obtain continuous movement (Kirman, 1975, 1983). Szaniszlo found the same result, but only when he kept the total path length constant and varied only the number of stimuli. When he varied the path length by applying more stimuli, the range of ISOI values where good movement was perceived remained unaltered. In this case, the amount of temporal overlap between multiple successively activated stimuli proved to be more crucial than when only two stimuli were activated, especially for longer SDs (>50 ms). Another contradictory result was reported by Sherrick (1968): Adding stimuli increases the range of ISOI where good apparent movement can be obtained. SD however did not interact with the number of stimuli, except for very short stimulus durations (< 35 ms; Szaniszlo et al., 1998; see also Kirman, 1975).

In these studies, the distance in-between stimuli was confounded with the number of stimuli: It was therefore not possible to determine if the increasing number of stimuli or the simultaneous decrease of the interstimulator spacing accounted for the better movement judgments. But Kirman (1975) assumes that, as earlier studies (Sherrick & Rogers, 1966) didn't show an effect of interstimulator spacing on the optimal ISOI value for apparent movement, it is more likely that the number of stimuli is responsible for the enhancement of movement judgments.

Stimulus frequency In Sherrick's experiment (Sherrick, 1968a), subjects had to adjust the ISOI to produce "best" (meaning the longest uninterrupted) tactual movement between two vibrotactile stimuli that were delivered to the distal thigh with a stimulus duration of 200 ms. Variation of stimulus frequency (60, 150, and 250 Hz) had no effect on the quality of movement or the optimal ISOI value for obtaining "best" movement.

Direction discrimination Direction discrimination (that is the capability to differentiate between opposing directions of stimuli moving across the skin) is known to be influenced by the type of stimulus used in an experiment: Stimuli may vary in the amount they stretch and translate the skin. They either move naturally or movement is simulated by presenting stimuli successively (Essick, 1998). We will now concentrate on the latter type of stimuli, as this type will be used in our experiments.

Subjects' ability to discriminate the direction of a moving tactile stimulus depends primarily on the number of pulses, not on the spatial or temporal dimensions–interstimulus spacing, path length or interstimulus interval–of the stimulus pattern (Gardner & Sklar, 1994). Discrimination accuracy increases with increasing number of pulses delivered by an OPTACON[3] stimulator and reaches near-perfect performance, when eight or more stimuli are sequentially activated. When only two pulses are presented, discrimination performance is random, irrespective of interstimulus spacing (1.2 – 4.8 mm in Gardner's experiments; note that 4.8 mm exceeds any threshold measure for tactile spatial acuity; ISOI was 20 ms). Consequently, it does not seem to matter whether overlapping or distinct groups of cutaneous afferents are excited. Rather, the number of activated mechanoreceptors and thus the amount of information transferred is critical (Essick, 1998). Gardner and Sklar (1994) conclude that "direction discrimination is not simply a matter of point localization on the skin, but rather appears to involve the integration of a spatiotemporal sequence, in which additional inputs improve the accuracy of performance" (p. 2426).

According to Essick (1998), the width of a stimulus affects direction discrimination: Discriminability was poorer for stimuli that are wider in the direction of motion. Additionally, for wider stimuli, faster velocities are needed to reach the same discrimination performance, as for narrower stimuli. The width of a stimulus *perpendicular* to the direction of motion is also crucial for direction discrimination. Sparks (1979) showed that when the electrocutaneous stimuli he was testing consisted of rows of four electrodes, one above the other, discrimination performance was better than when stimuli consisted of a single electrode.

ISOI has only a minor effect on direction discrimination (direction discrimination for an ISOI of 20 ms is somewhat better than discrimination for an ISOI of 40 ms or 10 ms). Velocity or duration of movement didn't affect discriminability. But, in Gardner's and Sklar's

[3] The OPTACON is a tactile array that serves as sensory substitution aid for blind and deaf people. It consists of 144 vibrating probes, arranged in a matrix of 6 columns and 24 rows (size of the array: 11 x 26 mm). Text or speech can be translated into vibrating patterns that are presented to the finger.

experiment (1994) path length, stimulus timing and spacing were varied simultaneously. When the number of stimuli and interstimulus spacing are held constant, and only ISOI is varied, duration of movement influences direction discrimination in such a way that percent correct discriminations increased with increasing duration of movement (increasing ISOI) (Sparks, 1979). Essick (1998) found an inverted U-shaped function between directional sensitivity and stimulus velocity. When investigating the threshold length for direction discrimination with a dense-array stimulator (built from two OPTACON arrays) Essick (1998) found that "direction was discriminated, when the product of the length of skin traversed and the duration of stimulation attained a criterion" (p. 45). The different results reported above might be due to the different experimental settings (number of pulses delivered to each contactor, test site, experimental variables to be varied, e.g. varying only ISOI or also the distance in-between contactors).

The site of skin tested is also crucial for direction discrimination: There is a strong positive correlation between innervation density and discriminability on the forearm (Gardner & Sklar, 1994). On less-well innervated test sites like the abdomen more stimulators (and thus more activated receptor units) are required for better direction discrimination (see also Sparks, 1979). These findings suggest that there is a topographical pattern of variations in directional sensitivity – as it is for vibratory thresholds (see Figure 2.2) or error of localization – that is correlated to innervation density and cortical representation of skin areas (see e.g. Essick & Whitsel's, 1985 results for natural moving stimuli).

Directional sensitivity is independent of the orientation of motion. Sparks (1979) used a tactile display that consisted of rows of several electrodes that were placed on the skin in an either horizontal or vertical direction. Discrimination performance was found to be nearly identical for both orientations. Note that electrocutaneous stimuli may activate all neurons in range of the contactor, whereas mechanical stimuli used in other studies excite predominantly specific populations of mechanoreceptors, depending on stimulus features like type of stimuli or stimulus frequency. In particular the use of bipolar current–like in Spark's study–produces sensations difficult to localize, as cathodic (negative) current excites axons parallel to the skin surface and thus suggests to the brain that the mechanoreceptor at the end of the axon has been stimulated. Thus the veridical point of electrocutaneous stimulation may differ from the locus of sensation (Kajimoto, Kawakami, Maeda, & Tachi, 2001), which is usually not true for mechanical stimulation.

3.2.2 Explanatory approaches for tactile apparent movement

Responses of cutaneous mechanoreceptors to tactile apparent motion When movement is simulated by successive activation of stimuli (bar patterns produced by OPTACON) on glabrous primate skin, rapidly adapting afferents (RA) and Pacinian corpuscles are excited, but slowly adapting afferents are not. About 25% of RAs show responses that are observed in only one specific direction of motion. PCs encode the direction of motion mainly by changing their receptive field size. Receptive field boundaries of RAs and most PCs shift in the direction of motion, indicating facilitation of receptor potentials between adjacent receptive fields. Essick (1998) suggests that information about the direction of a moving stimulus is largely transferred by the number and sequence of sequentially activated stimuli, as other aspects like variations in discharge intensities and patterns due to changes in direction only play a negligible role[4].

Total spike output of RAs and PCs doesn't vary significantly with speed of motion (30-120 mm/s), but their firing rates increase with faster velocities of movement (Gardner & Palmer, 1989a; see also Essick & Edin, 1995, using a brush stimulus). Receptor units of different skin types–glabrous versus hairy skin–are variably responsive to changes in the speed of a natural moving object (brush): Mechanoreceptors innervating hairy skin appeared to be more responsive than those innervating glabrous skin (Essick & Edin, 1995), although the experimenters suppose that this might also be due to differences in skin compliance. Hair follicle afferents, which are sensitive to hair movement (Greenspan & Bolanowski, 1996) appear to be jointly responsible for the detection of motion (Hamalainen, Warren, & Gardner, 1985), and they also display different response rates to different directions of natural movement (Greenspan, 1992; Vallbo et al., 1995).

The width of a stimulus (here: number of activated rows on the OPTACON) is encoded by RAs total spike output, i.e. wider stimuli lead to an increase in the duration of firing (Gardner & Palmer, 1989b). The same is true for PCs, but, in contrast to RAs, 50 % of PCs summate responses when wider stimuli are presented. Stimulus spacing (<5 mm) of a moving bar pattern also accounts for total spike output of RAs: Widely spaced bars evoke stronger responses (more spikes per sweep) than closely spaced bars and furthermore activate a larger population of RAs. PCs on the other hand show only little change in the number of spikes per

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[4] Note that we only discuss apparent motion produced by successive stimuli here. In case of natural moving stimuli, we would have to consider also the role of SA II units, because they show a directional sensitivity to lateral skin stretch in their discharge pattern (Johansson, 1978; Johnson et al., 2001).

sweep when stimulus spacing is varied; thus they fail to differentiate spatial details of the stimulus pattern.

Responses of somatosensory cortical neurons to tactile apparent motion According to Gardner, Palmer, Hämäläinen, and Warren (1992; see also Gardner & Palmer, 1989a), who used OPTACON stimuli on the glabrous skin of the monkey hand, the temporal frequency of stimulation defines the cortical firing patterns (note: Cortical neurons show a much stronger dependency on stimulus frequency than cutaneous mechanoreceptors): Low-frequency stimuli produce more spikes per sweep and are tightly locked to the stimulus pulses, meaning bursts of impulses and silent intervals in cortical neurons reflect the interstimulus intervals of the OPTACON stimuli. Low-frequency stimuli (25 Hz → ISOI of 40 ms → velocity of 30 mm/s) thus feel more punctuate. High-frequency stimuli (100 Hz → ISOI of 10 ms → velocity of 120 mm/s) on the other hand produce more uninterrupted, smooth movement, because cortical neurons fire more continuously at lower, weakly modulated firing rates. Here, cortical responses to consecutive stimuli seem to merge. Also, there seems to exist a central mechanism that reduces firing rates of RAs and PCs when successive stimuli are presented at high velocities.

Receptive field size of cortical neurons also varies with temporal frequency: The dimensions of the receptive field was found to expand with slower velocity of stimulation (Gardner & Palmer, 1989a). The reduction of firing rates and the contraction of receptive fields at smaller ISIs (higher velocities), brought Gardner and Palmer (1989a) to the assumption that a time-dependent inhibitory process (strong inhibition at short ISIs), links successive stimuli and leads to the perception of continuous apparent motion.

Discriminating the direction of natural moving stimuli In primary somatosensory cortex SI (mostly in areas 3b and 1), there are direction-sensitive neurons which signal the direction of movement by their excitatory responses (Constanzo & Gardner, 1980; Essick & Whitsel, 1985; Whitsel, Ropollo, & Werner, 1972). They have quite large receptive fields–often covering the entire hand or arm–on glabrous and hairy skin and their response properties are alike on both types of skin. They also encode the width of the stimulus, most of them showing stronger responses to broad edges than to narrow edges. Velocity of movement has only little effect on the mean firing rates of direction-sensitive neurons (Costanzo & Gardner, 1980; stimuli were metal or plastic edges that were moved over the skin of the forearm or hand). Directional sensitivity seems to be best for velocities between 1 and 30 cm/s. One class of direction sensitive neurons (direction invariant neurons; their preferred direction does not vary with stimulus position in the receptive field) shows an increase of directional sensitivity, when the stimulus traverses over a longer distance on the skin, another class of neurons (direction variant neurons; their preferred direction varies with stimulus location) does not. Also, the minimal length of skin that must be traversed to activate directional sensitive neurons is smaller for neurons having receptive fields at a distal body region, than for those having a receptive field on a proximal body region (e.g. the trunk) (see summary of Essick & Whitsel, 1985). But, the direction of motion is not transferred by one direction-sensitive neuron only, graduated degrees of activity within one population of direction-sensitive neurons and also the shift of activation from one population of cortical neurons to another provides information about the direction of movement (Constanzo & Gardner, 1980).

3.2.3 Apparent movement in other senses

An interesting question for researchers was whether sensory systems with different encoding and processing systems show the same space-time constrains for the perception of apparent movement. As in saltation, apparent motion can also be perceived in vision and audition. Whereas a number of studies have investigated apparent movement in vision, only a few studies exist, that address apparent movement in the auditory sense.

Audition Burtt (1917a) was the first scientist who described the phenomenon of apparent motion in the auditory modality. Since then, several studies on auditory apparent movement have been conducted, using either dichotic (Briggs & Perrott, 1972) or binaural open field stimuli (e.g. Strybel, Witty, & Perrott, 1992). They asked subjects to classify their perception of the stimuli into one of five categories: single sound, simultaneous sounds, continuous movement, broken movement and successive sounds.

Like in the tactile sense, ISOI for optimal apparent motion increases with stimulus duration, although at a slower rate. In audition, the optimal values for ISOI were lower than in vision and touch for comparable SDs (e.g. Briggs & Perrott, 1972; Strybel, Span, & Witty, 1998). This also implies that in audition the amount of temporal overlap between successive stimuli can be significantly higher than in vision and touch. Non-overlapping stimuli also induce the perception of continuous motion, at least for SDs < 100 ms (Briggs & Perrott, 1972). The values for ISOI where auditory apparent movement can be heard vary from study to study, but are in the range of 20-100 ms (depending on SD) for monaural and binaural listening conditions (Strybel & Neale, 1994). Figure 3.3 plots apparent motion in the visual, tactual, and auditory sense as a function of ISOI and SD (here called signal duration). Optimal values for ISOI decrease with smaller SDs in all three senses, but the functions for the visual and tactile senses are much steeper than in the auditory sense.

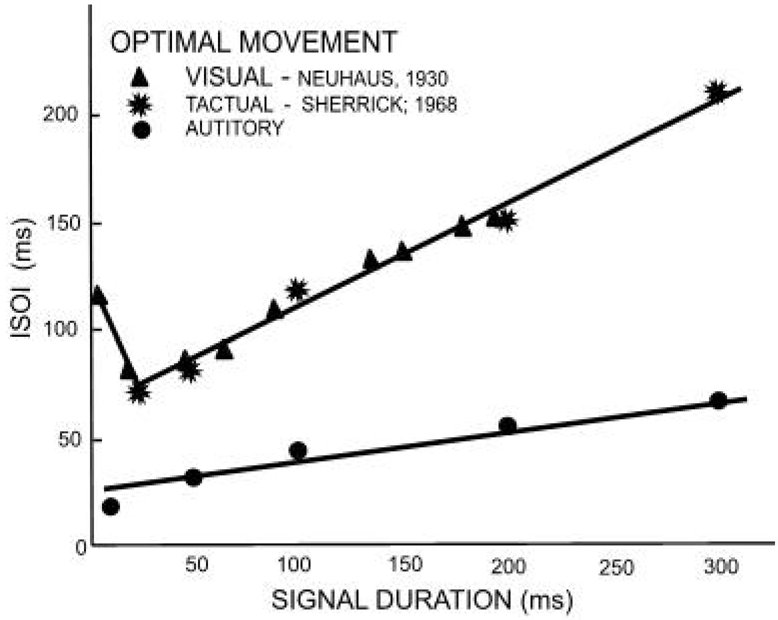


Figure 3.3: ISOI values for optimal apparent movement in the visual, tactual and auditory modalities as a function of SD. The data for visual apparent movement originate from Neuhau's (1938) experiment, those for tactual apparent movement from Sherrick's (1968) experiment and those for auditory apparent movement from Briggs' and Perrott's (1972) experiment.
From: Briggs & Perrott, 1972, p. 90.

Longer SDs produce more frequent reports of continuous motion, just as in touch. SDs optimal for apparent motion differ in the auditory and visual sense. There seems to be a minimum SD (approx. 25 ms; Strybel et al., 1998) to generate apparent movement in audition. This minimum SD value is not affected by the spatial separation between the auditory stimuli. In vision, the minimum SD value for apparent motion can be as low as 5 ms (Strybel et al., 1992). The number of sound sources (two or three) did not affect the perception of continuous motion nor were any interactions with temporal variables found (Strybel & Neale, 1994).

The distance between two auditory stimuli does not affect the quality of motion, nor the ISOI range where continuous motion can be perceived (for auditory separations between 6 and 160 degrees and ISOIs between 20 ms and 45 ms; Strybel & Vatakis, 2004), equivalent to touch, but different to visual movement, where the spatial separation between two stimuli determines the range of ISOIs where continuous motion can be generated (Strybel, Manligas, & Perrott, 1989; Strybel et al., 1992; Strybel & Vatakis, 2004). Whereas in vision there is a narrow limit for the spatial separation between two stimuli where motion can be perceived, this limit is much wider for the auditory sense; auditory stimuli can be separated from 2.5° up to 160° (Strybel et al., 1992; Strybel & Neale, 1994). This is true for binaural listening conditions. For monaural listening conditions, the quality of motion decreases with increasing interstimulus distance (Strybel et al., 1989), and continuous motion can only be heard with separations from 10° to 80° (Strybel & Neale, 1994).

The order of stimulus presentation (left to right or vice versa) does not affect the quality of perceived movement nor directional sensitivity (Strybel et al., 1989). Apparent motion can be heard in the horizontal as well as in the midsagittal plane (Strybel et al., 1998). This is also true in touch.

Discriminability of the direction of motion is independent of ISOI when the distance between stimuli exceeds the minimum audible angle (that means the minimum distance where subjects are able to discriminate between the locus of two sounds; Briggs & Perrott, 1972). In vision, discrimination of direction of motion is affected by distance and ISOI (see review in Strybel & Vatakis, 2004). In contrast to previous research, Strybel & Vatakis (2004) showed that SD and ISOI affected direction discriminability in the same way in the visual and auditory sense. In touch, the effect of ISOI is ambiguous, depending strongly on the type of stimulus used. Lakatos and Shepard (1997) who compared direction discriminability in the visual, tactile and auditory sense found that in all three senses the critical ISOI needed to discriminate direction increased with interstimulus spacing, although the slope of the function varied between the senses. In touch, ISOI increases fastest, compared to the other two senses.

Direction discriminability does not vary with the distance (>10°) between two successively presented stimuli for binaural listening. For monaural listening, direction discrimination barely exceeds chance for separations up to 40° centered about the body midline (Strybel et al., 1989).When more sound sources are involved (three instead of two), discrimination performance increases (Strybel & Neale, 1994). Discrimination performance also depends on the plane of separation: Direction was more frequently determined correctly, when the auditory stimuli were presented horizontally (Strybel & Neale, 1994).

Vision The first study on apparent motion in vision was carried out by Wertheimer 1912. He used simple figures that were presented successively to produce the perception of apparent movement in vision. Korte investigated in 1915 the correlations between optimal apparent movement and stimulus duration, interstimulus interval, distance in-between stimuli and stimulus magnitude. The resulting relationships between those variables are known as "Korte's laws" (see summary of Burtt, 1917b or Sherrick, 1968a).

According to Gardner et al. (1992) the major difference between apparent motion in touch and vision is the ISI at which successively presented stimuli merge to the percept of continuous motion: In vision the ISI is smaller than 160 ms, in touch it has to be lower than 20 ms. Apart from this fact, visual stimuli that are perceived as distinct events produce cortical responses in striate cortex and middle temporal cortex that are similar to those from cortical neurons in SI. Spatially, apparent motion was reported up to 7° of visual angle spatial separation (at proper timing parameters) and the illusion is still vivid when it crosses the body-midline (Naikar & Corballis, 1996).

One explanation for apparent movement is provided by Ramachandran and Anstis (1986): The visual system looks for "correspondence" in successive pictures, i.e., the brain compares the pictures, and when they differ only slightly, the illusion of motion can be generated. In contrast to the previous view that presumes that the brain compares each element of the pictures, Ramachandran and Anstis (1986) believe that the illusion of motion is created in earlier stages of visual processing and only salient features of the pictures are compared. Another way of facilitating the comparison is to look for perceptions that also occur in the real world, e.g. to assume that moving objects usually continue their path linearly instead of suddenly changing their direction.

Recent research (e.g. Kaneoke, Bundou, Koyama, Suzuki, & Kakigi, 1997; Kawakami, Kaneoke, & Kakigi, 2000; Muckli, Kriegeskorte, Lanfermann, Zanella, Singer, & Goebel, 2002; Zhou, Zhou, Rao, Wang, Meng, Chen, et al., 2003) found a cortical region in the human brain that was activated by apparent as well as real motion (middle temporal area MT/V5), although response latencies differ for real and apparent motion. It seems that long-range apparent motion activates additional cortical areas, compared to short-range apparent motion (implying smaller displacement, usually less than 0.25° of visual angle, and faster alteration of successive stimuli in contrast to long-range apparent motion) (Zhou et al., 2003). Larsen, Kyllingsbæk, Law, and Bundesen (2005) conclude from their experiments, that MT is always activated when stimuli are successively presented, whether or not they are connected by apparent motion. The filling-in process that generates percepts of uninterrupted movement "occurs in the network of visual areas with which MT is reciprocally connected rather than occurring in MT itself" (Larsen et al., 2005, p. 1069). This notion is supported by an experiment, where Larsen, Madsen, Lund, and Bundesen (2006) showed that the pattern of activity in primary visual cortex (area V1), is similar for real and apparent motion; during apparent motion, the gaps between activated sites are filled-in with activation. This filling-in process occurs in lower visual areas (like V1), in connection with feedback from higher-level areas. Effects of attention on shifts in activation and the magnitude of responses in MT have been demonstrated by various authors (see summary of Greenlee, 2000).

3.3 Differences between saltation and apparent motion

Saltation produces mislocalized taps whereas phi-movement appears to be a "gray ghost" (Geldard, 1982; p. 139). Geldard (1975, p. 33) calls the saltation phenomenon a "Ding an sich", meaning that saltation produces discrete taps and can therefore never be confused with apparent motion. Thus, saltation and Phi-movement differ in regard to their *qualitative appearance*: Whereas saltation produces mislocalized taps at distinct locations on the skin, phi is perceived as uniform and unbroken movement (Geldard & Sherrick, 1986). However, Geldard (1982) reports that saltation and apparent movement can co-exist in perception given the appropriate spatio-temporal stimulus parameters (ISI between 50 and 100 ms); both illusory patterns can be compared directly by shifting one's attention from location to movement in the pattern. To my knowledge, in no study about apparent movement was the occurrence of saltation reported, probably because the response paradigm didn't allow subjects to give an account of mislocalizations of stimuli, rather they had to concentrate on the "goodness" of motion.

A second difference is that Phi movement can cross the *body-midline* at properly chosen ISIs (<= 100 ms), but saltation never does, as experiments e.g. on the forehead show. Geldard and Sherrick (1986) reason that "it seems clear that the neural mechanism responsible for phi is not the one that causes saltation" (p. 94). Additionally, in apparent movement an *interaction between SD and ISI* can be found (e.g. Sherrick & Rogers, 1966), that hasn't been reported in saltation previously. Finally, saltation requires *repetitive stimulation of a stimulus location*, whereas apparent motion can be produced by one stimulus at each location.

3.4 Similarities between saltation and apparent motion

Temporally, saltation occurs at ISIs between 20 and 300 ms, varying a little with the saltatory paradigm used (multiple rabbit, reduced rabbit,…). Apparent movement is perceived at timely separations between 60 and 200 ms. Consequently the *temporal range* for the appearance of both tactile illusions is quite similar.

Both illusions are *not limited to one sense alone*, they both appear as well in the tactile, as in the auditory and visual sense. It can thus be presumed, there are similar processing mechanisms.

In one experiment Geldard (1975) varied the saltatory paradigm by delivering two stimuli to each of three contactors that were placed on the right arm. On the left arm, six contactors were arranged over the same distance and activated sequentially. Timing parameters were identical for both arrangements. When subjects had to compare the two patterns that were alternately presented, they judged them to be equivalent. The same result was found by Cholewiak and Collins (2000) in a more comprehensive study: Quality judgments of tactile movement–either presented by successive activation of seven tactors or by saltation–along a linear array on the finger, forearm, and back showed, that both stimulus patterns produce equal sensations. With body site, direction of movement (proximodistally or distoproximally), stimulus patterns (successive activation versus saltation), SD, and ISI being the independent variables in this experiment, only very few significant differences in the mean quality judgments could be found between the two stimulus patterns. Only temporal stimulus parameters (SD/ISI) had an effect on quality judgments, with only few exceptions, the other variables did not.

These findings suggest, that–at least for arrays containing more than three activated sites–, the two different stimulus patterns lead to *similar percepts*. It seems that our perception fills in missing stimuli to create the percept of continuous motion, no matter whether each stimulus site is activated once or multiple times.

The saltatory phenomenon is not clearly distinguished from apparent movement, mislocalization and another spatio-temporal illusion called tau-effect (see Chapter 1): The presentation of two physically presented stimuli in quick succession is the basis of "synthetic" or apparent movement. Depending on the time interval between two stimuli mislocalizations occur, there might be a connection to the false estimation of tactual distance ("tau"-effect).

Although the phenomenal appearance of saltation and apparent motion might differ, both illusions require the temporal integration of spatial location.
"One question to be faced in considering saltatory phenomena is that of the difference between saltation and the movement illusion" (Geldard, 1982; pp. 136).

4 Content of the dissertation

Whereas saltation comprises the mislocalization of stimuli, apparent movement creates the perception of continuous motion. Cholewiak and Collins (2000) could show that by using tactile arrays containing several stimulus sites, appropriately chosen temporal stimulus parameters lead to equivalent percepts of motion. The two different stimulus patterns apparently pass through the same integration process, that fills in missing stimulus spots to induce the percept of uninterrupted motion.

The following experiments are an expansion of the work of Cholewiak and Collins (2000). By concentrating on one test site only (the trunk) and varying additional stimulus characteristics (such as vibration frequency), we wanted to test which stimulus characteristics best elicit the illusory percept of movement when two stimuli are either successively presented (apparent motion) or presented as saltatory patterns.

There are a number of reasons why it is important to expand the study on the arm to include the abdomen. There are important differences between the two sites. For example, the trunk is less sensitive (higher vibratory threshold; see Figure 2.2; also less accurate point localization and higher two-point threshold; Schiffman, 1996), it has many types of underlying tissue (including ribs, spine, gut, and fat, which affect the travelling waves produced by a vibrating stimulus; see Békésy, 1967), and its two sides are represented separately in the two hemispheres of the brain.

Since a tactile array on the trunk can span both body halves, we can test whether tactile patterns presented in the saltatory mode cross the body-midline like successively presented stimulus patterns are assumed to do.

The results might shed further light on the processing of spatio-temporal stimuli. When two different stimulus patterns produce equal sensations, this might be a psychophysical indication of equal cortical representations of both patterns (compare experiments of Blankenburg et al., 2006; Chen et al., 2003) as well as the functional relevance of cortical topographic maps (maps correlated with perception).

The results will also be beneficial for the design of tactile torso displays (see Chapter 1). Torso displays have the advantage, that an operator can still use both hands and has unrestricted freedom of movement. In addition, the torso is known to provide a frame of reference for orientation and mobility – where the torso points is the direction in which we are travelling, unlike the head or other more mobile body parts. There is also experimental evidence from studies with patients with hemineglect that the trunk midline serves as physical anchor for the identification of the body's position with respect to external objects (Karnath, Schenkel & Fischer, 1991).

5 Aim of the study and hypothesis

The aim of this study is to investigate the parameters of the integration of spatio-temporal tactile stimulus patterns into a unitary (illusory) percept of continuous motion. For this purpose we use two different stimulus patterns: First, we successively stimulate each of a number of test sites around the torso to elicit a percept of apparent motion, a stimulus pattern that we will consequently call “successive activation”. Second, we create saltation by delivering multiple stimuli to every second test site. In this case, displacement of a stimulus towards the subsequent stimulus dependent on ISI is expected (Geldard, 1975). However, Geldard (1982) and in more detail Cholewiak and Collins (2000) could demonstrate that saltation can as well produce a sensation equivalent to the illusion of apparent motion, which might show that the different stimulus patterns undergo the same integration process and produce comparable representations in somatosensory cortex. If we find similarities in the parameters within which the two phenomena (saltation and apparent motion) occur, these would suggest that the dynamics of perceptual organization could be associated with a common underlying mechanism, possibly located in somatosensory cortex. This study is an expansion of the work of Cholewiak and Collins (2000) and is based on Wiemer’s neural network model (1998, 2000) that states that somatosensory cortex adapts dynamically to spatio-temporal stimulus characteristics and which is in line with Chen et al.’s (2003) and Blankenburg et al.’s (2006) observations that illusory percepts are somatotopically represented in cortex as an outcome of such plastic changes within neural networks. As possible perceptual correlates of dynamic changes, we will measure judgments of the qualities of movement (Experiment 1) and discrimination performance (direct comparison between the two patterns to judge whether the two patterns are the same or different respectively which of the two patterns is best in terms of continuous movement; Experiment 2).

We also want to test whether repetitive stimulation might induce changes in the cortical representation of the stimulus patterns, which in turn affects discrimination performance when the two different patterns are to be directly compared. Regarding saltation, previous studies (Stolle, 2003) have already shown that a few stimulus repetitions are sufficient to cause plastic changes that are reflected in a perceptual bias of the saltatory area.

Psychophysical characteristics of the illusion of motion might thus shed further light on the dynamic behavior of neural networks.

From a practical point of view the results might be instrumental in the design of vibrotactile displays. Positioning a vibrotactile display on the torso has the advantage that the hands of an operator are left free to handle tools or controls. On the other hand problems might arise from the fact that due to breathing and small changes in subjects' posture the tactors might loose contact to the skin and therefore alter subjects' perception. For this reason it seems worthwhile to concentrate on the torso as a seldom-studied test site. Moreover an array around the torso will enable us to investigate an additional variable crucial for saltation: The crossing of the body midline.

In this study we investigate the spatio-temporal stimulus characteristics which are optimal for evoking the illusion of motion–or as Cholewiak and Collins (2000) say, to draw a "vibrotactile line" (p. 1220)–using different stimulus patterns. Such lines might serve as directional vectors that provide navigational information or information about the body's orientation in space.

In a first calibration study we determined vibratory thresholds at six different body sites around the abdomen for six different stimulus frequencies, to test if the tissue characteristics or the distribution of mechanoreceptors affect the perception of vibrotactile stimuli at different sites on the torso. Different vibratory thresholds might affect the comparability of the two different stimulus patterns, as in the saltatory pattern only every second site is activated.

Then, the stimulators (tactors) and the experimental procedure–both were identical to Cholewiak and Collins (2000) study (on the arm)–are evaluated to test if a tactile array around the torso is feasible to evoke the illusion of movement. Thus, in a first pilot study, we test the equipment and also examine, if direction of movement is a quality of movement that should be included in the succeeding experiments. In a second pilot study we test if there are limits to the integration of different saltatory patterns into a unitary percept of motion dependent on the number of stimuli delivered to a test site and consequently the distance between activated sites.

Following these pilot studies, three main experiments are carried out. The aims of the first two were already described above. In a third experiment, we investigate whether the integration of spatio-temporal stimulus patterns differ for unilateral and bilateral presentation. For better readability the Experiments 1 and 2 are combined in the following paragraphs–unless otherwise noted–because the only major difference is the dependent variable (quality judgments/discrimination performance), i.e. the correlative to neural network behaviour, and we expect our independent variables to have comparable effects on both dependent variables. Nevertheless, using different response paradigms (quality judgments/discrimination performance/forced-choice paradigm “which is best”) might reveal the role of attention in the perception of illusory movement, as each response paradigm directs subjects’ attention to a certain aspect of illusory movement.

Pilot-Study 1: Identification of the direction of tactile movement around the torso

A number of studies have been carried out (see Essick, 1998 or Gardner & Constanzo, 1980a) to examine the impact of different variables (number of stimuli, velocity of motion, width of stimuli,..) on direction discrimination, to evaluate, how direction is encoded by neural mechanisms. To my knowledge only one study (Cholewiak & Collins, 2000) examined whether different stimulus patterns (saltatory/ successive stimulation) affect direction discrimination. Using a 7-tactor array that was placed on the volar forearm, Cholewiak found that subjects could always distinguish the direction of tactile movement correctly, irrespective of the stimulus pattern used.

The number of stimuli is known to be the most relevant factor for direction discrimination (e.g. Essick, 1998; Gardner & Sklar, 1994). While we keep the number of stimuli constant (8 or 12 stimuli), the number of loci activated is different in the saltatory and successively activated stimulus patterns: In the saltatory mode every second locus is activated twice while in the successively activated pattern, each site is activated once, in series. In a first pilot study we therefore test direction discriminability for the two stimulus patterns presented at a fixed distance and with a constant number of stimuli, but with different numbers of activated loci. The distance chosen is a full circle around the torso as in the experiments to follow.

Because velocity is another factor that has been shown to significantly impact direction discrimination we vary the velocity of motion around the torso, again in the same manner as in the experiments to follow by combining different levels of SD and ISI.

There is also a practical reason to investigate subjects’ ability to discriminate direction: We want to determine whether direction is a quality useful for encoding information about the type of movement we present in our experiments, potentially disclosing differences between the stimulus patterns. On the other hand, if subjects are always able to distinguish the direction of motion correctly, we will drop this quality in the experiments to follow.

The most important factor for direction discrimination is the number of sequential inputs by afferent fiber channels, rather than the length of skin traversed (Gardner & Sklar, 1986, 1994), however, no one has ever tested lengths as long as the distance around the abdomen–as much as 100 cm in our subjects. Consequently, innervation density of the skin is a relevant factor for direction discrimination: Direction discrimination is more accurate for more densely innervated regions of the skin (like the digits). On less densely innervated regions (like the torso), more stimuli should be needed and the path to be traversed will have to be longer. Experiments with moving bar patterns on the index finger show that most subjects achieved 99% correct answers with eight or more stimuli (Gardner & Sklar, 1994). When motion is simulated on the torso, probably more tactors should be applied to achieve the same performance.

The longer the length of skin traversed, the broader the range of velocities over which subjects may correctly discriminate direction (Essick, 1998; Essick et al., 1989). For long lengths of skin traversed–where "long" depends on the test site and thus on its innervation density–direction discrimination is nearly perfect and stimulus velocity has only a minor effect on directional sensitivity.

In our experiments movement will always travel around the whole torso, along an array of 12 tactors. Thus, the length of our array should exceed by far the criterion for "long", which is 1.0 cm on the finger, 6.0 cm on the arm (Essick, 1998), and, due to the lower innervation density on the abdomen, supposedly longer around the trunk, but most likely still shorter than a full circle around the waist. We therefore do not expect velocity to have an impact on direction discrimination.

Sparks (1979) investigated the effects of the number of stimuli and the distance in-between them on directional sensitivity. While holding the number of stimuli (electrodes), constant, he varied the spacing between them and found that when the stimulus sequence crossed the body-midline on the abdomen, performance was poorer. But since these findings were confounded with stimulator spacing, they must be considered carefully.

Hypothesis: *When motion around the torso is simulated by using an array containing 12 stimulators, direction discrimination is near-perfect.*

Hypothesis: *Temporal stimulus parameters (SD/ISI) have no effect on direction discrimination.*

With the spatiotemporal parameters chosen for this experiment, we expect the saltatory stimulus pattern to produce a percept of continuous movement, therefore no difference in direction discrimination is expected between the different stimulus patterns (saltatory/successive stimulation).

Hypothesis: *Different stimulus patterns (saltatory/successive stimulation) have no effect on direction discrimination.*

If we don't find any variation in subjects' ability to distinguish the direction of movement over the range of spatio-temporal stimulus characteristics tested, we will exclude this quality from the succeeding experiments.

Pilot Study 2: Limits of spatio-temporal integration dependent on the number of stimuli delivered to a stimulus location in the saltatory paradigm

In one experiment Geldard (1982) directly compared apparent movement with saltation: He placed six contactors on the left forearm, delivering one stimulus to each contactor. On the right forearm, three contactors were placed over the same total distance and each contactor was activated twice. The perceptions evoked by the two stimulus patterns were identical, when ISI ranged between 50 and 100 ms. Apparently, at this range of ISI, stimuli of both patterns are integrated such that missing spots between the activated loci are filled-in and an illusion of continuous motion is created.

According to Geldard (1982) saltation is vivid when the number of stimuli ranges between 2 and 16 per stimulus location. The larger the number of stimuli, delivered to a locus, the shorter ISI must be to obtain the saltatory effect. Also, the size of the saltatory area depends on the number of stimuli per location: When more stimuli are delivered to P2 in the reduced rabbit paradigm, the size of the saltatory area increases. Geldard found a parabolic function between the number of stimuli delivered to a locus and the extent of the saltatory leap when the dorsal thigh served as test site.

The question to be answered in this pilot study is, whether or not we still obtain comparable percepts of movement as reported above, when we vary the saltatory paradigm delivering different number of pulses to each stimulus site. Because we want to keep the total distance of the tactile array (a complete circle around the torso) as well as the total number of stimuli constant, the number of pulses given at each site will be confounded with the distance between activated sites. There are 12 contactors equally spaced around the torso. Each contactor is either successively activated or different saltatory patterns are applied: Every second contactor is activated twice or every third contactor is activated three times or every fourth contactor is activated four times. Thus, the more stimuli that are delivered to a contactor, the greater the distance in-between activated sites will be. But since the saltatory area should increase with the number of stimuli delivered to a locus, we should still be within the distance limits where saltation can be observed (up to 150 cm with the original 5-5-5 rabbit sequence), so we don’t expect to obtain significantly different percepts.

Like in Geldard’s (1982) experiment we allowed subjects to compare two patterns of stimulation: One of the above described saltatory patterns with successive activation of every single one of the 12 contactors, to test if both patterns are integrated into the same percept of continuous motion. One practical aim of our experiments was to find the optimal spatio-temporal parameters for apparent movement for the design of tactile displays, so we wanted subjects to judge which of the two stimulus patterns was “best” in terms of smooth, uninterrupted movement. If both patterns produce the same percept, subjects should prefer one pattern over the other in 50% of the trials–basically indicating “no preference”. In the second pilot study we will thus examine if there are limits to the integration of saltatory patterns into a percept of continuous motion, when the number of activated sites and thus the distance in-between them is varied.

Hypothesis: *As the successively activated and saltatory patterns are expected to produce equivalent percepts of apparent motion within the spatiotemporal limits used in this pilot study, there should be no preference for one pattern, regardless of the varying number of pulses in the different saltatory patterns and the varying distance in-between activated sites.*

Spatio-temporal integration of different tactile patterns to produce illusory movement depends on spatio-temporal parameters (Experiment 1 and 2)

Temporal stimulus parameters

ISI Psychophysical studies on motion percepts evoked by discrete vibrotactile stimulation (Cholewiak & Collins, 2000; Kirman, 1974a, 1974b; Sherrick & Rogers, 1966; Szaniszlo et al., 1998) showed that the quality of motion percepts and thus the extent of spatio-temporal integration of successive stimuli doesn't depend on the interstimulus onset interval (ISOI) in a linear manner. Rather the ISOI interval optimal for the spatio-temporal integration of successive stimuli varies with SD and number of stimuli. In contrast, the saltatory phenomenon clearly shows a linear relationship between ISI and the amount of mislocalization (Geldard, 1982; Geldard & Sherrick, 1986).

Note that two different measures for the temporal distance between two stimuli are used in studies of apparent movement and saltation: ISOI (that is the time between the onset of the first and the onset of the second stimulus) and ISI (that is the time between the offset of the first stimulus and the onset of the second stimulus). In our studies we will concentrate on ISI, as due to technical constraints we were not able to produce temporal overlap between successive stimuli.

According to Wiemer et al. (1998, 2000) the integration of spatio-temporal stimuli depends on the temporal interval between them. Stimuli following closely in time are expected to belong together, therefore they should be represented close to each other in somatosensory cortex.

Hypothesis: *Shorter ISIs enhance the integration of spatio-temporal stimuli into a percept of continuous motion for successively activated as well as saltatory stimulus patterns. (Thus better quality judgments for both stimulus patterns and less distinctions between the patterns are found for shorter ISIs.)*

SD Increasing SD had a positive effect on the goodness of motion in studies of apparent motion. Moreover, increasing SD led to increasing ISOI values and also increased the range of ISOI values where good motion was perceived.

In studies of saltation, SD has often been an unattended variable. But in Cholewiak and Collins study (2000), SD has been systematically varied and they found that SD influenced only specific qualities of movement (length/straightness) produced by saltatory stimulus patterns. We assume in this work that percepts of illusory movement are influenced by SD, as increasing SDs might enhance the fusion of discrete stimuli.

Hypothesis: *Longer SDs enhance the integration of spatio-temporal stimuli into a percept of continuous motion for successively activated as well as saltatory stimulus patterns. (Thus better quality judgments for both stimulus patterns and less distinctions between the patterns are found for longer SDs.)*

Interactions between ISI and SD Interactions between ISI and SD have been found in studies of apparent movement and to a minor degree also in Cholewiak and Collins (2000) study on movement simulated by saltatory stimulus patterns. We assume that there is an interaction between SD and ISI: An increase in SD supports the integration of stimuli, such, that when SD increases, stimuli are integrated as well for longer ISIs.

Hypothesis: *Increasing SD increases the range of ISIs over which the integration of different spatio-temporal stimulus patterns occurs. (Increasing SD increases the range of ISIs over which better quality judgments for both stimulus patterns and less distinctions between the patterns are found.)*

Spatial stimulus parameters

Number of stimuli The number of successively activated stimuli has proved to be a crucial factor for the integration of stimuli into an illusory percept of movement, though it was usually confounded with the distance between adjacent stimuli (e.g. Kirman, 1975; Szaniszlo et al., 1998). The more stimuli were activated, the smaller the distance between two stimuli became, and the more the quality of motion percepts improved.

Because in previous studies of saltation usually only two (reduced rabbit) or three (original 5-5-5 paradigm) stimulus sites were used, we have no available data about the influence of the number of test sites on the illusion of saltation. But since we assume that the spatial relatedness of stimuli enhances their cortical integration, we expect that increasing the number of stimulus sites and thus decreasing the distance between activated sites will lead to better quality judgments.

Hypothesis: *Increasing the number of stimulus sites and thus decreasing the distance between activated sites will enhance the integration of spatio-temporal stimuli into a percept of continuous motion for successively activated as well as saltatory stimulus patterns. (Thus better quality judgments for both stimulus patterns are achieved.)*

Stimulus width When multiple stimuli are presented simultaneously at different points on the skin (within certain spatial limits), a single sensation at the centre of the stimulus pattern results, even if no physical stimulus occurs at that site. This sensation is broader, i.e. spread out laterally, and also grater in magnitude when compared to a single stimuli. This illusion is called tactile funneling (Békésy, 1958, 1967; Gardner & Constanzo, 1980b, 1980c; Gardner & Spencer, 1972). We therefore assume that three closely-spaced, simultaneously-activated tactors are perceived as a line or wide spot. Subsequently we will call the sensation produced by three vertical, simultaneously activated tactors the wide stimulus compared to the single moving dot produced the activation of a single tactor (called narrow stimulus).

From experiments regarding subjects' ability to discriminate the direction of moving tactile stimuli (e.g., Essick, 1998) we know that the size of the stimulus plays an important role in the sense that direction discrimination was better for wider stimuli than for narrower, presumably due to spatial summation. Vibrotactile sensation magnitude is also affected by the number of simultaneously presented stimuli in a tactile pattern: With more stimuli, loudness increases (Cholewiak, 1979). Cholewiak (1979) suggests that loudness summation might cause a form of masking and hence impair pattern perception.

However, it is unclear if stimulus width–equivalent in our experiments to the size of the stimulated area–affects the perception of apparent tactile movement, as it affects direction discrimination or sensation magnitude. If we find that stimulus width alters the perception of moving vibrotactile stimuli we expect to find different quality judgments (for a specific set of spatiotemporal conditions) when the stimulus is a moving point as opposed to a moving line.

Hypothesis: *Stimulus width does not affect the integration of different spatio-temporal stimulus patterns into a percept of continuous motion. (Thus quality judgments for both stimulus patterns and distinctions between the patterns are not affected by stimulus width.)*

Two qualities of special interest: Length and straightness of movement

Two qualities of movement are of special interest: Straightness and length. The psychophysical conditions that underlie them, are important to correct percepts of the distance and path of a tactile stimulus as it moves on the skin (Cholewiak & Collins, 2000; Langford et al., 1973; Whitsel, Franzen, Dreyer, Hollins, Young, Essick et al., 1986). Experiments have been conducted using different types of stimuli (e.g. brushing stimuli or the OPTACON), different test sites (e.g. finger, forearm, back) and different response paradigms (e.g. drawing a line or scaling methods) to evaluate the effects of stimulus velocity on perceived stimulus distance and path.

It is known that judgments of the qualities straightness and length depend on the velocity of motion:

1. Deviation from a perceived straight line increases as the rate of movement decreases (Langford et al., 1973).

2. Perceived length decreases as rate of movement increases (e.g. Essick, Franzen, McMillian, & Whitsel, 1991; Greenspan & Bolanowski, 1996).

Furthermore Cholewiak (1999) describes that both, physical separation and ISI affect estimates of the extent of the sensation produced by two 230 Hz stimuli, such that perceived distance increases with increasing physical separation and with increasing ISI, with a spatiotemporal interaction observed over all conditions. Specifically, when physical separation exceeds the two-point threshold, length is generally underestimated.

In experiments to be described below, we want to reinvestigate these effects by using discrete stimuli that travel around the whole torso (note: in the experiments mentioned above stimuli only moved on one body site, never crossing the body-midline).

Hypothesis: *When the velocity of simulated motion on the torso increases, lines feel straighter, thus judgments for the quality straightness will improve.*

Hypothesis: *When the velocity of simulated motion on the torso increases, lines feel shorter, thus judgments for the quality length will decrease.*

Cholewiak & Collins (2000) demonstrated that the stimulus pattern (successively activated or saltation) had no effect on perceived length and straightness for stimuli presented to the fingertip, forearm, and thigh. For both saltatory and successively activated conditions the relationships between velocity and length, and velocity and straightness were consistent with the findings described above. Because the impact of velocity was quite similar for all test sites–except for a shift in range–we also expected to find the same relationships in our studies on the abdomen, independent of stimulus pattern.

Hypothesis: *Stimulus pattern has no effect on the judgments for straightness and length.*

Vibration frequency

According to the four channel model of cutaneous mechanoreception, different vibration frequencies activate different populations of mechanoreceptors in both smooth (glabrous) and hairy skin (Bolanowski et al., 1988, Bolanowski et al., 1994). Detection thresholds for vibratory stimuli as well as subjective stimulus magnitude are influenced by the frequency of vibratory stimuli. The perceptions evoked by stimuli of different frequencies also differ. Whereas low-frequency stimuli appear to be dull, high-frequent stimuli produce bright, sharp taps (see Chapter 1). But, on the other hand, two-point threshold and localization error are not affected by vibration frequency (Bolanowski & Gescheider, 1996). Due to these results (that vibration frequency affects at least certain psychophysical measures and the perception of tactile stimuli), we want to use vibratory stimuli of two different frequencies (80/250 Hz) to test whether vibration frequency alters the integration of different spatio-temporal stimulus patterns into a percept of continuous motion. However, since previous studies have shown that vibration frequency has only a minor effect on apparent motion or the saltatory illusion, we do not expect to find any significant differences in our measures of quality judgments or discrimination performance.

Hypothesis: *Vibration frequency does not affect the integration of different spatio-temporal stimulus patterns into a percept of continuous motion. (Thus quality judgments for both stimulus patterns and distinctions between the patterns are not affected by vibration frequency.)*

Time dependent shifts in response behaviour (Experiment 2)

Stolle (2003) showed that brief repetitive stimulation (reduced and utterly reduced rabbit paradigm) resulted in changes of the tactile body map, as the space of the stimulated area on the forearm was contracted in perception. In our study we will concentrate on the equivalence of different stimulus patterns (successive activation and saltation) that induce illusory movement, so our experimental design was different from Stolle's and generally didn't involve repeated measures of temporal stimulus parameters within subjects. The exception is the pattern discrimination experiment (Experiment 2), where every possible combination of temporal parameters was repeated twice. Because in Stolle's experiment the biggest change in the perceived space of the simulated area occurred between the first and the second stimulus repetition, we assume that one repetition is enough to cause plastic changes.

We therefore assume that:

1. If training enhances the discrimination between two stimulus patterns (successive activation and saltation), then discrimination performance should improve (Note that we didn't give any feedback about the correctness of a subject's response).
2. But, if, according to Wiemer et al.'s neural network model (1998, 2000), stimuli presented close together in time are integrated and their representational distance in somatosensory cortex is reduced with stimulus repetition, then both patterns should feel more and more alike and discrimination performance should decline. One may

also compare Braun et al.'s (2000) results, where when fingers are stimulated in a fixed order, the distance between the cortical representations of these fingers is decreased and Stolle's (2003) findings where she found that the size of the saltatory area was contracted in perception after repeated successive stimulation, and also a decrease in point localization was observed.

Hypothesis: *If the two different stimulus patterns have to be discriminated repeatedly, then discrimination performance deteriorates due to plastic changes in neural networks.*

Experiment 3: Unilateral and bilateral presentation of stimulus patterns

Geldard (1982; Geldard & Sherrick, 1983, 1986) conducted several experiments to explore the spatial limits of saltation (saltatory areas) on different body-sites like the thigh, arm, or forehead. He found that the size and shape of the saltatory area varies with body region–and hypothesized that the areas so defined might correspond to the receptive field sizes and shapes of the different body parts. In addition, experiments using the reduced rabbit paradigm on the forehead, or anterior thorax showed that the saltatory illusion never crossed the body-midline, the saltatory area was always truncated at the body-midline.

As already stated above, increasing the number of stimuli delivered to P2 in the reduced rabbit paradigm increased the size of the saltatory area (Geldard, 1982). Additionally, the size of the saltatory area can be altered with repetitive stimulation (Stolle, 2003) and also varies with the exact position (proximal or distal on the forearm) of the saltatory pattern (Trojan et al., 2006), indicating dynamic adjustments of neural networks to spatio-temporal stimulus characteristics. Considering these findings, it is reasonable to ask if the attenuation of the saltatory area at the body-midline also occurs when a saltation mode other than the reduced rabbit is applied. In the third experiment we will thus examine if saltatory stimulus patterns still produce the illusion of continuous motion when presented bilaterally.

When multiple stimulus locations are involved (7-tactor array), we expect to attain a relatively stable illusion of saltatory movement that is also vivid when it crosses the body-midline. Once the stimulation of discrete contactors produces the illusion of movement, this illusory movement shouldn't stop at the body-midline as the cortex integrates perceptions from the two body-sites into an integral whole. We can deduce therefore that subjects' ability to discriminate between saltation and successive activation is not different for unilateral and bilateral presentation.

Hypothesis: *When subjects have to discriminate between saltatory and successively activated stimulus patterns they reach similar results when the illusory movement travels the body-midline and when it travels on one body site only.*

6 General methods

Here, the apparatus, stimulus characteristics and the general experimental procedure, which will be the same for each experiment will be described. A detailed description of each of the several experiments will follow in the individual sections.

6.1 Subjects

Subjects for the experiments were recruited from the Naval Schools Command at the Naval Air Station in Pensacola, Florida. They were (male and female) pilot candidates awaiting their flying training. All subjects participated voluntarily, there was no reimbursement for their participation. Their ages ranged from 21 to 33, averaging 24.2 years old.

In total, 139 subjects took part in 5 experiments (Pilot Studies 1 and 2, Experiments 1, 2, and 3). Usually, the subjects had no prior experience with tactile experiments, but in the calibration and first pilot study, one of the subjects was a research psychologist working for NAMRL. In the second pilot study we had one subject who also participated in Pilot Study 1.

Every subject was asked to report any medical condition that might effect his/her tactile sensitivity of the trunk or ability to operate the testing devices. Only subjects who didn’t report any serious medical condition that might affect their ability to participate in the experiment were included. In fact, no subjects had to be excluded based on medical criteria.

Because the subjects in our pool had limited availability, our research designs were generally between-subjects rather than within-subject designs.

6.2 Apparatus

Tactile stimuli were provided by electrically driven transducers (“C2-Tactors”) manufactured by Engineering Acoustics, Inc. of Winter Park, FL, USA (see Figure 6.1). They have a round metal surface (made of anodized aluminum), are 3 cm in diameter and 0.8 cm deep. The vibrating circular skin contactor in the middle is 0.7 cm in diameter and centered in a 0.9 cm hole so that there is a 0.1 cm gap between the moving element and the rigid surround. This perpendicular moving element is raised 0.05 cm above the housing to assure proper skin contact and is pre-loaded when it touches the skin. The tactor weighs about 17 gm. These C2-

Tactors can be driven at different frequencies, provide good control over frequency, waveform, and stimulus duration and are convenient to use: They are small, lightweight, and don't heat up. By attaching a piece of Velcro "hook " material on the back of each tactor, their locations and the spacing in between them can easily be varied by sticking them to a stretch material that has a Velcro "loop" texture.

Initially, the force exerted by the tactors was measured with four subjects, by using a calibrated pressure transducer (developed at NAMRL) that resembles these tactors in appearance. This load cell replaced tactors at certain locations around the torso (such as navel, 3 o'clock position, spine, and 9 o'clock position) and the variation in loading was measured under different circumstances (like when the subject inhales or exhales or when she/he sits upright or bends over,…). The subjects in this calibration study wore a "sweat belt", that the tactors were attached to, as well as an additional supportive belt (both described below) during the measure, like they did in the formal experiments themselves.

The force varied considerably between and within subjects (range 4.51-52.38 gr; Mean=21.69 gr), depending on a subjects posture and breathing movements, which, of course, cannot be avoided during the experiments. However, studies have shown that cutaneous spatial resolution is relatively independent of the force of application (Johnson, Van Boven, & Hsiao, 1994). Nevertheless, we tried to avoid changes in force by carefully fastening the belt containing the tactors around the subjects' waist and by having them sit in an upright position by using a kneeling-chair (chair that did not have a back-sometimes called an "ergonomic" chair).

Figure 6.1: Vibrotactile stimulator: C2-tactor. A detailed description is given in the text above.

The tactors were driven with sinusoidal waveforms of 250 Hz and 80 Hz. Displacement amplitude and stimulus waveform could be monitored by a small accelerometer attached to the open back of the tactor. Driving the tactors with frequencies lower than 80 Hz wasn't possible, because the frequency response of the system distorted the sinusoidal waveform at higher intensities, thus changing the stimulus' characteristics. Driving signals were generated by a Wavetek function generator that could be programmed to produce various patterns of voltage (such as sine waves) at a variety of frequencies and amplitudes. An IEEE-488 bus provided control over vibration frequency and intensity and could activate a single one or a group of tactors for any duration.

The perceived stimulus intensity was set to a level of 20 dB SL: In order to ensure that every subject perceived the stimuli with perceptible and comparable vibrotactile loudness, a threshold measure was carried out prior to each testing session. The stimuli were presented at an intensity level of ten times this threshold measure. A detailed description of the measuring procedure will be given below.

As many as thirty-six of the Velcro-mounted tactors were placed in equal distances around the subject's waist on an elastic belt (a commercially available "sweat-belt"), in three rows of 12 tactors. The belt was 19 cm wide and the spacing between each row was 5 cm, as shown in Figure 6.2. The distances between the columns varied with the subject's waist-circumference. To absorb the sound produced by the tactor's vibration a special acoustic foam-like material (about 1 mm thick, invented at NAMRL) was wrapped around the belt. Furthermore subjects wore headphones to eliminate any acoustical cues or distractors. To help keep the subjects in an upright position an additional supportive belt (with "ribs" in the back, like a corset) was wrapped around the subjects' waist.

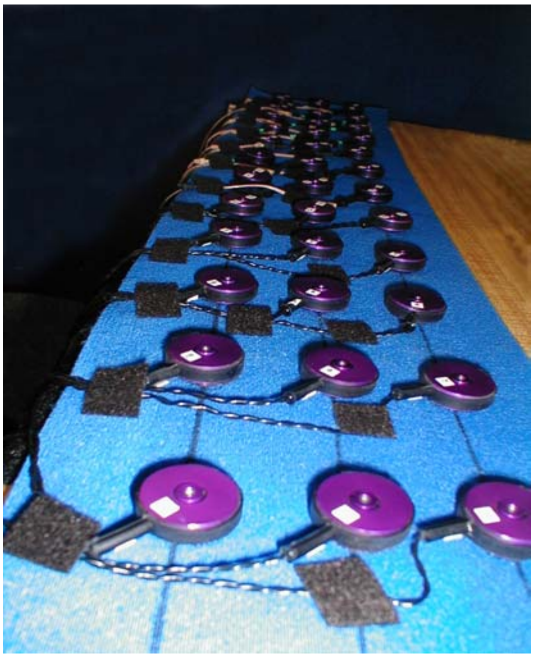


Figure 6.2: Vibrotactile array: "Sweat-belt" with three rows of 12 tactors each. The array was wrapped around the subject's waist, while the subject was seated in an upright position at the table.

A ten-button keyboard, as shown in Figure 6.3, served as the response device in all experiments. If fewer than ten keys were required, the unused keys were covered with a paper strip. The response keys in a particular experiment were labeled according to their usage. On one side of the keyboard there was an additional key, labeled "AL" (for: Alignment button), which subjects had to press to go to the next step in the testing procedure or to initiate the next stimulus during the test series.

Figure 6.3: Response device: Ten-button-keyboard; the "Alignment button" can be seen at the far left side; the keyboard could be moved to the position that is most comfortable for subjects.

An alpha-numeric display was mounted on the wall in front of the subjects, providing task-related information, like the current phase of the experiment ("Rotating Tactors", "Threshold Measure", "Block 1"'…) or short instructions to let the subjects know what keys they were supposed to press. A computer controlled the stimulus parameters, stored the data and was programmed to calculate descriptive statistics such as frequencies.

6.3 Vibrotactile Stimuli

During each experiment the percepts evoked by different spatio-temporal patterns were studied. The impact of the period of time that each tactor vibrates (SD) and the interval between the end of vibration of one tactor and the beginning of vibration of the next tactor (ISI, as in the papers of Geldard and Cholewiak) are of interest, as well as the effect of different spatial settings.

Seven different SDs and seven ISIs spaced at roughly logarithmic intervals were generated for the two vibration frequencies of 80 Hz and 250 Hz. For 80 Hz stimuli 12.5 ms were required to complete a full sinusoidal cycle, while only 4 ms were required to cover a sinusoidal cycle at 250 Hz. To have similar temporal parameters for 80 Hz and 250 Hz stimuli patterns we chose the following durations:

For 250 Hz stimuli we used: 16 ms, 24 ms, 32 ms, 48 ms, 64 ms, 96 ms and 128 ms. These durations are equivalent to 4, 6, 8, 12, 16, 24 and 32 sinusoidal cycles of the 250 Hz signal (4 ms period).

For 80 Hz stimuli we used: 12 ms, 25 ms, 37 ms, 50 ms, 75 ms, 100 ms, 125 ms. These durations are equivalent to 1, 2, 3, 4, 6, 8 and 10 sinusoidal cycles of the 80 Hz signal (12.5 ms period).

All possible combinations of these intervals resulted in a set of 49 SD-ISI temporal stimulus patterns. It is known that saltation occurs over a broad range of time intervals: It is vivid at ISIs between 20 and 200 ms, which is the reason why the above range of temporal intervals were chosen.

Four different spatial settings were used in the experiments: Either all three rows of tactors or just the middle row was activated. Also either 8 or all 12 tactors-columns were activated. The combinations of these conditions resulted in four different spatial settings. Although saltation has been observed at spacings ranging from 2 cm to 35 cm between activated loci, a distance of 10 cm (on the forearm) has typically been used to study the phenomenon. The circumference of our subjects' waist varied approximately between 75 cm and 100 cm. The application of 12 tactors, equally spaced around the torso, resulted in spatial separations of 6-8 cm between the tactors. If the number of tactors was reduced to eight, the distances increased to 9-13 cm. Thus, the spatial separations employed in this study were close to the intensely studied distance of 10 cm among taps. There was also a practical reason to use 12 or 8 tactors: One application for the "Tactile Situation Awareness System" (TSAS), on which this belt is modeled, is to provide threat or target location to aircraft pilots. They are typically trained to use clock times (12 o'clock,…) or the eight cardinal points on the compass (north, northeast,…) to specify a location in space.

Stimuli consisted of successive bursts of vibration presented to each or a subset of tactors on the belt in order to simulate movement on the body. In these experiments, two presentation modes were used: The successively activated and the saltatory modes. Corresponding patterns had identical temporal parameters and the total number of bursts was the same, but the number of loci activated differed. In the successively activated mode, every tactor was activated successively (see Figure 6.4), while in the saltatory mode, only every second tactor was vibrating (see Figure 6.5; note: In Pilot Study 2 also every third and every forth tactor was activated; a detailed description will be given in the corresponding chapter). During the saltation mode two bursts of vibration were presented at the first location (the navel), two at the third, two at the fifth and so on, with an additional final single burst at the first tactor at the navel. The pattern of activation started and ended each time at the navel, so that subjects could not tell the difference between the successively activated and the saltatory patterns on the basis of the traversed lengths of the patterns. In addition, in order to get the stimuli at the last location to "jump" in saltation, we needed a final "attractant"–the single tap at the end of the sequence. Consequently, in the 8-tactor condition there were actually nine bursts, while in the 12-tactor condition, there were 13 bursts of vibration. Subjects weren't told that there were two different stimulus patterns (successively activated and saltatory). Figures 6.4 and 6.5 describe the time course of stimulation for the two different stimulus patterns.

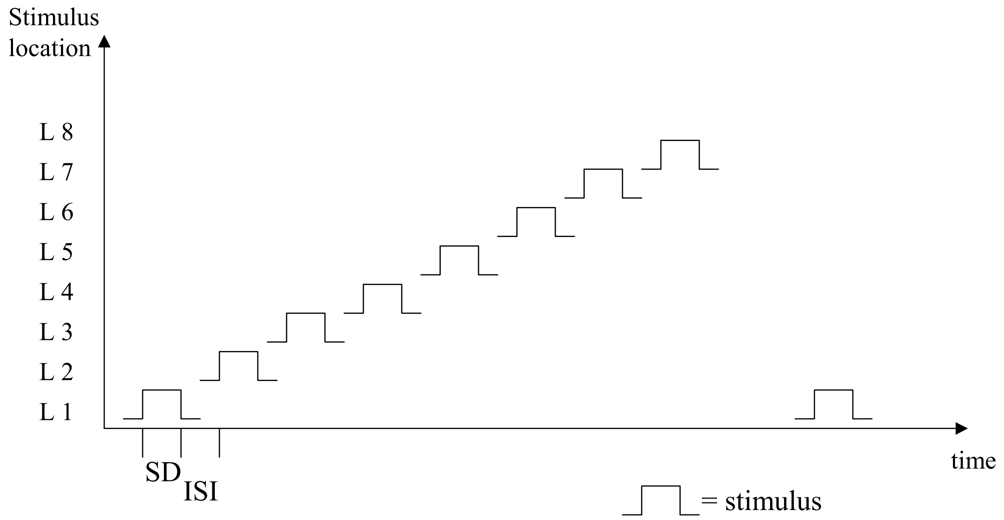


Figure 6.4: Schematic representation of a successively activated stimulus pattern consisting of eight tactors; L1-L8 mark the different stimulus locations around the torso (L1 marking the navel; L5 marking the spine; note: Movement always starts and ends at the navel); SD is the time, a tactor vibrates, ISI is the time between the offset of one and the onset of the next stimulus. Each tactor is successively activated once.

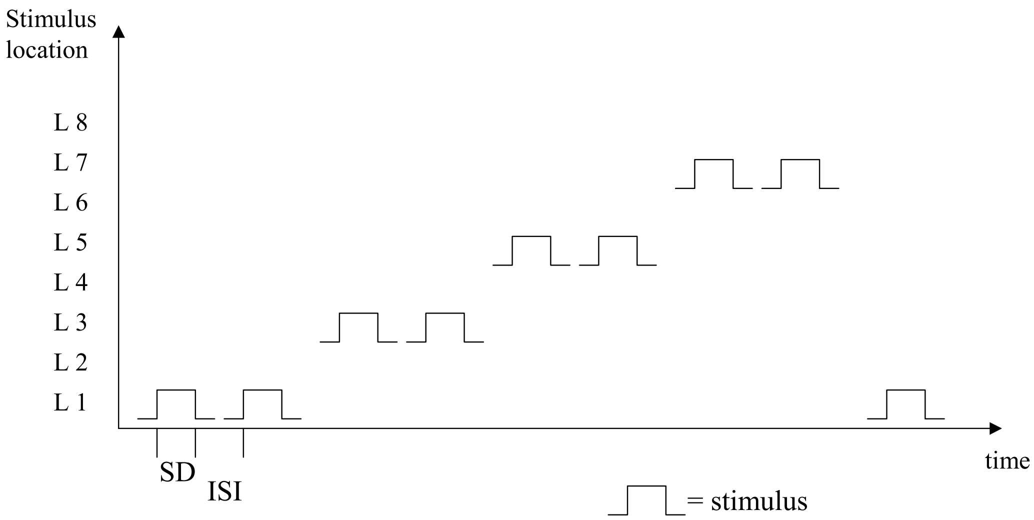


Figure 6.5: Schematic representation of a saltatory stimulus pattern consisting of eight tactors; L1-L8 mark the different stimulus locations around the torso (L1 marking the navel; L5 marking the spine; note: Movement always starts and ends at the navel); SD is the time, a tactor vibrates, ISI is the time between the offset of one and the onset of the next stimulus. The first, third, fifth, and seventh tactor are activated twice, and the navel (L1) activated once to complete a full circle around the torso.

6.4 Experimental Procedure

After subjects were informed about the purpose of the study, they filled out a "Voluntary Consent Form" and a "Medical Questionnaire" (see Annexes A[5] and B). Only subjects who didn't report any medical conditions that might affect their ability to participate in the study were allowed to go on. Skin temperature was measured and it was taken care that temperature ranged between 31° and 35° Celsius, as skin temperature is known to influence vibratory

[5] Note: As the reported experiments and the preceding localization experiments (Cholewiak, Brill & Schwab, 2004) have been applied for in the same "Human Use Protocol" there is a common "Voluntary Consent Form" for both experiments. Thus, the "Voluntary Consent Form" in the annex contains passages that have been formulated for the localization experiments, nevertheless, the form was also signed by our subjects, after they have been informed about the purpose of our experiments.

threshold, dependent on the type of mechanoreceptor activated (see Verrillo & Bolanowski, 1986; Weitz, 1941). In every experiment subjects' age, waist, and handedness were recorded.

Subjects wore a standard all-cotton T-shirt provided by the laboratory for testing to make sure that everybody wore the same type of clothing between the tactors and the skin. After subjects changed into the T-shirt, their waist was measured and their naval was marked with a felt-tip pen on the shirt. To determine the position of the belt, a mark was set one inch (2.54 cm) above the navel. For testing, subjects were seated in a comfortable, ergonomic kneeling-chair, which had no backrest. The belt was placed around the torso, so that the tactor activated first and last in the pattern was located at the mark set before. Standardized instructions were read to the subjects by the experimenter and important contents were reviewed by either the computer-controlled visual display or paper boards.

Before the test started, subjects were presented with a familiarization pattern in which each of the (8 or 12) tactors in the middle row was activated sequentially, producing a sensation of "rotation" around the trunk. This pattern served two purposes: First it insured that all of the tactors were working properly and second, that they were making adequate contact with the skin. The visual display read "Rotating Tactors", indicating the availability of the familiarization pattern and subjects could then feel the bursts of vibration by starting the patterns themselves by pressing the "AL"-key. After a preparatory delay of 600 ms, a 110 ms long burst of vibration occurred sequentially at each of the tactors, with an ISI of 300 ms between each burst. The "Rotating Tactors" could be repeated as often as necessary–but was presented at least three times–to ensure that every tactor touched the skin, which is especially critical at the spine where the circumference shows a more or less distinctive "indentation". Subjects were requested to count the tactors as they went along to guarantee that they felt a tactor activate at every position.

To ensure that subjects perceived the test-patterns with clearly palpable and comparable levels of intensity, the next step in the procedure was a threshold measure. Subjects were instructed to rerun the "Rotating Tactors", starting at a clearly suprathreshold level. If subjects couldn't feel any one tactor, they informed the experimenter and intensity was increased by 20% steps until the subject was able to feel every tactor clearly. Now, with every repetition, the intensity level was decreased by 10%. As soon as the subjects could not feel any one tactor, the procedure stopped–by subjects pressing the number 1 key on the keyboard–and the actual intensity level (in volts) was measured, recorded and increased 10 times (20 dB SL) for the experiment to follow. Every subject's threshold, the number of steps until one tactor couldn't be felt and the tactor's number were recorded.

Each testing session consisted of several blocks of trials. A trial is defined as a single presentation of a stimulus pattern. The numbers of blocks and trials was a function of levels of the variables tested. To move to the next stimulus the subjects had to press the "Alignment button" on the keyboard, so they were in control when the next stimulus was presented. In between the blocks the subjects could take a brief break if they wished. There was no time limit for the subjects' responses and no feedback was given.

After each testing session the subjects were interviewed to determine whether they experienced any difficulties during the test and notes were taken on any remarks the subjects made.

6.5 Overview of Experimental Designs

In most experiments there were two groups of subjects: One group was tested with 80 Hz stimuli, one group with 250 Hz stimuli. Every experiment's design was a multifactor design with repeated measures. As the experimental design varies for each experiment, it will be presented in detail in the corresponding chapters (Chapters 7-12). Below, an overview of the independent and dependent variables is given.

6.5.1 Independent Variables

1. Stimulus patterns:
    - Successively presented stimuli (one stimulus, that is one burst of vibration at each location)
    - Saltatory stimuli (two or more stimuli at every second, third, … location)

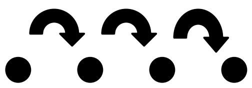
2. Vibration frequency:
    - 80 Hz
    - 250 Hz

3. Seven different levels of SD

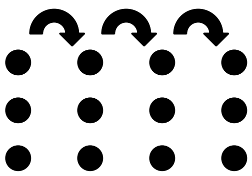
4. Seven different levels of ISI

5. Number of tactors on the linear array:
    - 8 tactors
    - 12 tactors

6. Stimulus width:



moving dot; every dot represents an activated tactor



moving line; again every dot represents an activated tactor; three tactors, one upon the other, are simultaneously activated

7. Direction of movement (only Pilot Study 1):
    Clockwise or counter clockwise around the subjects' torso

8. Different modes of saltation (only Pilot Study 2):
    Saltatory patterns differed with regard to the number of pulses delivered to each activated site, concurrently the distance in-between activated sites varied

9. Stimulus onset location (only Experiment 3)
    The onset location of a seven tactor array–that spanned half of the torso−varied: The starting point was either the navel, the spine or left or right side of the torso

Note that detailed information about the independent variables for each experiment is given in the corresponding chapters.

Figure 6.6 below provides an overview of the variations of the independent variables for a 80 Hz stimulus. The figure would look the same for a 250 Hz stimulus.

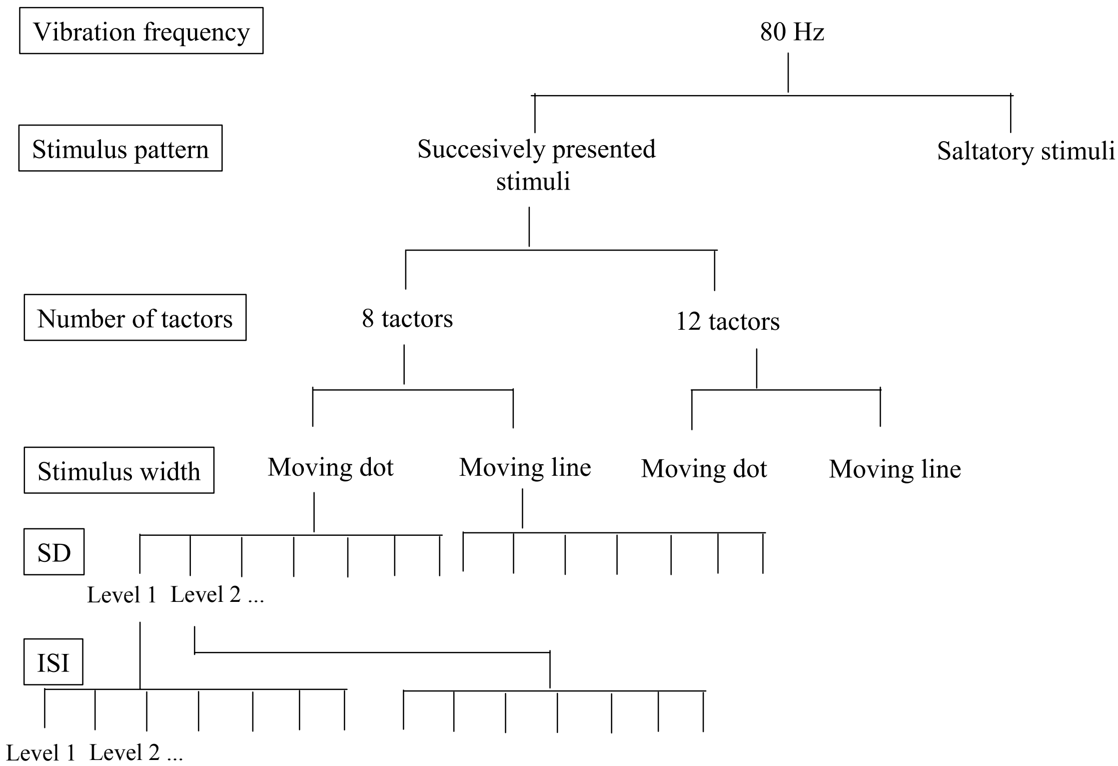


Figure 6.6: Overview over the independent variables and their variations for an 80 Hz stimulus.

6.5.2 Dependent variables

The constructs measured are the following dependent variables:

Pilot Study 1: Direction discrimination

Pilot Study 2: Discriminability between saltatory and successive motion

In this pilot study discriminability was specified as preference for one stimulus pattern. If no difference between the patterns is perceivable preferences should be randomly distributed over trials between the two stimulus patterns (saltatory and successively activated).

Experiment 1: Perception of the “goodness” of apparent movement

The “goodness” of movement was described by the four qualities straightness, smoothness, spatial distribution, and length that had to be judged by the subjects. If saltatory and successively activated stimuli produce the comparable percepts of movement, both patterns should be affected similarly by our independent variables.

Experiments 2&3: Discriminability between saltatory and successive motion
Discriminability was specified as either corrects discriminations or preference for one stimulus pattern.

6.6 Measures

Pilot Study 1: Subjects had to indicate if the direction of movement was clockwise or counter-clockwise by pressing a corresponding key on a keyboard. The number of correct and incorrect responses was counted for each subject and over subjects.

Pilot Study 2: In a two-alternative-forced-choice paradigm subjects had to choose the stimulus pattern that felt "best" in terms of continuous motion around the torso. Every trial consisted of one saltatory and one successively activated stimulus pattern with varying spatio-temporal parameters (see Chapter 9 for detailed description). When subjects chose a saltatory stimulus pattern a score of 0.00 was recorded, when a successively activated stimulus pattern was picked, a score of 1.00 was entered. The number and percentage of votes for one stimulus pattern was calculated for each subject and over all subjects.

Experiment 1: Perception of apparent movement was measured by subjects' ratings of four qualities of movement that describe the "goodness" of motion on a 10-point scale. The qualities to be judged were straightness, smoothness, spatial distribution, and length. On the 10-point scale "1" marked the least straight and smooth movement, the poorest spatial distribution and the shortest range of the flow. The number 10 indicates the straightest and smoothest movement as well as the most equal spatial distribution of the stimuli. For the quality length there is a specific feature: The number 9 on the scale marks a full circle around the waist (from navel to navel), the "10" suggests on overshoot (movement outreached its origin at the navel). For a detailed description of the different qualities see Annex C and Chapter 10. Subjects' ratings (1-10) served as row score.

Experiments 2&3: The ability to discriminate between saltatory and successively activated motion was measured using a same-different design. On each trial the subjects had to decide whether two stimulus patterns presented were the same or different. The answer "same" is a correct response to same pattern pairs (both patterns saltatory or both patterns successively activated) and an incorrect response to different pattern pairs (one pattern saltatory the other pattern successively activated). The number of “same” answers was counted over trials and subjects, separately for same and different pairs. Additionally in Experiment 2, subjects had to decide in a two-alternative-forced-choice paradigm, which of the two presented patterns displays the best percept of continuous motion. Like in Pilot Study 2, preference for a saltatory pattern was coded with 0.00, preference for a successively activated pattern was coded with 1.00. Again, the number and percentage of votes for one stimulus pattern was calculated for each subject and over all subjects. In Experiment 3 we calculated first the total number and percentage of correct responses, that is correct discriminations, over all subjects and trials. In a next step we differentiated between same pairs and different pairs and used the number of “same” answers as a measure of discriminability between saltatory and successive motion.

6.7 Statistical Analyses

Mean (M), range, and minimum (Min.) and maximum (Max.) describe the distribution of the subjects’ age.

Pilot Study 1: As we expect only very few incorrect responses (wrong identification of direction) we will only describe the stimulus parameters where discrimination errors accumulated and will forgo statistical tests.

Pilot Study 2: χ^2-Tests were performed for each subject to test if the number of votes for the saltatory and successively activated stimulus patterns fit to a 50:50 distribution. Additionally, χ^2-tests were applied to test if subjects’ preferences for one stimulus pattern are equally distributed over the seven levels of SD and ISI.

Experiment 1: The data for the statistical analysis are subjects’ judgments on the 10-point scale for each quality. There were no missing values since subjects could only proceed to the next trial when they had pushed a button on the 10-key-keyboard. Since it cannot be assumed that the intervals on the 10-point scale are equidistant in subjects’ perception, nonparametric methods were used. As a measure of central tendency the median is chosen. The range or interquartile range served as a measure of statistical dispersion. To test differences between independent samples (effect of vibration frequency on judgments) a Mann-Whitney U-Test was calculated. For related samples (effect of number of tactors on the linear array on judgments and effect of stimulus width) a Test of Marginal Homogeneity was used. To assess if the seven levels of the temporal parameters SD and ISI or the duration of movement exerted an increasing influence on the integration of discrete stimuli, a Trend test (Page 1963) was applied. To check interaction effects between SD and ISI, correlation coefficients (Kendall's Tau) between ISI and the quality ratings were calculated for each subject, broken down by the lowest and highest value of SD. The two sets of correlation coefficients–one for the lowest level of SD and one for the highest level of SD–were then tested with a sign-test. If the difference between the correlation coefficents equals null, we proceed according to Bortz, Lienert & Boehnke (2000, p. 257): If we get even-numbered null differences one half will receive a positive, the other half a negative algebraic sign. If the number of null differences is odd-numbered, the number of observations will be reduced by one.

Experiments 2&3: To test whether every level of SD and ISI accounted for the same percentage of "same" answers, separate χ^2-tests were performed for each subject, and a binomial test was used to test if the number of significant results exceeds chance. McNemar χ^2-tests were used to test if stimulus width affected discriminability and to evaluate the effect of stimulus repetition. To check for effects of frequency, χ^2-tests were conducted. In the second part of Experiment 2 ("which is best") we performed χ^2-tests for each subject to test if subjects' preference for one stimulus pattern is randomly distributed between the two patterns. A Binomial test over all subjects tested if the significant results from the multiple χ^2-tests occur more frequently than random. To test the effects of the remaining independent variables we used the same tests as described above.

In Experiment 3 we used χ^2-tests to evaluate if the number of correct responses and the number of "same" answers are equally distributed over the different positions of the 7-tactor array. Temporal effects were tested in the same way as in Experiment 2.

The level of α was always set to .01. Some of the tests and correlation coefficients (Mann-Whitney U-Test, Kendall's Tau) were conducted with the help of the statistic software SPSS, other tests (χ^2-tests, Page test) were carried out with a pocket calculator. The statistical procedures that we used are described by Bortz, Lienert, and Boehnke (2000) and Bortz (1999). We also made use of the tables for the significance of the test statistics provided by these authors.

7 Calibration Study: Determination of vibrotactile thresholds on the torso

In this preliminary study the variations in tactile sensitivity around the circumference of the trunk at the level of the tactile array to be used in the later studies was explored. For this purpose vibratory thresholds were measured at six different body sites around the abdomen for six different stimulus frequencies. Variations in threshold magnitudes over sites would be expected, since the tissue characteristics vary from the belly around to the spine and because the different types of mechanoreceptors vary in their density and location. This preliminary study is of importance for the following experiments as variations in detection sensitivity might influence the perception of movement around the torso: If we find significantly different thresholds over body sites we might have to vary intensity over sites to ensure that sensation magnitude does not serve as a cue to differentiate between different patterns of movement. This study was carried out at the Cutaneous Communication Laboratory at Princeton University, whereas the following studies took place at the Tactile Research Laboratory at NAMRL. The results of this study have been published in Perception & Psychophysics (Cholewiak, Brill & Schwab, 2004).

In a comparable study Sherrick (1953) found quite similar sensitivity curves for the tongue (bone-free tissue) and the index finger (bony tissue). More specifically, Wilska (1954) examined vibratory thresholds on a number of body sites, but to my knowledge no study has ever systematically examined vibratory thresholds at different locations *around* the torso.

7.1 Subjects

Five subjects participated in this experiment: One male and four females. Four subjects were students at Princeton University, one was a member of the laboratory staff. The average age of the subjects was 24 (range 20-29). They all had prior experience with tactile experiments, as well as with threshold measures. This was desirable because of the demands of this particular task, including the time commitment and attention to threshold-level stimuli. None of them reported any medical condition that might have affected their ability to perceive the stimuli used in this study. Students received a reimbursement for their participation.

7.2 Apparatus

A wide-band vibratory device was used to stimulate the skin in this study, a Bruel & Kjaer 4810 minishaker (Figure 7.1), whose moving skin contactor is 7 mm in diameter, indenting the skin 0.5 mm beyond the static Plexiglas® surround. Between the contactor and the surround there is a gap of 1 mm. The contactor itself is actually a PCB 303A accelerometer that is used to monitor the stimulus waveform and to measure the actual amplitude of the threshold stimulus intensity at the end of the session (described below). The shaker is mounted on a jointed balance-arm that allows the contactor to be placed on different positions perpendicular to the subject's body while maintaining a fixed static force. The pressure that is exerted by the shaker on the subject's skin was about 50 grams.

The frequency and intensity of the sinusoidal stimuli, as well as their timing parameters were controlled by a computer. This computer also stored and analyzed the data. A four-button keyboard (with keys labeled with the numbers 1-4) served as the response device. Task-related information was shown to the subjects on a portable visual display.

Figure 7.1: Bruel & Kjaer 4810 minishaker used as stimulator in this study. Please refer to the text above for a detailed description.

7.3 Vibrotactile stimuli

In this experiment, the vibrotactile thresholds were determined for six different stimulus frequencies: 25, 50, 80, 160, 250 and 320 Hz. These cover the greatest part of the range of frequencies to which the skin is sensitive. The sinusoidal stimuli had a rise-fall time of 25 ms and a duration of 500 ms. The test method used was a two-alternative forced-choice adaptive tracking (2-AFC) paradigm. This is a highly efficient and robust method, providing reliability even for small samples (Levitt, 1971). Subjects were presented with a series of trials, each of which included two intervals: The stimulus occurred during one of the two intervals (randomly chosen) while the vibrator was silent during the other interval. Subjects had to judge which of the two intervals contained the vibratory stimulus. If they identified the interval incorrectly, the stimulus intensity was increased by one step. If the interval was identified correctly three times in a row the intensity was reduced by one step. A constant step size of 1 dB was used except in the initial trials in which it was 3 dB so as to quickly converge to near-threshold levels. The intervals were separated in time by 1000 ms.

Subjects had to track the changing intensity until they completed a total of twelve reversals (a change from increasing to decreasing or vice versa) or a maximum of 90 trials, whichever occurred first. There was a total of six blocks, one for each frequency. The blocks were always presented in the same order, from the lowest to the highest frequency.

7.4 Procedure

First the testing sites on the torso were marked: At a level one inch above the navel the 12, 2, 4, 6, 8, 10 o'clock positions were tagged. These positions resemble a clock where the 12 o'clock position is the navel and the 6 o'clock position the spine. The subject would then lay down on a table that was covered with a mattress. Different pillows were used to stabilize the subject in a position that allowed the experimenter to place the contactor on the bare skin so that the surface of the skin and the contactor were both level (Figure 7.2). The skin temperature was measured and if it fell below the range of 31°and 35° Celsius, a heating pad was used to warm it up. During the experiment the subjects wore earplugs to eliminate the sound of the bursts at the higher frequencies.

Figure 7.2: Positioning of the contactor on the subject's skin. Test sites were six sites, located equidistant around the abdomen, at a level one inch above the navel. The subject's body was carefully stabilized and the Bruel & Kjaer 4810 minishaker on the balance-arm was placed horizontally on the bare skin.

The starting intensity value was determined by a rough measurement of threshold at the beginning of the session, as follows: After the contactor was placed on the testing site for that session, the stimulus frequency was set to 25 Hz and the experimenter initiated a bursting 500-ms stimulus pattern interrupted by short silent intervals every 2 s. The intensity of this stimulus was increased manually by the experimenter from a level clearly below threshold until the subject could just start to feel the bursts. This level was then automatically increased by the computer program by 6 dB for the very first trial. This step was conducted at 25 Hz because it is the frequency to which the skin is least sensitive, so the level obtained represents the strongest stimulus that might be expected during the session. Following this measurement, subjects began to track the stimuli in the 2-AFC test.

Before the test series started, the following instructions were read to the subjects:

> In each trial there will be two time intervals. During one of these intervals, a stimulus will be presented. Your job is to press the key that corresponds to the interval in which the stimulus was presented. This means press the

key labeled “1” if you feel the burst during the first interval and press the key labeled “2” if you feel the burst during the second interval.

Most of the time the stimulus will be weak. There may be trials in which you don’t feel anything in any of the intervals, but make your best guess. We do expect that you will get some of them wrong, so try not to get frustrated.

We will start at a level where you should be able to feel the stimulus. When you answer correctly the intensity of the stimulus will be reduced and when you answer incorrectly the intensity will be increased.

To start the testing sequence, subjects had to press the number four key on the keyboard. The visual display showed the word “READY” and the next keystroke on either of the two response keys initiated the first trial. After the two intervals were presented and the subjects had responded, the visual display read “READY” again and then subjects could start the next trial by pressing one of the response keys. Consequently, subjects controlled when the next trial was presented. There was no feedback given whether their answers were correct. A flashing light and a loud click (clearly audible even with the earplugs) marked each of the two intervals. Additionally, the numbers 1 and 2 were counted off on the visual display to indicate the intervals.

Subjects were informed of the number of blocks and told that the number of trials in each block would vary depending on how quickly they would reach their threshold. From their participation in prior threshold measures on other body sites (finger, palm of the hand), subjects were aware of the changes in the perceived quality of the vibration that would occur over blocks of trials as the stimulus frequency changed. Each body site was tested in a separate session, the order of body sites was counterbalanced over subjects. Three of the subjects were tested twice at each body site. One subject could only be tested once at the six different sites and one subject served in only one testing session.

7.5 Results and discussion

At the end of the session, before removing the stimulator from the subject's body, threshold (in dB) was calculated from the average of the function generator settings over the final seven reversals for every frequency (25, 50, 80, 160, 250 and 320 Hz). After each physical dB setting was calculated, the threshold stimulus (frequency/ intensity combination) was again presented to the subject's skin. The physical stimulus intensity was then measured while the shaker was loaded by the skin using the integral contactor/ accelerometer. Threshold acceleration was converted to physical displacement (in microns), and the average calculated over subjects and sessions. Seven observations were made for each frequency and body site except for the 12 o'clock position where eight observations were obtained. Figure 7.3 shows the average of the thresholds for each frequency and body site, expressed in decibels (dB) with reference to 1-µm peak displacement . This measurement unit is used here because it is the unit that is commonly seen in the literature on tactile psychophysics. Specifically, the total peak-to-peak displacement of the sinusoidal stimulus that was calculated from the acceleration measurement is divided in half (producing peak displacement), and then converted into the logarithm of a ratio to 1 microm. The formula is:

20 * log10(peak displacement in microm/1 microm).

Consequently, a change of 6 dB indicates a doubling or halving, while 20 dB on this scale reflects a ten-fold difference in magnitude. Thus the 80-dB range on the ordinate represents a total of 4 log units - a 10 000-1 range of intensity.

The standard errors for the different test sites and frequencies varied between 1.50 and 7.12 dB, showing a quite large variation in the data. The largest standard errors were obtained at the 6 o'clock position (the spine). Because the body shape shows a more or less distinctive indentation at this site, it was difficult to ensure proper contact of the contactor with the skin at this site, adding to the variability.

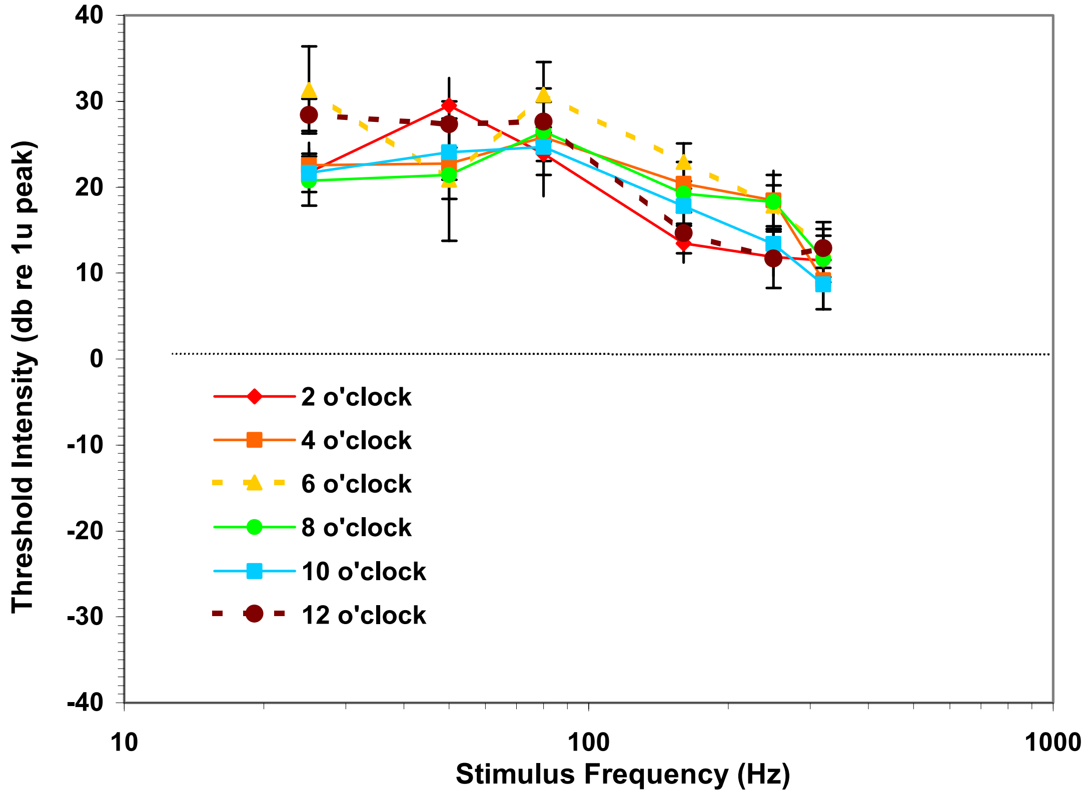


Figure 7.3: Vibrotactile thresholds in decibels with reference to 1-µm peak displacement for six different body sites on the abdomen and six different frequencies. Error bars signify the standard error of the means. The means are based on seven observations for the 2, 4, 6, 8, and 10 o'clock position and on eight observations for the 12 o'clock position. The threshold-frequency relationships for the different body sites do not seem the differ significantly.

A nonparametric test (Friedman Test) showed no significant differences among the different body sites at each of the frequencies. The subject who served in only one testing session was excluded. Table 7.1 shows the χ^2-values, corrected for ties, resulting from the Friedman Test.

Table 7.1: Results (χ^2-values) of the Friedman Test to evaluate if there are similar vibrotactile thresholds for each body site tested

Vibration frequency	Effect of test site (2, 4, 6, 8, 10 or 12 o'clock)
25 Hz	$\chi^2_{(.01;5;n=7)}=7.60$ n.s.
50 Hz	$\chi^2_{(.01;5;n=7)}=3.28$ n.s.
80 Hz	$\chi^2_{(.01;5;n=7)}=1.378$ n.s.
160 Hz	$\chi^2_{(.01;5;n=7)}=6.06$ n.s.
250 Hz	$\chi^2_{(.01;5;n=7)}=5.52$ n.s.
320 Hz	$\chi^2_{(.01;5;n=7)}=3.49$ n.s.

Note: Six body sites have been tested with six different vibration frequencies to evaluate detection thresholds around the torso. There were seven observations for each condition. Separate Friedman Tests have been carried out for each frequency. χ^2-values have been corrected for ties where necessary. None of the χ^2-values exceeds the critical level of $\chi^2=15.09$ ($\alpha=.01$, df=5), that is thresholds do not vary significantly with test sites.

In Figure 7.4, data from this study is plotted along with those from previous studies of the thresholds on the left index fingertip and the thenar eminence (large pad at the base of the thumb) of the left hand (from Goble, Collins, & Cholewiak, 1996). The same contactor and a similar method were used, the only difference was that in the study on the hand, there were three intervals, two silent ones and one containing the stimulus. (A study that directly compared the 2-AFC and 3-AFC tracking techniques at Princeton University found no significant differences between the two in these measures.)

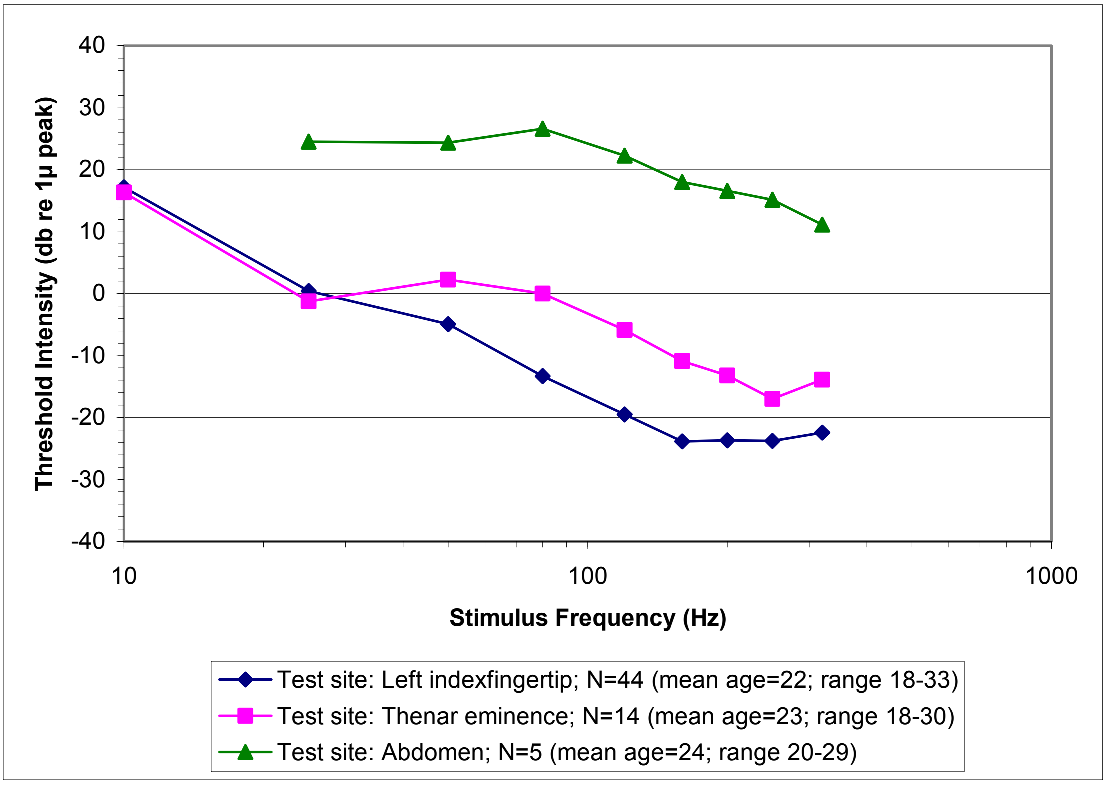


Figure 7.4: Comparison of thresholds (decibels with reference to 1-µm peak displacement) of three body sites (finger, thenar, and abdomen). Thresholds on the left index fingertip (blue line) and the thenar eminence (pink line) have been taken from the experiments of Goble, Collins & Cholewiak (1996). The green line is an average of the six different body sites of the abdomen, missing data points have been interpolated. The threshold-frequency relationship for the abdomen clearly differs from the threshold-frequency relationship for the glabrous skin of the hand.

Figure 7.4 compares the thresholds at the three body sites: Finger, thenar, and abdomen. The data of the finger and thenar showed much less variation: The standard error of the means ranged between 0.67 and 1.45, although the data were obtained from almost four to-nine times the number of subjects .

As Figure 7.4 illustrates, the vibratory threshold on the abdomen is significantly higher than the thresholds on the finger and thenar. In addition, the threshold-frequency relationship for the hairy skin of the abdomen is different from the threshold-frequency relationship for the glabrous skin of the finger and thenar. Although the threshold for the abdomen also decreases with higher frequencies, the curve is more flat than those for the finger and thenar which shows a more noticeable decline and a maximum sensitivity at 250 Hz (specifically, this is a manifestation of the contribution of the Pacinian Corpuscle population). The fact that the abdomen has a lower density of neural elements and a different receptor structure than the glabrous skin of the hand (see Chapter 2) might explain the differences in shape, the higher threshold level, as well the higher variability.

Weinstein (1968) evaluated tactile sensitivity for points touching the skin, but not vibrating against it, at numerous body sites using three different measures: Pressure sensitivity, two-point discrimination and point-localization. The two spatial measures, two point discrimination and point-localization correlated highly, showing that the fingers and the palm are significantly more sensitive than the belly. Alternatively, looking at pressure sensitivity thresholds, the fingers and the palm were significantly less sensitive compared to the belly.

Wilska's (1954) data are consistent with our findings: Vibratory thresholds are significantly higher on the abdomen than on the finger and thenar (compare Figure 2.2: Vibratory thresholds on a number of body sites). It seems that depending on the nature of the stimulus – single pulse or vibration – and the method used, different thresholds are obtained.

As a practical outcome of this preliminary study for the experiments to follow we decided to carry out threshold measures at the beginning of each testing session to ensure that stimuli are clearly perceivable. However, we will not vary stimulus intensity over testing sites on the abdomen as detection thresholds did not vary significantly over sites. Thus, every site will be stimulated with the same intensity level. This intensity level will be adjusted for each subject due to the large variation in the threshold data of this study.

8. Pilot Study 1: Identification of the direction of tactile movement around the torso

Essick (1998) describes in his review article a number of studies where a linear relationship between directional sensitivity and the length of skin traversed was discovered. In these studies different kinds of stimuli like brushing stimuli, moving patterns on the OPTACON, an air stream, or a rolling wheel were used at different body sites. The length of skin traversed varied from a few mm to less than 10 cm. At less-well innervated test sites like the back, longer distances were required to achieve the same directional sensitivity as at highly innervated test sites like the finger pad.

The velocity of the moving stimuli also has an impact on discrimination performance: Essick cites studies that proved that the connection between directional sensitivity and the logarithm of velocity could be described as an inverted U-shaped function, with poor directional discrimination at the lowest and highest velocities employed while the best discrimination performance occurred at intermediate velocities. The velocity of motion at which subjects' directional sensitivity reached its peak differed with the test site: At highly innervated test sites, the peak sensitivity occurred at lower velocities than at less-well innervated test sites. There is also an interaction between the velocity and the traversed length: The effect of velocity on directional sensitivity was smaller for long lengths of skin traversed. At long lengths (note: the criteria for "long" differs with test site due to its innervation density), subjects obtained nearly 100% correct responses, even at high velocities; the longer the length of skin traversed, the higher the velocity limit could be.

Gardner & Sklar (1994) used the OPTACON to produce motion by successive activation of stimuli on the fingertip when they studied discrimination performance. They found that the length of skin that was stimulated was not crucial, but the number of pulses was (that is the number of activated mechanoreceptors). Stimulation of only two points was not sufficient for direction discrimination independent of the spacings between the two points (1.2-4.8 mm, two-point threshold on the finger is 2 mm). But discrimination performance increased linearly with the number of pulses and was close to 100% when eight or more pulses were delivered.

To my knowledge, no study has yet published data that examined directional discrimination for saltatory stimulus patterns, although Cholewiak and Collins (2000) did mention pilot work that explored this question with patterns presented to the arm. But studies on the impact of continuity of tactile motion suggest that stimuli delivered over long lengths of skin are judged primarily on the basis of positional cues (changes in position). Therefore, the discrimination performance should be independent of the stimulus patterns (successively activated or saltatory) applied in this pilot study.

In our first pilot study simulated movement travels around the whole circumference of the waist, which is a distance that exceeds by far the distances traversed in previous studies. We therefore expect discrimination performance to be nearly perfect, independent of temporal parameters (SD/ISI) and stimulus patterns (saltatory or successive activation).

If our data verifies our hypothesis we will drop the quality direction in the experiments to follow, as it adds no additional information about the quality of apparent motion or the differences in the perception of the successively and saltatory patterns.

8.1 Subjects

Seven subjects participated in the study: Six males and one female, aged between 23 and 33, mean age was 27. The male subjects were recruited from the Naval School's Command (in Pensacola, Florida)–future pilots waiting for their flying training. The female subject was a psychologist, working for NAMRL. Two subjects had prior experience with tactile experiments, but the equipment and the task of this earlier experiment were entirely different. None of the subjects reported any medical condition that might affect his/her sensitivity of the trunk or ability to operate the keyboard. Five subjects were right-handed as tested with the Edinburgh Handedness Survey.

8.2 Tactile stimuli

A description of the experimental equipment used in this pilot study is given in the "General Methods" section. Only the middle row of the 36 tactor array was activated. The distances between the tactors varied with the subjects' waist-circumference, which ranged between 67 and 97 cm, with an average of 89 cm. Thus, the distance between each activated tactor ranged between 5.6 and 8.1 cm. Stimulus frequency was 250 Hz. The tactors were activated sequentially in order to simulate movement around the torso.

Seven different levels of stimulus duration (SD) and interstimulus interval (ISI) spaced at roughly logarithmic intervals were studied: 16 ms, 24 ms, 32 ms, 48 ms, 64 ms, 96 ms and 128 ms. The direction of movement was either clockwise or counterclockwise. The combination of seven SD and seven ISI levels and two directions resulted in 98 trials per block. These trials were randomly presented in each block. Each testing session consisted of two blocks of trials: In one block every tactor was successively activated, in the other block only every second tactor was activated twice (saltatory pattern). The movement started and ended at the navel, so that subjects couldn't tell the difference between the two stimulus patterns on the basis of the traversed lengths of the patterns. Although the number of loci activated differed in the successively activated and saltatory stimulus patterns, the temporal parameters (SD/ISI) corresponded, as did the number of stimuli in both modes. Subjects were not told how many sites were activated, nor did they know that there were two different modes of presentation. The order of the two presentation modes varied randomly, some subjects started with the successively activated patterns block, some with the saltation block.

8.3 Apparatus

To judge the direction of tactile movement the subjects had to press one of two keys of a ten-key-keyboard. Eight of the keys were covered with a paper strip, so that only the two response keys were visible. These keys were labeled “1 clockwise” and “2 counterclockwise” and a small drawing, showing the corresponding direction, was added. On one side of the keyboard there was an additional key, labeled “AL” (Alignment button) which subjects had to press to go to the next step in the testing procedure or to get the next stimulus during the test series. An alpha-numeric display was mounted on the wall in front of them, providing task related information.

8.4 Procedure

The experimental procedure followed the steps described in the “General Methods” section: First the “familiarization pattern” was presented to make sure that tactors had proper skin contact. Subsequently they were presented with the threshold measure, followed by the trial series. A standardized instruction (see Annex D) was read to the subjects. They were asked to hit the key corresponding to the direction of movement as quickly and as accurately as possible. There was no time limit for entering an answer and no feedback given as to whether the answers were correct or incorrect.

In order to get the next stimulus, subjects had to press the “AL”-key, so they were in control of when the next stimulus was presented. Subjects were instructed that there were two blocks of trials and they could take a brief break in between the blocks if they wished. Before the subjects started the first trial, they were asked if they had any questions and requested to wear headphones to eliminate any acoustical cues or distractors.

After subjects pressed the “AL”-Key, there was a preparatory delay of 600 ms and then the first stimulus pattern was presented. When subjects had made their decision and pressed the number corresponding to the direction of the simulated movement, the visual display read "Ready" and subjects could press the "AL"-Key again to get the next stimulus pattern. After the test was completed subjects were interviewed if they had any difficulties performing the task, if the equipment was comfortable and if they noticed any differences between the presented patterns. On the average it took 13 minutes to complete the trial series.

8.5 Results

Post-test interviews with the subjects indicated that the equipment was comfortable and easy to handle. Nobody had problems understanding the task. Most people recognized when they made a mistake and many said that they pushed the wrong key only erroneously. Nobody realized that the two blocks were presented in different modes, but some subjects noted that the saltatory patterns would feel "smoother" and "less intense" than the successively activated patterns.

The percentage of correct direction discriminations exceeded 98% of the trials for each of the seven subjects. None of the subjects made more than three errors in the testing session, which consisted of 196 trials at a time:

- One subject made 0 mistakes
- Five subjects made 1 mistake
- One subject made 3 mistakes

There was no accumulation of errors at any particular SD/ISI condition. Errors occurred over the whole range of possible velocities, from the slowest (SD=128 ms and ISI=128 ms; based on the average waist circumference of 89 cm this equals a velocity of 27.8 cm/s) to the fastest (SD=16 ms, ISI=16 ms, velocity = 222.5 cm/s). Figure 8.1 shows the different combinations of SD and ISI, where errors were found.

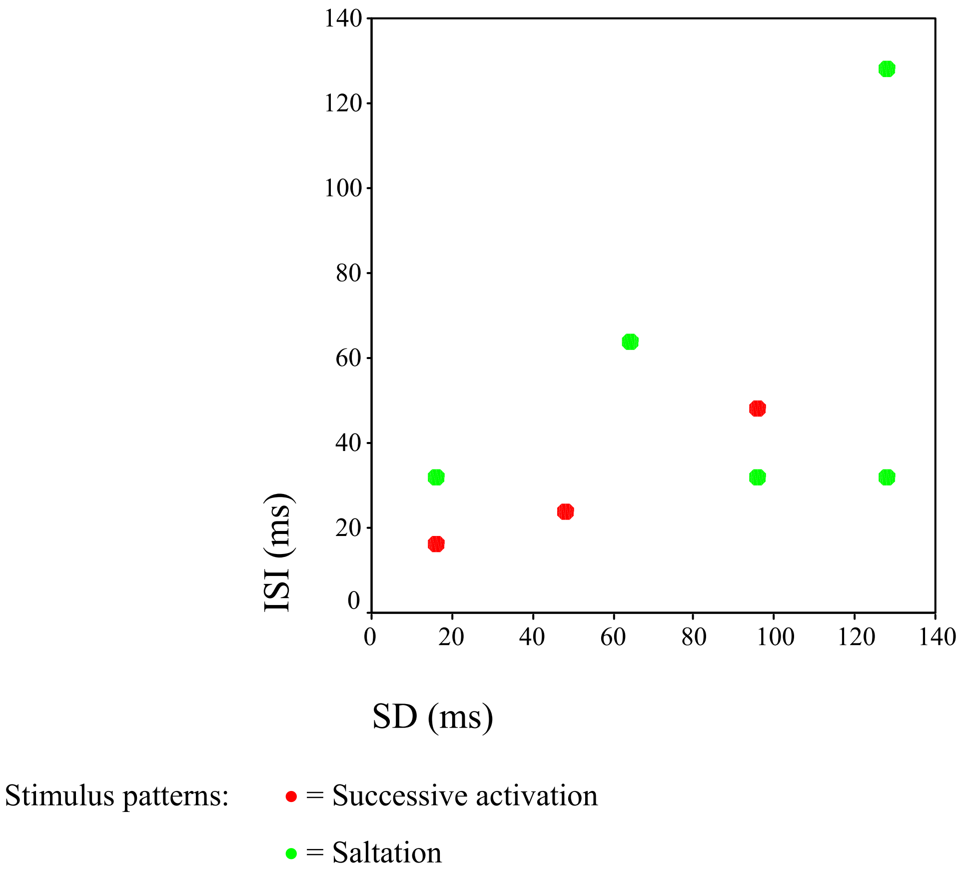


Figure 8.1: Distribution of discrimination errors at different SD/ISI combinations and stimulus patterns. Each dot represents a discrimination error that occurred at a certain temporal condition. Red dots mark errors that happened when successively activated patterns were presented, green dots, when saltatory patterns were presented. In total, eight errors were made by the seven subjects. Errors could be found over the whole range of SD/ISI combinations.

Figure 8.1 also demonstrates that about the same number of errors occur within each stimulus pattern:

- 5 out of 8 errors could be found for saltatory stimulus patterns,
- 3 out of 8 errors could be found for successively activated stimulus patterns.

Because the number of errors was so small (over all seven subjects there were eight errors in a total of 1372 trials), the percentage of correct answers so high, no statistical tests were performed.

We specifically explored if there were any other testing conditions where discrimination errors accumulated, but for the same reason as mentioned above, no statistical significance test could be carried out. There was a slight tendency that the direction of counterclockwise patterns was more often misjudged than the direction of clockwise patterns.

Because some of the subjects stated that the task was “very easy” and “boring” we examined the data for any evidence of fatigue, such as an accumulation of errors at the end of the testing session (which lasted between 10 and 15 minutes). But the same amount of errors occurred in the first and in the second block. It is most likely that the discrimination errors are due to a short lack of concentration.

8.6 Discussion

In the first pilot study we studied subjects’ ability to discriminate the direction of vibrotactile movement around the torso. Movement varied in terms of stimulus pattern (saltatory/successive activation), direction (clockwise/counterclockwise) and temporal parameters (SD/ISI). For the length of skin traversed in this study (movement around the torso), subjects’ direction discrimination performance was close to 100%, independent of temporal parameters and stimulus patterns (saltatory/successive activation). These findings correspond with those of Cholewiak and Collins (2000): In their experiment with a vibrotactile array on the arm (seven tactors, inter tactor distance of 27.5 mm, total extent of the array: 165 mm) subjects didn’t make mistakes in either stimulus pattern.

When movement travels around the torso along an array consisting of 12 tactors, velocity has no impact on directional sensitivity. With the temporal parameters and the length of the array we used in our study we have exceeded the criterion where direction can be undoubtedly discriminated.

As a practical conclusion of this first pilot study, we decided to drop the quality direction from further consideration in the experiments to follow. Furthermore, the experimental procedure as well as the testing equipment proved to be feasible for the following experiments. No subject had problems understanding the task and the belt that the tactors were attached to fit well.

For the main experiments we should keep one interesting point in view: While percepts of continuous movement requires spatiotemporal integration of discrete activated points, direction discrimination requires separation of activated sites in space and time. It will be interesting to see if the spatiotemporal parameters that are best for direction discrimination are also best or different for percepts of smooth, continuous movement.

9 Pilot Study 2: Limits of spatio-temporal integration dependent on the number of stimuli delivered to a stimulus location in the saltatory paradigm

In the second pilot study we want to explore the effect of the distance between activated stimulus sites, which is in these studies related to the number of stimuli at each activated site. The question was whether these variables limit the integration of saltatory stimulus patterns into a percept of continuous motion, where perceptual processes fill-in missing spots between activated sites.

In a two-alternative, forced-choice comparison subjects were asked to decide which of two vibrotactile patterns is best in terms of straightness, smoothness, and spatial distribution (for a definition of these qualities see Annex C). One of the patterns in each trial was successively activated, the other pattern was presented in one of three saltatory modes. The saltatory patterns differed with regard to the number of pulses delivered to each activated site, consequently varying the distance in-between activated sites (see Figure 9.1). In every case, the same overall distance was covered by the tactors and the same total number of stimuli was delivered in each stimulus pattern. Within a trial, the temporal parameters of the two patterns to be compared were identical.

Geldard (1982) compared veridical movement with saltation using a six tactor array that was placed on both forearms. On the left forearm the six contactors were stimulated successively, whereas on the right forearm three tactors, covering the same distance (the exact distance isn't specified by Geldard), were activated twice each. At interstimulus intervals (ISI) between 50 and 100 ms both patterns produced equal sensations: "A more or less continuous sweep punctuated by six evenly spaced taps" (Geldard, 1982, p. 140). When both patterns (successive activation and saltation) were alternately presented, the only difference was that saltatory patterns felt somewhat weaker.

In their experiment Cholewiak and Collins (2000) also tested if two vibrotactile patterns presented vertically on the back–one successively activated, one saltatory–produced comparable sensations. In successively activated stimulus patterns one stimulus was presented sequentially at all seven sites. In the saltatory mode, seven stimuli were presented at three sites: Three at the first, three at the fourth and one at the seventh site of a linear array. The experimental procedure they used was similar to ours. Their results indicate a strong equivalence of the two stimulus patterns. When subjects were asked to discriminate between the two stimulus patterns, their discrimination performance was better for short ISIs, but independent of SD. But, when subjects had to judge which of the two stimulus patterns was best in terms of continuous movement, neither SD nor ISI had a significant effect on the preference for one stimulus pattern (successively activated or saltatory).

These results show that different response paradigms (patterns are the same/different versus which of the two patterns produces better movement perception) lead to different results concerning the comparability of simulated movement produced by successively activated and saltatory stimulus patterns. Maybe the different response paradigms direct subjects' attention to different stimulus criteria: When subjects had to discriminate between the two stimulus patterns they might identify gaps between activated sites in the saltatory presentation mode–but then one would expect that these gaps occur at large ISIs, when stimuli are not as easily integrated. It remains an open question why the highest discriminability was found for the shortest ISIs.

When subjects had to decide which of two stimulus patterns is best they might focus more on the quality of movement of each pattern presented, to a lesser extent on the distinctions between the patterns. Since one practical aim of our experiments is to find the optimal spatio-temporal parameters for simulated movement for the design of tactile displays, we wanted subjects to judge which of the two stimulus patterns was best in terms of continuous movement. In the experiments to follow we will choose the best saltation mode for simulating movement and apply both response paradigms to further explore the results they generate.

Varying the number of stimuli per test site, as we do in our second pilot study, influences the temporal conditions for saltation as well as the size of the saltatory area: Increasing the number of pulses at each contactor requires shortening of the ISI to achieve well-distributed jumping between activated sites. Using the reduced rabbit paradigm, Geldard (1982) could show that the number of pulses at the first stimulus location influences the size of the saltatory area: The more pulses were delivered, the larger the saltatory leaps became.

The purpose of our studies is to find the optimal spatio-temporal parameters where successively and saltatory patterns both generate a percept of continuous motion. In this pilot study we focus on the spatial conditions, i.e. the distance between activated stimulus sites, respectively the number of stimuli at each activated site. We will thus test if there are there limits to the integration of saltatory patterns into a percept of continuous motion, when the number of activated sites and thus the distance in-between them is varied. We expect that as the successively activated and saltatory patterns are expected to produce equivalent percepts of apparent motion within the spatiotemporal limits used, there should be no preference for one pattern, regardless of the varying number of pulses in the different saltatory patterns and the varying distance in-between activated sites.

If the results of this pilot study show that the similarity between saltatory and successively activated patterns requires a certain distance in-between activated sites, or that a certain number of pulses has to be delivered to each site, these specifications for saltatory patterns should be selected for the experiments to follow.

9.1 Subjects

Six male subjects, recruited from the Naval Schools Command, participated in the study. They were between 24 and 30 years old, mean age was 26.3. Four subjects were right-handed. One subject was also tested in the prior pilot study (identification of direction). Nobody indicated any medical condition that might affect his ability to serve in the experiment.

9.2 Tactile stimuli

The same equipment as described in the General Methods section was used. Only the middle row of the 36-tactor-belt (three rows of 12 tactors) was activated. Seven levels of stimulus durations (SD) and interstimulus intervals (ISI) were studied: 16 ms, 24 ms, 32 ms, 48 ms, 64 ms, 96 ms and 128 ms. This time, the direction of movement was only clockwise. Stimulus frequency was again 250 Hz, as in the first pilot study.

In each trial, two patterns were presented: One saltatory, one successively activated. The patterns had identical temporal parameters, but the number of loci activated differed. Every tactor was either activated sequentially, or, in the saltatory patterns, the distance between activated tactors and thus the number of pluses delivered to each tactor varied. As before, in every presentation the number of stimuli was kept constant.

We generated three different modes of saltation in this pilot study:

In the **saltation mode 1** condition, two stimuli were presented at the first location (the navel), two at the third, two at the fifth and so on.

In the **saltation mode 2** condition, there were three stimuli at the first location, three at the fourth, three at the seventh and so on.

In the **saltation mode 3** condition every fourth tactor was activated four times.

Note, that the total number of stimuli was always the same, only the number of loci activated–and thus the distance in-between activated tactors–and how often a single locus was activated changed. Each time the movement started and ended at the navel although the last presentation was only a single presentation in every case. Figure 9.1 illustrates the different saltatory stimulus patterns:

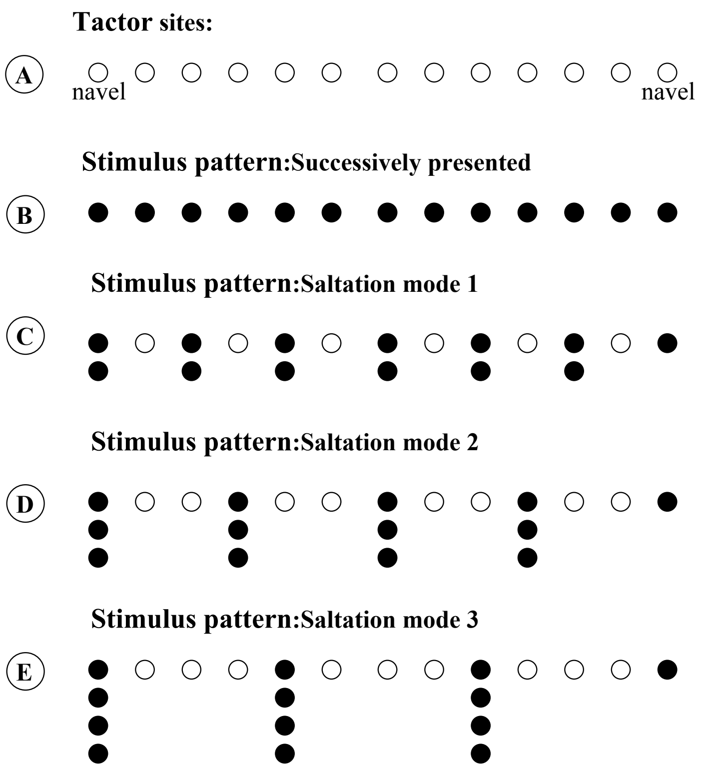


Figure 9.1: Visual representation of the different vibrotactile spatiotemporal patterns. Twelve stimulus locations (A) were spaced equally around the torso. Note, that the contactor at the navel was stimulated twice to complete a full circle around the torso. In the successively activated patterns (B) thirteen stimuli (the first and the last at the navel) were presented sequentially along the tactor sites. (Filled in circles indicate activated tactor sites.) In the saltation modes 1-3 (C-E) multiple pluses were delivered to tactors sites, although the total number of stimuli was kept constant (13 stimuli in each mode). The figure shows that the distance in-between activated tactor sites and the number of pulses at each site were concurrently varied.

The subjects' waist circumference ranged between 78 and 97 cm with a mean of 89.3 cm. Considering this average of 89 cm the spacings in-between the activated loci for the veridical and the three different saltation modes were as follows:

Successive activation: 7.4 cm

saltation mode 1: 14.8 cm

saltation mode 2: 22.3 cm

saltation mode 3: 29.7 cm

To compare the three different saltation modes to the successively activated stimulus patterns, three blocks of trials were generated. In each block the successively activated stimulus patterns were to be compared to one of the three saltation modes. Each block consisted of 98 trials: All possible combinations of the seven levels of SDs and ISIs were utilized and the order of the two different patterns (one successively activated, one saltation) was randomized. Subjects did not know that there were different stimulus patterns. The order of the three blocks was varied for each subject: Some subjects started with a comparison between the successively activated stimulus patterns and saltation mode 3 condition, some with a comparison between the successively activated stimulus patterns and the saltation mode 2 condition and some with a comparison between the successively activated stimulus patterns and the saltation mode 1 condition.

9.3 Apparatus

As response device, we used the same keyboard as in the previous pilot study, but eight of the ten keys were covered with a paper strip so that only the two response keys were visible. These were labeled “1” and “2”, indicating which of the two presented patterns the subject preferred – the first or the second one in the sequence.

The alpha-numeric display on the wall displayed task-related information to the subjects, like the current phase of the experiment (“Rotating Tactors”, “Threshold Measure”, “Block 1”’…) or short instructions (“Which is best 1 / 2”) to let the subjects know what keys they were supposed to press.

9.4 Procedure

The experimental procedure of this pilot study resembled the procedure specified in the General Method section. When the subjects were comfortably seated in the kneeling-chair they were instructed to judge, which of two stimulus patterns feels best in terms of continuous motion around the torso. Guidelines to determine this judgment were provided, and included: Which line feels straighter, smoother, and equally distributed in both, space and time (for complete instructions see Annex E). These guidelines were written on a piece of paper and hung on the wall in front of the subjects, just above the visual display, so the subjects could refer to the definition of "best" during the whole testing session. Subjects responded by pressing a button on the keyboard (number 1 for the first stimulus pattern and number 2 for the second). There were advised that there were no correct or incorrect responses and no feedback will be given.

After the familiarization pattern (each of the 12 tactors was sequentially activated) and the threshold measure, the first block of trials was presented. Subjects could start the presentation of the patterns themselves by pressing an extra key on the keyboard ("Alignment-key"). When subjects had started a trial there was a preparatory delay of 600 ms, before the first pattern was presented. After the first pattern, there was a short break of 2.4 s, before the second pattern was presented automatically. There was no time limit for the subjects' decision of which of the two patterns was best. Subjects were told that the testing session consisted of three blocks of trials and that they could take a brief break between the blocks if they wished and could start the following block themselves.

Before starting the first block subjects could ask questions and were required to wear headphones. On the average the testing duration was 36 minutes (Min.=27 minutes, Max.=46 minutes). After the test ended the experimenter interviewed the subjects to ask if they experienced any difficulties during the test. Notes were taken on any remarks the subjects made.

9.5 Results

The judgments were encoded as follows: When a saltatory stimulus pattern was chosen as best, a score of 0.00 was recorded, when a successively activated stimulus pattern was chosen, a score of 1.00 was entered. Subjects clearly preferred the successively activated stimulus patterns over all of the three saltation modes: In 85.3 percent of trials (accumulated over subjects) successively activated patterns were preferred. As the saltatory effect varies from subject to subject (see Stolle, 2003), we calculated χ^2-tests separately for each subject and also for each saltation mode to evaluate if the subjects' preferences are randomly distributed over the saltatory or successively activated patterns. Table 9.1 shows the results. None of the subjects preferred the saltatory stimulus pattern over the successively activated pattern. In the saltation mode 1 and saltation mode 2 condition there was one subject at a time which had no significant preference for one stimulus pattern. The preference for the successively activated patterns is clearest for the saltation mode 3 condition where the inter-tactor distance is the largest: Here, every subject preferred the successively activated patterns significantly more often and χ^2-values are predominantly largest.

Table 9.1: Results of the χ^2-tests to evaluate if subjects' preferences were randomly distributed over the two different stimulus patterns (saltatory versus ssuccessively activated patterns)

Subject	Saltation mode 1	Saltation mode 2	Saltation mode 3
AB	$\chi^2_{(.01;1;n=98)}=14.73$	$\chi^2_{(.01;1;n=98)}=62.08$	$\chi^2_{(.01;1;n=98)}=82.65$
MB	$\chi^2_{(.01;1;n=98)}=21.59$	$\chi^2_{(.01;1;n=98)}=2.00$ n.s.	$\chi^2_{(.01;1;n=98)}=50.00$
TW	$\chi^2_{(.01;1;n=98)}=62.08$	$\chi^2_{(.01;1;n=98)}=90.16$	$\chi^2_{(.01;1;n=98)}=94.04$
CD	$\chi^2_{(.01;1;n=98)}=52.90$	$\chi^2_{(.01;1;n=98)}=90.16$	$\chi^2_{(.01;1;n=98)}=18.00$
BH	$\chi^2_{(.01;1;n=98)}=1.47$ n.s.	$\chi^2_{(.01;1;n=98)}=75.47$	$\chi^2_{(.01;1;n=98)}=75.47$
MT	$\chi^2_{(.01;1;n=98)}=62.08$	$\chi^2_{(.01;1;n=98)}=65.31$	$\chi^2_{(.01;1;n=98)}=82.65$

Note: Successively activated and saltatory stimulus patterns were presented in one trial and subjects had to decide, which was best. χ^2-tests (α=.01, df=1) were performed separately for each subject and for each of three saltation modes. Each subject had to complete 98 trials (n=98) for each saltation mode. With two exceptions (denoted n.s.=not significant) subjects preferred the successively activated patterns significantly more often.

As can be learned from the χ^2-values in Table 9.1 the preferences for the successively activated patterns vary to a great extent between subjects and saltation modes: A large χ^2-value indicates that in a large number of trials a subject preferred the successively activated pattern over the saltatory pattern, a small χ^2-value indicates that the preferences are nearly evenly distributed over both patterns (preferences are close to 50 percent for both patterns). To illustrate the variation in subjects' data, Figure 9.2 shows the preference (in percent of trials) for the successively presented stimulus patterns for each saltation mode and for each subject:

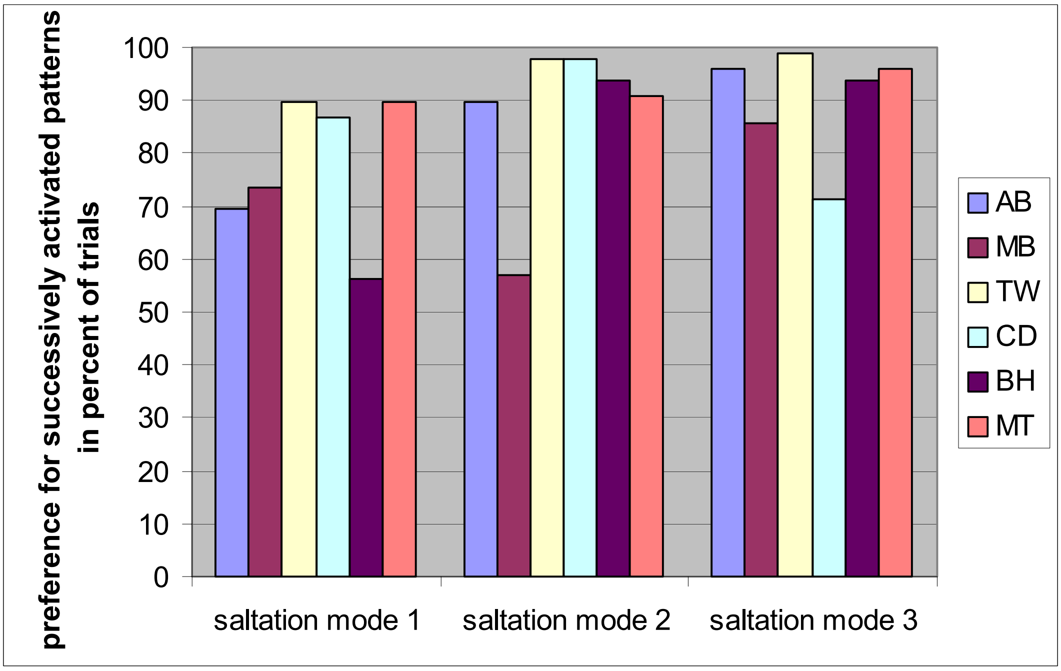


Figure 9.2: Subjects' preference (in percent of trials) for the successively presented stimulus patterns dependent on the saltation mode for each subject (N=6). Each subject had to complete 98 trials (*n*=98) for each saltation mode. The saltatory modes differed with respect to the number of stimuli delivered to a stimulus site (mode1: two stimuli at each activated site; mode 2: three stimuli at each site; mode 3: four stimuli at each site) and the distance between activated sites (smallest for mode 1, largest for mode 3). The preference for successively activated patterns was not always highest for saltation mode 3 (largest distance in-between activated sites) as one would expect: See for example subject CD, light green bar.

For most subjects the preference for the successively presented stimulus patterns tends to be largest for saltation mode 3, where the distance between activated sites is largest. It seems that with increasing distances in-between activated sites, saltatory movement feels more discontinuous and thus the successively presented stimulus patterns are preferred. But, if we look at subject CD (light green bar) we see a different result: The preference for the successively presented stimulus patterns is lowest for saltation mode 3. Subject CD started with the saltation mode 3 condition. Taking a closer look on the serial effects of the presentation of the stimuli, it becomes obvious that subjects' preference for one stimulus pattern depends on which saltation mode was presented first (a clear order effect). Table 9.2 shows the preference for successively activated patterns dependent on the saltation mode which generated the first block of trials.

Table 9.2: Percentage of trials (accumulated over subjects) where the successively activated patterns were preferred, dependent on the saltation mode which was presented in the first block in the forced-choice paradigm and subdivided into different saltation modes

	Preference for the successively activated patterns in %		
	Saltation mode 1	Saltation mode 2	Saltation mode 3
Start with saltation mode 1	62.8	91.8	94.9
Start with saltation mode 2	81.6	74.0	90.8
Start with saltation mode 3	88.3	98.0	85.2

Note: The shaded cells mark the condition, subjects started with. The preference for the successively activated patterns is not always highest for saltation mode 3 where the distance between activated sites is largest, it also depends on the saltation mode the subjects started with. This serial effect is discussed below.

Table 9.2 indicates that subjects' preference for the successively activated patterns increases with increasing distance in-between activated sites in the first block of trials (percentages increase diagonally from the top left corner of the diagram down to the right). Moreover, these data suggest that subjects' preference for the successively activated patterns is in each case lowest in the first block presented (percentage in the shaded cell is always the lowest percentage within one column). For example one can examine the last column: When the distance between activated tactors in the beginning of the experiment (block 1) is largest (saltation mode 3), so that the successively activated pattern are frequently preferred, they are even more frequently preferred in the subsequent conditions (saltation modes 2 and 1), even though the distance is smaller.

Next, temporal effects on subjects' preference were evaluated. Figure 9.3 shows the frequency of preference for stimulus patterns for each set of ISIs within a paired-comparison trial.

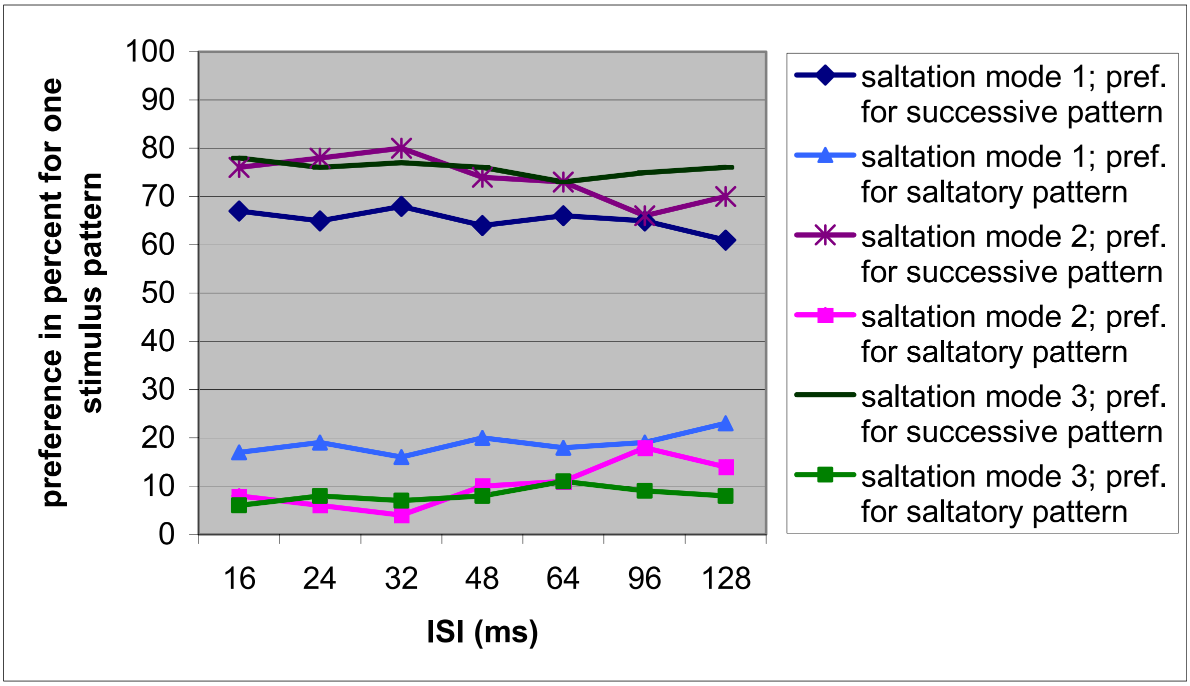


Figure 9.3: Preference (pref.) for one stimulus pattern (in percent of trials accumulated over six subjects) dependent on the saltation mode within a paired-comparison trial and ISI. Subjects had to decide which of two patterns (successively activated or saltatory) displayed best a percept of continuous movement. The saltatory modes differed with respect to the number of stimuli delivered to a stimulus site (mode1: two stimuli at each activated site; mode 2: three stimuli at each site; mode 3: four stimuli at each site) and the distance between activated sites (smallest for mode 1, largest for mode 3). There does not seem to be much variation in subjects' preference dependent on ISI.

Several χ^2-tests for each subject and each saltation mode showed that subjects' preference for successively activated stimulus patterns did not vary significantly with the level of ISI. The results of the χ^2-tests are shown in Table 9.3.

Table 9.3: Results of the χ^2-tests to evaluate if subjects' preferences for successively activated stimulus patterns were equally distributed over the seven levels of ISI

Subject	Saltation mode 1	Saltation mode 2	Saltation mode 3
AB	$\chi^2_{(.01;6;n=68)}=1.79$ n.s.	$\chi^2_{(.01;6;n=88)}=0.77$ n.s.	$\chi^2_{(.01;6;n=94)}=0.13$ n.s.
MB	$\chi^2_{(.01;6;n=72)}=0.33$ n.s.	$\chi^2_{(.01;6;n=56)}=6.75$ n.s.	$\chi^2_{(.01;6;n=84)}=1.83$ n.s.
TW	$\chi^2_{(.01;6;n=88)}=0.45$ n.s.	$\chi^2_{(.01;6;n=96)}=0.10$ n.s.	$\chi^2_{(.01;6;n=97)}=0.06$ n.s.
CD	$\chi^2_{(.01;6;n=85)}=0.24$ n.s.	$\chi^2_{(.01;6;n=96)}=0.10$ n.s.	$\chi^2_{(.01;6;n=70)}=0.60$ n.s.
BH	$\chi^2_{(.01;6;n=55)}=1.89$ n.s.	$\chi^2_{(.01;6;n=92)}=0.52$ n.s.	$\chi^2_{(.01;6;n=92)}=0.37$ n.s.
MT	$\chi^2_{(.01;6;n=88)}=0.45$ n.s.	$\chi^2_{(.01;6;n=89)}=0.58$ n.s.	$\chi^2_{(.01;6;n=94)}=0.13$ n.s.

Note: Successively activated and saltatory stimulus patterns were presented in one trial and subjects had to decide, which was best. χ^2-tests (α=.01, df=6) were performed separately for each subject and for each of three saltation modes. *n* varies, as the number of trials where subjects voted for successively activated patterns differed between subjects and saltation modes. No subject showed for no saltation mode a significant variation in its preference for successively activated stimulus patterns over the seven levels of ISI.

Next, we evaluated the effect of SD on the subjects' preferences, as shown in Figure 9.4. Again we performed χ^2-tests for each subject and each saltation mode to evaluate if subjects' preference is equally distributed over the levels of SD. The results are presented in Table 9.4.

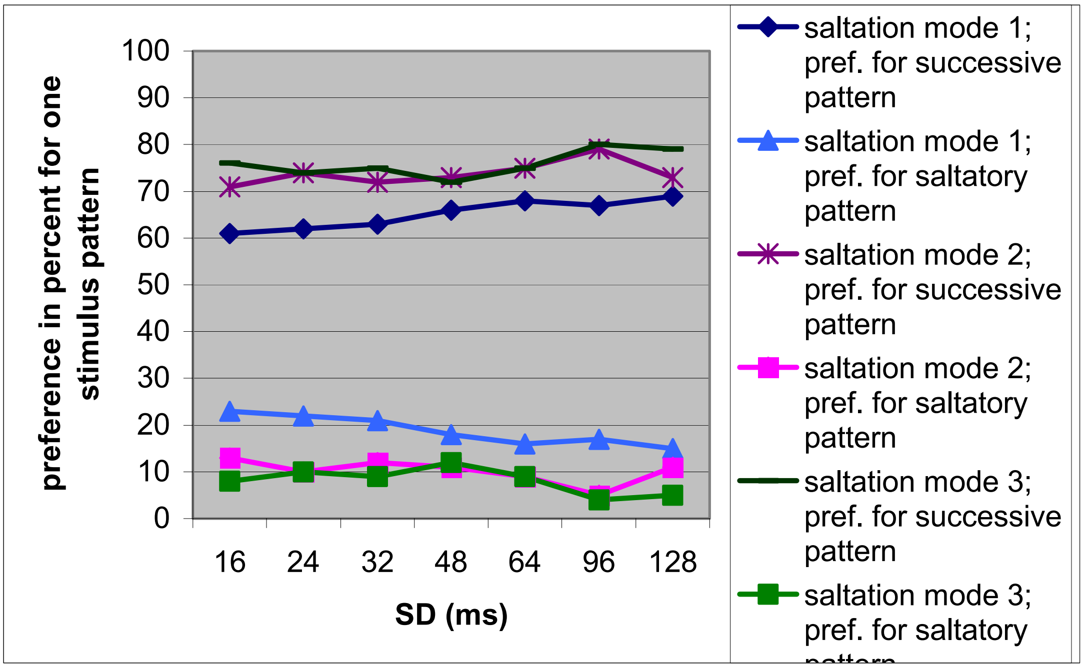


Figure 9.4: Preference (pref.) for one stimulus pattern (in percent of trials accumulated over six subjects) dependent on the saltatory mode within a paired-comparison trial and SD. Subjects had to decide which of two patterns (successively activated or saltatory) displayed best a percept of continuous movement. The saltatory modes differed with respect to the number of stimuli delivered to a stimulus site (mode1: two stimuli at each activated site; mode 2: three stimuli at each site; mode 3: four stimuli at each site) and the distance between activated sites (smallest for mode 1, largest for mode 3). Only for saltation mode 1 there seems to be a tendency, that the preference for successively activated patterns increases with increasing SD.

Although there is a tendency–at least for saltation mode 1, where the distance in-between activated tactors is smallest–that with increasing SD, subjects prefer the successively activated stimulus patterns more often, there is no significant difference in the preferences for successively activated stimulus patterns for the seven levels of SD (see Table 9.4).

Table 9.4: Results of the χ^2-tests to evaluate if subjects' preferences for successively activated stimulus patterns were equally distributed over the seven levels of SD

Subject	Saltation mode 1	Saltation mode 2	Saltation mode 3
AB	$\chi^2_{(.01;6;n=68)}=0.76$ n.s.	$\chi^2_{(.01;6;n=88)}=0.45$ n.s.	$\chi^2_{(.01;6;n=94)}=0.13$ n.s.
MB	$\chi^2_{(.01;6;n=72)}=0.72$ n.s.	$\chi^2_{(.01;6;n=56)}=4.00$ n.s.	$\chi^2_{(.01;6;n=84)}=0.33$ n.s.
TW	$\chi^2_{(.01;6;n=88)}=0.61$ n.s.	$\chi^2_{(.01;6;n=96)}=0.10$ n.s.	$\chi^2_{(.01;6;n=97)}=0.06$ n.s.
CD	$\chi^2_{(.01;6;n=85)}=1.88$ n.s.	$\chi^2_{(.01;6;n=96)}=0.10$ n.s.	$\chi^2_{(.01;6;n=70)}=2.60$ n.s.
BH	$\chi^2_{(.01;6;n=55)}=2.40$ n.s.	$\chi^2_{(.01;6;n=92)}=0.22$ n.s.	$\chi^2_{(.01;6;n=92)}=0.37$ n.s.
MT	$\chi^2_{(.01;6;n=88)}=0.77$ n.s.	$\chi^2_{(.01;6;n=89)}=1.06$ n.s.	$\chi^2_{(.01;6;n=94)}=0.28$ n.s.

Note: Successively activated and saltatory stimulus patterns were presented in one trial and subjects had to decide, which was best. χ^2-tests (α=.01, df=6) were performed separately for each subject and for each of three saltation modes. *n* varies, as the number of trials where subjects voted for successively activated patterns differed between subjects and saltation modes. No subject showed for no saltation mode a significant variation in its preference for successively activated stimulus patterns over the seven levels of SD.

9.6 Discussion

In this pilot study a forced-choice paradigm was used to investigate the equivalence between motion simulated by successively activated patterns and saltation. In each trial subjects had to compare a successively activated pattern to a saltatory pattern, generated with three different modes of saltation, each varying the distance between activated tactor sites and the number of pulses delivered to each site.

Effect of the distance between activated stimulus sites and the number of pulses at each site on subjects' preference for one stimulus pattern Contrary to our expectation, that there would be no preference for one stimulus pattern, regardless of the number of pulses in the different saltatory patterns and the corresponding variation in the distance in-between activated sites, we found the following result: Regardless of the distance between activated stimulus sites and the number of pulses at each site, subjects always preferred the successively activated patterns over the saltatory stimulus patterns. Thus, the percepts produced by both stimulus patterns seem to be different. We seemed to have crossed the spatial limits where saltatory patterns seem to be as evenly distributed as successively activated patterns.

If we try to compare our results to those of Cholewiak and Collins (2000) we should only consider trials where subjects started with the saltation mode 2 condition–three pulses at each contactor (since this is the saltatory stimulus pattern used by Cholewiak and Collins)–and only take into account the results of the first block to eliminate serial effects. The mean frequency of the judgments (binary coded: 0=saltation and 1=successively activated) was 0.64 in Cholewiak's experiment–indicating no significant difference between the different stimulus patterns–compared to 0.74 in our experiment. This small difference may be due to three factors:

1. Different spacing between tactors: In the "Princeton linear array" tactor separation was 27.5 mm, while in our experiment it was 74 mm on an average–nearly three times as much. But since saltatory leaping occurs over distances of 2-35 cm (Geldard, 1975) between activated sites on the arm, the illusion should also be demonstrable at the distances we used in the present experiment, even though innervation density on the torso is poorer.

2. Different placement on the torso: Cholewiak and Collins (2000) placed their array vertically on the lower aspect of the back, whereas our array was placed horizontally around the torso. Mrsic et al. (2004) could demonstrate that the amount of displacement, using the reduced rabbit paradigm depends amongst others on the direction of the saltatory stimulus pattern in relation to the body axis. This may account for the observed differences.

3. Crossing the body-midline: In our experiment, the saltatory movement crossed the body-midline, while in Cholewiak and Collins' (2000) experiments it did not. Experiments using the reduced rabbit paradigm showed that a saltatory area–no matter what body site was tested–was always truncated at the body-midline, when contactors were placed bilaterally (e.g. Geldard, 1982, Geldard & Sherrick, 1986). Geldard (1975) did mention, however, that if an additional stimulator is placed on the body-midline,

saltation occurs. In our present experiment we had three stimuli at the navel and three at the spine (saltation mode 2), so we would have expected that this saltatory stimulus pattern generates evenly distributed taps. Perhaps stimulating the body-midline initiated saltatory leaping to some extent, but not as evenly as the saltatory leaping would have been when the patterns were applied unilaterally as in Cholewiak and Collins (2000).

Effect of temporal stimulus parameters (ISI/SD) on subjects' preference for one presentation mode An effect of temporal parameters was not observed for any of the saltation modes. In their experiments Cholewiak and Collins (2000) also found, that temporal parameters (SD/ISIs in the range of 4-139 ms) did not affect equivalence between the two stimulus patterns. They explained these findings with a previous experiment that indicated that the quality of a line produced by vibrotactile stimuli–either successively presented or saltatory–depends strongly on temporal parameters. As these temporal parameters were held constant in the paired comparison, lines presented in either mode should feel the same. Consequently, the temporal parameters of the successively and saltatory patterns ought to differ within one trial to obtain an effect of ISI or SD. So, the lack of an effect of ISI might be due to the experimental setting, although in our experiment the two stimulus patterns failed to produce comparable sensations.

Serial effects Although this was not the main purpose of this pilot study we also analyzed serial effects of pattern presentation. Depending on the order in which the two stimulus patterns were presented in one trial and the order of the saltation modes, subjects' preference for the successively activated versus the saltatory stimulus patterns changed. It appeared that once subjects recognized that some tactors were skipped while others were activated several times (saltation)–which is most obvious at the saltation mode 3 condition–they may be more likely to perceive the difference between the two stimulus patterns. It is more likely then that they will find the successively activated pattern as straighter, smoother and more equally distributed compared to the saltatory pattern. Once subjects detect the principle of saltation, they may pay more attention to the spatial distribution of the pulses and are able to make a distinction between the saltatory and successively activated patterns, also if the gaps between the activated sites get narrower.

This result is reminiscent of the findings of Kilgard and Merzenich (1995): They added a fourth stimulus to the reduced rabbit at the second stimulus site. When subjects were told to concentrate on the proximal or distal region of the forearm, where the stimuli were delivered, the location of the second and third taps shifted up and down the forearm in the attended direction. Therefore they stated that “the perceived location of stimulus pairs were largely determined by subjects’ selective attention and/or expectation” (Kilgard & Merzenich, 1995, p. 663). Subjects who have detected that stimuli are bunched up at certain locations (saltatory patterns) might thus more-easily localize the veridical position of stimuli in the succeeding stimulus patterns.

The dynamic behaviour of neural networks might help to interpret our findings: That the cortical representation of the tactile body map adapts dynamically to the focus of attention was demonstrated amongst others by Braun et al. (2001). Once subjects in our pilot study detect gaps in-between activated sites (in the saltatory patterns) they may subsequently concentrate on these gaps to differentiate saltatory from successively activated patterns. Thus the cortical representation of the distance in-between activated sites might expand for saltatory patterns, facilitating the detection of gaps in subsequent trials, even when those gaps become smaller. This finding would agree with Braun et al.’s (2001) finding that if subjects focus their attention on certain stimulus locations (in our present experiments these would be the stimulus sites were multiple stimuli are presented in the saltatory patterns) the cortical representation of the distance between those sites would be larger than when subjects concentrate on the whole stimulated area (which would be the case when the saltatory and successively activated patterns produce the indistinguishable percepts of motion).

As a practical outcome of this pilot study, we wanted to choose the saltation mode that was most similar to the successively activated patterns. If we only consider trials where subjects started with the saltation mode 1 condition and only look at the results of the first block (comparison between a saltation mode 1 and a successively activated pattern), the mean of the judgments was 0.63, which is still significantly different from a value of 0.5 which would indicate that there is no preference for one stimulus pattern ($\chi^2_{(.01;1;n=196)}$=12.76). However, if the result was a mean of 0.59 judgments would be randomly distributed. In only seven more trials–out of 196–subjects would have had to answer "the saltatory pattern is better" to reach this random distribution.

For the following experiments we therefore chose the saltation mode 1, as it produces the most similar sensations compared to the successively activated patterns.

10 Experiment 1: Integration of different spatio-temporal stimulus patterns into a percept of continuous motion measured by quality judgments

In the first experiment we will focus on the question whether two different stimulus patterns–one saltatory, one successively activated–can be comparably integrated into a percept of continuous motion. Such a transformation of tactile information by central neural networks would comprise the perceptual merger of successive stimuli, i.e. the blanks between successive stimuli are filled in to create the illusion of uninterrupted movement. The premises of such an integration process are studied by varying different spatio-temporal stimulus parameters. Judgments of the quality of movement will serve as correlates for the success of this integration process. Stimuli are presented along an array around the trunk about 2.5 cm above the navel.

Temporal effects By varying SD and ISI we will analyze the temporal conditions for the integration of discrete stimuli (saltatory and successively activated stimulus patterns) into a precept of continuous motion. According to the hypothesis described in Chapter 5 we expect that shorter ISIs enhance the merger of discrete stimuli, thus quality judgments should improve for shorter ISIs for both stimulus patterns. The effect of SD on the illusory percept of motion produced by successively presented stimuli is such that increasing SD has been found to improve the quality of apparent motion, but for saltatory stimulus patterns the effect of SD is largely unknown. If we assume that both stimulus patterns undergo the same integration process we hypothesize that longer SDs enhance the integration of both stimulus patterns into a percept of continuous motion, thus quality judgments should improve for longer SDs. An increase in SD should also support the merger of saltatory and successively activated stimulus patterns into a percept of continuous motion over a wider range of ISIs, i.e. we expect to find an interaction between SD and ISI.

Spatial effects In this experiment we will vary the number of test sites, that is the number of activated tactors on the array that spans the whole circumference of the torso. Since we will keep the total length of the array constant, the number of test sites will be confounded with the spacing in-between activated tactors: The more tactors are active in a particular pattern, the shorter the distance in-between them will be. Since we expect that not only the temporal, but also the spatial relatedness between discrete stimuli enhances their integration we assume that increasing the number of stimulus sites and thus decreasing the distance between activated sites will lead to better quality judgments for both stimulus patterns.

Stimulus width as defined as in Chapter 5–three vertically placed, simultaneously activated tactors–is not expected to affect the integration of either spatio-temporal stimulus pattern into a percept of continuous motion. Thus quality judgments for both stimulus patterns should not differ for wide (three tactors) and narrow (single tactor) stimuli.

Effects of vibration frequency In this experiment we will use two different vibration frequencies: 80 and 250 Hz. The effect of vibration frequency on the integration of the two stimulus patterns into a percept of continuous motion should not be significant. Thus quality judgments for both stimulus patterns should not differ for the two different vibration frequencies.

10.1 Method

Subjects In this experiment we tested 28 subjects with 250 Hz stimuli and 20 subjects with 80 Hz stimuli. In the 250 Hz group there were 22 males and 6 females. The subjects' age ranged between 22 and 33 years (M=25.0). 21 subjects were right-handers, and 7 subjects were left-handers. Out of the 20 subjects tested with 80 Hz stimuli there were only two females and 18 males. The youngest subjects were 22 years old, the oldest subject was 29 years old (M=23.8), 16 were right-handed, 3 were left-handed, and one was ambidextrous.

Procedure For this experiment we used the apparatus and stimulus parameters described in the General Method section. The task of the subjects was to judge each one of the following qualities:

- Length
- Straightness
- Smoothness
- Spatial Distribution

These qualities are identical to those used in Cholewiak and Collins (2000) study. After extended pilot testing the authors found that these qualities are the most suitable ones to reveal differences between the two stimulus patterns and are the most relevant for potential applications in mobility, orientation, threat notice, and direction-finding. Due to the results of Pilot Study 1 we excluded direction as a studied quality.

All of the possible combinations of SD and ISI levels and the two stimulus patterns (saltatory and successively activated) were presented in one block (resulting in 98 trials per block). Only one quality was to be judged in each block, so there were four blocks per session. The order of qualities was randomized in each session. There were four sessions per subject, each session representing a different spatial condition (8 versus 12 tactors, one versus three simultaneously activated tactors). The spatial conditions were also randomly ordered over the four testing sessions, which took place on four consecutive days. The direction of movement was always clockwise and the first and last stimulus were presented on the navel.

The experimental procedure followed the steps described in the General Method Section with one exception: To acquaint subjects with the temporal varieties of the stimulus patterns they were presented with three sample patterns before the test series started. The visual display read “Flo Samples” and subjects were able to start the sample, consisting of consecutively presented stimuli, by pressing the “AL”-button. The first sample pattern presented was the fastest one in terms of stimulus duration around the torso (250 Hz stimuli: SD=16 ms/ISI=16 ms; 80 Hz stimuli: SD=12 ms/ISI=12 ms). The visual display read “Fast Ready” and after pressing the “AL”-key again, the pattern was initiated after a 600 ms delay. The second sample pattern was presented at medium velocity (250 Hz stimuli: SD=48 ms/ISI=48 ms; 80 Hz stimuli: SD=50 ms/ISI=50 ms) following the same procedure while the third pattern was the slowest one possible (250 Hz stimuli: SD=128 ms/ISI=128 ms; 80 Hz stimuli: SD=125 ms/ISI=125 ms).

Just before the test series started, instructions were read to the subjects (see Annex F). They were told to make judgments of a certain quality of movement after the presentation of a stimulus pattern, by pressing a button on the keyboard (number 1 meaning “least” to number 10 meaning “most”). They were also informed that there were no correct or incorrect answers. In addition, a definition of each quality was given to the subjects.

<u>Length:</u> How much surface area does the line cover along the length of the array? This may vary depending on the time of the bursts und burst durations. You may perceive the

length as being a complete circle, a little shorter than a circle, or a little longer than a circle as though the stimulus overshoots its origin at your navel.

Straightness: Does the line feel straight? Does the line zigzag at all? Does it bend over? Does the line stray to one side or another?

Smoothness: Does the line feel smooth? Is the line movement smooth or choppy? Some lines may feel like distinct taps in different locations (coarse), while others seem to be a unitary event (smooth).

Spatial Distribution: Does the line feel well distributed spatially? Do the taps seem to be equally distant from one another spatially? Do the lines feel bunched up at certain locations?

Subjects were instructed that the sensation will often fall in-between the extremes of the 1-10 scale; in this case they should press the one of the numbers from 2-9 that correlates best with the sensation. To indicate the poorest parameter value (the shortest, less straight, less smooth or most spatially irregular line), subjects had to press the button labeled “1” on the keyboard. If they perceive the movement to be the straightest, smoothest and most regularly distributed possible, they were to press the button labeled “10”. Only for the quality length was a different instruction applied: To indicate a full circle around the torso (starting and ending at the navel) subjects were to press the button labeled “9”, if they perceived an overshoot of any extent they were to press the number “10”.

At the beginning of each block, the name of the quality to be judged was indicated on the visual display. In addition, a paper board with the particular definition of the quality to be judged was placed in front of the subjects for the whole duration of the block. By pressing the “AL”-button the subjects could start a trial. After a preparatory interval of 600 ms the stimulus pattern was presented. Afterwards, subjects could take as much time as they needed to report their judgment by pressing one of the ten buttons on the keyboard. No feedback was given throughout the testing sessions. Subjects were allowed to take a brief break in between the blocks if they wished.

Stimuli In accordance with the results of Pilot Study 2 we chose the following saltation pattern: Two stimuli were presented at the first location, two at the third, two at the fifth and so on. That is, in the saltatory pattern every second location was stimulated twice. The second pattern consisted of single stimuli consecutively presented at each location (successively activated pattern).

Experimental design Independent variables were SD (seven levels), ISI (seven levels), number of tactors on the linear array (8 or 12 tactors), stimulus width (single tactor versus three simultaneously activated tactors), and vibration frequency (80 and 250 Hz). Dependent variables were the four qualities of movement to be judged on the 10-point scale. Because of the large number of independent variables, every subject was tested with every combination of the independent variables only once.

10.2 Results

In the following analyses the four different qualities of movement: Straightness, smoothness, spatial distribution, and length will be regarded separately, as in Cholewiak and Collins (2000) study where they found that spatio-temporal stimulus parameters affected the different qualities to different extents. The medians of the judgments were calculated for each stimulus condition to be examined. Since we cannot prove that our data complies with the requirements of a cardinal scale, we will use nonparametric tests.

10.2.1 Temporal effects

In the following analyses we will concentrate on tactile arrays containing only one row of tactors. The effects of stimulus width (one row of tactors versus three rows of tactors) will be considered separately.

Effect of ISI on quality judgments

The effect of ISI on the integration of spatio-temporal stimulus patterns will be examined separately for the two different stimulus patterns (saltatory and successively activated), the different vibration frequencies (80 and 250 Hz), and the different number of tactors on the linear array (8 and 12 tactors).

Figures 10.1 to 10.4 show the effect of ISI on the quality ratings.

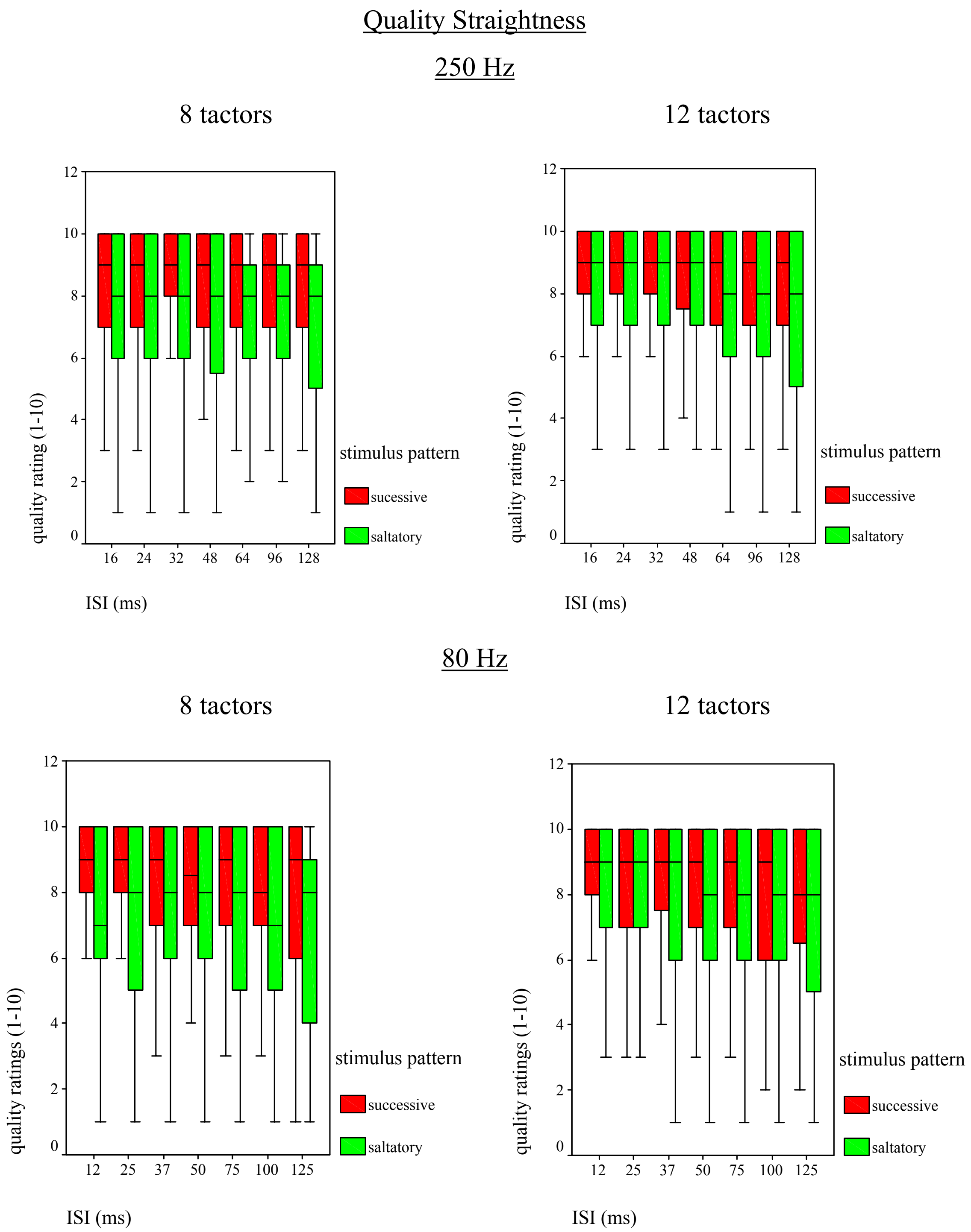


Figure 10.1: The effect of ISI on the quality ratings for straightness on the 10-point scale is shown for the two different stimulus patterns (successively activated patterns are diagrammed in red bars, saltatory patterns in green bars), the number of tactors on the linear array (8 and 12 tactors), and the two vibration frequencies (250 Hz and 80 Hz). The boxplots represent the median, quartiles and extreme values (up to 1.5 fold of the interquartile range) of the ratings for every level of ISI over subjects tested in the particular condition. It seems that only for saltatory patterns containing 12 tactors is there a trend where quality ratings decrease with increasing ISI.

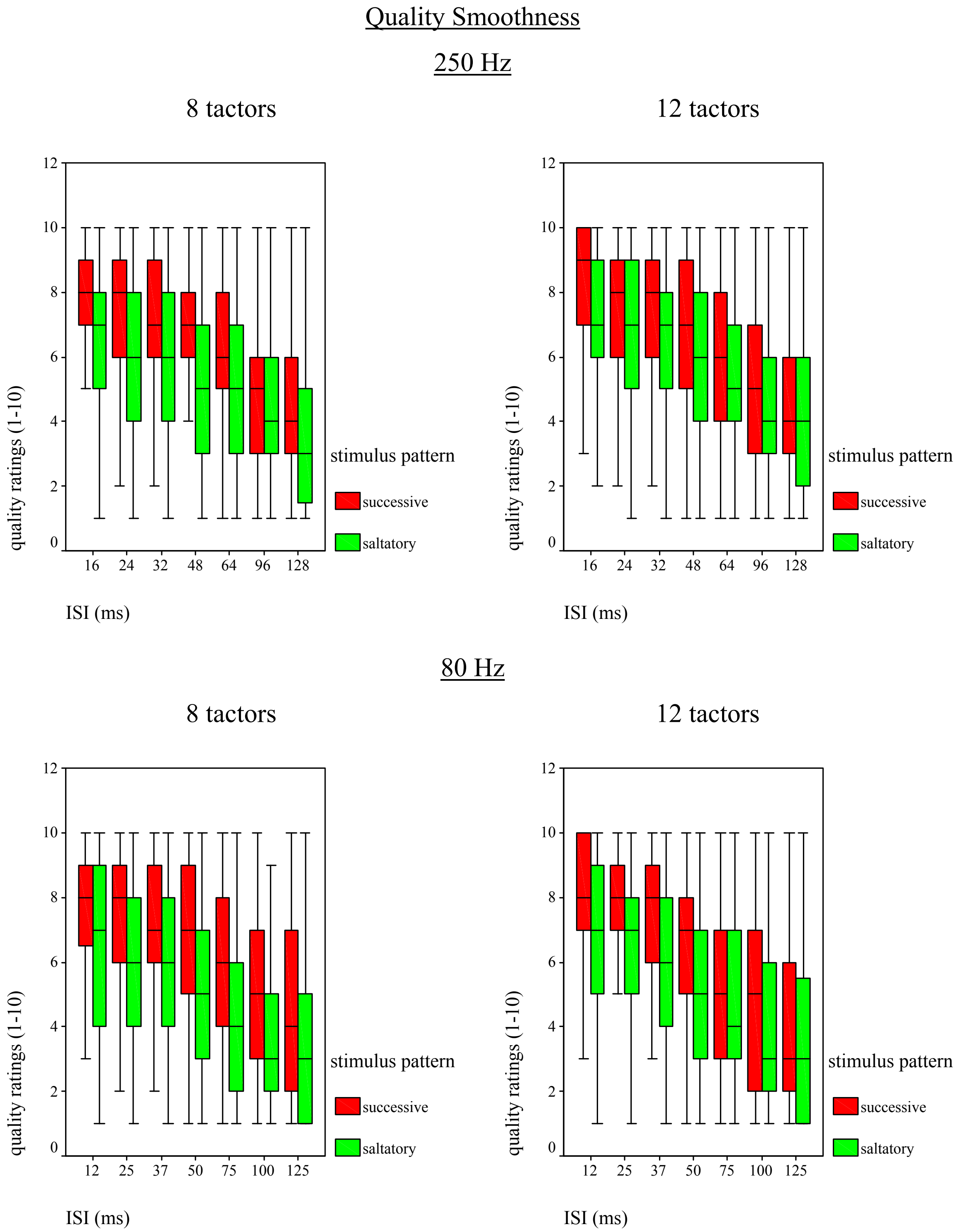


Figure 10.2: The effect of ISI on the quality ratings for smoothness on the 10-point scale is shown for the two different stimulus patterns (successively activated patterns are diagrammed in red bars, saltatory patterns in green bars), the number of tactors on the linear array (8 and 12 tactors), and the two vibration frequencies (250 Hz and 80 Hz). The boxplots represent the median, quartiles and extreme values of the ratings for every level of ISI over subjects tested in the particular condition. It seems that the quality ratings always decrease with increasing ISI.

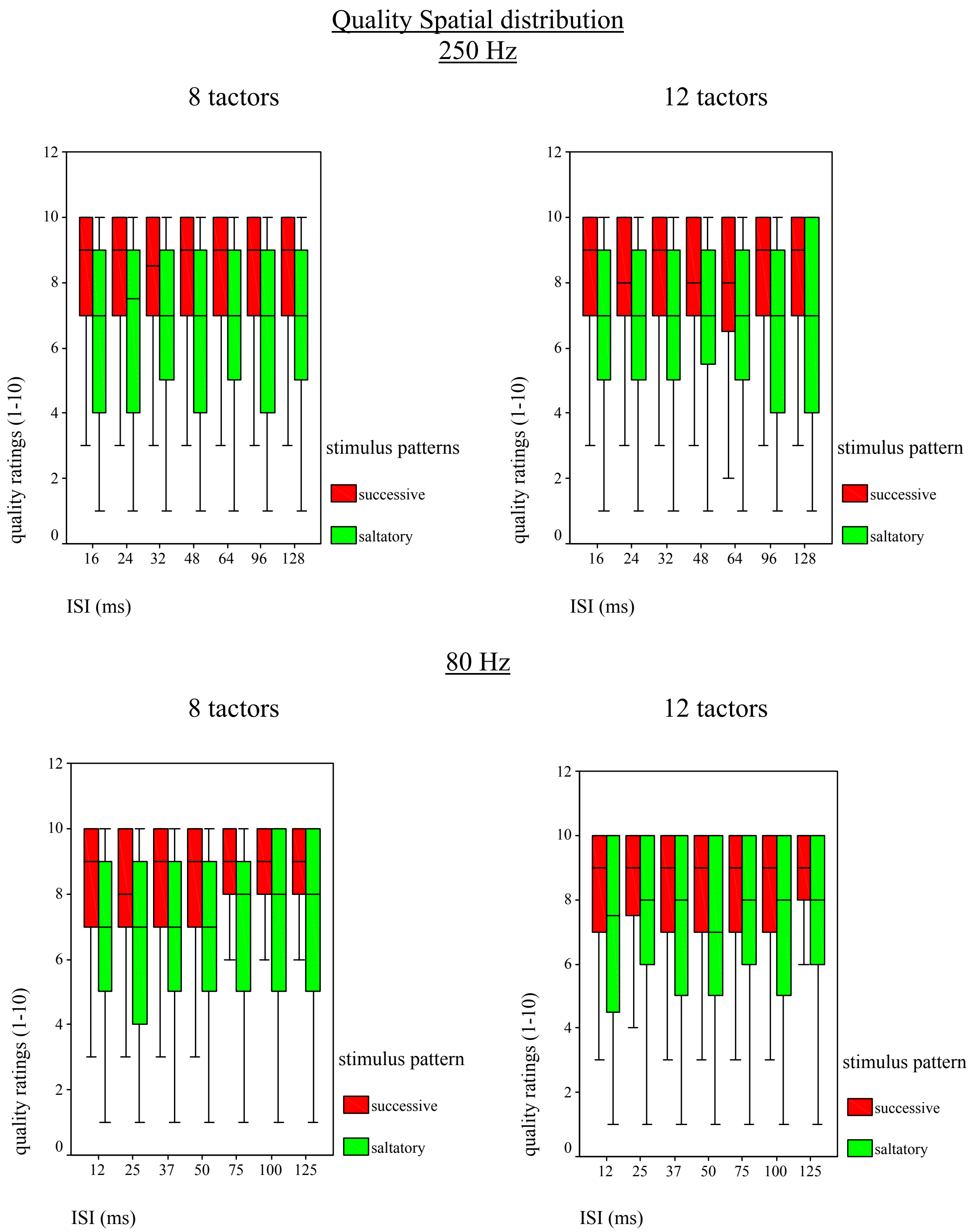


Figure 10.3: The effect of ISI on the quality ratings for spatial distribution on the 10-point scale is shown for the two different stimulus patterns (successively activated patterns are diagrammed in red bars, saltatory patterns in green bars), the number of tactors on the linear array (8 and 12 tactors), and the two vibration frequencies (250 Hz and 80 Hz). The boxplots represent the median, quartiles and extreme values of the ratings for every level of ISI over subjects tested in the particular condition. From visual inspection there seems to be little variation in the ratings as a function of ISI with the exception of the 80 Hz, 8 tactors saltatory patterns where the patterns seems to be more evenly distributed with increasing ISI.

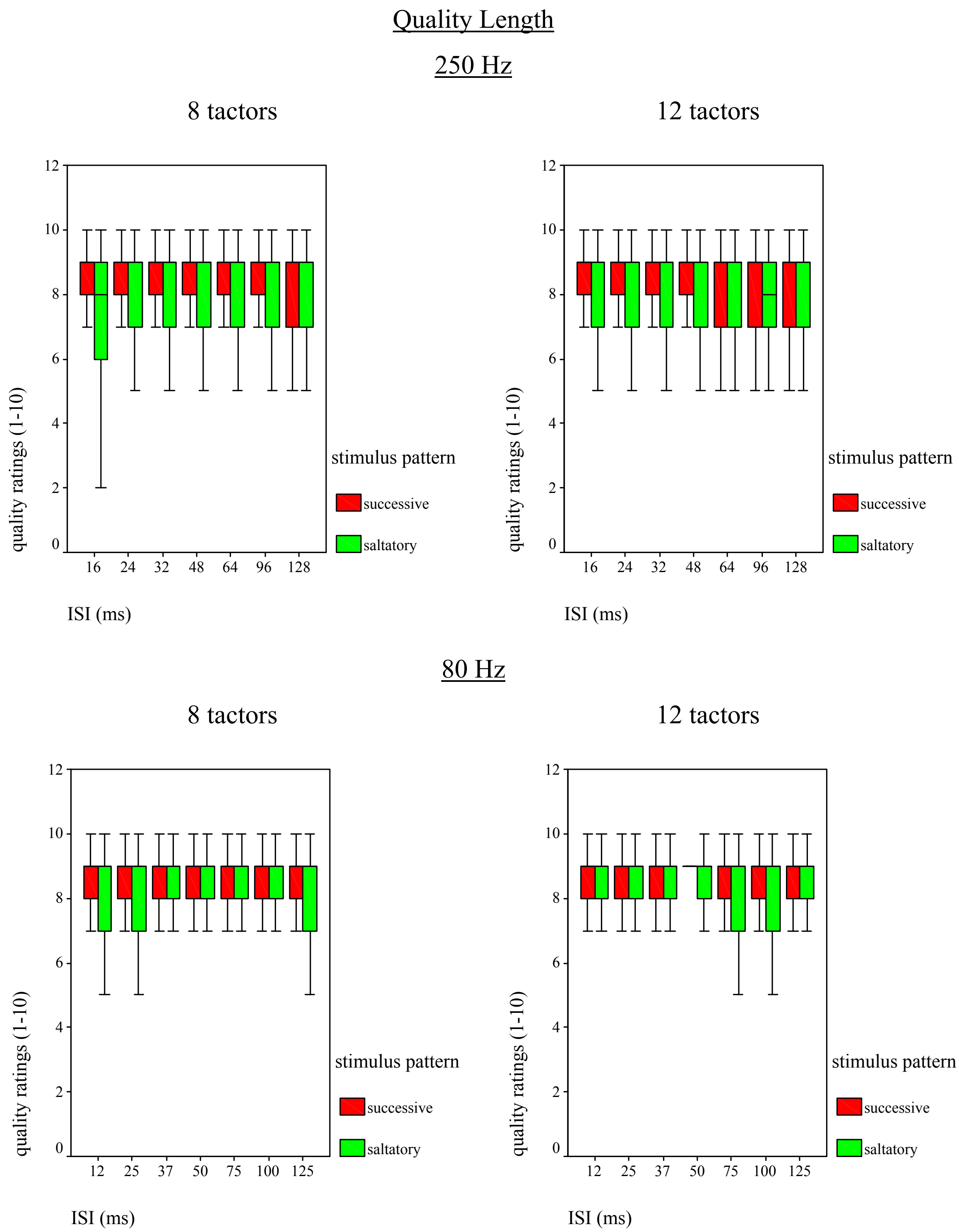


Figure 10.4: The effect of ISI on the quality ratings for length on the 10-point scale is shown for the two different stimulus patterns (successively activated patterns are diagrammed in red bars, saltatory patterns in green bars), the number of tactors on the linear array (8 and 12 tactors), and the two vibration frequencies (250 Hz and 80 Hz). The boxplots represent the median, quartiles and extreme values of the ratings for every level of ISI over subjects tested in the particular condition. From visual inspection there seems to be very little variation in subjects' ratings. Most subjects indicate that they perceive the length of the movement as a full circle around the torso (rating "9").

To evaluate the statistical significance of the trends that can be observed in the figures above (Figures 10.1 to 10.4), a trend test was performed. Since every subject was exposed to all levels of ISI, a trend test for dependent samples: Page test (Page 1963; see also Bortz, 1999; Bortz et al., 2000) was conducted. Each level of ISI was combined with each level of SD–and thus seven ratings were obtained for each ISI level–and so medians were calculated for each ISI level, which formed the basis for the trend test. The results are reported in table 10.1.

Table 10.1: Results of trend test of Page for effects of ISI on the median ratings for each quality

250 Hz

Quality	**8 tactors; successive activation**	**8 tactors; saltation**	**12 tactors; successive activation**	**12 tactors; saltation**
Straightness	u=1.33 P=0.09 n=1372	u=1.42 P=0.08 n=1372	u=2.69 P=0.00 n=1372	u=4.50 P=0.00 n=1372
Smoothness	u=9.85 P=0.00 n=1372	u=8.85 P=0.00 n=1372	u=10.47 P=0.00 n=1372	u=9.52 P=0.00 n=1372
Spatial distribution	u=-0.17 P=0.43 n=1372	u=-0.45 P=0.33 n=1372	u=-0.28 P=0.39 n=1372	u=-0.20 P=0.42 n=1372
Length	u=1.68 P=0.05 n=1372	u=0.94 P=0.17 n=1372	u=2.52 P=0.00 n=1372	u=1.85 P=0.03 n=1372

80 Hz

Quality	8 tactors; successive activation	8 tactors; saltation	12 tactors; successive activation	12 tactors; saltation
Straightness	u=2.57 P=0.01 n=980	u=1.30 P=0.10 n=980	u=3.72 P=0.00 n=980	u=4.25 P=0.00 n=980
Smoothness	u=8.12 P=0.00 n=980	u=7.18 P=0.00 n=980	u=9.43 P=0.00 n=980	u=7.97 P=0.00 n=980
Spatial distribution	u=-2.82 P=0.00 n=980	u=-2.3 P=0.01 n=980	u=-1.68 P=0.05 n=980	u=0.40 P=0.34 n=980
Length	u=-0.11 P=0.46 n=980	u=0.26 P=0.40 n=980	u=1.50 P=0.07 n=980	u=1.31 P=0.10 n=980

Note: The underlying hypothesis was that decreasing ISIs produce higher quality judgments; indicated are the asymptotic test statistic (u), its significance (P), and the number of observations (trials accumulated over subjects; n); Shaded cells mark highly significant effects of ISI ($P<\alpha=.01$). Negative values of u indicate a trend opposite to the hypothesis. The first table shows the results for the 250 Hz group, the second table for the 80 Hz group.

Qualities straightness and smoothness In agreement with our hypothesis, the qualities of straightness and smoothness are rated significantly higher when ISI decreases for a vibration frequency of 250 Hz and an array containing 12 tactors. For an 8 tactor array this trend is also observable, but fails to be significant at a significance level of $\alpha=.01$. For a vibration frequency of 80 Hz we get similar results for the qualities of straightness and smoothness with only one exception: Successively presented stimulus patterns containing 8 tactors are rated significantly straighter, when ISI decreases.

Compared to Cholewiaks and Collins' (2000) experiment we find the same effect for the quality of straightness (tactile patterns always appear to be straighter with shorter ISI) for saltatory patterns presented on the back, but for veridical patterns this effect was only found when the array was placed either on the finger or the forearm. Regarding the quality of smoothness, the same main effects of ISI−tactile patterns appear to be smoother with shorter ISIs−were observed in Cholewiak and Collins' (2000) study.

Quality spatial distribution Contrary to our hypothesis, there is no effect of ISI on the quality spatial distribution for 250 Hz patterns, which is surprising at least for saltatory patterns: The relationship between ISI and the amount of mislocalization should be linear in saltatory patterns. This means that saltatory patterns should feel more or less evenly distributed–i.e. illusory stimuli are mislocalized to a variable extent between activated loci−depending on ISI. However, in our experiment, ISI doesn't seem to affect the perceived distribution of stimuli. If we examine the comments that subjects made after each session, it becomes clear that most of them had difficulties judging spatial distribution since they didn't notice a difference among the patterns, they all felt evenly distributed, especially when the speed of movement was high. So they developed different strategies, some based their judgments on the speed of movement, some on intensity, some looked for gaps, some judged the distribution of stimuli in relation to other trials. Correspondingly, some subjects rated spatial distribution higher with increasing ISI, some with decreasing ISI and for some subjects, judgments were uniformly distributed over all levels of ISI.

Surprisingly, ISI exerts an effect on the perceived spatial distribution of the 80 Hz stimulus patterns that is contrary to the hypothesis: Both successively activated or saltatory stimulus patterns appear to be more evenly distributed when ISI increases. This trend is significant only for stimulus patterns containing less tactors (that is 8 tactors), but is still observable for stimulus patterns containing 12 tactors. Some subjects reported that it was easier to judge the stimulus patterns containing 8 tactors, as soon as they realized that some sites were activated twice (saltatory patterns). Nevertheless, the effect of ISI on their judgments was the same for saltatory and successively activated patterns.

Cholewiak and Collins (2000) found a significant main effect of ISI for saltatory patterns in that a shorter ISI produced a more equally-distributed tactile pattern. This effect was true of patterns presented on the finger and forearm, but not on the back. When stimulus patterns were presented successively, the same effect could be found for patterns presented only to the finger. For tactile patterns presented on the back no significant main effects could be found either for SD nor for ISI–at least for the quality of spatial distribution.

Quality length There is only one significant effect of ISI on perceived length of the stimulus patterns: Successively activated patterns with a vibration frequency of 250 Hz that contain 12 tactors appear to be longer at shorter ISIs. In Cholewiak and Collins' (2000) study there was only a significant main effect of ISI when successively activated and saltatory patterns were presented on the forearm, but their effect was contrary to ours: In their study patterns appeared longer at longer ISI.

With only two exceptions (250 Hz, length, 12 tactors and 80 Hz straightness, 8 tactors), is the effect of ISI on subjects' judgments equal for both stimulus patterns (successively and saltatory activated).

Effect of SD on quality judgments

Again, the effect of SD on the integration of spatio-temporal stimulus patterns will be examined separately for the two different stimulus patterns (saltatory and successively activated), the different vibration frequencies (80 and 250 Hz), and the different number of tactors on the linear array (8 and 12 tactors). Figures 10.5 to 10.8 show the effect of SD on the quality ratings.

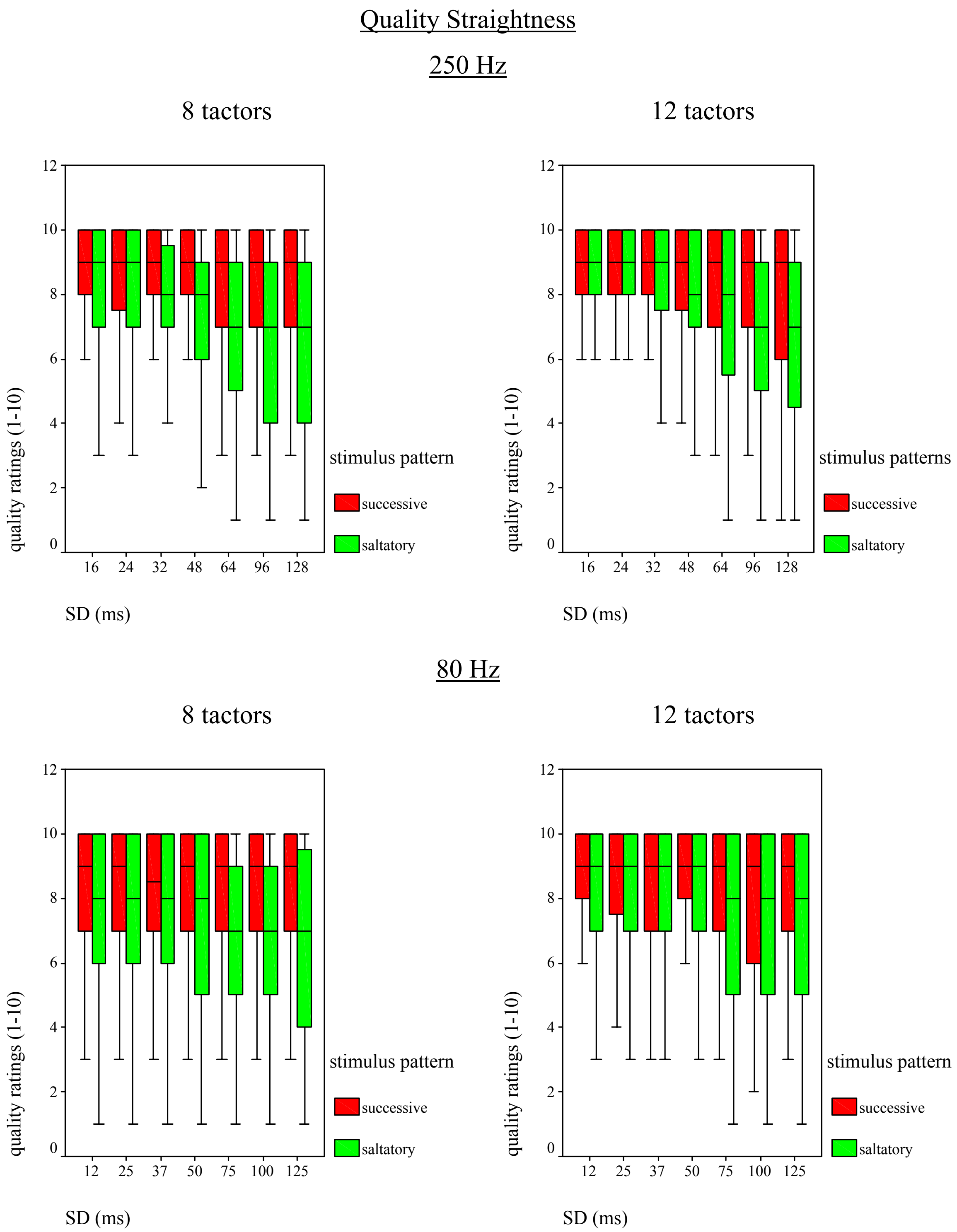


Figure 10.5: The effect of SD on the quality ratings for straightness on the 10-point scale is shown for the two different stimulus patterns (successively activated patterns are diagrammed in red bars, saltatory patterns in green bars), the number of tactors on the linear array (8 and 12 tactors), and the two vibration frequencies (250 Hz and 80 Hz). The boxplots represent the median, quartiles and extreme values of the ratings for every level of SD over subjects tested in the particular condition. From visual inspection it seems that SD has little effect on successively presented stimulus patterns. In contrast, saltatory pattern appear to be less straight as SD increases.

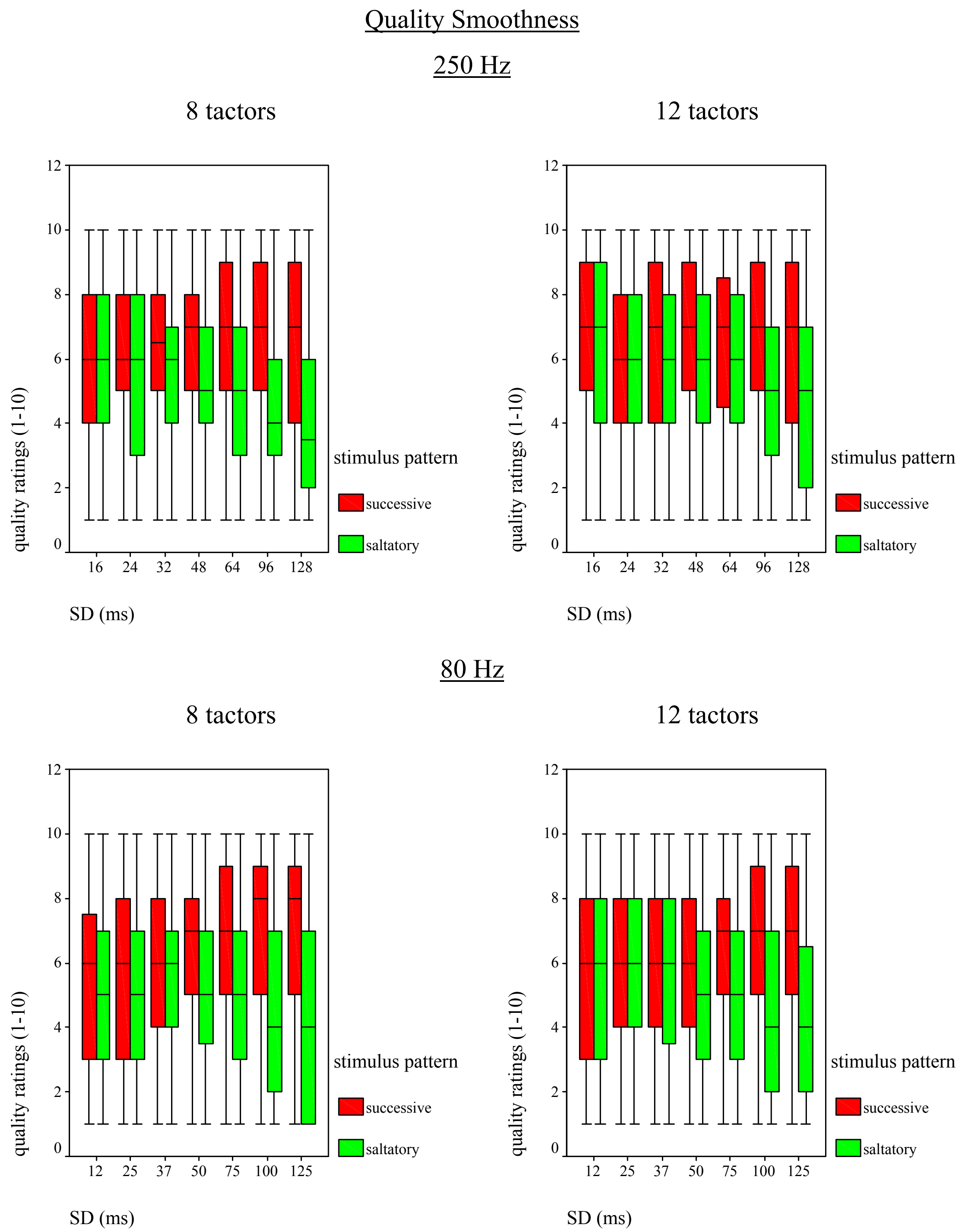


Figure 10.6: The effect of SD on the quality ratings for smoothness on the 10-point scale is shown for the two different stimulus patterns (successively activated patterns are diagrammed in red bars, saltatory patterns in green bars), the number of tactors on the linear array (8 and 12 tactors), and the two vibration frequencies (250 Hz and 80 Hz). The boxplots represent the median, quartiles and extreme values of the ratings for every level of SD over subjects tested in the particular condition. SD appears to have opposite effects on the two stimulus patterns. Whereas successively activated patterns feel smoother with increasing SD, saltatory patterns were reported to feel smoother as SD decreased.

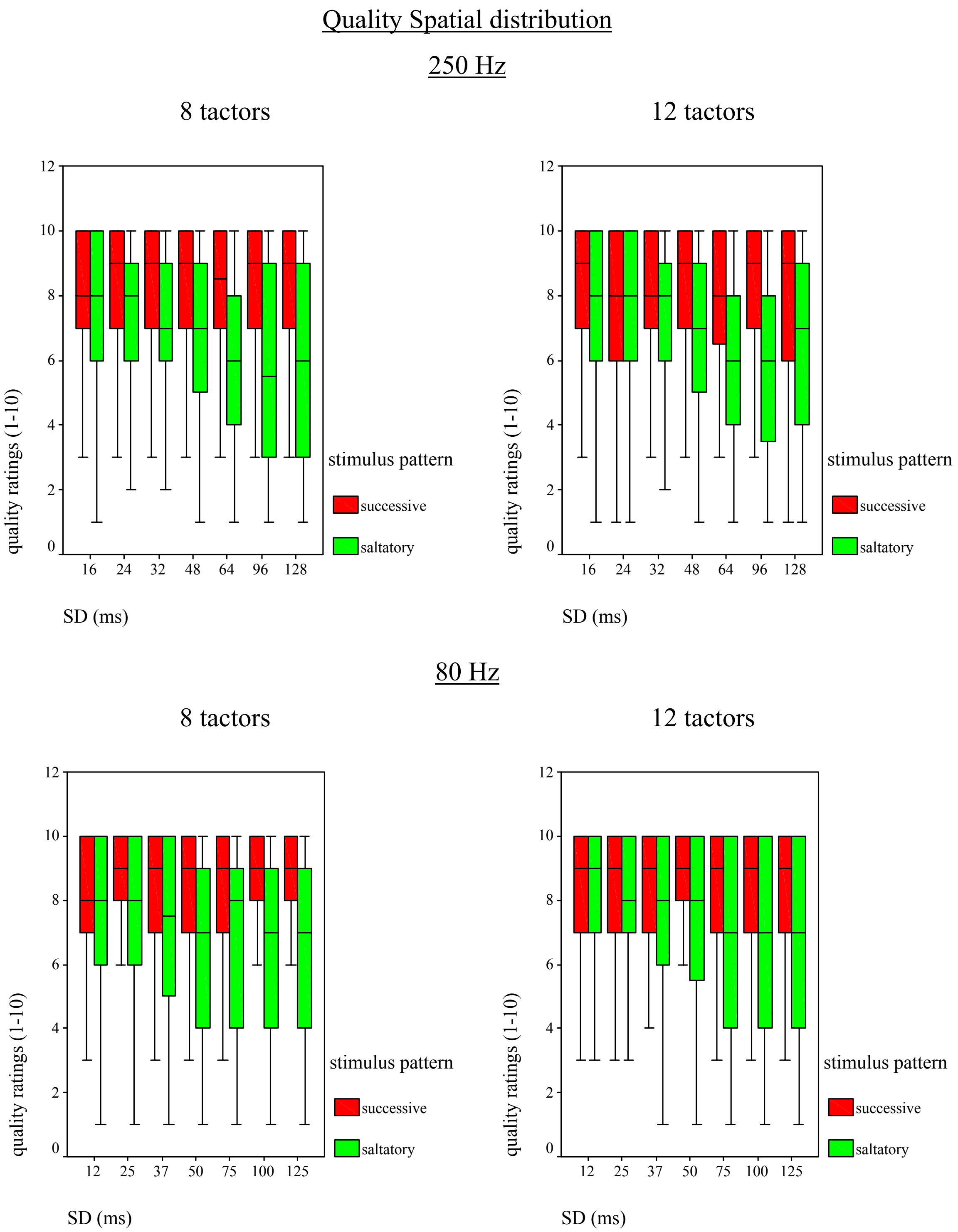


Figure 10.7: The effect of SD on the quality ratings for spatial distribution on the 10-point scale is shown for the two different stimulus patterns (successively activated patterns are diagrammed in red bars, saltatory patterns in green bars), the number of tactors on the linear array (8 and 12 tactors), and the two vibration frequencies (250 Hz and 80 Hz). The boxplots represent the median, quartiles and extreme values of the ratings for every level of SD over subjects tested in the particular condition. Whereas the ratings for successively activated patterns seem to be only marginally affected by SD, saltatory patterns were rated more evenly-distributed with decreasing SD.

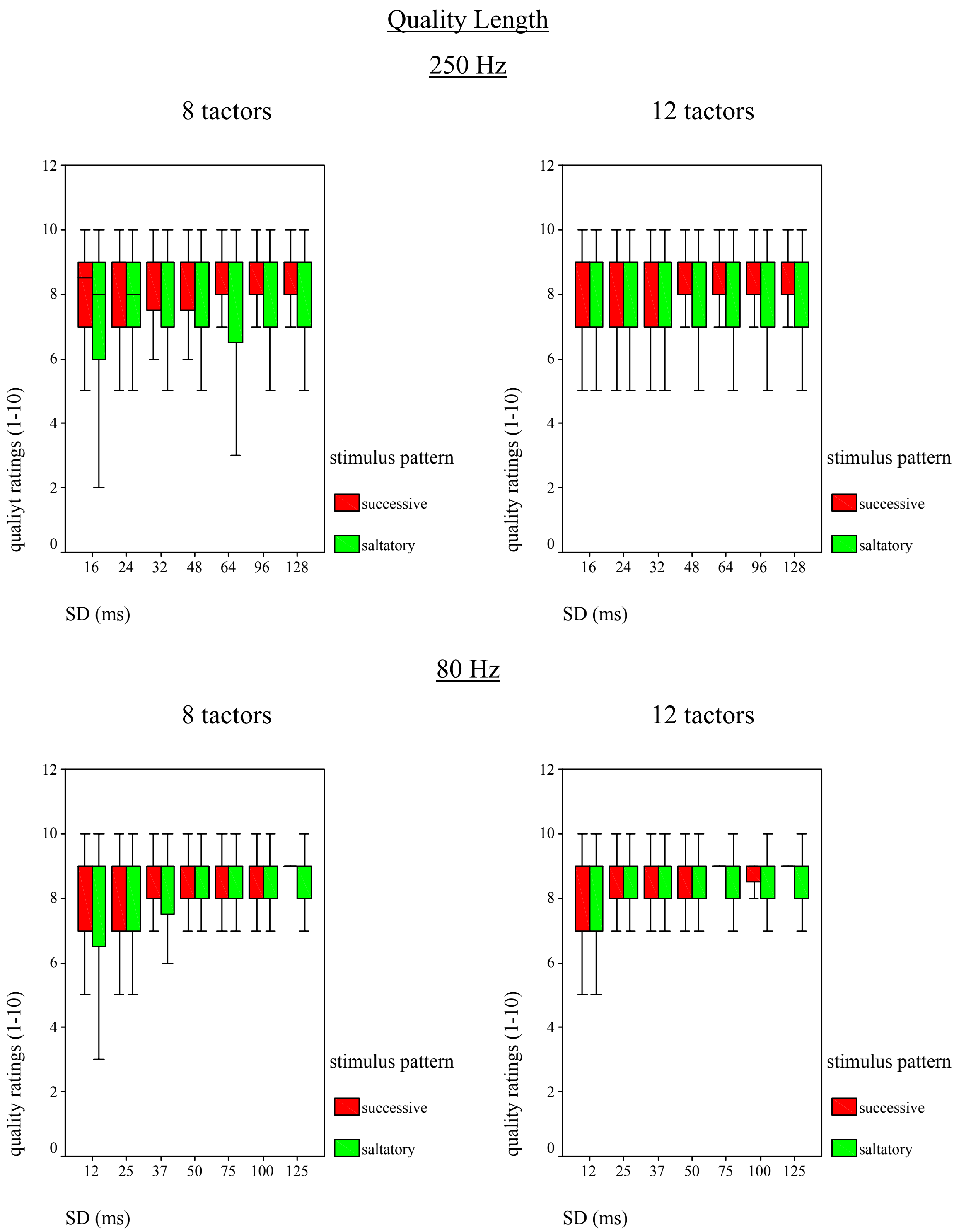


Figure 10.8: The effect of SD on the quality ratings for length on the 10-point scale is shown for the two different stimulus patterns (successively activated patterns are diagrammed in red bars, saltatory patterns in green bars), the number of tactors on the linear array (8 and 12 tactors), and the two vibration frequencies (250 Hz and 80 Hz). The boxplots represent the median, quartiles and extreme values of the ratings for every level of SD over subjects tested in the particular condition. There appears to be little variation in subjects' ratings. Most subjects indicate that they perceive the length of the movement as a full circle around the torso.

As before, as every subject was exposed to all levels of SD, a trend test for dependent samples (Page test) was conducted. The results can be seen in Table 10.2:

Table 10.2: Results of trend test of Page for effects of SD on the median ratings for each quality

250 Hz

Quality	8 tactors; successive activation	8 tactors; saltation	12 tactors; successive activation	12 tactors; saltation
Straightness	u=-1.12 P=0.13 n=1372	u=-5.94 P=0.00 n=1372	u=-3.0 P=0.00 n=1372	u=-6.98 P=0.00 n=1372
Smoothness	u=1.64 P=0.05 n=1372	u=-4.62 P=0.00 n=1372	u=0.78 P=0.22 n=1372	u=-3.18 P=0.00 n=1372
Spatial distribution	u=1.42 P=0.08 n=1372	u=-4.55 P=0.00 n=1372	u=-0.17 P=0.43 n=1372	u=-4.69 P=0.00 n=1372
Length	u=2.55 P=.01 n=1372	u=0.83 P=0.20 n=1372	u=1.73 P=0.04 n=1372	u=0.23 P=0.41 n=1372

80 Hz

Quality	8 tactors; successive activation	8 tactors; saltation	12 tactors; successive activation	12 tactors; saltation
Straightness	u=0.67 P=0.25 n=980	u=-2.88 P=0.00 n=980	u=-0.97 P=0.17 n=980	u=-2.87 P=0.00 n=980
Smoothness	u=3.39 P=0.00 n=980	u=-2.09 P=0.02 n=980	u=3.07 P=0.00 n=980	u=-3.53 P=0.00 n=980
Spatial distribution	u=1.59 P=0.06 n=980	u=-1.87 P=0.03 n=980	u=-0.58 P=0.28 n=980	u=-3.78 P=0.00 n=980
Length	u=3.10 P=0.00 n=980	u=3.10 P=0.00 n=980	u=1.85 P=0.03 n=980	u=1.24 P=0.11 n=980

Note: The underlying hypothesis was that quality judgments should improve with increasing SDs; indicated are the asymptotic test statistic (u), its significance (P), and the number of observations (trials accumulated over subjects; n); Shaded cells mark highly significant effects of SD ($P<\alpha=.01$). Negative values of u indicate a trend opposite to the hypothesis. The first table shows the results for the 250 Hz group, the second table for the 80 Hz group.

Quality straightness For saltatory patterns, perceived straightness increased significantly with decreasing stimulus duration. For successively activated patterns, this trend is only significant for 250 Hz stimuli containing 12 tactors. This result is in agreement with the findings of Cholewiak and Collins (2000).

Quality smoothness Saltatory stimulus patterns show a decrease of quality ratings with increasing stimulus duration. This trend can be found for 80 Hz and 250 Hz stimuli, although it is not always statistically significant. Cholewiak and Collins (2000) found this effect only on the forearm.

For successively activated patterns this trend runs in the opposite direction: Successively activated stimulus patterns are smoother when SD increases. This trend becomes statistically significant only for 80 Hz stimuli. There is no comparable result in Cholewiak and Collins'

(2000) study which is not unexpected, since they use a vibration frequency of 230 Hz; our results for the 250 Hz stimuli weren't significant either.

Quality spatial distribution The shorter the SD, the more equally distributed are saltatory patterns perceived. This is true for both vibration frequencies with the only exception of 80 Hz stimuli containing 8 tactors. For successively activated patterns there is no significant trend.

In Cholewiak and Collins' (2000) study, a significant effect of SD as described for saltatory patterns was only found when a tactile array was placed on the finger and forearm, not on the back. On the forearm the same effect could also be found for successively activated patterns.

Quality length Successively activated stimulus patterns appear to be longer with increasing stimulus duration when they contain only 8 tactors–with the exception of 250 Hz saltatory patterns. When the inter-tactor distance becomes smaller (12 tactors), no significant trend can be observed. In this case there is much less variation in subjects' answers, they generally perceive the length of movement correctly–as a complete circle around the torso.

Cholewiak and Collins (2000) found this effect for all test sites and also for both stimulus patterns.

To summarize, SD has an antagonistic effect on the ratings of the qualities of smoothness and spatial distribution for the two stimulus patterns (successively activated and saltatory).

Interaction between SD and ISI

We assume that the following interaction exists between SD and ISI: An increase in SD supports the integration of stimuli, such that when SD increases, stimuli are integrated even for longer ISIs, and judgments of the different qualities improve.

In Annex G median ratings for the different levels of SD for each ISI are shown for all qualities and for both vibration frequencies. Visual inspection of those figures indicate that our hypothesis may apply only for the quality spatial distribution. Here there seems to exist the following interaction for saltatory patterns: For shorter SDs, judgments appear to be largely uninfluenced by ISI, whereas for longer SDs, stimuli feel more evenly distributed for longer ISIs. This effect can be observed for both vibration frequencies, but in the 80 Hz group the effect is more distinct for 12 tactors patterns.

As a statistical indicator for the significance of this interaction the correlation coefficients (Kendall's Tau) between ISI and the quality ratings were calculated for each subject, broken down by the lowest and highest value of SD. Thus we get two sets of correlation coefficients, one for the lowest level of SD, and one for the highest level of SD. According to our hypothesis, the second set of correlation coefficients (highest level of ISI) should contain higher values.

In the 80 Hz group we get the following results: When the array contained 8 tactors, half of the subjects had a higher correlation coefficient when SD was largest, for the other half, the opposite was true (subjects with no variation in their judgments, and for whom the correlation coefficient thus could not be calculated were excluded). When the array contained 12 tactors, only five subjects had larger correlation coefficients when SD was largest, for nine subjects the correlation coefficients were lower and two subjects showed no difference. A sign-test was performed to test the significance of these results, but the results were not statistically significant for either 8 or 12 tactors (8 tactor array: N=18, x=9, P=0.59; 12 tactor array: N=16, x=6, P=0.23; N=sample size; x=number of subjects with higher correlation coefficient for large SD; P=probability for $\pi<0.5$). For the 250 Hz group, results were different: When the array contained either 8 or 12 tactors, the majority of the subjects (17 out of 25 subjects for the 8 tactor array and 20 out of 26 subjects for the 12 tactor array) showed larger correlation coefficients when SD was longer. A sign-test showed that these results were statistically significant for 12 tactor arrays, but not for 8 tactor arrays (12 tactor array: N=26, x=6, P=0.00; 8 tactor array: N=25, x=8, P=0.05; N=sample size; x=number of subjects with lower correlation coefficient for large SD; P=probability for $\pi<0.5$).

Cholewiak and Collins (2000) reported no significant interaction between SD and ISI, but they used parametric procedures for the analysis of their experiments which might account for some of the differences between their and our results.

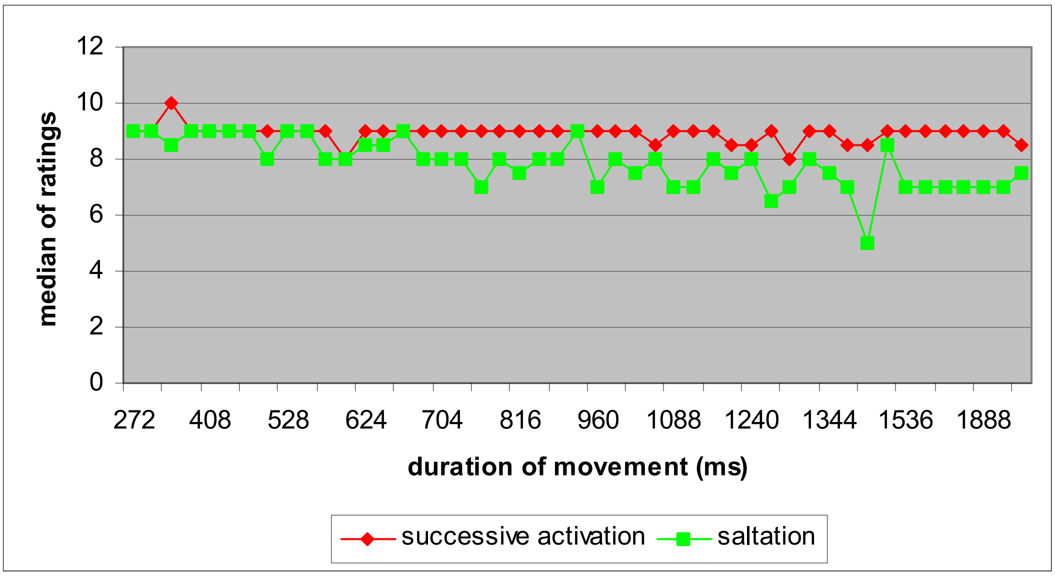
Effect of duration of movement on the qualities straightness and length

The total duration of movement was calculated as the sum of 13 times SD (for the 12 tactor-array; respectively nine times SD for the 8 tactor-array) and 12 times ISI (for the 12 tactor-array; respectively eight times ISI for the 8 tactor-array) for each combination of the different levels of SD and ISI. Since the circumference of each subject's abdomen varied, we decided to choose duration of movement as our measure, not speed of movement (which would require that we divide circumference by duration).We wanted to focus on the effect of the temporal parameters only, uninfluenced by the girth of each subject. To be able to compare our results to those of other studies (Cholewiak & Collins 2000, Langford 1973, and Whitsel et al 1986) we will include only arrays containing one row of tactors in the following analysis.

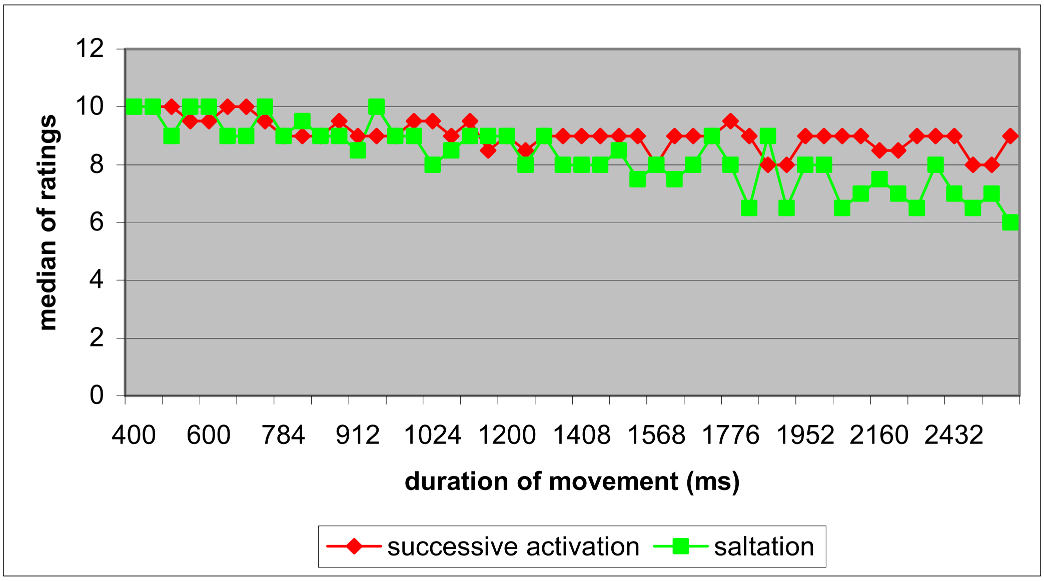
Quality straightness Figure 10.9 below shows the effect of the duration of movement on the median ratings for the quality of straightness separately for successively activated and saltatory patterns and for both vibration frequencies.

250 Hz

8 tactors

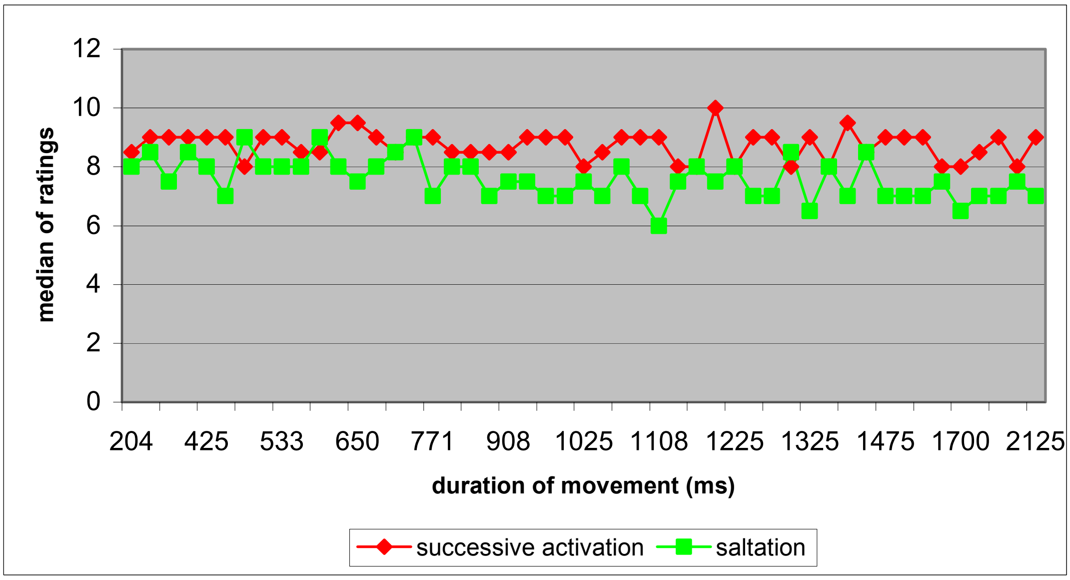


12 tactors



<u>80 Hz</u>

8 tactors



12 tactors

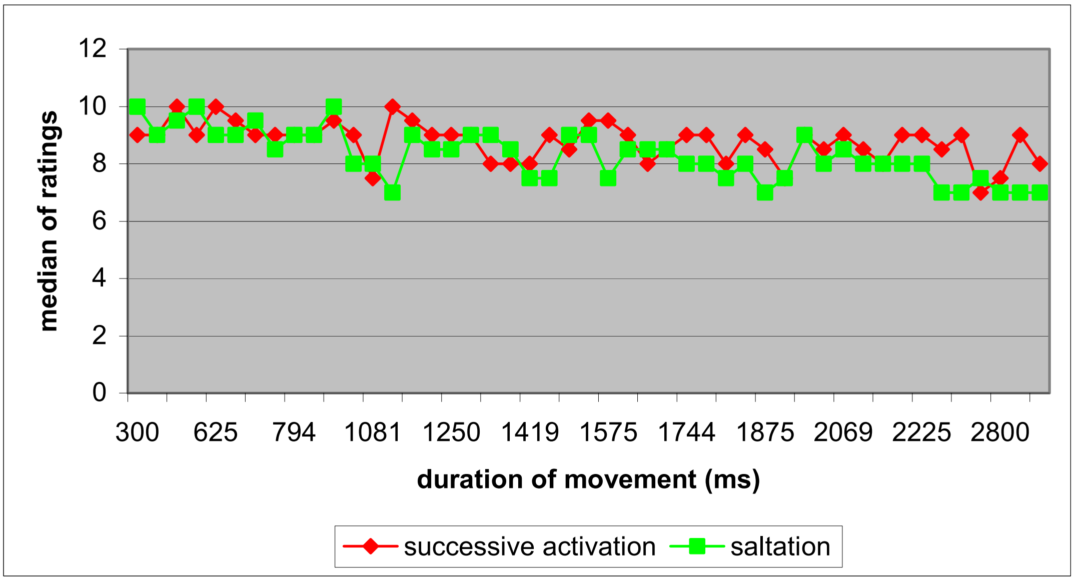


Figure 10.9: Medians of the ratings (on a 10-point scale) of the quality straightness as a function of the duration of movement for the two stimulus patterns (successively activated and saltation), the number of tactors on the array (8 versus 12 tactors), and the two vibration frequencies. Each data point represents the median of the ratings of 28 (250 Hz) or 20 (80 Hz) subjects. For a better legibility of the data points error bars are not displayed. The variability in subjects' data dependent on temporal parameters (ISI/SD) can be extracted from Figures 10.1 and 10.5. Saltatory patterns seem to be less straight with increasing duration of movement, for successively activated patterns this effect is barely observable.

A Paige test was conducted to test if the duration of movement affects the medians of the ratings such that ratings of straightness increase with shorter duration. Results are shown in Table 10.3:

Table 10.3: Results of trend test of Page for effects of the duration of movement on the ratings of straightness of movement

Vibration frequency	**8 tactors; successive activation**	**8 tactors; saltation**	**12 tactors; successive activation**	**12 tactors; saltation**
250 Hz	u=4.66 P=0.00 n=1372	u=9.32 P=0.00 n=1372	u=7.86 P=0.00 n=1372	u=13.12 P=0.00 n=1372
80 Hz	u=2.05 P=0.02 n=980	u=5.36 P=0.00 n=980	u=4.57 P=0.00 n=980	u=7.84 P=0.00 n=980

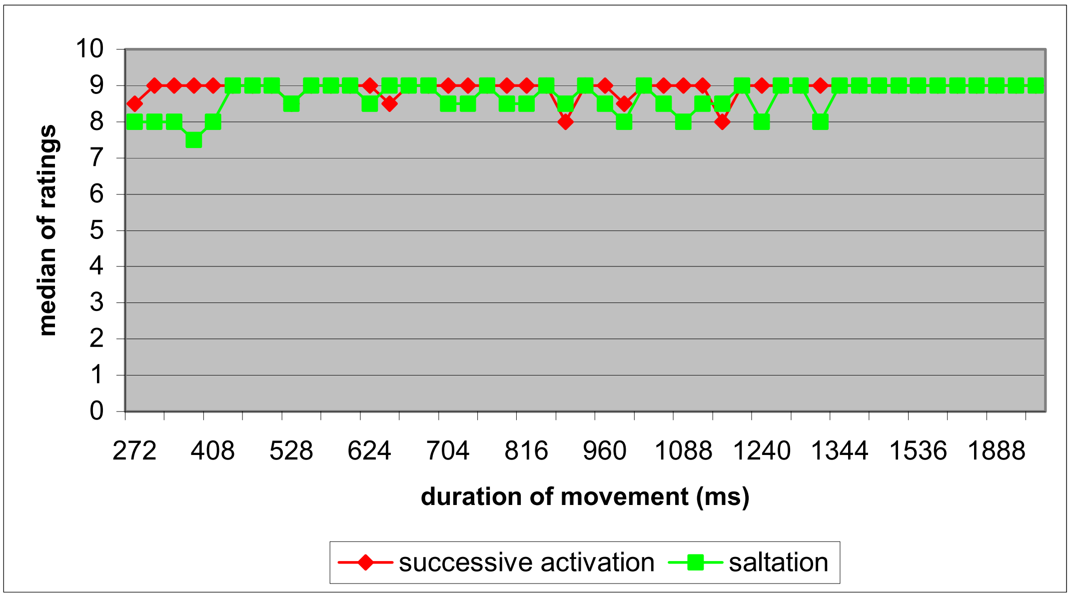
Note: The underlying hypothesis was that quality judgments should improve with shorter duration of movement. The asymptotic test statistic (u), its significance (P), and the number of observations (trials accumulated over subjects; n) are shown. Shaded cells mark highly significant effects of the duration of movement ($P<\alpha=.01$) in the expected direction.

According to our hypothesis, movement feels significantly straighter when the duration of movement decreases, i.e. when stimuli move faster over the skin, for both stimulus patterns (successively activated and saltation) and both vibration frequencies (250 and 80 Hz) with the only exception of 80 Hz, 8 tactors stimulus patterns. This effect is even more distinct for saltatory patterns.

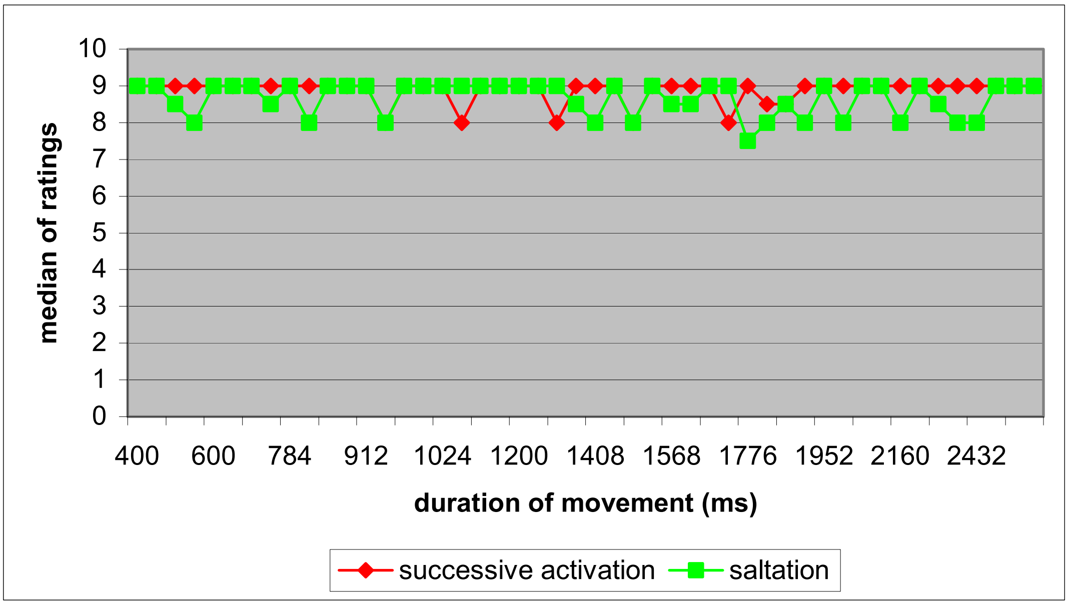
Quality length According to our hypothesis, perceived length of movement should decrease with increasing speed,i.e. shorter duration of movement. Figure 10.10 below shows the median ratings of length dependent on the duration of movement for successively activated and saltatory patterns and for both vibration frequencies.

250 Hz

8 tactors

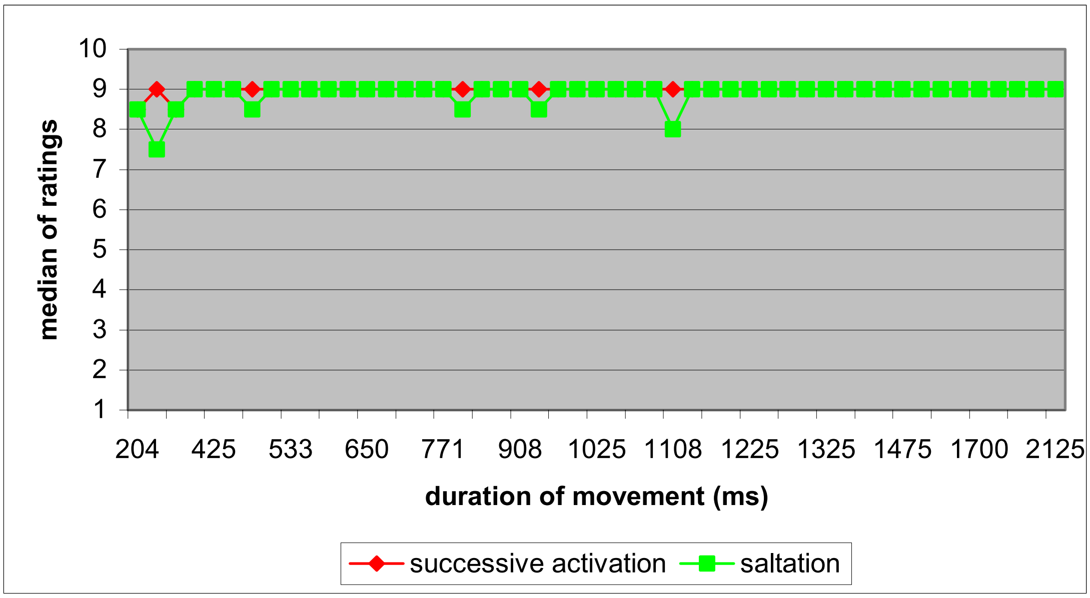


12 tactors



<u>80 Hz</u>

8 tactors



12 tactors

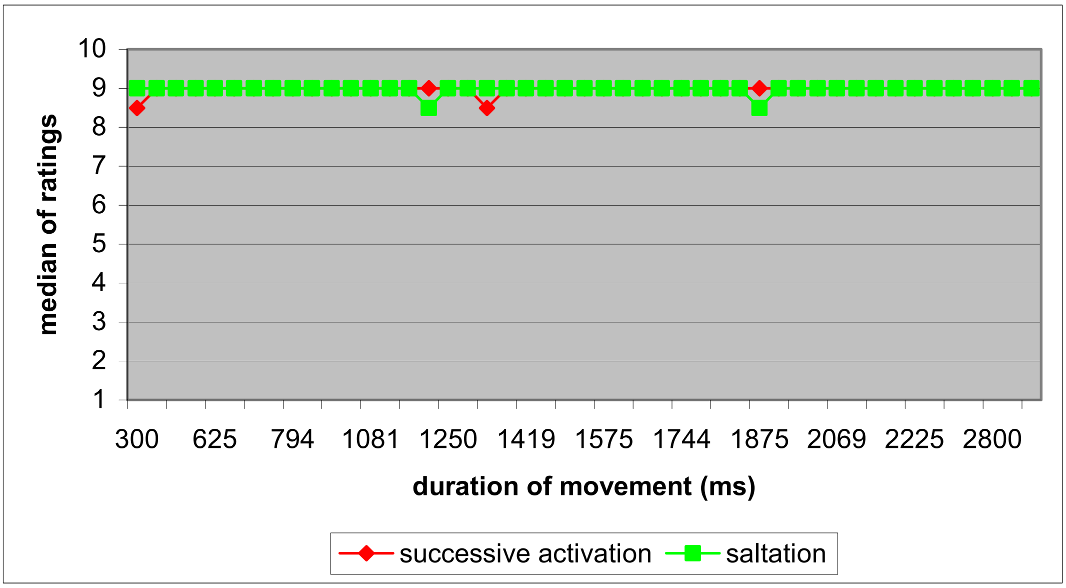


Figure 10.10: Medians of the ratings (on a 10-point scale) of the perceived length of movement as a function of the duration of movement for the two stimulus patterns (successively activated and saltation), the different numbers of tactors on the array (8 versus 12 tactors), and the two vibration frequencies. Each data point represents the median of the ratings of 28 (250 Hz) or 20 (80 Hz) subjects. For a better legibility of the data points error bars are not displayed. The variability in subjects' data dependent on temporal parameters (ISI/SD) can be extracted from Figures 10.4 and 10.8. There seems to be no observable effect of the duration of movement on perceived length.

Again, a Page test was conducted to see if the duration of movement affects the medians of the ratings such that ratings of perceived length of movement decrease with shorter duration. Results are shown in Table 10.4:

Table 10.4: Results of trend test of Page for effects of the duration of movement on the ratings of perceived length of movement

Vibration frequency	**8 tactors; successive activation**	**8 tactors; saltation**	**12 tactors; successive activation**	**12 tactors; saltation**
250 Hz	u=0.70 P=0.24 n=1372	u=-1.82 P=0.03 n=1372	u=-0.62 P=0.27 n=1372	u=-1.87 P=0.04 n=1372
80 Hz	u=3.24 P=0.00 n=980	u=2.62 P=0.00 n=980	u=1.89 P=0.03 n=980	u=0.18 P=0.43 n=980

Note: The underlying hypothesis was that quality judgments should improve with longer duration of movement. Indicated are the asymptotic test statistic (u), its significance (P) and the number of observations (trials accumulated over subjects; n). Shaded cells mark highly significant effects of the duration of movement ($P<\alpha=.01$) in the expected direction. Negative values of u indicate a trend oppositional to the hypothesis.

We found our hypothesis verified only for 80 Hz stimuli and the 8 tactor array, i.e. with decreasing duration of movement, perceived length of movement decreases.

Next, the conditions for a perceived overshoot of the length of movement will be examined. Recall that the rating “9” indicated a full circle around the torso (navel to navel), lower ratings indicated proportionately shorter circuits. When an overshoot was perceived, subjects were instructed to answer “10”, no matter how far this overshoot reached. The overestimation of length occurs relatively rarely, in less than 10% of all trials. Table 10.5 shows the mean durations of movement where such an overshoot is perceived.

Table 10.5: Conditions for the incidence of a perceived overshoot of length (response "10" on the response scale)

		n **Frequency in %**	**Mean duration of movement**	**StdDev**	**Range of duration**
250 Hz successive activation	8 tactors	81 5.9%	796.05 ms	395.79 ms	270-2200 ms
	12 tactors	89 6.5%	1187.06 ms	602.12 ms	400-3200 ms
250 Hz saltation	8 tactors	66 4.8%	578.06 ms	287.98 ms	270-2200 ms
	12 tactors	78 5.7%	1294.26 ms	696.51 ms	400-3200 ms

		n **Frequency in %**	**Mean duration of movement**	**StdDev**	**Range of duration**
80 Hz successive activation	8 tactors	62 6.3%	957.77 ms	480.76 ms	200-2100 ms
	12 tactors	58 5.9%	1298.12 ms	699.65 ms	300-3100 ms
80 Hz saltation	8 tactors	69 7.0%	968.00 ms	470.07 ms	200-2100 ms
	12 tactors	72 7.3%	1251.93 ms	737.66 ms	300-3100 ms

Note: The number of trials (accumulated over subjects), where an overshoot is perceived (n) and percentage of trials (frequency), also mean duration of movement and standard deviation are listed. Additionally the range (minimum and maximum) of the duration of movement is denoted.

The duration of movement where an overshoot of length is perceived is relatively low compared to the whole range, as Table 10.5 indicates. When the inter-tactor distance is smaller (specifically when we used 12 tactors), the duration of movement where an overestimation of length is perceived decreases, i.e. the movement has to travel faster over the skin for an overshoot to be perceived.

10.2.2 Effect of vibration frequency

To evaluate the effect of vibration frequency on quality judgments we collapsed over the different spatial parameters (8 and 12 tactors, one and three rows of tactors). Within each quality, judgments differ significantly for 250 Hz and 80 Hz stimuli (U-test for grouped ranks; Bortz et al., 2000). An examination of the raw data (see Annex H) shows, that low-frequency stimuli (80 Hz) appear to be less straight, less smooth, slightly more equally distributed in space and longer in perceived physical length than high-frequency stimuli (250 Hz). The results of the U-tests can be seen in table 10.6:

Table 10.6: Results of the U-test which tested if vibration frequency (80 or 250 Hz) affects quality ratings

<u>Successively activated patterns</u>

Quality		**Straightness**	**Smoothness**	**Spatial distribution**	**Length**
80 Hz versus 250 Hz	u	4.97	2.99	-0.70	-6.38
	P	0.00	0.00	0.48	0.00
	n	9408	9408	9408	9408

<u>Saltatory patterns</u>

Quality		**Straightness**	**Smoothness**	**Spatial distribution**	**Length**
80 Hz versus 250 Hz	u	5.87	6.34	-4.05	-9.04
	P	0.00	0.00	0.00	0.00
	n	9408	9408	9408	9408

Note: Shown are the test statistic (u) and its significance (P) as well as the number of observations (trials accumulated over subjects; n). Shaded cells mark significant differences in the judgments as a function of vibration frequency ($P<\alpha=.01$). Positive values of u indicate that 250 Hz produce higher quality ratings, negative values of u indicate that 80 Hz stimuli produce higher ratings. There are separate tables for successively activated and saltatory patterns.

With the exception of the quality of spatial distribution these differences were also found for each stimulus pattern, i.e. judgments for successively and saltatory activated patterns differ significantly for the two different vibration frequencies. Only for the quality of spatial distribution, and only for saltatory stimulus patterns were judgments dependent on vibration frequency: Low-frequency saltatory stimulus patterns appear to be more evenly distributed ,but there is no difference in perceived spatial distribution of successively activated stimulus patterns.

10.2.3 Spatial effects

Number of tactors on the linear array

Since subjects were exposed to all four spatial conditions (8 tactors, 12 tactors, one row of tactors referred to as narrow stimuli, three rows of tactors referred to as wide stimuli), a non-parametric test for related samples, the Test for Marginal Homogeneity was conducted to test if the different number of tactors produces different judgments. We hypothesised that increasing the number of stimulus sites and thus decreasing the distance between activated sites will lead to better quality judgments for both stimulus patterns. We focused on tactile arrays containing one row of tactors only. In a next step the effect of stimulus width is examined. The results are reported in Table 10.7:

Table 10.7: Results of the Test for Marginal Homogeneity which tested if the number of tactors on the array and therefore the inter-tactor distance affects quality ratings

Successively activated patterns

Quality		**Straightness**	**Smoothness**	**Spatial distribution**	**Length**
8 tactors versus 12 tactors 80 Hz	u	0.95	-0.49	0.73	-0.14
	P	0.17	0.31	0.23	0.44
	n	980	980	980	980
8 tactors versus 12 tactors 250 Hz	u	1.56	0.93	-2.13	-0.33
	P	0.06	0.18	0.02	0.37
	n	1372	1372	1372	1372

Saltatory patterns

Quality		**Straightness**	**Smoothness**	**Spatial distribution**	**Length**
8 tactors versus 12 tactors 80 Hz	u	5.80	1.87	4.22	5.47
	P	0.00	0.03	0.00	0.00
	n	980	980	980	980
8 tactors versus 12 tactors 250 Hz	u	5.17	4.20	1.31	3.60
	P	0.00	0.00	0.10	0.00
	n	1372	1372	1372	1372

Note: Shown are the test statistic (u) and its significance (P) as well as the number of observations (trials accumulated over subjects; n). Shaded cells mark significant differences ($P<\alpha=.01$) in the judgments as a function of the number of tactors (8 versus 12). Positive values of u indicate that 12 tactors produce better quality judgments. The results for successively activated patterns are reported in the first table, the results for saltatory patterns are reported in the second table.

The number of stimuli and the corresponding variation in the distance in-between stimuli doesn't alter the quality ratings for successively activated patterns. When saltatory patterns were presented, however, quality judgments depended on the number of tactors, with some interactions with stimulus frequency. When we look at the judgments we find that

- saltatory patterns containing 12 tactors felt more straight for vibration frequencies of 80 and 250 Hz

- saltatory patterns containing 12 tactors felt smoother, but this difference was only significant for a vibration frequency of 250 Hz
- saltatory patterns containing 12 tactors were more equally distributed, but only for a vibration frequency of 80 Hz
- saltatory patterns containing 12 tactors appear to be longer for vibration frequencies of 80 and 250 Hz

Accordingly the number of stimuli on a linear array affects the perception of illusory movement differently for successively and saltatory stimulus patterns.

Width of stimulus

As before, a non-parametric test for related samples, the Test for Marginal Homogeneity was conducted to test if stimulus width affects subjects' judgments. No effects of stimulus width on quality ratings are expected. Table 10.8 shows the results:

Table 10.8: Results of the Test for Marginal Homogeneity which tested if stimulus width affects subjects' judgments

Successively activated patterns

Quality		**Straightness**	**Smoothness**	**Spatial distribution**	**Length**
8 tactors	u	-2.56	-2.06	-2.43	0.14
1 versus 3 rows	P	0.01	0.04	0.02	0.89
80 Hz	n	980	980	980	980
8 tactors	u	-1.02	-3.46	1.49	-0.26
1 versus 3 rows	P	0.31	0.00	0.14	0.80
250 Hz	n	1372	1372	1372	1372

Quality		Straightness	Smoothness	Spatial distribution	Length
12 tactors	u	-3.56	-2.78	-1.62	3.94
1 versus 3 rows	P	0.00	0.01	0.11	0.00
80 Hz	n	980	980	980	980
12 tactors	u	-3.17	-3.42	5.34	1.38
1 versus 3 rows	P	0.00	0.00	0.00	0.17
250 Hz	n	1372	1372	1372	1372

Saltatory patterns

Quality		Straightness	Smoothness	Spatial distribution	Length
8 tactors	u	-3.41	-1.61	3.13	1.89
1 versus 3 rows	P	0.00	0.11	0.00	0.56
80 Hz	n	980	980	980	980
8 tactors	u	0.22	-0.41	1.76	2.96
1 versus 3 rows	P	0.83	0.68	0.08	0.00
250 Hz	n	1372	1372	1372	1372

Quality		Straightness	Smoothness	Spatial distribution	Length
12 tactors	u	-6.98	-3.89	-0.79	2.19
1 versus 3 rows	P	0.00	0.00	0.43	0.03
80 Hz	n	980	980	980	980
12 tactors	u	-1.41	-5.08	4.72	2.40
1 versus 3 rows	P	0.16	0.00	0.00	0.02
250 Hz	n	1372	1372	1372	1372

Note: One row of tactors is referred to as narrow stimuli, three rows of tactors are referred to as wide stimuli. Shown are the test statistic (u) and its significance (P) as well as the number of observations (trials accumulated over subjects; n). Shaded cells mark significant differences ($P<\alpha=.01$) in the judgments as a function of stimulus width (one versus a row of three stimuli). Negative values of u indicate that narrow stimuli–composed of only a single stimulus–are superior to wide stimuli–composed of three stimuli on top of each other. Positive values of u indicate that wide stimuli are judged better. There are separate tables for successively activated and saltatory stimuli and for the different numbers of tactors on the array.

Quality straightness When vibration frequency is 80 Hz, narrow stimuli–composed of only a single stimulus–feel significantly straighter than wide stimuli–composed of a row of three stimuli–, as the marginal distribution of the judgments for the narrow versus wide stimuli shows. This is true for 8 and 12 tactors as well as for successively and for saltatory stimulus patterns. For vibration frequencies of 250 Hz, the only significant difference was found for successively activated patterns containing 12 tactors. With only one exception (250 Hz/12 tactors), stimulus width affects the perception of the straightness of illusory movement produced by successively activated and saltatory stimulus patterns equally.

Quality smoothness When the array contains more tactors (that is 12 tactors), a narrow stimulus feels smoother compared to a wide stimulus. This is true for vibration frequencies of 80 and 250 Hz and for successively activated as well as for saltatory stimulus patterns. When the array contains only 8 tactors there is only one significant difference in subjects' judgments: For successively activated patterns of a vibration frequency of 250 Hz. Aside from this exception (8 tactors, 250 Hz), stimulus width affects the perception of the smoothness of illusory movement produced by successively activated and saltatory stimulus patterns equally.

Quality spatial distribution When the array contains more tactors (that is 12 tactors), a wider stimulus at 250 Hz vibration frequency produces more-evenly distributed movement, regardless of the stimulus pattern mode. When the stimulus frequency is 80 Hz and 12 tactors form the array there is no significant difference in subjects' judgments over stimulus widths for either stimulus pattern. When the array contains only 8 tactors there is only one significant difference in subjects' judgments: For saltatory patterns of a vibration frequency of 80 Hz. Aside from this exception (8 tactors, 80 Hz), stimulus width affects the perception of the spatial distribution of illusory movement produced by successively activated and saltatory stimulus patterns equally.

Quality length Only two comparisons (narrow versus wide stimuli) were statistically significant: Saltatory patterns with a vibration frequency of 250 Hz containing 8 tactors and successively activated patterns with a vibration frequency of 80 Hz containing 12 tactors. In both cases, wider stimuli felt longer. Aside from these two exceptions, stimulus width affects the perception of the length of illusory movement produced by successively activated and saltatory stimulus patterns equally.

Recapitulating, there are only few instances in which stimulus width affects the perception of illusory movement produced by successively activated and saltatory stimulus patterns differently.

10.3 Summary and discussion

The different independent variables affected subjects' judgments differently dependent on the quality to be judged. Like in Cholewiaks and Collins' (2000) experiment, there is no specific set of spatio-temporal parameters that generates the very best ratings for each quality.

Temporal effects We expected that shorter ISIs would enhance the integration of spatio-temporal stimuli into a percept of continuous motion in similar ways for successively activated and saltatory stimulus patterns. This expectation was borne out for the qualities straightness and smoothness. There was no effect of ISI on the quality spatial distribution for 250 Hz stimuli although there was a significant opposite effect for 80 Hz stimuli which disappeared when more tactors were involved and the inter-tactor distance decreased. An explanation for this finding might be found in the remarks of the subjects who stated that most of the patterns felt evenly distributed and they applied different strategies to make their judgments, so no uniform trend could be found. Patterns containing 12 tactors appear to be longer at shorter ISIs, but there is only one significant effect of ISI that occurred with successively activated patterns at a vibration frequency of 250 Hz. This effect is contrary to the studies of Cholewiak (1999, 2000), where estimates of length were higher for longer ISIs.

Although the effects of ISI were similar for both stimulus patterns (successively activated and saltatory), the situation was different when we considered the effects of SD: In general SD affects the quality ratings of successively and saltatory stimulus patterns in different ways. Whereas the effect of SD on saltation is largely unexplored, increasing SD was found to have a positive effect on the "goodness" of motion in studies using successively activated stimulus patterns. But, in our experiment, the effect of SD varied with the quality being judged as well as the vibration frequency and the number of tactors. There is no consistent effect of SD on the “goodness” of movement simulated by successively activated patterns and only few trends are statistically significant. The differences with previous studies that might account for these results were: Test site (Kirman, 1974a, 1974b, 1975: finger; Szanislo et al., 1998: face), stimulator (Kirman: vibrating bronze rods; Szanislo: vibrating rows of a dense array tactile stimulator), vibration frequency (Kirman: 100 Hz; Szanislo: 200 Hz), and experimental method (Kirman: categorization of “goodness” of motion; Szanislo: method of limits/magnitude estimation for “goodness” of motion).

SD mostly affects quality ratings (except length) for saltatory patterns such, that quality ratings decreased with increasing SD. In saltation experiments SDs chosen were brief, e.g. 10 ms in Geldard’s original experiments (1982) or 20 ms in Stolle’s experiment (2003). In our experiment, with such low levels of SD (16 ms for 250 Hz stimuli, 12 ms for 80 Hz stimuli), there seems to be no variation in subjects’ ratings of the spatial distribution of stimuli with ISI as might be expected from previous experiments (compare Annex G). At longer SDs (128 ms for 250 Hz stimuli, 125 ms for 80 Hz stimuli) there is a tendency, that saltatory patterns feel more evenly distributed with increasing SD, which becomes more obvious for smaller inter-tactor distances (with the 12 tactor array), but the interaction between SD and ISI was only partly significant for the 250 Hz group. It seems though that both ISI and SD play an important role in eliciting the saltatory illusion.

Movement feels straighter when duration of movement decreases, i.e. stimuli move faster over the skin. These results were also found by Cholewiak and Collins (2000) and Langford (1973). We expected to find the same result for length–like Cholewiak and Collins (2000) and Whitsel et al. (1986)–but in our case the perceived length of movement mostly did not vary significantly with duration. (Note: In our case, since we have a circular array and tried to insure (by adding the extra stimulus at the end) that completion occurred around the body, we might have worked against the expectation of “shorter” stimulus extents.) The rare effect of the duration of movement on perceived length is related to the effect of SD and the more distinct effect of the duration of movement on straightness is influenced by SD as well as by ISI.

Although several researchers confirm these effects, a full explanation is missing. It is possible that at higher velocities stimuli are being interpolated strongly as the tactile system’s ability to discriminate between successive stimuli decreases when velocity increases. Thus, there are fewer spots where movement can be perceptually “measured” at high velocities, making movement feeling straighter and shorter. At slower velocities, the tactile system may be able to distinguish more spots where movement can be observed, allowing movement to stray from a straight line.

That perceived length depends first of all on SD parallels findings in the auditory sense: Strybel et al (1998) found that estimates of separation between two successively presented *auditory* stimuli is affected first of all by stimulus duration, as well as by ISOI and the physical separation between the stimuli. Longer SDs, longer ISOIs and greater physical separations lead to higher estimates of separation. It seems that subjects use different strategies to judge physical separation: They either base their judgments on total stimulus duration, physical separation, or a mixture of both, which might also apply to our results and explain the large variation in subjects' responses.

Of special interest were the instances in which subjects overestimate length, i.e. When do they perceive the length of movement as being longer than a full circle around the torso? We find that an overshoot of length–which occurs relatively rarely–is perceived at low durations of movement, the probability of which decreases with increasing duration of movement for both stimulus patterns. This finding agrees with studies in vision: When a moving object (movement can be illusory, i.e. generated by successive presentation of stimuli or veridical) abruptly vanishes, subjects place the final position ahead of the physical final position, which has been referred to as "representational momentum" or "displacement in the direction of motion" (Hubbard, 2005; p. 822). Representational momentum is regarded as a memory bias of the final position and the observed forward displacement increases with the speed of movement (Hubbart, 2005, Nagai & Saiki, 2005). The difference is that in these subjects were asked to point at the perceived final position of the moving target, whereas in our experiment subjects had to judge the length of movement on a 10-point scale, and answer "10", if movement exceeded the physical final position, without specifying the amount of "overshoot". However, one could interpret the forward displacement as an overestimation of length of movement, as was supported by the experiment of Hubbart and Motes (2002). They had subjects judge the initial and final position of a visual moving target and found a backward displacement of the initial position (i.e. the initial position was displaced in the direction opposite to movement) and at the same time a forward displacement of the final position. These findings indicate that the remembered length of the trajectory was larger than the physical length, an effect that increased with the speed of movement. Their results suggest that representational momentum does not result from a forward displacement of the whole trajectory but from an overestimation of overall length.

Representational momentum has been explained as an automatic process of extrapolation based on physical regularities which can be modified by attention or expectation (Kerzel, 2003). There is experimental evidence that rather high-level cognitive processes underlie forward displacement than low-level sensory processes (Hubbart, 2005).

Forward displacement of moving stimuli has also been found in audition for different types of stimuli (series of tones ascending or descending in frequency or continuous noise or noise pulses), but the effects of velocity differed with the stimulus type used (Getzmann, Lewald, & Guski, 2004; Hubbart, 2005). To our knowledge, no systematic study has ever investigated the existence of representational momentum in the tactile sense, so it is unclear whether our findings can be replicated in other experimental settings (different response paradigms, different test sites,...). Nor is it obvious whether or not the same motion-perception mechanisms generate the representational momentum in the visual, auditory, and tactile senses.

Effect of vibration frequency Contrary to our hypothesis, vibration frequency affected the perception of the different qualities of movement: 80 Hz stimuli are perceived to be less straight, less smooth, more equally distributed in space and longer than 250 Hz stimuli.

Low-frequency stimuli are known to appear dull, whereas high-frequent stimuli produce bright, sharp–maybe also more punctiform–taps. According to Békésy (1967) there is an increase in lateral spread of travelling waves produced by vibratory stimuli with decreasing frequency. It is possible that 80 Hz stimuli feel larger, less distinct, or less punctuate as their surface waves travel further over the skin, activating distant receptors, letting the single stimuli "melt together", and making the stimulus patterns feel more evenly distributed. However, it should be noted that the presence of a rigid surround around the vibrating element of our tactors, should restrict these surface travelling waves. Goble, Collins and Cholewiak (1996) showed that vibratory thresholds increase with the presence of a rigid surround at high frequencies, whereas at low frequencies <50 Hz, threshold is reduced, due to the properties of the activated mechanoreceptors. Nevertheless, deeper waves may still continue to spread laterally. This lateral spread may also account for the result that 80 Hz vibratory stimuli appear to be longer and seem to be less straight and less smooth, since they are not as spatially defined as 250 Hz stimuli[6].

[6] Pacinian afferents resolve spatial detail poorly (Johnson & Hsiao, 1992), when *static tactile patterns* are presented (like Braille characters). Note, however, we are talking about *vibratory patterns* and the travelling waves they elicit here, so our results and the study of Johnson and Hsiao do not seem to be contradictory.

Spatial effects

Number of tactors on the linear array We expected that increasing the number of stimulus sites and thus decreasing the distance between activated sites will enhance the integration of spatio-temporal stimuli into a percept of continuous motion for successively activated as well as saltatory stimulus patterns.

Variation in the number of stimuli and the resulting changes in distance in-between activated sites doesn't alter the quality ratings for successively activated patterns. At first view, this contradicts the findings of Kirman (1974) and Szaniszlo et al. (1998) who found that the quality of motion percepts improved with more activated stimuli. But in Kirman's study the number of stimuli and the length of the path travelled was confounded: Each contactor was separated by a fixed distance of 0.5 cm, so the total length of the array varied with the number of stimuli (2, 4, 8 stimuli; test site: finger). In our experiment the total length of the array was kept constant, so the results cannot be compared directly.

Szaniszlo et al. kept the total length of the array constant and varied only the number of rows activated on the OPTACON (test site: face). The goodness of motion percepts increased with increasing number of activated rows, but goodness of motion was very similar for the 4-, 8-, and 22 row pattern, only the 2-row pattern received judgments that were significantly worse.

In our experiment the differences in judgments between the 8 tactor and 12 tactor array were marginal, suggesting that we would have to reduce the number of tactors beyond the number of 8 to achieve different quality ratings. The distance in-between activated tactors varied between 5.8 cm and 9.2 cm for the 12 tactor array and 8.6 cm and 14.9 cm for the 8 tactors array. It seems that if once the number of tactors has exceeded a minimum, the distance doesn't effect the integration of discrete stimuli–and thus quality ratings–any more.

Nevertheless, in most cases, saltatory patterns containing 12 tactors produce better quality judgments than saltatory patterns containing 8 tactors, according to the hypothesis. According to Geldard and Sherrick (1972) or Geldard (1982) saltation is vivid at inter-tactor distances between 2-35 cm and could even be observed over a distance of 150 cm (5-5-5 tap arrangement). However, he only examined if taps were mislocalized from their origin, not if the quality of saltatory movement changed with increasing inter-tactor distance. It seems that although saltation occurs over a wide range of separations between stimuli, the quality of saltatory movement depends on the inter-tactor distance (or number of tactors, since the two factors were confounded in our experiments).

Width of stimulus Finally, we didn't expect that stimulus width affects the integration of different spatio-temporal stimulus patterns into a percept of continuous motion, but wide stimuli–composed a column of three stimuli–are mostly less straight and less smooth than narrow stimuli–composed of only a single stimulus. On the other hand, wide stimuli often feel more evenly distributed and longer than narrow stimuli. Thus, a larger stimulated area affects the perception of simulated movement. In most cases the effect is equal for the two different stimulus patterns–as opposed to the effect of the number of tactors.

11 Experiment 2: Discrimination between successively activated and saltatory stimulus patterns

In the second experiment we use a different response paradigm to analyze if the two stimulus patterns–successively activated and saltatory–can produce indiscriminable sensations and to determine the spatio-temporal limits where the two stimulus patterns feel the same. This question couldn't be answered unambiguously in Experiment 1 since there was there was no specific set of spatio-temporal parameters that generated best ratings for each quality. Rather each quality was affected by the spatio-temporal parameters in different ways.

In this experiment, using a paired-comparison paradigm, subjects made a direct comparison between successively activated and saltatory stimulus patterns. This experimental procedure was used in previous experiments (Cholewiak & Collins, 2000, and slightly modified by Eimer et al., 2005) to test the existence of the saltatory illusion. Since it is assumed that at appropriate spatio-temporal stimulus characteristics, the illusory saltatory stimulus is located between activated sites, as when successively activated stimuli are presented, this experimental procedure allows us to directly evaluate the spatio-temporal stimulus parameters when both patterns produce phenomenological similar percepts.

The first part of the experiment required a discrimination between movement produced in these two different ways (a "same/different" distinction), while in the second part the subjects' task was to chose the preferred stimulus pattern (by judging "which is best"). In addition, we will present every possible combination of our independent variables twice, which allows us to investigate if repetitive stimulation leads to changes in the tactile body map that alter discrimination performance.

The spatio-temporal parameters we use in this experiment will be the same as in the previous experiment with only one exception: We will only use a 12 tactor array, thus inter-tactor distance will be held constant this time.

Temporal effects We know from Experiment 1 that there was no uniform effect of ISI on the different qualities. But, like in the first experiment, we expect that shorter ISIs enhance the integration of spatio-temporal stimuli into a percept of continuous motion. If ISI affects both stimulus patterns the same way, as it genrally did in the first experiment, then discriminability should decrease with shorter ISI.

With the direct-comparison paradigm ("which is best"), we expect that preferences for one stimulus pattern over another as a function of ISI would be revealed when subjects have to choose the pattern that is "best" in terms of smoothness, straightness and spatial distribution. For short ISIs, patterns should be indiscriminable, so there should be no preference for either pattern. For longer ISIs, quality ratings in Experiment 1 were slightly higher for successively activated patterns, thus we expect that for longer ISIs, subjects will have a preference for one pattern over the other.

The effect of SD on the quality judgments was different for the two stimulus patterns and qualities, but from Figures 10.5-10.8 we learned, that quality ratings are rather similar for short SDs (<50 ms), whereas for longer SDs quality ratings for successively activated and saltatory patterns diverge. Specifically, ratings for saltatory patterns decrease with increasing SD. We therefore expect (deviating from the hypothesis formulated in Chapter 5) that discriminability is poor for short SDs and improves for longer SDs.

At the same time, there should be no clear preference for one stimulus pattern for short SDs, but for longer SDs, successively activated stimulus patterns should be preferred over saltatory patterns.

Spatial effect In Experiment 1 we found that the size of the stimulated area–here the width of the stimulus–affected the perception of illusory motion. This effect was frequently the same for both stimulus patterns, although it differed between qualities. If stimulus width affects both patterns equally, we do not expect to find an effect of stimulus width on discriminability or on preference for one stimulus pattern over the other.

Effect of frequency Experiment 1 showed that the effect of vibration frequency was generally identical for both stimulus patterns. We therefore expect that vibration frequency doesn't affect discriminability or preference for one stimulus pattern.

Repetitive stimulation Stimulus repetition might improve discrimination performance, since with experience, subjects find perceptual cues to distinguish between the two stimulus patterns. Conversely, repetition can lead to a rapid adaptation of the cortical map to spatio-temporal stimulus characteristics–as Stolle (2003) demonstrated for saltation. Hegner et al.

(2006) showed that these plastic changes can arise within minutes. Tactile stimulation in a fixed order and in quick temporal succession–like in our stimulus patterns–might lead to a reduction in cortical representational distances. Thus, discrimination performance might decline, as the patterns feel more and more alike. Finally, if one stimulus patterns is preferred over the other, this preferential treatment should diminish with stimulus repetition.

11.1 Method

Subjects In the "same/different" experiment, 18 subjects were tested with 250 Hz stimuli, and 19 subjects with 80 Hz stimuli. Of the 18 subjects tested with 250 Hz stimuli, there were 13 males and 5 females. Their average age was 23.3 (Min.=21, Max.=31). Only two subjects were left-handed, the remaining 16 subjects were right-handed. In the 80 Hz group we had 18 male and one female subjects. The youngest subject was 21 and the oldest was 32 (M=24.3). Sixteen subjects were right-handed, two were left-handed, and one was ambidextrous.

In the second part of the experiment ("which is best") we tested 20 subjects with 250 Hz stimuli and another 20 subjects with 80 Hz stimuli. In the 250 Hz group there were 19 male subjects and only one female. Their age varied between 21 and 29 (M=22.9). Sixteen subjects were right-handed, three subjects left-handed, one was ambidextrous. Out of the 20 subjects tested with 80 Hz stimuli there were 18 males and two females. Their average age was 23.3 (Min.=22, Max.=28). Only two subjects were left-handed, the rest were right-handed.

Procedure The apparatus and stimulus parameters described in the General Method section were employed in this experiment.

In the first part of the experiment–that required a same/different distinction–one half of the trials were generated in the same mode (both stimuli were successively activated or both were saltatory) and in the other half they were different (one stimulus successively activated, one stimulus saltatory). A combination of the seven different levels of SDs and ISIs resulted in 49 pairs of same trials successively activated, 49 pairs of same trials saltatory. When all possible pairings of the levels of SD and ISI and the sequence of stimulus patterns (mode of the pattern presented first) were specified, we had 98 pairs of different trials. If we would have presented all possible same and different pairs in one block, we would have had a total of 196 trials. We knew from previous pilot studies that subjects have difficulties concentrating on a task like this over a long period of time. Consequently we designed each block to consist of only 98 trials, with two blocks required to sample the complete set of alternatives. Stimulus pairs within a trial were generated with identical temporal parameters so that the total duration for the patterns to be compared was the same within a trial. The number of same and different pairs in each block was the same to ensure equal probabilities for same and different judgments. Otherwise, same and different pairs were randomly presented. All possible 196 pairings were presented twice, so there was a total of four blocks per session. Subjects were tested in two separate sessions on two consecutive days. In one session the tactile array consisted of one row of 12 tactors (narrow stimulus), while in the other session there were three rows of 12 tactors (wide stimulus). The order of the two sessions was randomized. One group of subjects was presented with 80 Hz stimuli and the second group of subjects was presented with 250 Hz stimuli.

Subjects were able to initiate the trials themselves by a keystroke. After a brief preparatory delay (600 ms) the first pattern was presented and after a delay of 2.4 s the second pattern followed automatically. Subjects reported their responses on the first two keys of the 10-button keyboard. Eight keys were covered with a paper strip, so that only the two response keys were visible; labeled with “S” for “same” and “D” for “different”. Subjects had no time limit for entering their answer. No feedback was given, whether the subjects’ answers were correct or incorrect. In between the blocks subjects could take a brief break if they wished.

During the second part of the experiment**,** only different pairs of stimulus patterns were presented: One pattern was always successively activated, while the other pattern was saltatory, with the order of the two modes varied randomly. As in the previous protocol, there were 98 possible pairings when the two orders, seven levels of SD and seven ISIs were combined. Every pairing was presented twice in each session. Again, there were two sessions, one for one row of 12 tactors, and one for three rows of 12 tactors, but this time, both sessions were executed successively on one day, separated by a brief break when the belt was removed to change the tactor arrangement. In this study there were also two groups of subjects: One group received 80 Hz stimuli in all conditions, the other group received 250 Hz stimuli.

The question to be answered by the subjects in this forced-choice paradigm, was which of the two patterns was the “best”. The two visible response keys on the keyboard were labeled

"1" (for the first pattern) and "2" (for the second pattern). Because the definition of best could vary over subjects, a standardized definition–based on the criteria from Experiment 1−was read to subjects and was available for reference throughout the whole session:

WHICH IS BEST?

By which is best we mean which pattern felt overall better.

Guidelines to determine this include:

Which line felt:

-straighter

-smoother

-equally distributed in both space and time

Subjects were also instructed that there are no correct or incorrect responses simply because they are rating which of the two patterns feels best for them. Accordingly no feedback was given. For complete instructions for both parts of the experiment see Annexes I and K.

The design of Experiment 2 is a multifactor design with repeated measures on the factors SD, ISI, sequence of stimulus patterns (only for "different" pairs) and number of tactors. Frequency serves as a group variable.

11.2 Results ("same-different")

Subjects had a strong tendency to answer "patterns are the same" as Table 11.1 shows:

Table 11.1: Percentage of answers "patterns are the same" or "patterns are different" over all subjects and trials separately for the 250 Hz and 80 Hz group

Answer	250 Hz	80 Hz
Patterns are the same		
%	77,0%	72,6%
n (number of trials)	10870	10808
Patterns are different		
%	23,0%	27,4%
n (number of trials)	3242	4088
Total %	100%	100%
Total n (number of trials)	14112	14896

Note: The percentage of subjects' responses (either "patterns are the same" or "patterns are different" is specified for both frequency groups (250 Hz and 80 Hz). Also the number of trials over subjects for both groups is denoted. Subjects perceive the patterns to be the same the majority of cases, although in fact only 50% of the patterns were presented in the same mode.

For the following analysis same and different pairs were examined separately: When stimuli were presented in the same mode (both patterns successively activated or both patterns saltatory), about 86% (for 250 Hz stimuli) and 79% (80 Hz) of the answers were correct. But when one stimulus pattern was successively activated and the other one was saltatory the percentage of correct answers (reported different when the two patterns were actually different) dropped to 32% (250 Hz) and 34% (80 Hz). These data indicate that, although the two stimuli were, in fact, different, subjects still perceived them as feeling the same 68% of the time for 250-Hz stimuli and 66% of the time for 80-Hz stimuli. These data support the notion, introduced by Geldard (1972) that tactile patterns generated in the two modes are–under certain conditions–indistinguishable from one another.

To illustrate the strength of the saltatory illusion in mimicking the sensation produced by successive stimulation, Figure 11.1 presents the frequency of same answers. When subjects answered "the patterns felt the same" although they are presented in different modes, both patterns are indistinguishable.

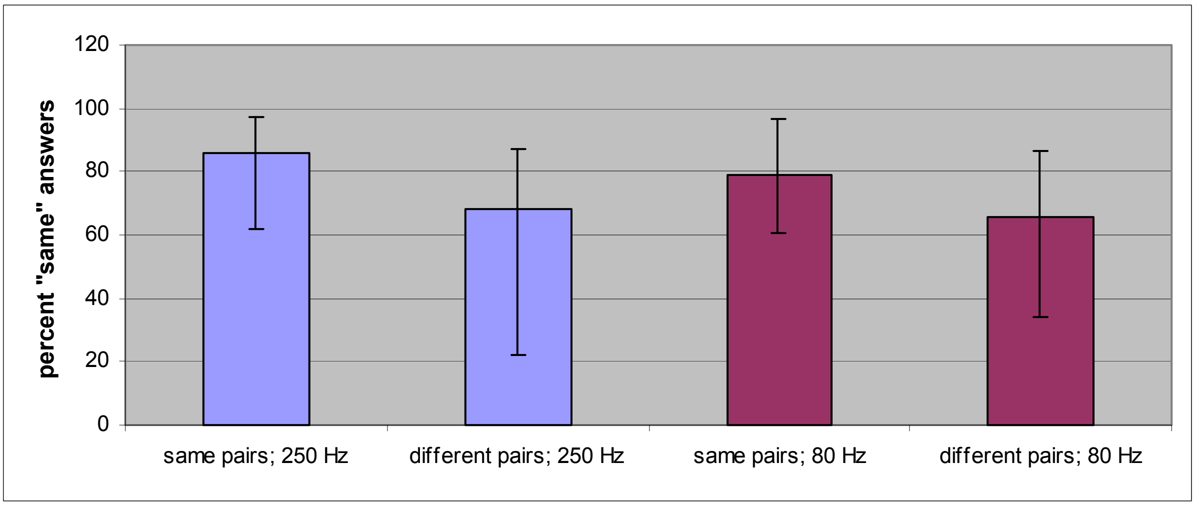


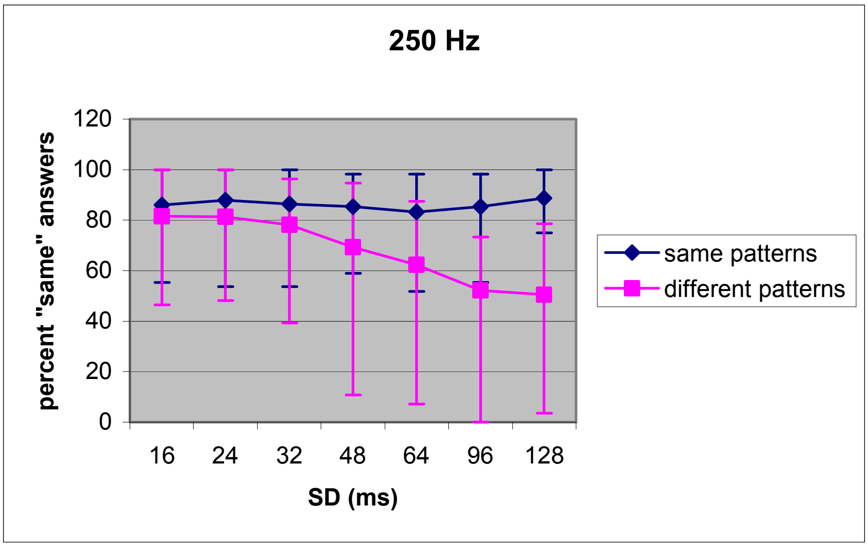
Figure 11.1: Percentage of "same" judgments for the different stimulus pairs (same pairs: both patterns successively activated or both patterns saltatory; different pairs: one pattern saltatory, one pattern successively activated) and vibration frequencies (250 Hz/80 Hz) over all subject and trials. Error bars mark minimum and maximum values. "Same" responses to same pairs are correct responses, "same" responses to different pairs are incorrect responses. In more than 65% of trials subjects respond "same" when in fact both patterns were presented in different modes, indicating that both stimulus patterns are oftentimes indiscriminable.

In more than 65% of the different pair trials, subjects answer "patterns feel the same", i.e. different stimulus patterns–one successively activated, one saltatory–are indistinguishable more frequently than random chance would predict. Although it should be noted that there is especially for different pairs a large variation in the frequency of "same" answers.

11.2.1 Temporal effects

Effect of SD

The effect of SD on discrimination performance is shown in Figure 11.2, separately for same and different pairs and for both vibration frequencies. Tactile arrays containing one and three rows of tactors are pooled. Denoted is the percentage of "same" answers. These are correct responses to the same pattern pairs and incorrect responses to the different pattern pairs. This comparison directly examines the strength of the saltatory illusion, because if subjects answered that the two patterns felt the same even when they were presented with different modes of generation, then the illusion would be truly complete.



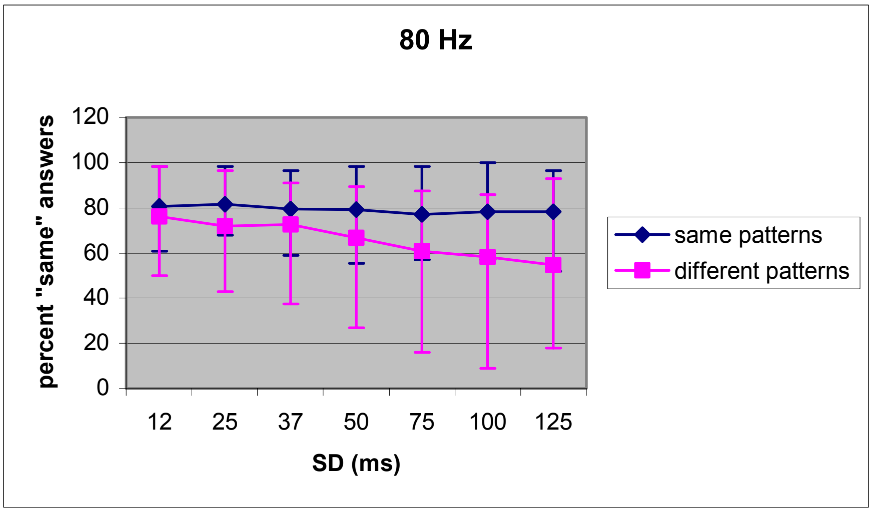


Figure 11.2: Effect of SD on subjects' ability to discriminate patterns of either the same generation mode (same pairs: both patterns successively activated or both patterns saltatory) or different generation modes (different pairs: one pattern saltatory, one pattern successively activated) correctly; denoted is the percentage "same" judgments over all subjects and trials, the error bars mark the minimum and maximum values. "Same" judgments for same pairs are correct discriminations, "same" judgments for different pairs mean that subjects can not discriminate between a successively and saltatory stimulus pattern correctly. Vibration frequency was either 250 Hz or 80 Hz. There seems to be a tendency for different pairs that the percentage of incorrect responses decreases with increasing SD.

The hypothesis was that discriminability increases for longer SDs. It was tested with $\chi 2$-tests. As there were large inter-individual differences in subjects' response behavior, separate $\chi 2$-tests were conducted for each single subject. The tests were again carried out separately for same and different pairs and for both stimulus frequencies (80/250 Hz). Annex L shows the results of the $\chi 2$-tests.

According to Figure 11.2 it seems that there are fewer "same" judgments for different pairs, as SD increases, i.e. different pairs are discriminated significantly more often correctly when SD increases for both stimulus frequencies. But significant differences in the number of "same" answers" as a function of SD, according to the $\chi 2$-tests (see Annex L), could only be found for seven out of 18 subjects in the 250 Hz group, and for four out of 19 subjects in the 80 Hz group. For the rest of the subjects in the two samples, the number of "same" answers did not vary significantly with SD.

Within the 250 Hz group, the probability of finding subjects where the number of "same" answers do show significant differences over the levels of SD is not statistically different from chance ($P=0.24$; binomial test; $\pi<0.5$). Within the 80 Hz group this probability is significantly less than chance ($P=0.01$; $\pi<0.5$). Thus, for the 80 Hz and for the 250 Hz group, the frequency of "same" answers does not vary significantly with SD.

For "same" pairs SD has no significant effect on discriminability. For neither subject, the frequency of "same" judgments varied significantly with SD.

However, note that the change in performance for the different pairs in Figure 11.2 is, in effect, a movement from a region in which both of the patterns feel the same the majority of the time (SD<=50 ms) to a region of uncertainty where subjects say "same" about 50% of the time (SD=125 ms).

Effect of ISI

As before, the effect of ISI on discrimination performance ("same" judgments) is shown in Figure 11.3, separately for same and different pairs and for both vibration frequencies.

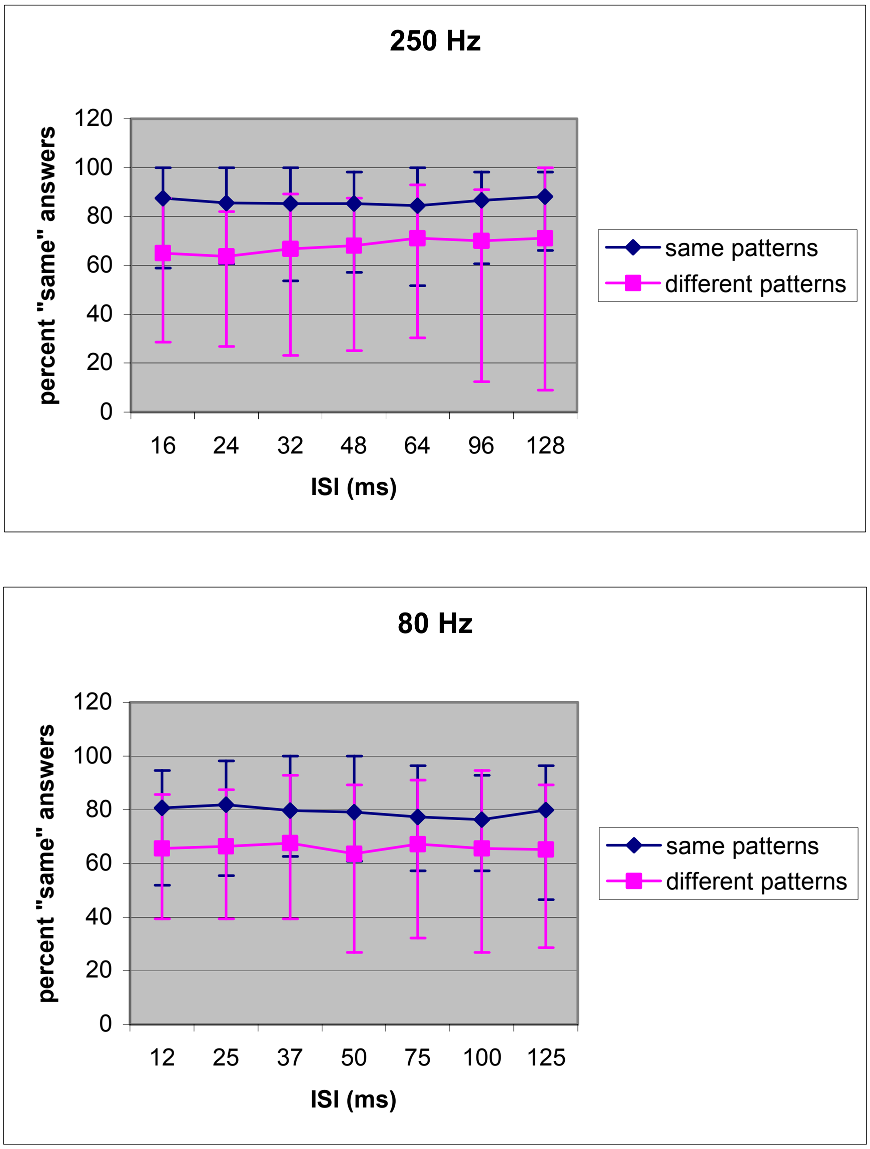


Figure 11.3: Effect of ISI on subjects' ability to discriminate patterns of either the same generation mode (same pairs: both patterns successively activated or both patterns saltatory) or different generation modes (different pairs: one pattern saltatory, one pattern successively activated) correctly; denoted is the percentage "same" judgments over all subjects and trials, the error bars mark the minimum and maximum values. "Same" judgments for same pairs are correct discriminations, "same" judgments for different pairs mean that subjects can not discriminate between a successively and saltatory stimulus pattern correctly. Vibration frequency was either 250 Hz or 80 Hz. There seems to be no clear effect of ISI on the percentage of "same" responses.

To test the effect of ISI on the number of “same” answers, the procedure described before was used: χ2-tests for every subject were conducted, separately for same and different pairs and for both stimulus frequencies (80/250 Hz). No subject showed a significant variation in its number of “same” responses as a function of ISI, as Annex M shows. Thus, ISI has no effect on the discrimination performance.

11.2.2 Spatial effect

Figure 11.4 compares discrimination performance for narrow stimuli–composed of only a single stimulus–and wide stimuli–composed of three stimuli on top of each other.

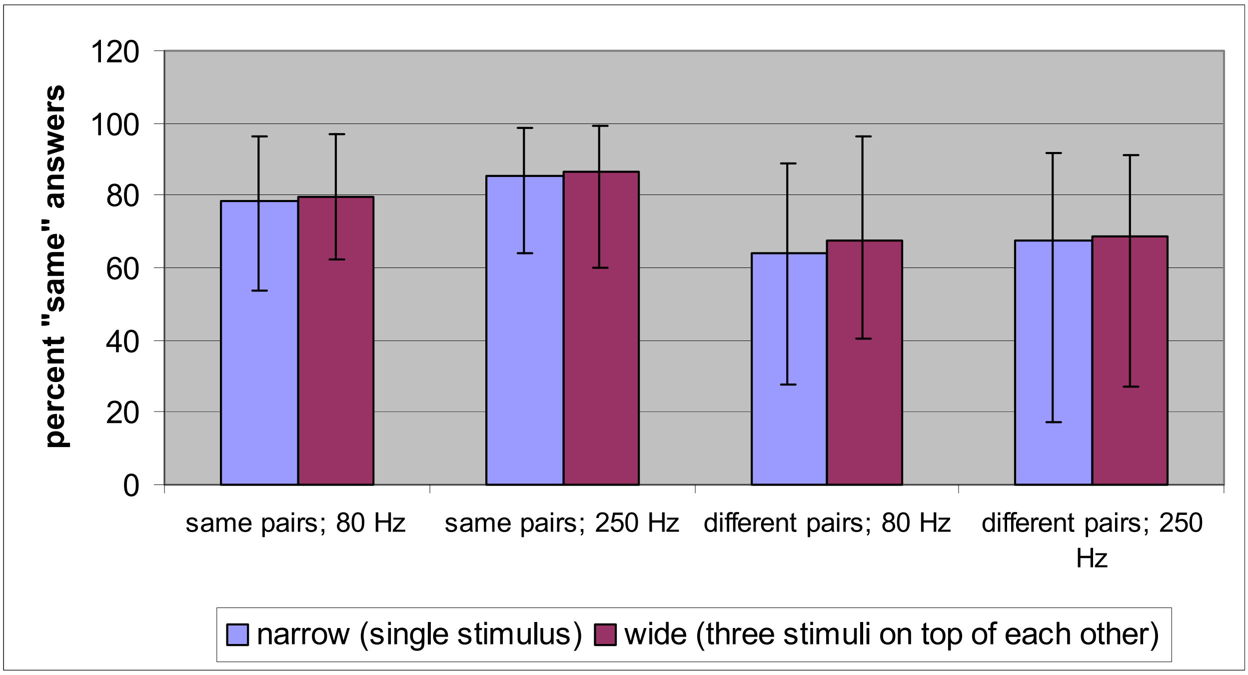


Figure 11.4: Percent “same” answers for same and different pairs dependent on stimulus width (one stimulus versus three stimuli on top of each other) and vibration frequency (80 versus 250 Hz) over all subject and trials. Error bars mark minimum and maximum values. Stimulus width seems to have only a marginal effect on discriminability.

The null hypothesis that the width of the stimulus (single stimulus versus three stimuli on top of each other) has no effect on the subjects' responses, i.e. discriminability was tested with McNemar χ^2-tests. Separate χ^2-tests were again conducted for same and different pairs. Results are shown in Table 11.2 below. Only for the condition presenting 80 Hz different pairs there was a significant difference between wide and narrow stimuli: As Figure 11.4 shows, for wider stimuli that were presented in different modes there were more "same" answers, i.e. they were less often discriminated correctly.

Table 11.2: Effect of stimulus width on discriminability tested with McNemar χ^2-tests

	Results of McNemar χ^2 tests	
	same pairs	different pairs
80 Hz	$\chi^2_{(.01;1;n=3724)}=1.87$	$\chi^2_{(.01;1;n=3724)}=9.98$
250 Hz	$\chi^2_{(.01;1;n=3528)}=1.76$	$\chi^2_{(.01;1;n=3528)}=1.47$

Note: χ^2-Tests have been carried out separately for same and different pairs and for both vibration frequencies to test if stimulus width has an effect on subjects' responses. In the 80 Hz group there were 3724 trials (n) for same and different pairs accumulated over 19 subjects, in the 250 Hz group there were 3528 trials each accumulated over 18 subjects. The χ^2-value that exceeds the critical level of $\chi^2=6.64$ ($\alpha=.01$, df=1) is graphically highlighted: Only for 80 Hz, different pairs stimulus width affects subjects' responses and thus discriminability.

11.2.3 Effect of frequency

Figure 11.5 shows the percentage of correct discriminations separately for same and different pairs for both vibration frequencies:

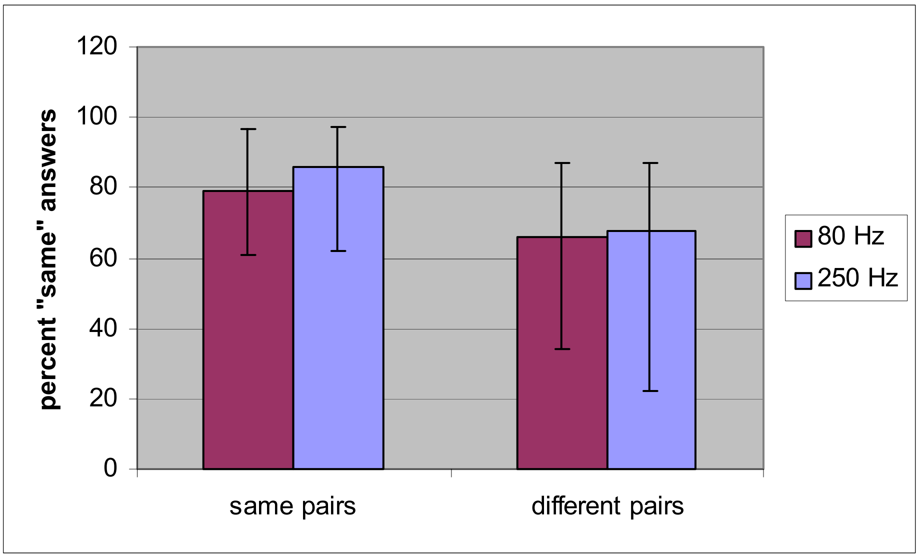
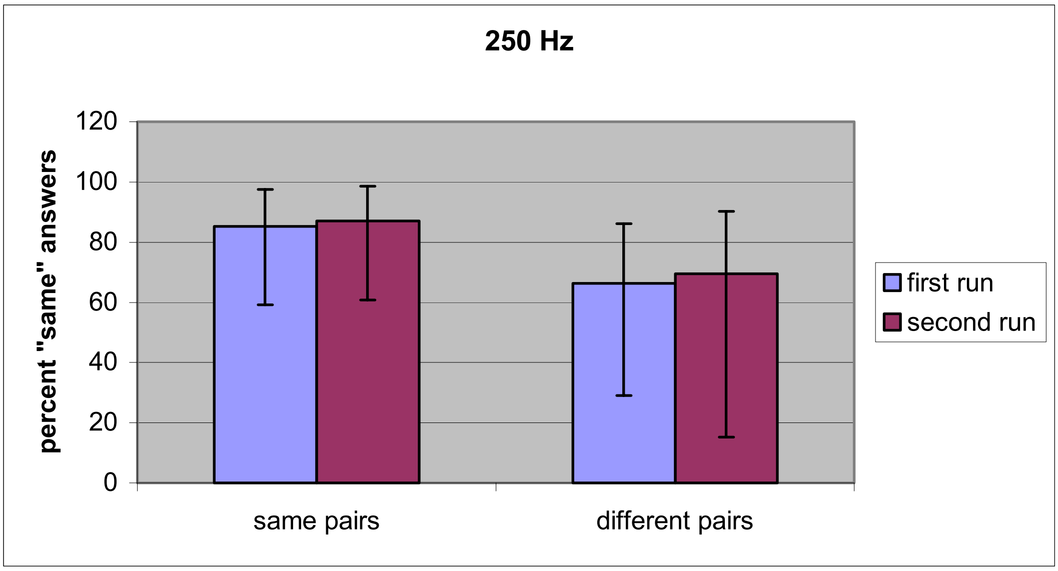


Figure 11.5: Percent "same" answers for same and different pairs dependent on vibration frequency (80 or 250 Hz) over all subject and trials. Error bars mark minimum and maximum values. There seem to be more "same" responses for 250 Hz pairs, indicating that 250 Hz pairs feel more alike than 80 Hz pairs.

According to Figure 11.5 it seems that there are more "same" answers for 250 Hz patterns, as well for same pairs–where "same" answers are correct discriminations–as for different pairs–where "same" answers are false discriminations. χ^2-tests showed that those differences are significant (same pairs: $\chi^2_{(.01;1;n=7448)}$= 296.72; different pairs: $\chi^2_{(.01;1;n=7448)}$= 14.28; there were 7448 trials accumulated over 19 subjects in the 80 Hz group). 250 Hz patterns feel more alike than 80 Hz patterns. Again, note that the large number of discrimination errors that occurred when the stimuli were presented in different modes supports the notion that subjects perceived them as being the same–saltation generates a spatially uniform pattern similar to that produced by the successively activated stimuli.

11.2.4 Effect of repetitive stimulation

We hypothesize that due to plastic changes, stimuli feel more and more alike with repetitive stimulation. Each combination of our spatio-temporal variables was repeated once. We compared the first and second run to each other regarding the number of "same" answers, to evaluate if the number of "same" answers increases, when identical blocks of trials are repeated. Figure 11.6 shows the percentages of "same" answers in the first and second run, separately for same and different pairs and for both vibration frequencies.



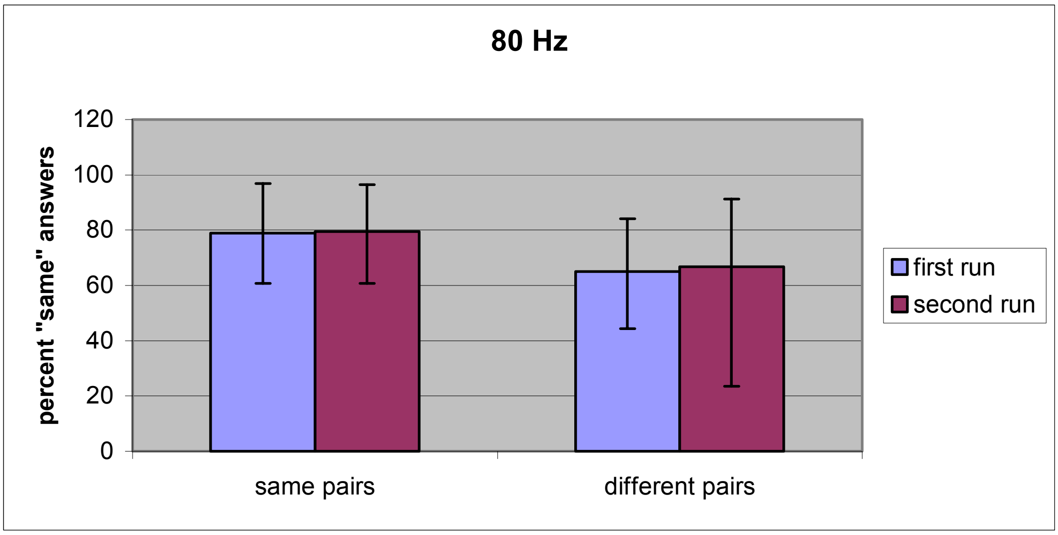


Figure 11.6: Comparison of "same" answers for identical blocks of trials (accumulated over subjects), separated for same and different pairs and vibration frequencies. Errors bars indicate minimum and maximum percentages of "same" answers. The percentage of "same" responses seems to increase slightly when trials are repeated.

Although there is a tendency, for the number of "same" answers to increase with stimulus repetition–especially for different pairs–, McNemar χ^2-tests show that only one of the comparisons achieves statistical significance: 250 Hz different pairs feel significantly more alike in the second run. Table 11.3 specifies the results of the χ^2-tests.

Table 11.3: Effect of stimulus repetition on discriminability tested with McNemar χ^2-tests

	Results of McNemar χ^2 tests	
	same pairs	different pairs
80 Hz	$\chi^2_{(.02;1;n=3724)}=0.52$	$\chi^2_{(.02;1;n=3724)}=3.74$
250 Hz	$\chi^2_{(.02;1;n=3528)}=4.93$	$\chi^2_{(.02;1;n=3528)}=7.75$

Note: χ^2-Tests have been carried out separately for same and different pairs and for both vibration frequencies to test if stimulus repetition has an effect on subjects' responses. In the 80 Hz group there were 3724 trials (n) accumulated over 19 subjects, in the 250 Hz group there were 3528 trials accumulated over 18 subjects. The χ^2-value that exceeds the critical level of $\chi^2=5.41$ ($\alpha=.02$, df=1) is graphically highlighted: Only for 250 Hz, different pairs stimulus repetition affects subjects' responses and thus discriminability.

11.3 Results ("Which is best")

In the second part of the experiment only different pairs–i.e. one pattern successively activated, one pattern saltatory, both patterns having identical timing parameters–are presented. When a saltatory stimulus pattern was chosen as "best", a score of 0.00 was recorded, when a successively activated stimulus pattern was picked, a score of 1.00 was entered, like in Pilot Study 2. As we learned from the previous experiment, in more than 65% of the trials–which is well above chance–subjects are unable to distinguish between successively activated and saltatory patterns. However, when subjects are forced to choose the pattern that is "best" in terms of "which line felt straighter, smoother, or had sites that felt equally distributed in both space and time" which pattern will they prefer? If they are unable to discriminate between the two patterns there should be no preference for either stimulus pattern. Figure 11.7 shows subjects' preferences for one stimulus pattern in this forced-choice paradigm.

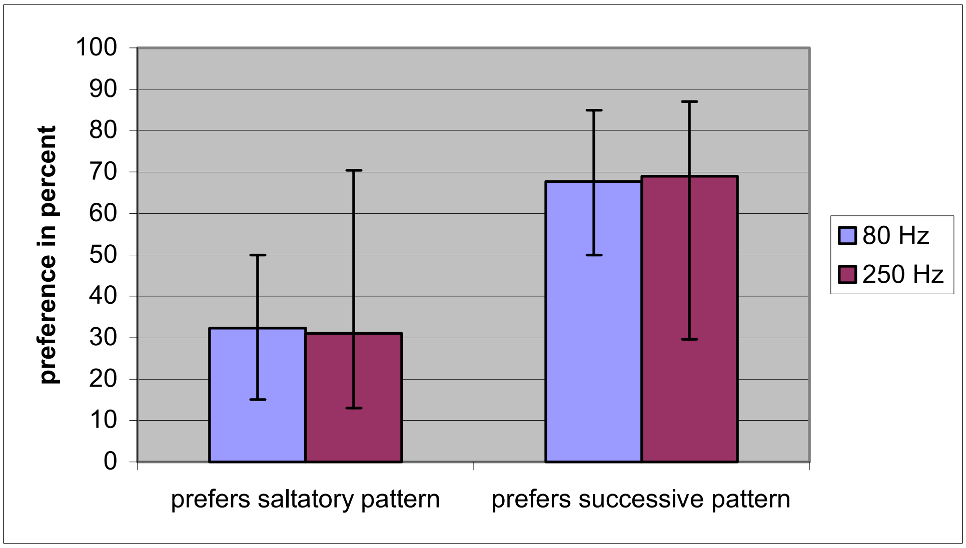


Figure 11.7: Preference in percent for the successively or saltatory stimulus pattern, when both patterns are presented in one trial and subjects have to decide "which is best" in terms of straightness, smoothness, and spatial distribution. Since we used a forced-choice paradigm, subject had to choose one pattern, thus percent preference for successively and saltatory patterns add up to 100% within each frequency-group (80 or 250 Hz). The indicated percentage comprises all subjects and trials in the two frequency groups. Error bars mark minimum and maximum percentages. Subjects always prefer the successively activated patterns more often.

In the 80 Hz group, 17 out of 20 subjects preferred the successively activated patterns significantly more often. For the rest of the subjects, the difference was not significant (see Annex N). A binomial test showed that significantly more subjects preferred the successively activated patterns (P=0.00; π>0.5).

In the 250 Hz group, 18 out of 20 subjects preferred the successively activated patterns significantly more often. One subject preferred saltatory patterns significantly more often, and for one subject the difference in preference for either stimulus pattern was not significant (see Annex N). Again, a binomial test indicated that significantly more subjects preferred the successively activated patterns, as in the 80 Hz group (P=0.00; π>0.5).

11.3.1 Temporal effects

Effect of SD

We expect that for longer SDs, the preference for successively activated stimulus patterns should increase, while the preference for saltatory patterns should decline. The effect of SD on subjects' preference for one stimulus pattern is shown in Figure 11.8, separately for both vibration frequencies. Data from tactile arrays containing one and three rows of tactors are pooled. Shown is subjects' preference for either the successively presented or saltatory stimulus pattern.

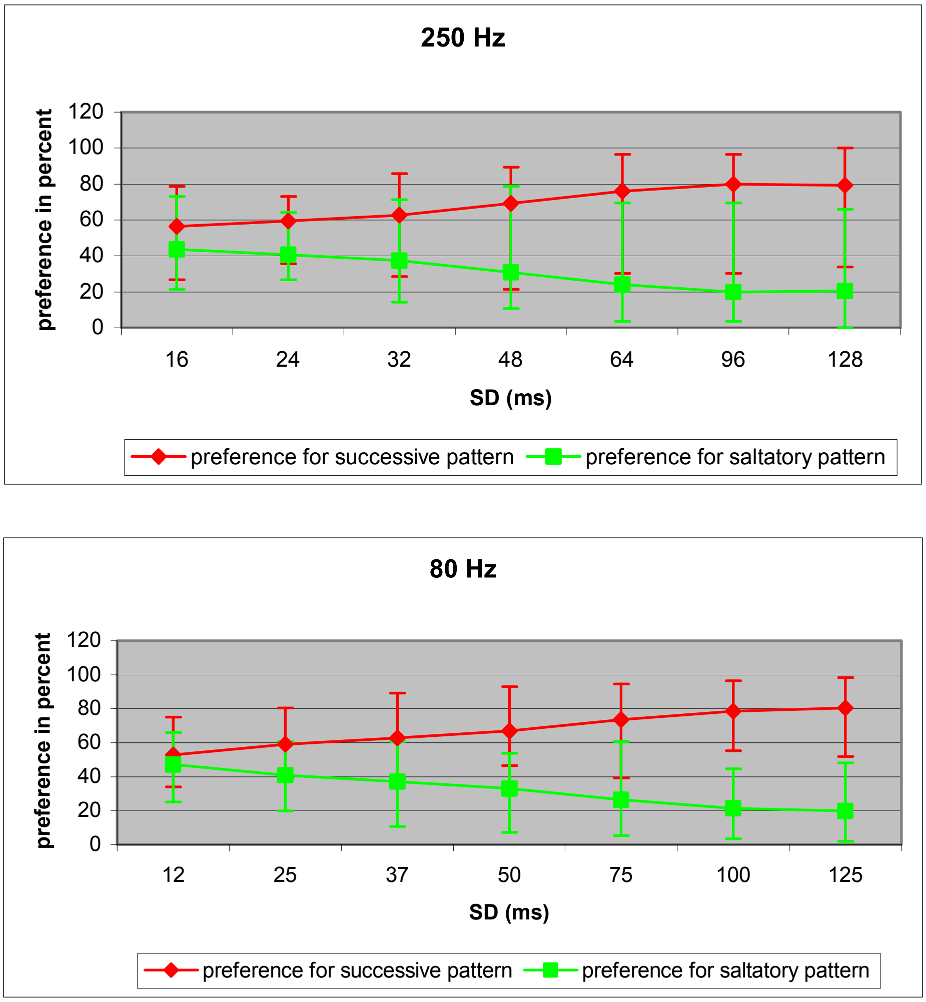


Figure 11.8: Effect of SD on subjects' preference for either successively activated or saltatory stimulus patterns in a forced-choice paradigm, where subjects had to decide, which pattern was "best". Shown is the percentage of preference for one stimulus pattern over all subjects and trials; the error bars mark the minimum and maximum values. Vibration frequency was either 250 Hz or 80 Hz. With increasing SD the preference for saltatory patterns seems to decrease.

To test if the preference for saltatory stimulus patterns was equally distributed over all seven levels of SD, χ^2-tests were performed, separately for each subject, since subject's answers vary considerably. Annex O shows the results.

In the 80 Hz group as well as in the 250 Hz group, 9 out of 20 subjects show significant differences in their preference for one stimulus pattern, dependent on SD. Preference for saltatory patterns in these cases always decreased with increasing SD–implying that preference for successively activated patterns increased with SD. Using a binomial test, the number of subjects showing significant differences in their preference is not significantly different from chance ($P=0.41$; $\pi<0.5$). We reason therefore, that SD has no effect on subjects' preference for one stimulus pattern for both vibration frequencies. However, it should be noted that over all subjects (see Figure 8.8), when SDs are very small (<20 ms), subjects do not clearly prefer one pattern over the other.

Effect of ISI

As before, Figure 11.9 shows subjects' preference for one stimulus pattern as a function of ISI, for each vibration frequency.

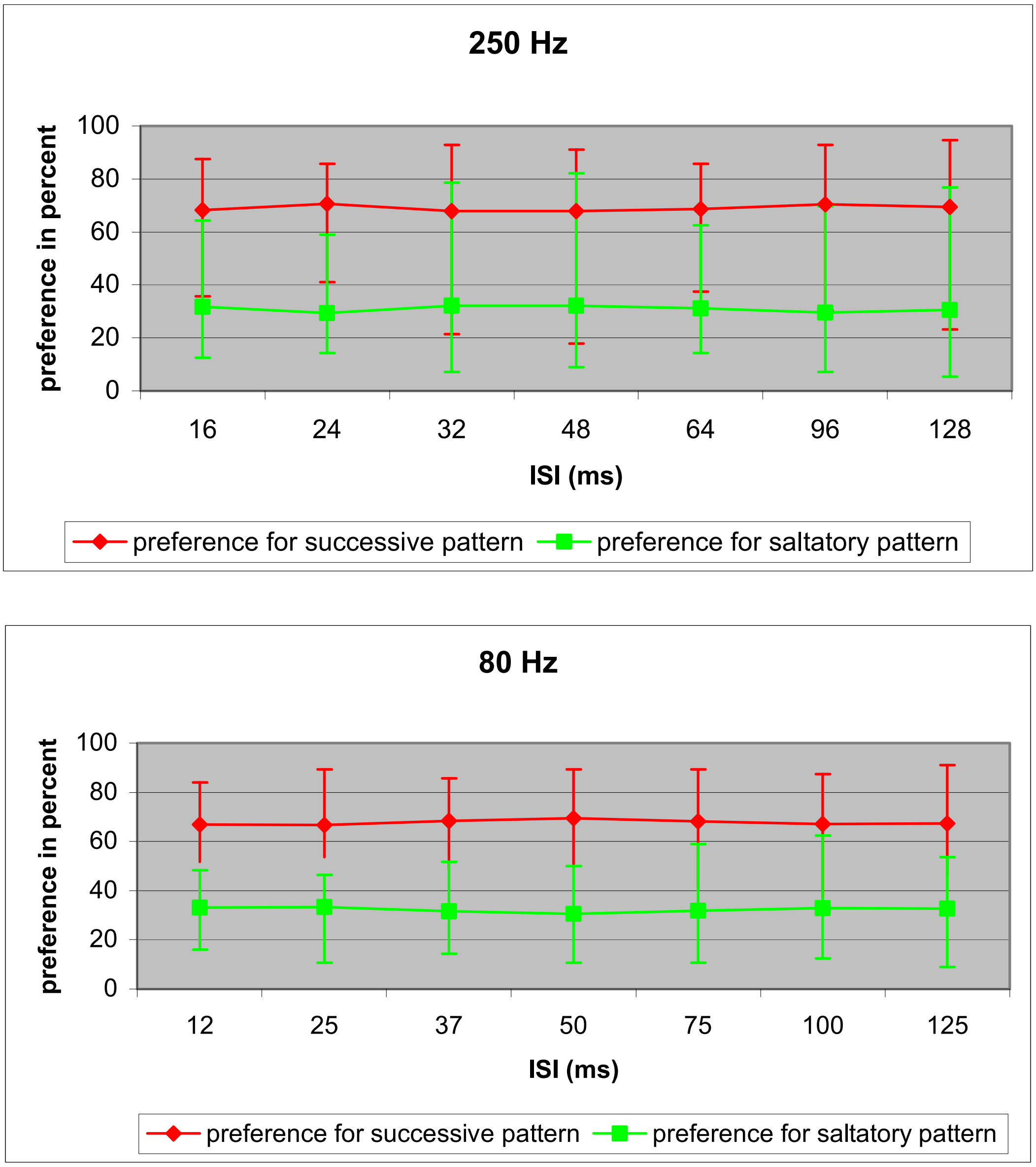


Figure 11.9: Effect of ISI on subjects' preference for either successively activated or saltatory stimulus patterns in a forced-choice paradigm, where subjects had to decide, which pattern was "best". Shown is the percentage of preference for one stimulus pattern over all subjects and trials; the error bars mark the minimum and maximum values. Vibration frequency was either 250 Hz or 80 Hz. ISI does not seem to affect the preference for one stimulus pattern.

Again, for each subject χ^2-tests were performed, to test whether the preference for one stimulus pattern is equally distributed over all seven levels of ISI (see Annex P).

In the 80 Hz group, no subject showed a variation of their preference for one stimulus pattern as a function of ISI.

In the 250 Hz group, 2 out of 20 subjects show significant differences in their preference for one stimulus pattern over the levels of ISI. In both cases, subjects prefer saltatory patterns more often, as ISI decreases. However, a binomial test ($P=0.00$; $\pi<0.5$) proved, that the number of subjects showing significant variations in their preferences is lower than chance.

We can conclude that ISI has no effect on subjects' preference for one stimulus pattern for both vibration frequencies.

11.3.2 Spatial effect

Figure 11.10 compares subjects' preference for one stimulus pattern (saltatory or successive) for narrow stimuli–composed of only a single stimulus–and wide stimuli–composed of three stimuli in a column.

To test if the width of the stimulus (single stimulus versus three stimuli on top of each other) has an effect on subjects' preference for one stimulus pattern, McNemar χ^2-tests ($\alpha=.01$, df=1) were performed for each frequency group (80 Hz versus 250 Hz group). In both groups stimulus width had no significant influence on subjects' preference (80 Hz: $\chi^2_{(.01;1;n=3920)}=3.16$; 250 Hz: . $\chi^2_{(.01;1;n=3920)}=2.41$; n is the number of trials accumulated over subjects).

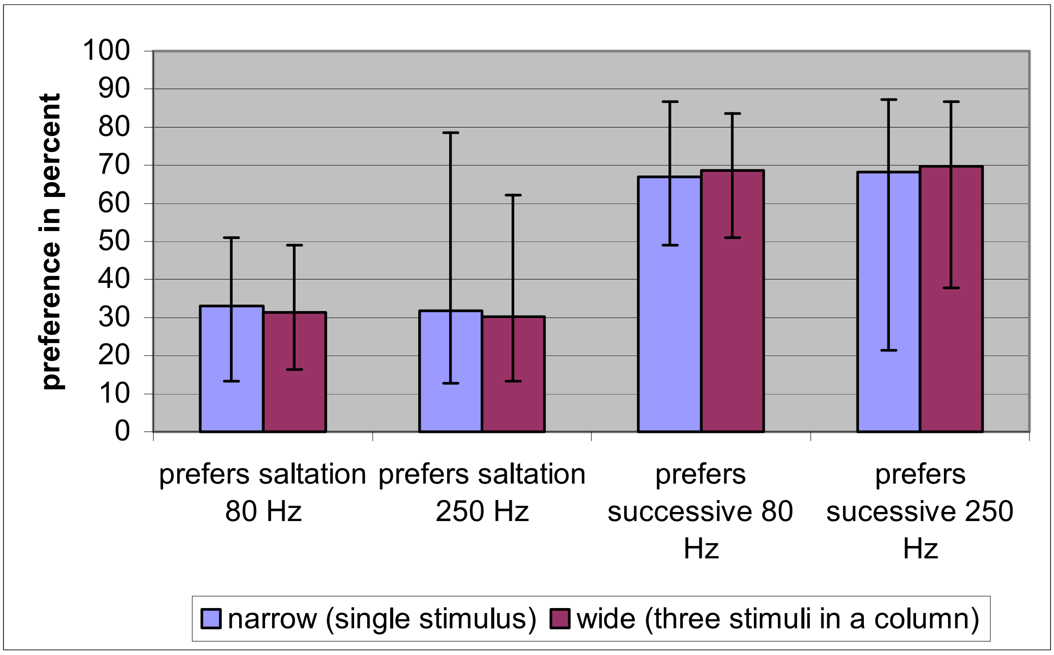


Figure 11.10: Percent preference for one stimulus pattern (saltatory or successively activated) dependent on stimulus width (one stimulus versus three stimuli in a column) and vibration frequency (80 versus 250 Hz) over all subjects and trials. Error bars mark minimum and maximum values. Stimulus width seems to have only a marginal effect on subjects' preferences for one stimulus pattern.

11.3.3 Effect of frequency

Figure 11.7 showed that subjects preferred saltatory patterns a little more frequently in the 80 Hz group, compared to the 250 Hz group, where successively activated patterns are favored. But, according to a χ^2-test ($\chi^2_{(.01;1;n=7840)}$=5.71; there were 7840 trials accumulated over 20 subjects in the 250 Hz and in the 80 Hz group) this difference is not statistically significant.

11.3.4 Effect of repetitive stimulation

As we know from Figure 11.7 significantly more subjects preferred the successive over the saltatory patterns. If the perceived difference between the two patterns diminishes due to plastic changes–as we expect–then, significantly more subjects should show a stronger preference for saltatory patterns, when stimuli are repeated. Figure 11.11 compares the preferences for one stimulus pattern in the first and second run of trials, for both vibration frequencies.

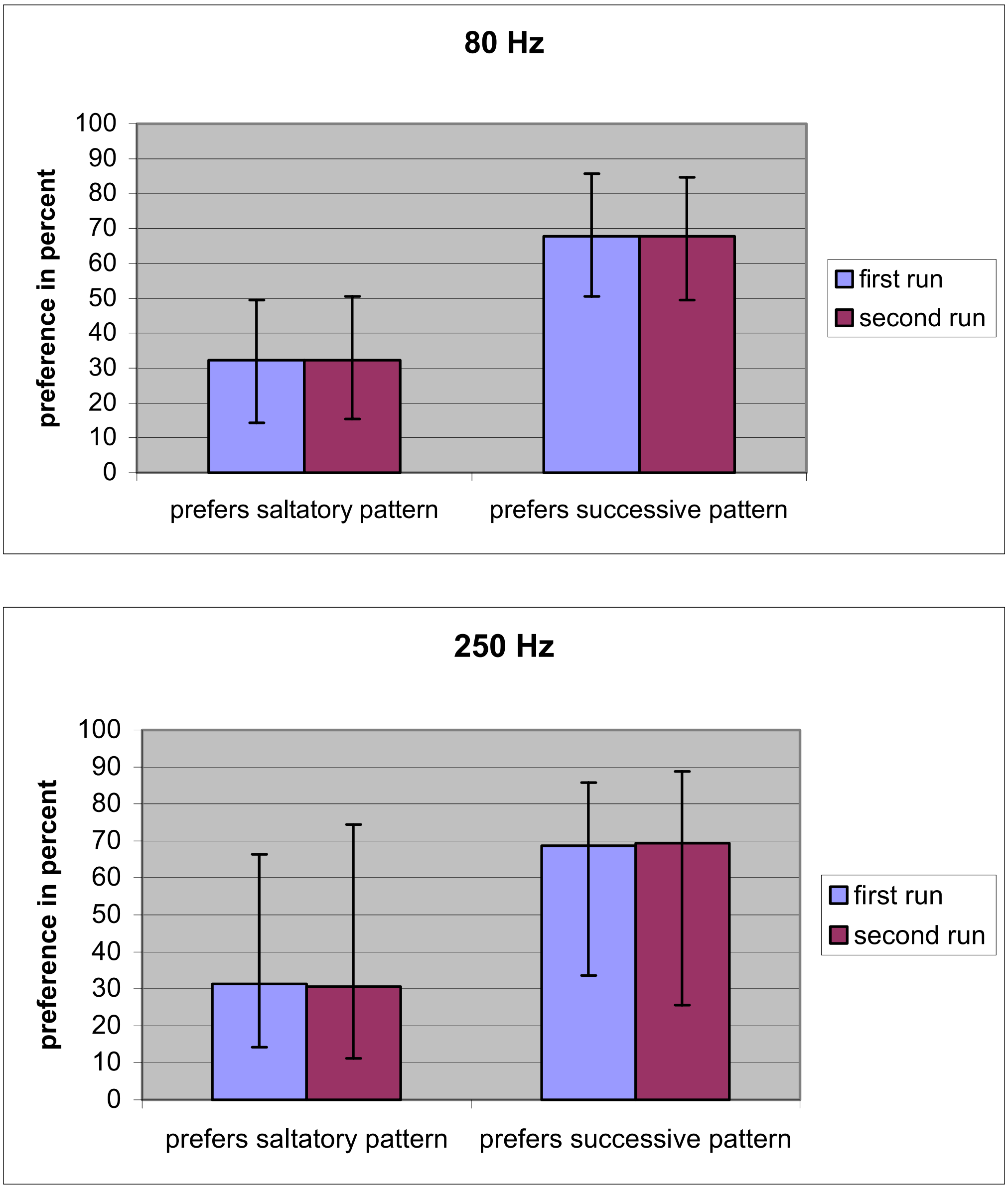


Figure 11.11: Comparison of the preferences for one stimulus pattern for identical blocks of trials, for both vibration frequencies. Subjects were asked which of two patterns–saltatory or successive–felt "best" in terms of continuous movement. The percentages of preferences for one pattern over trials and subjects in the first and second run are specified. Errors bars indicate minimum and maximum percentages. Stimulus repetition seems to have only a marginal effect on subjects' preferences for one stimulus pattern.

We learn form Figure 11.11 that the differences between the first run and stimulus repetitions are marginal in both frequency groups. McNemar χ^2-tests show that none of the comparisons achieves statistical significance (80 Hz: $\chi^2_{(.02;1;n=3920)}$=0.01; 250 Hz: $\chi^2_{(.02;1;n=3920)}$=0.59; critical level of χ^2=5.41).

We can conclude that stimulus repetition does not have an effect on subjects' preference for one stimulus pattern.

11.4 Summary and discussion

One aim of the study was to identify spatio-temporal conditions where the successively activated and saltatory stimulus patterns produce comparable percepts of motion. A paired comparison (patterns are the same or different) and a forced-choice paradigm (which is best) were used to test the similarity between the two stimulus patterns. The patterns varied in terms of (a) SD, (b) ISI, (c) width of stimulus, (d) vibration frequency.

Temporal parameters To answer the question of whether the successively activated and saltatory stimulus patterns produce discriminable sensations we should particularly look at subjects' performance when different pairs were presented in the first part of the experiment. Although there is a strong tendency for discriminability to be poor for short SDs, increasing for longer SDs (consistent with our hypothesis), the trend is not statistically significant.

In the second part of the experiment we changed the response paradigm (to "which is best") and obtained similar results: There was a trend for short SDs to produce no clear preference for one stimulus pattern over the other, but with longer SDs, successively activated stimulus patterns were preferred over saltatory patterns–again corresponding with our hypothesis, but the results fail to be significant.

We expected that discriminability should decrease with shorter ISI, and that there should be no preference for either pattern for shorter ISIs. However in both parts of the experiment ISI had no effect on subjects' responses. If we compare these results to those of Cholewiak and Collins (2000) who generated vibrotactile lines up and down the back (vibration frequency: 230 Hz), using the same experimental procedure, we find some analogies. They also found that subjects predominately answered "patterns are the same". When same pairs were presented, 82% of the answers were correct (in our study: 86% (at 250 Hz) and 79% (at 80 Hz)). When successively activated and saltatory lines (different stimuli) were paired, 37% of the answers were correct (in our study: 32% (250 Hz) and 34% (80 Hz)). Cholewiak and Collins (2000) noted a significant main effect of ISI on accuracy in that discriminability was better for shorter ISIs; we found no such effect.

These results are contrary to other studies: Eimer et al. (2005) using tactile stimuli, Philips et al. (2002), Boehnke and Philips (2005) using auditory stimuli, showed that subjects are unable to distinguish saltation and continuous motion at short ISIs. In line with these findings are the experiments of van Erp (2007): Localization of successively presented stimuli (indicating if the second stimulus is located left or right from the first) also decreases when ISOI and SD decrease−whereas the effect of SD is less distinct. Since the temporal parameters for good localization performance are in the range where apparent motion can be observed, van Erp argue that subjects used motion cues in this localization task.

We found at least a trend that SD affects discriminability which was not reported by Cholewiak and Collins (2000).

For the occurrence of the saltatory illusion the interstimulus interval is crucial according to Geldard (1975, 1982) and Geldard and Sherrick (1986)−because the amount of mislocalization depends linearly on ISI between S2-S3 (reduced rabbit). But in order to discriminate veridical from saltatory patterns, we find that stimulus duration is the more important factor. To produce comparable percepts of tactile apparent motion, short SDs are needed.

Stimulus width We hypothesized that there would be no effect of stimulus width on discriminability or on the preference for one stimulus pattern over the other. This was supported with one exception: For 80 Hz different pairs there were more "same" answers for wider stimuli, i.e. they were less often discriminated correctly. Obviously, in this case, a wider stimulated skin area allows single stimuli to meld together more easily.

Vibration frequency We didn't expect that vibration frequency would affect discriminability or preference for one stimulus pattern. In the first part of the experiment (same-different) we found that 250 Hz patterns felt significantly more alike than 80 Hz patterns, whereas in the second part of the experiment (which is best) vibration frequency had no effect on subjects' responses.

The first result is somewhat surprising, since saltation and apparent movement are known to be largely uninfluenced by vibration frequency (refer to the Chapter 3). A possible explanation could be that we used a different experimental paradigm, one that requires pattern discrimination ("same-different" judgments). Although the existence of saltation and apparent movement per se might not be affected by vibration frequency, the resolution of fine spatial details in these percepts of movement might well be (compare also the results of Experiment 1: 80 Hz stimuli appear to be less straight, less smooth, slightly more equally distributed in space and longer in perceived physical length than 250 Hz stimuli).

Thus it seems worthwhile to review how vibration frequency influences spatial acuity. The two standard measures of tactile acuity, two-point threshold and localization error, are not affected by frequency (Cholewiak, Collins & Brill, 2001; Greenspan & Bolanowski, 1996; Vierck & Jones, 1970)[7], but these measure are not sufficient to study spatial resolution (Johnson, van Boven & Hsaio, 1994). Recently, a study by Bensmaia, Craig, and Johnson (2006) showed that the ability of detecting gaps in a grating decreased with increasing vibration frequency over the range of 5-80 Hz.

Physiologically, mechanoreceptive afferent fibres convey spatial information to a varying extent: PC and SAII afferents are not able to resolve spatial detail, and note that PCs are the structures most sensitive to 250 Hz stimuli. Predominantly RA (FAI) and SAI afferents in glabrous skin provide information about the spatial structure of a stimulus, whereat SAI afferents are more effective than RA afferents in this connection, especially at low vibration frequencies (Bensmaia et al., 2006; Johnson & Hsiao, 1992; Johnson & Lamb, 1981). In hairy skin, we do not find FAI type fibres, here, hair follicle afferent fibres (having larger receptive fields than type I units) respond to vibration stimuli up to 80 Hz. At higher frequencies vibrotactile sensitivity depends on PC receptors which are located deep to the hairy skin. Because of the distance, the vibratory signal has to travel until it reaches the hairy skin PC receptor, its strength (and maybe also irregularities or gaps in the stimulus pattern) is attenuated, hence vibratory thresholds are higher on hairy than on glabrous skin (Mahns et al., 2006; one can also see the difference in Figure 7.4, page 83, of this Dissertation). It is

[7] One exception is mentioned by Sherrick, Cholewiak and Collins (1990): They found a better localization performance for low-frequency vibratory stimuli (25 Hz) compared to high-frequency stimuli (250 Hz), but only at a proximal locus on the palm of the hand. This effect disappeared, when a more distal locus was stimulated, indicating that receptor density and its gradient across the skin might contribute to the results obtained.

possible that the perception of spatial details in tactile patterns is degraded at higher frequencies, which would explain why discriminability decreases with vibration frequency and we obtain more "same" answers in the same/different experiment for 250 Hz patterns than for 80 Hz patterns.

Repetitive stimulation Applying spatio-temporal stimulus patterns with ISIs smaller than 130 ms, should lead to an integration of the single stimulus points and their representational distances in somatosensory cortex should be reduced (Wiemer et al., 1998, 2000; see Chapters 1 and 2). In our experiments no feedback was given, so we didn't expect that a learning process took place, which would presumably have increased discrimination performance over the time course of the experiment. Instead, we expected that in agreement with Wiemer's theory, the integration of stimulus patterns consisting of stimuli following close together in time would be enhanced with stimulus repetition and discrimination performance would decrease as the patterns begin to feel more and more alike. Additionally, if one stimulus pattern is preferred over the other, this preferential treatment should be diminished with stimulus repetition.

In our studies, although there was a tendency that the number of "same" answers increased with stimulus repetition in the first part of the experiment ("same/different" judgments), this trend was only statistically significant for 250 Hz different pairs. In the second part of the experiment (which is best), stimulus repetition had no effect on subjects' responses. It is likely that only one repetition of the whole set of spatio-temporal stimulus parameters was insufficient to cause plastic changes.

12 Experiment 3: Different stimulus onset locations and their effects on tactile movement crossing the body midline

When Geldard (1982; Geldard & Sherrick, 1983, 1986) explored the spatial limits of saltation (which he called saltatory areas) he found that the saltatory illusion never crossed the body midline. In some of these experiments he placed two stimulators on opposite sides on the forehead. When he varied the time interval between those two tactors as well as the distance between them (11 cm–1 cm), saltatory jumping was never reported. In contrast, apparent movement could often be experienced–especially at interstimulus intervals of about 100 ms (Geldard, 1982). A repetition of this experiment on the torso also showed that the saltatory area was truncated at the body-midline. Geldard reasoned that different neural mechanisms form the basis for the two tactile illusions (apparent movement versus saltation). In another experiment he compared synthetic motion (comparable to the successive activation in our experiments) with saltation. Here he placed six equidistant contactors along the left forearm that were each stimulated once in sequence while on the right forearm he placed three contactors covering the same distance, each being activated twice. The total duration of stimulation was identical for both arms, and six pulses were presented in both cases. At ISIs between 50 and 100 ms "the observed patterns were identical, a more or less continuous sweep punctuated by six evenly spaced taps… the two [stimulus patterns] were distinguished only by the observation that the former [saltatory pattern] had slightly weaker, less "bright" taps,…" (Geldard, 1982; pp. 139). These results, taken as a whole, show that both tactual illusions: Tactual phi or apparent movement and saltation can appear concurrently during unilateral stimulation. When stimulation crosses the body midline (which we call subsequently bilateral presentation in comparison to unilateral presentation, i.e. stimuli are presented on one body-half only), only phi-movement occurs and saltation is not observed.

The latter observation is supported by Wiemer et al. (2000): They offer a model for the processing of stimuli in somatosensory cortex that includes stimulus dynamics, i.e. the temporal course of stimuli. They presume that interstimulus intervals are transformed into representational distances in the cortical map. The perception of a mislocalized stimulus that occurs during saltation is due to time-dependent shifts of cortical responses. Because these shifts of neural activation should only happen between adjacent areas (and therefore within one hemisphere), the saltatory illusion should not cross the body midline.

Based on these findings, we could hypothesize that conformity between the percepts of saltatory movement and apparent movement produced by sequential activation should be better when movement travels on one side of the torso rather than when movement travels across the front or back of the torso. In the latter case the saltatory illusion would be expected to break down when it crosses the body midline. But in contrast to Geldard's experiments we did not use just two tactors, but a linear array of seven tactors. We assume that once we produce the illusion of saltatory movement on a linear array, then movement shouldn't stop at the body-midline, assuming that the cortex integrates perceptions from the two body-sites into an integral whole. When subjects have to discriminate between saltatory and successively activated stimulus patterns they should reach similar results when the illusory movement travels the body-midline and when it travels on one body site only.

This presumption is supported by the work of Stolle (2003). In her integrative model of spatiotemporal illusions, she assumes that tactile illusions like saltation, apparent movement, and the Békésy phantom (Békésy, 1967) are due to neural mechanisms in primary somatosensory cortex (SI). Processing of tactile stimuli is thereby influenced by higher cortical levels like SII– where a bilateral representation of the body exists–facilitating the integration of tactile stimuli presented at both body sites. Accordingly she presumes that the saltatory illusion might also occur when the stimuli cross the body midline, but the temporal conditions might differ considerably between unilateral and bilateral stimulation.

12.1 Method

Subjects There were two conditions in this study: One in which the stimulus sites in the middle of the array were located on either side of the body midline and thus "span the navel", the other in which one of the tactors in the middle of the linear array is actually sited on the body-midline, so we called this condition "with navel". Twenty-one subjects participated in the span the navel experimental condition (17 males, four females). The age of the subjects varied between 21 and 30 (M=23.5). Most of the subjects were right hander (18 subjects), only three of them were left hander. In the second–with navel –condition, 20 subjects participated (19 males, one female). These subjects' ages ranged between 21 and 25 (M=22.5). Eighteen subjects were right handed, two were left handed.

Procedure Vibrotactile movement was produced with the apparatus and stimuli described in the General Method section, although in this experiment only 250 Hz stimuli were used. The experimental procedure was similar to that of Experiment 2 (same/different comparison): Again the paired-comparison paradigm was employed to let subjects discriminate between the saltatory patterns and successive activation. The temporal stimulus parameters were also identical to those used in Experiment 2. How the same and different stimulus pairs were generated can be seen in the method section of Experiment 2 (Chapter 11.1).

The tactile array in all of the conditions in this study consisted of a line of 7 tactors. Their arrangement in the span navel and with navel conditions and placements on the body were as follows:

In the span navel conditions the tactile array covered only the front of the torso. The tactors were placed on the belt so that the navel lay in-between two tactors: Either between tactors three and four or tactors four and five in the line of seven. With this arrangement we can also test if the number of activated tactor sites (three or four) before the movement crosses the body midline has an effect on discriminability. These arrangements are pictured below in Figure 12.1:

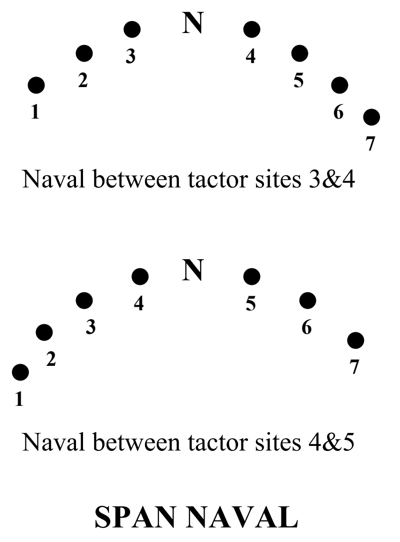


Figure 12.1: Tactor sites (presented as filled dots) for the span navel condition. N stands for navel. The navel is situated in-between two activated tactors: Either tactors three and four or tactors four and five. In total the array contained seven tactors. Note: The distance between the two tactors that spanned the navel (3&4 top figure, 4&5 bottom figure) was identical to the other distances between tactors but is exaggerated in the figure.

In the with navel condition the tactile array was placed around the torso in four different positions:

-Front: Tactor number one was placed on the left side (at 9 o'clock), number four on the navel (at 12 o'clock), and number seven on the right side (at 3 o'clock). This condition produces bilateral stimulation, since both body halves are stimulated. Movement traveled around the front of the torso (see Figure 12.2).

-Right: Tactor number one was placed on the navel (at 12 o'clock), number four on the right side (at 3 o'clock), and number seven on the spine (at 6 o'clock). This condition produces unilateral stimulation, since only the right half of the body was stimulated. Movement traveled around the right side of the torso.

-Back: Tactor number one was placed on the right side (at 3 o'clock), number four on the spine (at 6 o'clock) and number seven on the left side (at 9 o'clock). Again, this condition produces bilateral stimulation, since movement traveled across the back of the torso, stimulating both halves of the body.

-Left: Tactor number one was placed on the spine (at 6 o'clock), tactor number four on the left side (at 9 o'clock), and tactor number seven on the navel (at 12 o'clock). The last unilateral condition in which movement traveled around the left side of the torso.

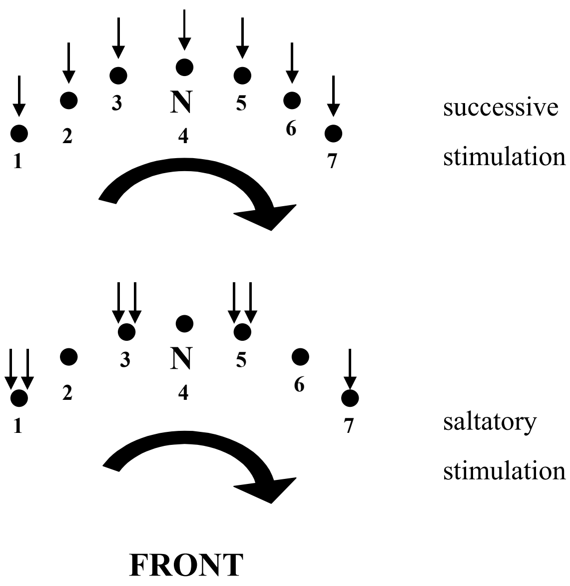


Figure 12.2: Tactor sites (presented as filled dots) for the position front with the position of the navel marked with an N. The arrows mark the activation of tactors. Successive activation: Every tactor is activated once; saltatory stimulation: The first, third , and fifth tactor is activated twice, the seventh tactor is activated once. The total number of stimuli is seven for both stimulus patterns.

These arrangements were chosen so that we could evaluate whether discriminability differs if the naval (at the body-midline) serves as a tactor site or if the navel is spanned and the tactors are placed on either side of it. This is an interesting question since the two patterns might be discriminated better when successively stimulated patterns involve the stimulation of the body-midline–a body-site where localization performance is near-perfect (Cholewiak, Brill & Schwab, 2004)–whereas patterns that leap (span) the body-midline may violate Geldard's requirement that a tactor should be placed there to provide a saltatory bridge–a condition where saltation is unlikely to occur (Geldard, 1982; Geldard & Sherrick, 1983, 1986)

When saltatory patterns were presented, the first, third, and fifth tactors were activated twice, while the seventh tactor was activated once, so that the number of stimuli was the same as for the successive activation, where every one of the seven tactors was activated once. The pattern of activation in all conditions was always clockwise (as shown in Figure 12.2). After the presentation of a stimulus pair, subjects responded by pressing a button on the keyboard: If they felt the patterns were the same they pressed the button labeled "S" for same, if they felt the patterns were different, they pressed the button labeled "D" for different. There was no time limit for entering their answer. No feedback was given throughout the experiment.

The two different tactor arrangements were tested in two different sessions, randomly ordered, on two consecutive days. In each session four blocks of trials were presented, each block including 98 trials. The 98 same pairs and 98 different pairs were presented twice, in random order, resulting in four blocks of 98 trials each. Because the subjects weren't available for more than two sessions, each subject could only be tested with two of the positions described above. Each position was tested in a separate session on two consecutive days. For complete instructions for this experiment see Annex Q.

12.2 Results

12.2.1 Effect of position of the 7-tactor array

Figure 12.3 shows how the percentage of correct discriminations between the different tactile patterns differs as a function of the position of the tactile array on the body. When same pairs (both saltatory or both successively activated) and different pairs (one saltatory and one successively activated) are considered altogether, then discriminability doesn't seem to differ much with the position of the array. Therefore same and different pairs were diagrammed separately.

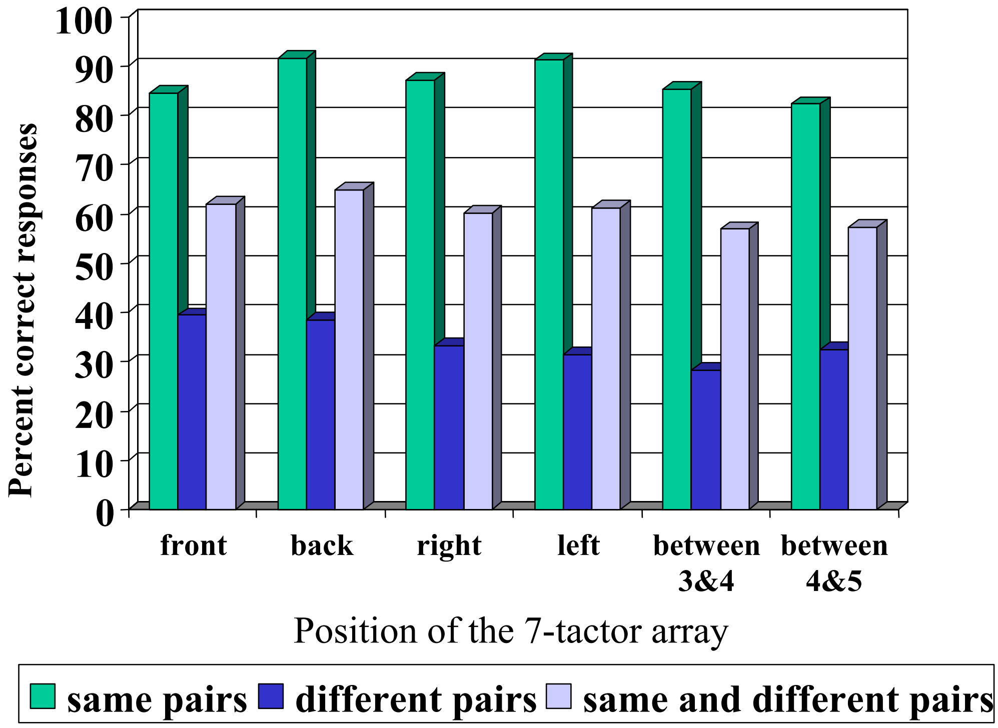


Figure 12.3: Percentage of correct discriminations (over all subjects and trials) as a function of position of the array. The "between" conditions indicate the location of the navel in the span navel sessions. Same pairs (both saltatory or both successively activated) and different pairs (one saltatory and one successively activated) are considered together (gray bars) and separately (green and blue bars).

The next figure (Figure 12.4) shows more clearly, how often subjects incorrectly distinguished the saltatory from the successively presented patterns as a function of the position of the array on the body. When subjects respond "patterns are the same" when in fact different patterns–one saltatory, one successively activated–were presented, then the two different patterns produce equal percepts of movement and subjects fail to discriminate correctly. In this case, the two illusions of movement would be indiscriminable.

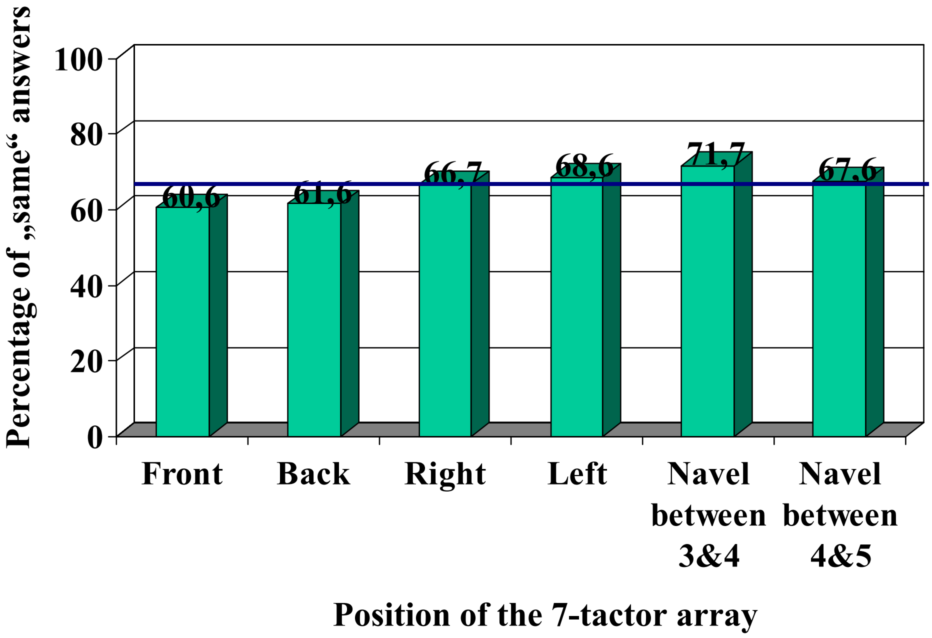


Figure 12.4: Percentage of “same” answers (over all subjects and trials) when different pairs–one saltatory, one successively activated–were presented on a 7-tactor array. When subjects answer “same”, they failed to discriminate the different patterns correctly. The solid blue line indicates the result of Experiment 2: 67.3% of the responses were “same” answers, i.e. in 67.3% of all trials subjects failed to discriminate the different patterns correctly, when movement traveled around the whole torso. Discriminability seems to be affected by the position as well as by the length of the array.

When the array is placed on the front or back of the torso (bilateral stimulation), subjects were able to discriminate the different patterns correctly more often than when the array was placed on the side of the torso (unilateral stimulation). Interestingly it seems that discriminability is also influenced by whether a tactor is placed on the body-midline (position front; here a tactor was placed on the navel) or if the tactors are placed on either side of the body-midline (position navel between 3&4 or 4&5). In the second case, discriminability is poorer. But when a tactor is placed on the body midline, subjects can distinguish successively activated from saltatory patterns better. These data suggest that there was less equivalence between the two generation modes, which might be expected if the saltatory mode was less effective because it had to cross the body midline without the "bridging" midline tactor.

The following statistical analysis shows that if same and different pairs are pooled for the analysis and the number of correct answers–i.e. correct discriminations between same and different pairs–serves as the dependent variable, then, the position of the array does produce only few statistical significant differences (see Figure 12.3). When same and different pairs are considered separately and the dependent variable is number of “same” answers, then the position of the array is of statistical relevance for different pairs only (see Figure 12.4). In each case χ^2-tests were performed to test whether the number of correct (same and different patterns) or “same” answers (same and different patterns considered separately) differs between different positions of the tactile array. Table 12.1 shows the number of correct and incorrect answers, when same and different pairs are pooled:

Table 12.1: Frequency of correct and incorrect responses (correct discriminations between two stimulus patterns of either the same or different presentation mode) dependent on the position of the array over all subjects and trials

Position of the 7-tactor array	Correct answers	Incorrect answers	sum
Front Frequency Percent	 2432 62,04%	 1488 37,96%	 3920 100%
Back Frequency Percent	 2549 65,03	 1371 34,97%	 3920 100%
Left Frequency Percent	 2404 61,33	 1516 38,67	 3920 100%
Right Frequency Percent	 2359 60,18%	 1561 39,82	 3920 100%
Navel between 3&4 Frequency Percent	 4680 56,85%	 3552 43,15%	 8232 100&
Navel between 4&5 Frequency Percent	 4720 57,34%	 3512 42,66%	 8232 100%

If we compare the tactor positions that used the navel (positions: front, back, left, right), the frequency of correct answers does not differ as a function of the position of the array ($\chi^2_{(.01;3;n=9744)}$=8.10; n is the number of correct responses accumulated over subjects and the four positions).

When we distinguish between unilateral (right/left pooled) and bilateral (front/back pooled) stimulation, then the χ^2-value ($\chi^2_{(.01;1;n=9744)}$=4.88) is significant only when we set α to .05., that is only at a significance level where α=.05 can we assume that number of correct responses differs for uni- and bilateral stimulation. In this case, discriminability, i.e. correct discrimination between the two stimulus patterns, is better for bilateral stimulation (positions: front and back).

Single comparisons between the number of correct answers at the positions

-front and navel between 3&4 ($\chi^2_{(.01;1;n=8232)}$=94.13; n is the number of trials for the span navel condition accumulated over subjects) and

-front and navel between 4&5 ($\chi^2_{(.01;1;n=8232)}$=77.33) show that the number of correct answers varies significantly at those positions. There are more correct discriminations when the navel serves as tactor site (position: front) than when the navel is spanned (positions: navel between 3&4 and navel between 4&5).

In Table 12.2 same and different pairs are considered separately and the number of "same" answers is taken as dependent variable. In the case of same patterns, the answer would be correct, but in the case of different patterns, the answer would be incorrect.

Table 12.2: Subjects' "same" answers to same and different patterns as a function of the position of the 7-tactor array on the body

Position of the 7-tactor array	**"Same" answers**	
	Same patterns	Different patterns
Front Frequency Percent	 1659 84,64%	 1187 60,56%
Back Frequency Percent	 1796 91,63%	 1207 61,58%
Left Frequency Percent	 1788 91,22%	 1344 68,57%
Right Frequency Percent	 1707 87,09%	 1308 66,73%
Navel between 3&4 Frequency Percent	 3517 85,44%	 2953 71,74%
Navel between 4&5 Frequency Percent	 3386 82,26%	 2782 67,59%

Note: Same patterns are generated in the same mode (both successively activated or both saltatory), different pairs are generated in different modes (one pattern successively activated, one pattern saltatory). When subjects answer "same" to same patterns, the answer would be correct, when they answer "same" to different patterns the answer is incorrect and the two different stimulus patterns create the same illusory percept of movement. Denoted are the absolute number of "same" answers (frequency) and the percentage of "same" answers within same patterns and different patterns over trials and subjects in the respective condition.

First, we consider same pairs: There is no significant difference in the number of "same" answers as a function of the position of the array when it is placed on the front, back, left, or right side of the torso ($\chi^2_{(.01;3;n=6950)}=7.52$; n is the number of "same" responses to same pairs accumulated over subjects and the four positions). When unilateral (right and left) and bilateral (front and back) positions are compared, we also find no significant difference in the number of "same" answers ($\chi^2_{(.01;1;n=6950}=0.23$). Finally, when we compare the positions where the illusory movement travels over the front of the torso, we find a significant difference only between the positions front and navel between 4&5 (front and navel between 3&4: $\chi^2_{(.01;1;n=4116)}$=2.05; and front and navel between 4&5: $\chi^2_{(.01;1;n=4116)}$=17.91; n is the number of "same" pairs in the span navel condition accumulated over subjects). Discriminability was better for the front position.

Next, we look at different pairs only: The number of "same" responses (errors, in this case) varies significantly with the position of the array when it is placed on the front, back, left, or right side of the torso ($\chi^2_{(.01;3;n=5046)}$=13.86; n is the number of "same" responses to different pairs accumulated over subjects and the four positions). There is also a significant difference in the number of "same" answers, when unilateral (right and left) and bilateral (front and back) positions are compared ($\chi^2_{(.01;1;n=5046)}$=13.19). Subjects respond "same" to different pairs more often, when the array is placed on either body side (left or right), i.e. discriminability is poorer for unilateral stimulation.

Again, single χ^2- tests were conducted for the comparison of "same" answers for the positions

- front and navel between 3&4 ($\chi^2_{(.01;1;n=4116)}$=215.35; n is the number of different pairs in the span navel condition accumulated over subjects) and
- front and navel between 4&5 ($\chi^2_{(.01;1;n=4116)}$=85.13) and again the number of "same" answers varies significantly with the positions of the array. In both cases there are more "same" answers, i.e. fewer correct discriminations between saltatory and successively stimulated patterns when the navel is spanned (positions: navel between 3&4 and navel between 4&5).

To test whether discriminability also varies with the length of the array we compared the results of Experiment 2, where the tactile array contained 12 tactors and spanned the whole torso, with the results of this experiment (except the skip navel conditions, as in Experiment 2, the navel always served as tactors site). We concentrate on different pairs only since we expect to find most of the statistical relevant results in this case.

Multiple χ^2-tests were conducted to compare the frequency of "same" answers when *only different pairs* were presented:

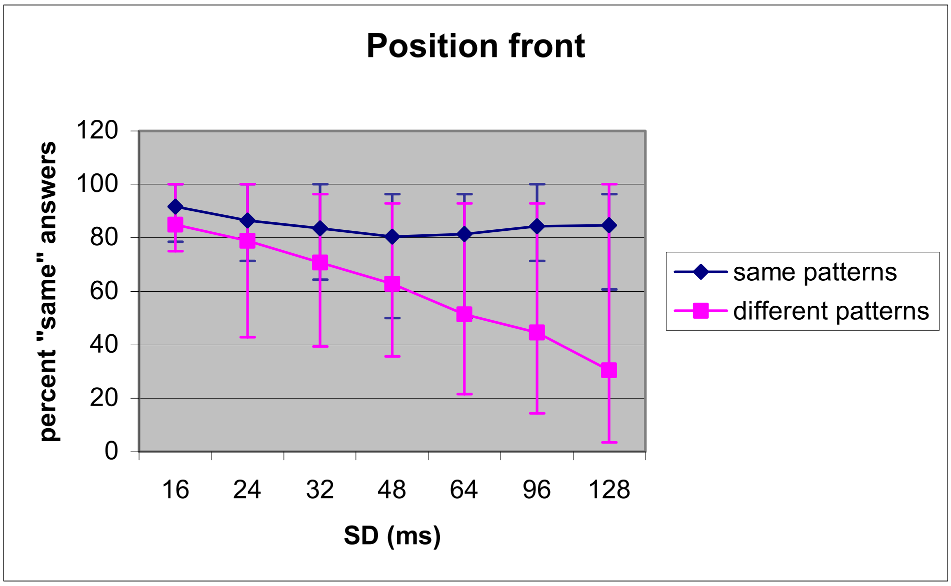
- When the position front (7-tactor array) is compared to the 12-tactor array around the torso (Experiment 2), then the number of "same" answers differs significantly ($\chi^2_{(.01;1;n=1960)}$=40.68; n is the number of different pairs for the positions in the 7-tactor array condition accumulated over subjects); discriminability was poorer for the 12-tactor array. The same result can be observed, when the 7-tactor array was placed on the back ($\chi^2_{(.01;1;n=1960)}$=29.32).

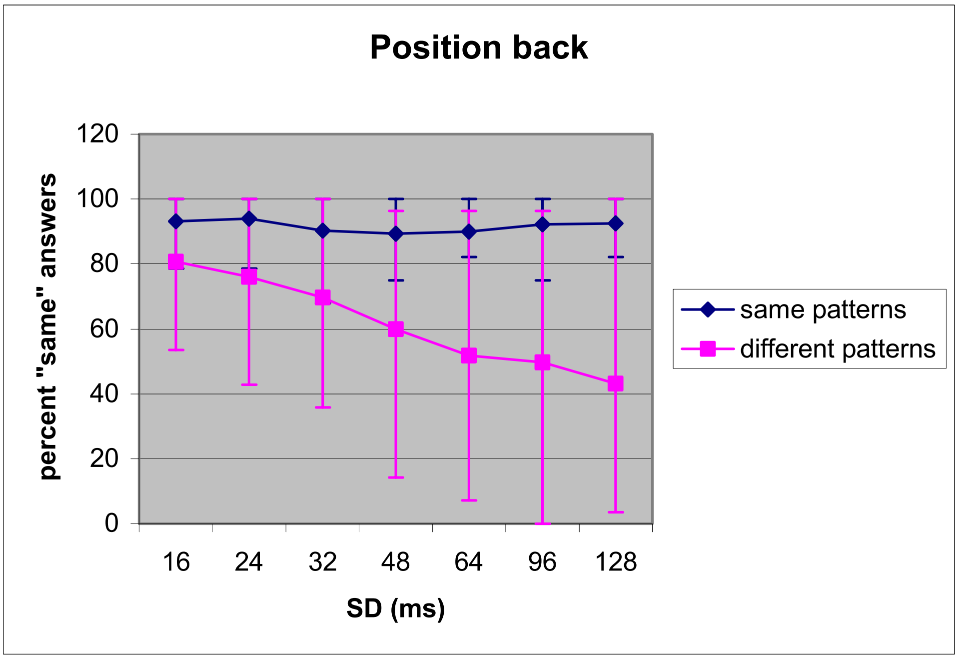
- But when the 7-tactor array was placed on the right side ($\chi^2_{(.01;1;n=1960)}$=0.30) or left side ($\chi^2_{(.01;1;n=1960)}$=1.40) then, no significant differences were found in the number of "same" responses when the data were compared against those for the 12-tactor array.

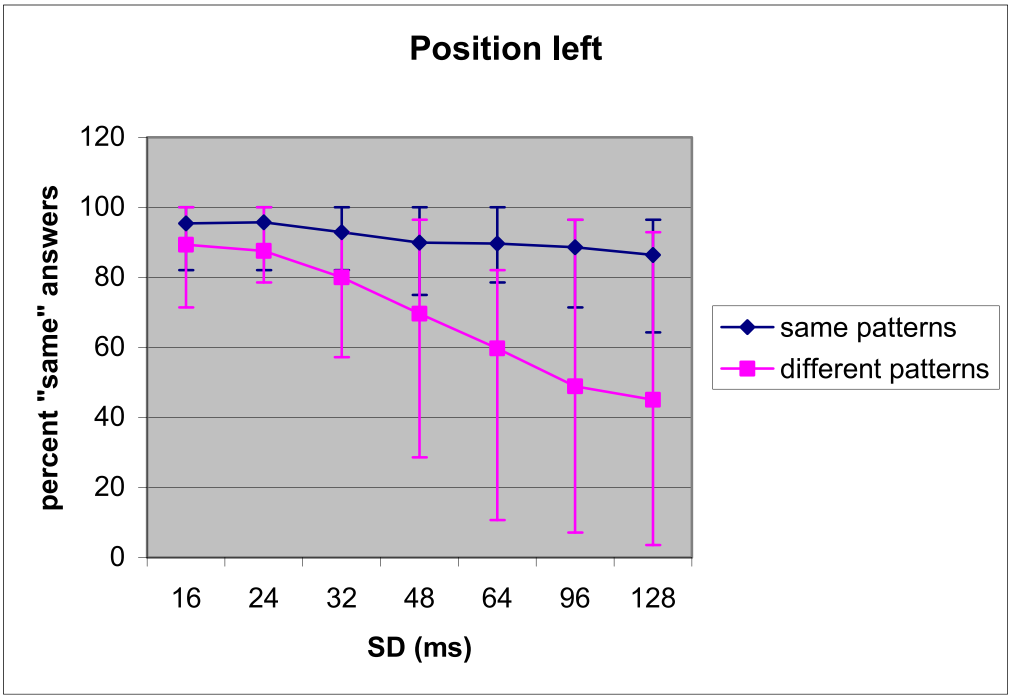
12.2.2 Temporal effects

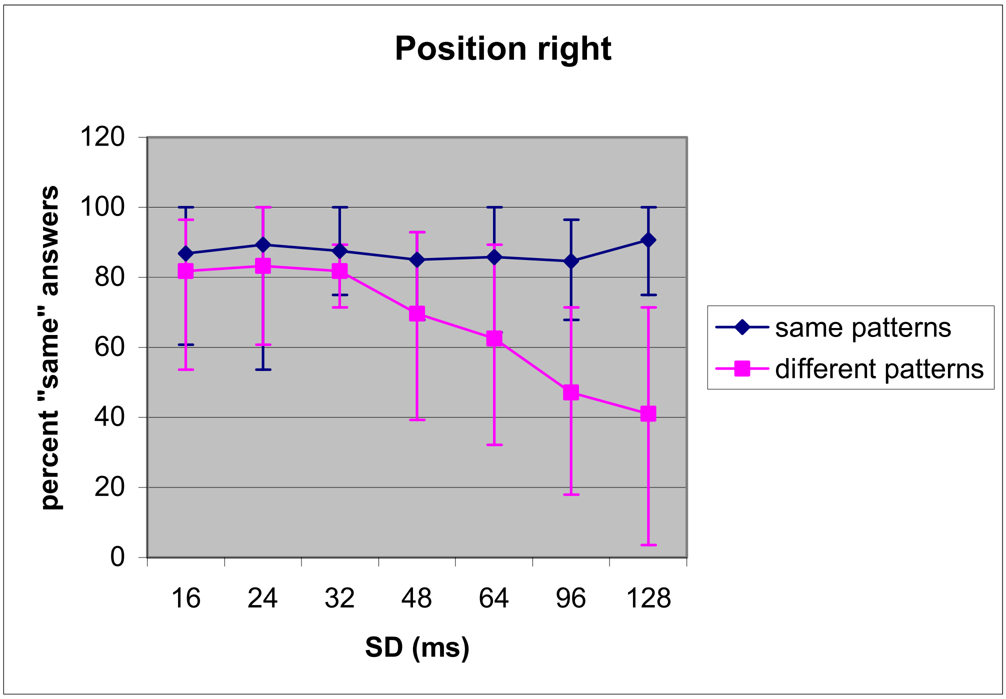
Effect of SD

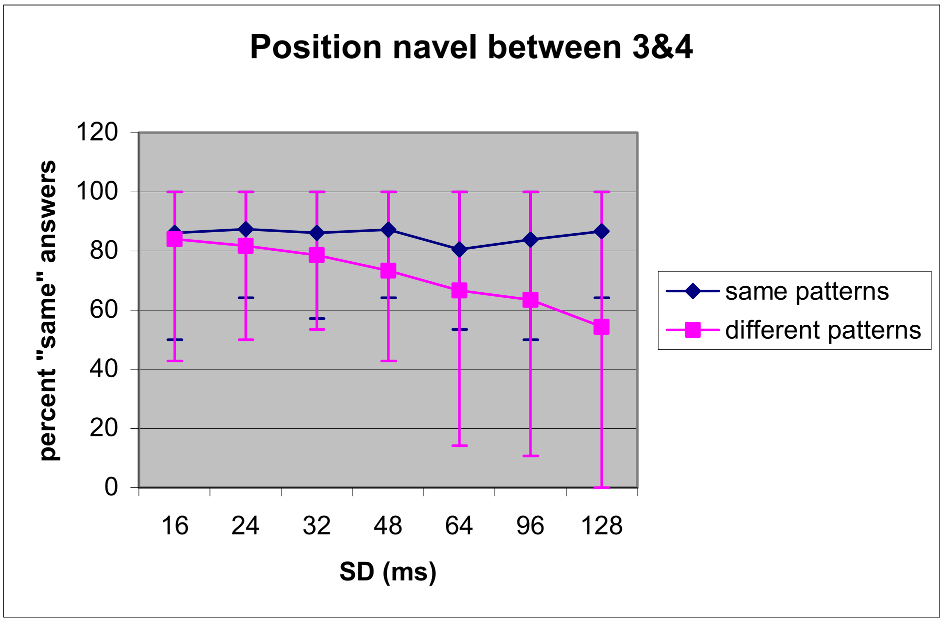
As in Experiment 2 we wanted to test if there are temporal stimulus parameters where the successive stimulation and saltatory stimulation modes produce equal percepts of movement and if those temporal parameters differ depending on the positioning of the array (Experiment 3) or length of the array (Experiment 2 versus Experiment 3). Figure 12.5 shows the effect of stimulus duration on the percentage of "same" answers for same and different pairs depending on the position of the array on the body:


Position front
percent "same" answers
120
100
80
60
40
20
0
16
24
32
48
64
96
128
SD (ms)
same patterns
different patterns


Position back
percent "same" answers
120
100
80
60
40
20
0
16
24
32
48
64
96
128
SD (ms)
same patterns
different patterns


Position left
percent "same" answers
120
100
80
60
40
20
0
16
24
32
48
64
96
128
SD (ms)
same patterns
different patterns


Position right
percent "same" answers
120
100
80
60
40
20
0
16
24
32
48
64
96
128
SD (ms)
same patterns
different patterns



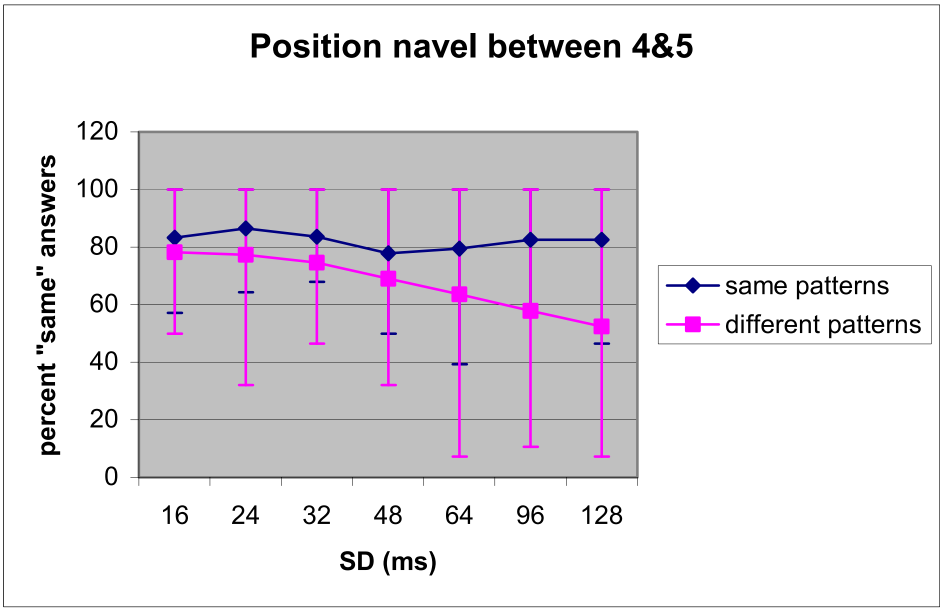


Figure 12.5: Effect of SD on subjects' ability to discriminate patterns of either the same generation mode (same patterns: both patterns successively activated or both patterns saltatory) or different generation modes (different patterns: one pattern saltatory, one pattern successively activated). Shown is the percentage of "same" responses over all subjects and trials. The error bars mark the minimum and maximum values. "Same" judgments for same pairs are correct discriminations, "same" judgments for different pairs mean that subjects incorrectly discriminate between the successively and saltatory stimulus patterns. For different pairs the percentage of incorrect responses seems the decrease with increasing SD.

Figure 12.5 shows that subjects' ability to discriminate between successive and saltatory stimulation (different patterns) improves with increasing stimulus duration. This is true for all arrangements of the 7-tactor array, as well as for the longer 12-tactor array. As in experiment 2, when SD is smaller than 50 ms, most subjects cannot discriminate between both patterns the majority of time (percent "same" judgments >70%). The discrimination of same patterns, however, seems to be uninfluenced by stimulus duration. Note that there are very large interindividual differences in discrimination performance as the error bars in Figure 12.5 indicate.

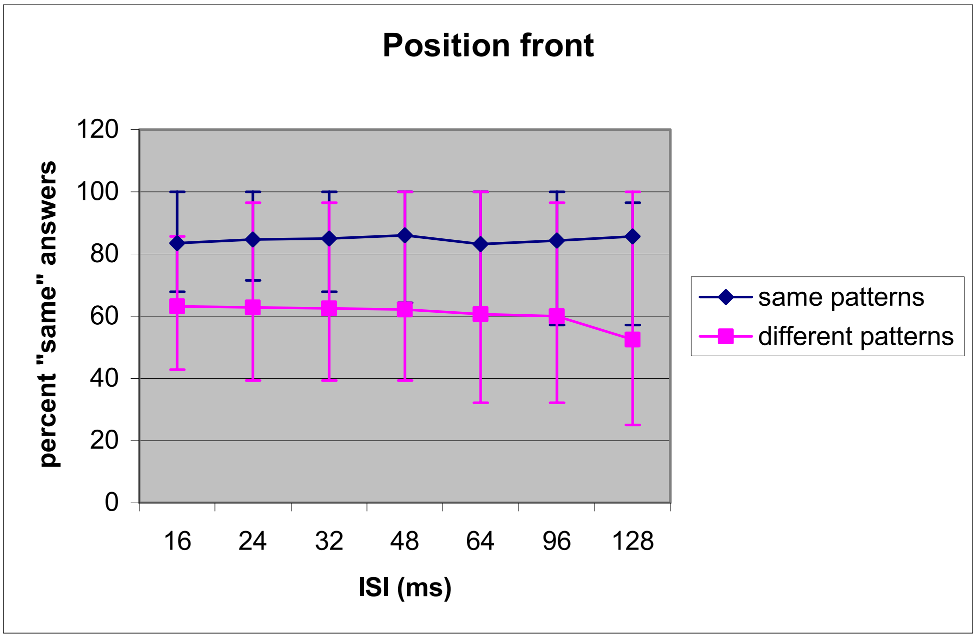
As in Experiment 2 the null hypothesis: For every level of SD there is the same frequency of "same" answers, was tested with $\chi 2$-tests. Separate $\chi 2$-tests were conducted for each subject. Again, the tests were carried out separately for same and different pairs. Annex R shows the results. Binomial tests (π=0.5; one-sided tests) were subsequently performed to test if the probability of finding subjects where the number of "same" answers do show significant differences over the levels of SD is significantly (α=.01) higher than chance.

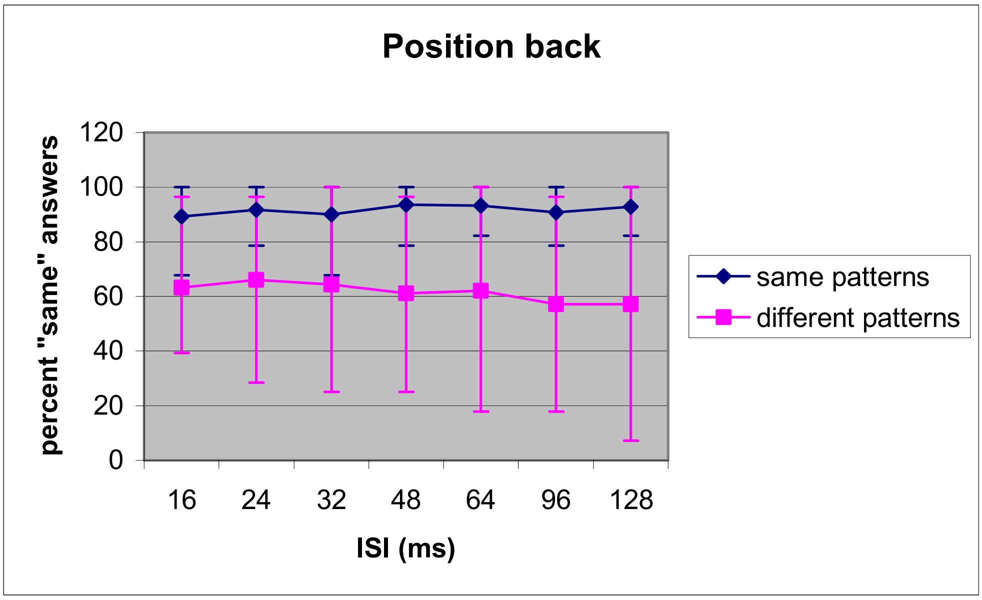
We found that for neither position of the 7-tactor array are there significant results. For same patterns none of the results were significant. For different patterns only few subjects showed a significant variation in the number of "same" answers over the range of SDs (see Annex R). Most of the binomial tests didn't reach statistical significance, for the span navel conditions the number of subjects with significant effects of SD was even significantly lower than chance (Position front: N=10, x=3, P=0.17; Position back: N=10, x=2, P=0.05; Position left: N=10, x=4, P=0.38; Position right: N=10, x=3, P=0.17; Position navel between 3&4: N=21; x=4, P=0.00; Position navel between 4&5: N=21, x=5, P=0.01; N=sample size; x=number of subjects where the frequency of "same" answers varies significantly with SD; P=probability for π<0.5).

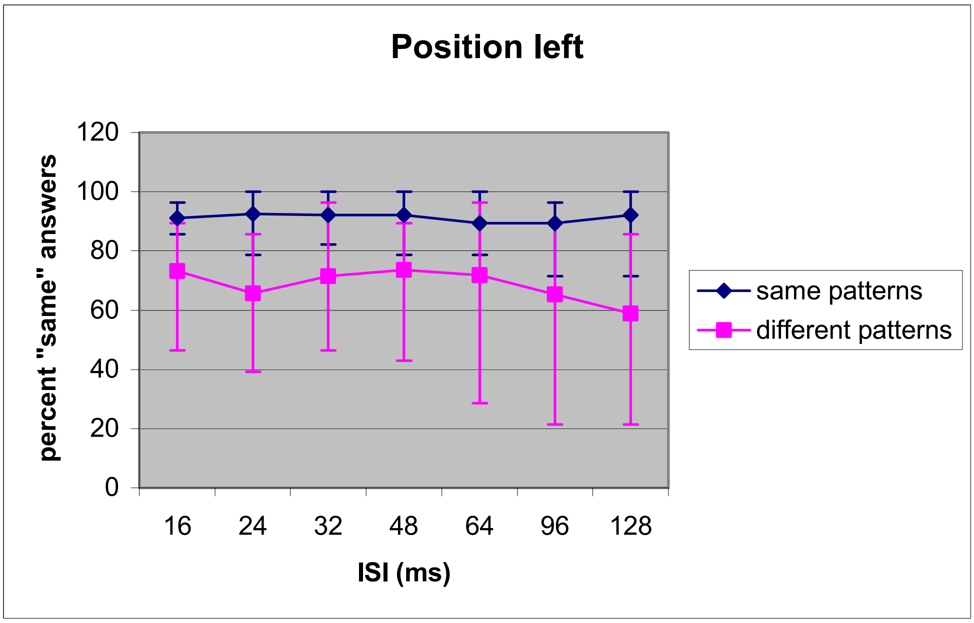
Goodness of apparent motion in other experiments is known to be influenced by stimulus duration (Kirman, 1974; Sherrick & Rogers, 1966; Szaniszlo et al., 1998), in that increasing stimulus duration leads to better percepts of continuous, uninterrupted movement. It seems that with longer stimulus durations we produce percepts of apparent movement that are distinguishable from saltation. Wiemer et al. (2000) also state that “the saltation phenomenon is clearly separable from apparent motion” (p. 182), as the first produces spatially assignable tabs whereas the later resembles an unbroken sweep, like a natural brush stroke. However, although the results fail to be significant there is a strong tendency that at short SDs successively activated and saltatory stimulus patterns produce comparable percepts of motion and in those cases , the relationship was not affected by the different positions of the array.

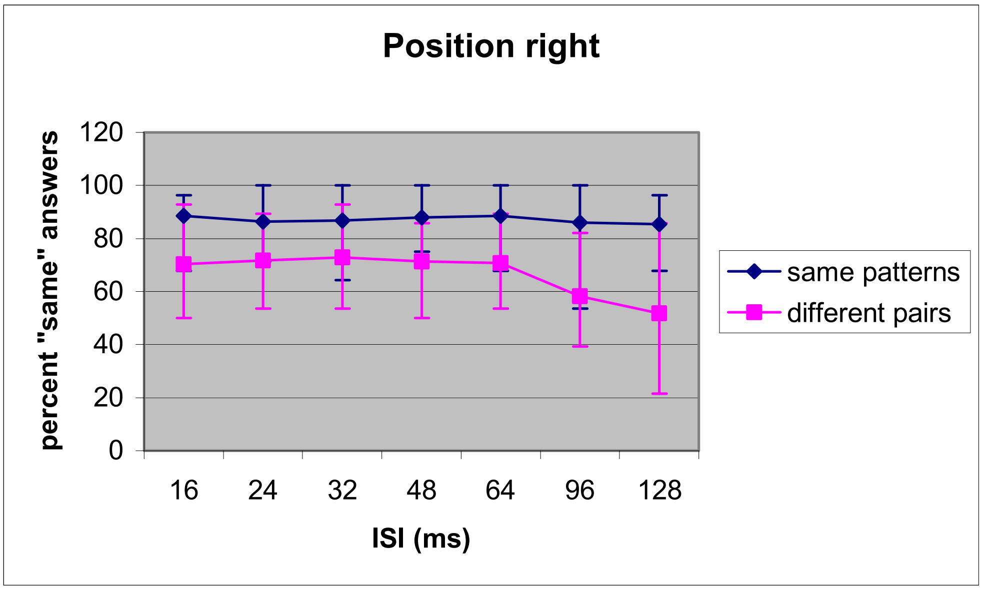
Effect of ISI

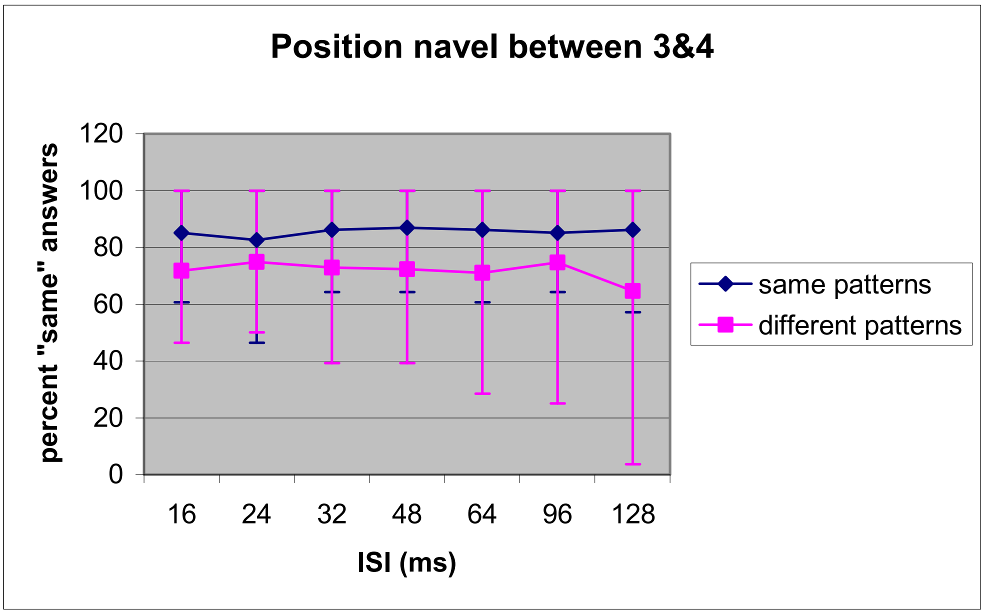
Next, the effect of ISI on the percentages of “same” answers for same and different pairs was examined and the results are represented in Figure 12.6:




Position back
percent "same" answers
120
100
80
60
40
20
0
16
24
32
48
64
96
128
ISI (ms)
same patterns
different patterns


Position left
percent "same" answers
120
100
80
60
40
20
0
16
24
32
48
64
96
128
ISI (ms)
same patterns
different patterns


Position right
percent "same" answers
120
100
80
60
40
20
0
16
24
32
48
64
96
128
ISI (ms)
same patterns
different pairs


Position navel between 3&4
percent "same" answers
120
100
80
60
40
20
0
16
24
32
48
64
96
128
ISI (ms)
same patterns
different patterns

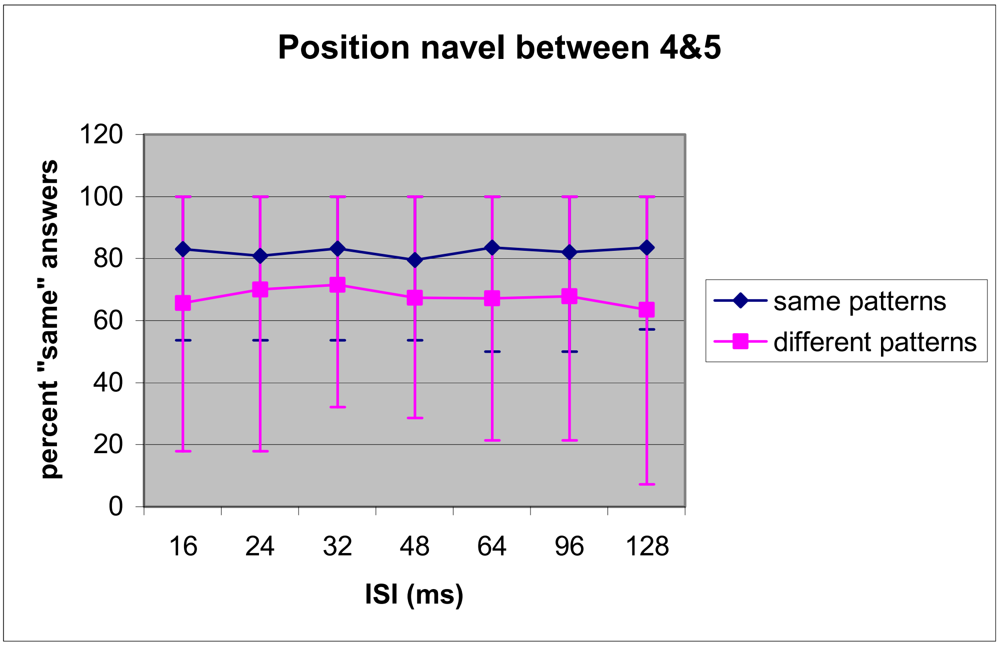


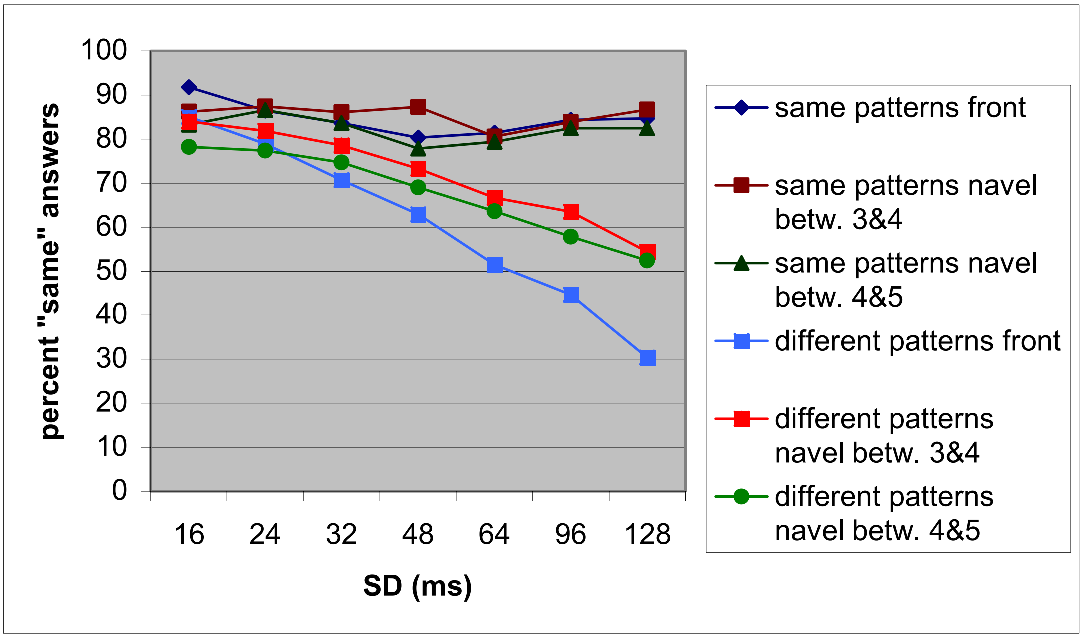
Figure 12.6: Effect of ISI on the percentage of "same" answers for the different positions of the 7-tactor array for same and different pairs (same patterns: both patterns successively activated or both patterns saltatory; different patterns: one pattern saltatory, one pattern successively activated). Shown is the percentage of "same" answers over all subjects and trials. The error bars mark the minimum and maximum values. "Same" judgments for same pairs are correct discriminations, "same" judgments for different pairs mean that subjects incorrectly discriminate between the successively and saltatory stimulus patterns. There seems to be no clear effect of ISI on the percentage of "same" responses.

It seems that for only high ISI's (>100 ms) discriminability for successive and saltatory stimulation (different pairs) may improve slightly (except for the position back). Because this is approximately the range in which phi-movement occurs (60-200 ms), it seems likely that at large ISIs we may be producing percepts of apparent or phi-movement which are distinguishable from saltation. If we compare this result to what we found in Experiment 2, we don't find this decline in the number of "same" judgments for different pairs at ISI>100 ms, when movement travels around the whole torso.

The same statistical procedure as before was used to test whether the number of "same" responses varies significantly with ISI. For same pairs, no significant results were obtained (see

Annex S). Similarly, for different pairs there were also no significant differences in the number of "same" answers over the seven levels of ISI for the positions front, back, left, right. The rare exceptions were for the position navel between tactors 3 and 4 for only one subject and for the position navel between tactors 4 and 5, where only two subjects showed significant effects of ISI (one showed a significant increase and the other one a significant decrease in the number of "same" responses with increasing ISI). But in both cases, a Binomial test (π=0.5; one-sided test) proved that the probability of finding subjects where the number of "same" responses show significant differences over the levels of ISI is significantly (α=.01) lower than chance (Position navel between 3&4: N=21; x=1, P=0.00; Position navel between 4&5: N=21, x=2, P=0.00; N=sample size; x=number of subjects where the frequency of "same" answers varies significantly with ISI; P=probability for π<0.5). Thus, ISI has no effect on discriminability.

If only bilateral stimulation is examined, we have already shown that subjects' ability to discriminate between different tactile patterns improves when the navel serves as tactor site (position front versus positions navel between tactors 3 and 4 and navel between tactors 4 and 5). Figure 12.7 shows how temporal conditions affect discriminability in different ways for the front (that is the navel serves as tactor site) and span navel (that is the navel lies in-between active tactor sites) conditions.



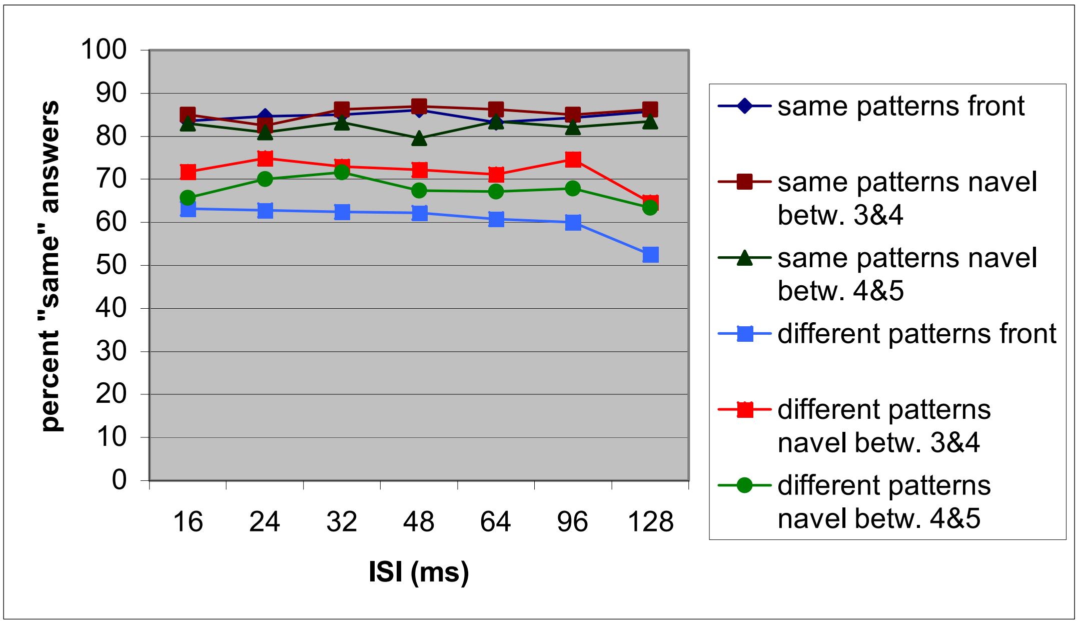
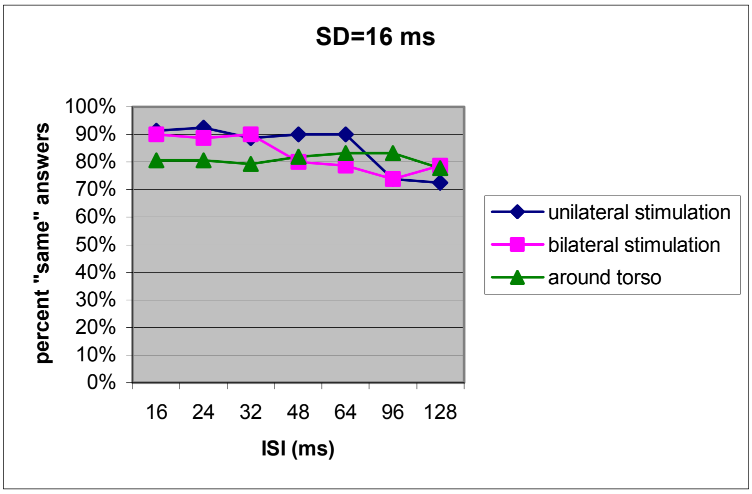


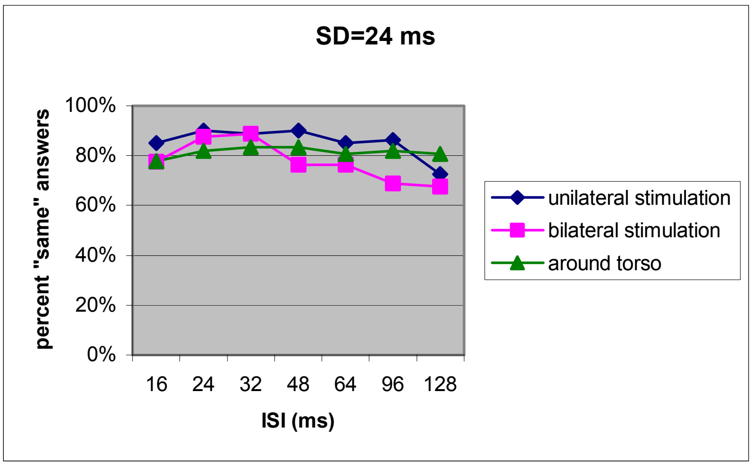
Figure 12.7: Effect of SD and ISI on "same" answers for bilaterally presented patterns on the front of the torso. Shown is the percentage of "same" responses over all subjects and trials, separately for same and different patterns (same patterns: both patterns successively activated or both patterns saltatory; different patterns: one pattern saltatory, one pattern successively activated). "Same" judgments for same pairs are correct discriminations, "same" judgments for different pairs mean that subjects can not discriminate between successively and saltatory stimulus patterns. The effect of SD on the percentage of "same" responses to different pairs is stronger for the with navel condition (front) than for the span navel conditions (navel between 3&4 and navel between 4&5). The effect of ISI seems to be comparable for both conditions.

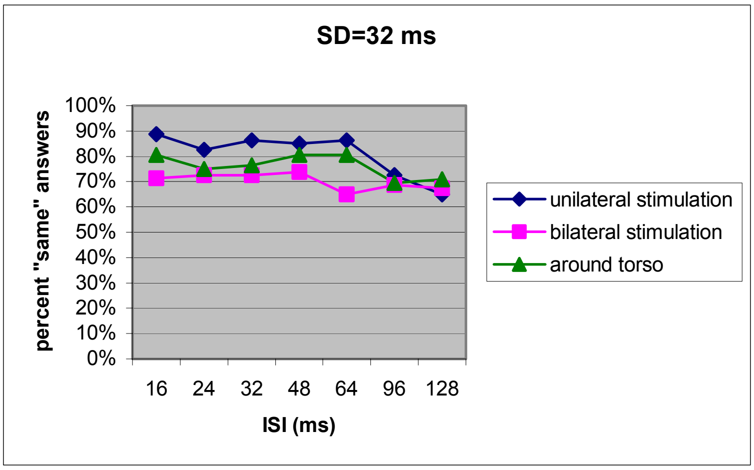
Again it can be seen that with increasing stimulus duration, discriminability between different patterns improves, but from visual inspection of Figure 12.7 it appears that the effect of SD is stronger for the front position, where the navel serves as tactor site (the light blue line, which represents different patterns presented on the front of the torso, is much steeper than the others). ISI seems to affect discriminability for the different array positions in a comparable way.

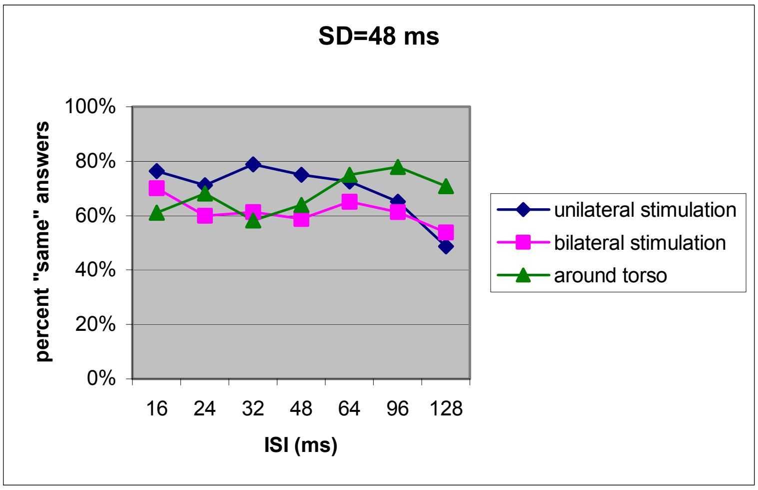
To take a closer look at the interaction between SD and ISI, and to review if the temporal conditions where successive and saltatory stimulation produce equal percepts of movement differ with unilateral and bilateral stimulation, we next show for every level of SD the percentage of "same" answers for different pairs only. We distinguish between unilateral (positions left and right) and bilateral (positions front and back) stimulation and include also the results of Experiment 2 (12-tactor array).

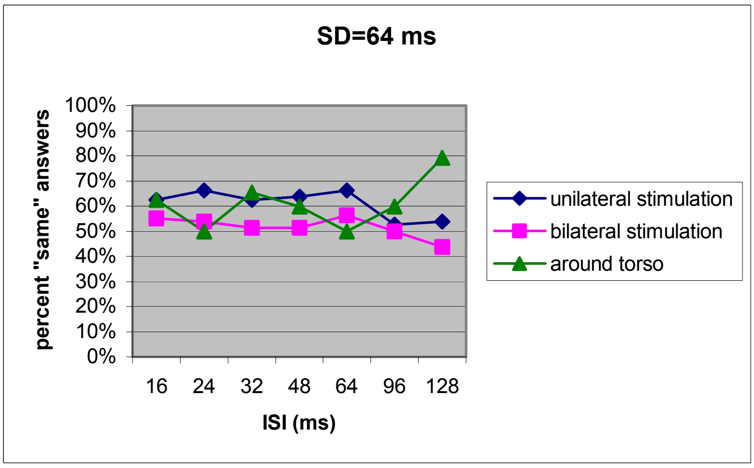
Note, scanning the graphs in Figure 12.8, how overall performance drops with increasing SD, and how for medium SDs (SDs between 32 and 96 ms) and medium ISIs (ISIs between 24 and 96 ms) subjects can discriminate between bilaterally presented stimulus patterns clearly better. It is also noteworthy that for the 12-tactor array around the torso, for longer SDs discriminability improves with decreasing ISI.

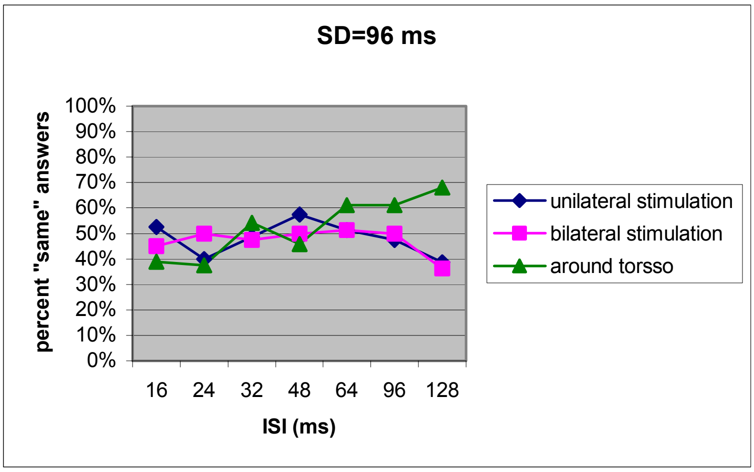





SD=32 ms
percent "same" answers
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
16
24
32
48
64
96
128
ISI (ms)
unilateral stimulation
bilateral stimulation
around torso


SD=48 ms
percent "same" answers
100%
80%
60%
40%
20%
0%
16
24
32
48
64
96
128
ISI (ms)
unilateral stimulation
bilateral stimulation
around torso


SD=64 ms
percent "same" answers
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
16
24
32
48
64
96
128
ISI (ms)
unilateral stimulation
bilateral stimulation
around torso



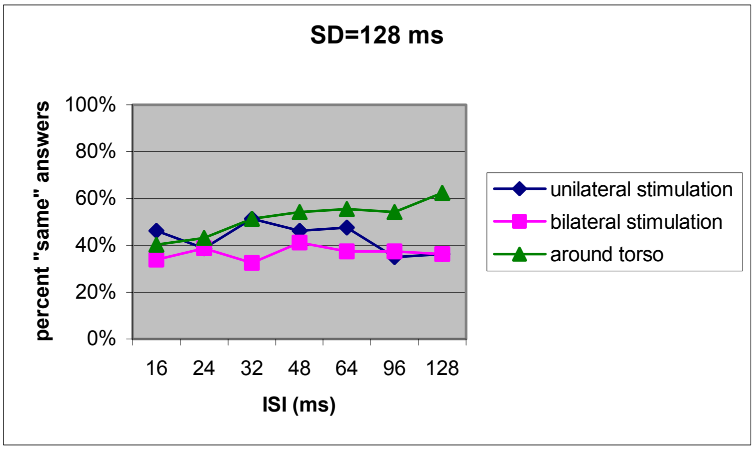


Figure 12.8: For every level of SD the percentage of "same" responses dependent on ISI over all subjects and trials is shown. Only different pairs are included, that means, "same" answers are incorrect answers, subjects can not distinguish correctly between successive and saltatory stimulation, both stimulus patterns produce comparable percepts. Shown are unilaterally (positions left and right) and bilaterally (positions front and back) presented patterns as well as patterns spanning the whole torso (from Experiment 2). For small SDs the effect of ISI on the percentage of "same" answers seems to be comparable for longer (12 tactors) and shorter (7 tactors) arrays. For longer SDs this effect seems to vary with the length of the array.

For increasing SDs the percentage of "same" answers (these are incorrect answers) drops, i.e. subjects' ability to discriminate correctly between successive and saltatory stimulation increases. For medium SDs unilateral stimulation produces more discrimination errors (more "same" answers) than bilateral stimulation, compared to longer SDs (except for long ISIs >100ms). At longer SDs and longer ISIs discriminability for the longer array (12-tactor array) decreases (more "same" answers) whereas for the shorter array (7-tactor array) discriminability seems to remain constant or drops somewhat (especially for ISIs >100 ms).

When they examined the quality of apparent movement, Kirman (1975) and Szaniszlo et al. (1998) both found an interaction between the number of stimulators and ISI: Using more stimulators increased the quality judgments for apparent movement and resulted in better movement at shorter ISIs. In both experiments they kept the total distance covered by the tactile array constant. This means that the more tactors were used, the shorter the inter-tactor distance became. If the number of equidistant stimulators and the total extent of the array is increased, no such interaction between number and ISI could be found. Our data suggest that despite varying the total length of the array by adding more stimulators, there still seems to be an interaction between the number of tactors and ISI: If we assume that discriminability between successive and saltatory stimulation improves when we meet the temporal criteria for apparent movement–since apparent movement and saltation are supposed to produce different percepts–then the longer array should produce less correct discriminations at longer ISIs (more "same" answers) in comparison to the shorter array. Visual inspection of Figure 12.8 indicates that this is true, but only for longer SDs.

12.3 Summary and discussion

Effect of position of the 7-tactor array Two different patterns of tactile movement–one: successive stimulation, one: saltatory stimulation–can be discriminated better–and therefore produce better distinguishable percepts of motion–when the 7-tactor array is placed on the front or back of the torso (bilateral stimulation) than when it is placed on the right or left side of the torso (unilateral stimulation). This result supports Geldard's finding that tactual phi and saltation only coexist when stimuli are presented unilaterally. However, it should be noted that even for bilateral stimulation the percentage of incorrect responses exceeded 60%, which is significantly more than chance (50%). That means, in more than 60% of trials percepts of motion produced by successive and saltatory stimulation crossing the body-midline are not discriminable. Thus, bilaterally presented saltation and successive stimulation can produce similar percepts, they seem to be integrated on higher cortical levels. Yet, the resemblance between saltation and successive stimulation is greater for unilateral stimulation.

The better discrimination performance for bilaterally presented stimulus patterns may be due to the better localization of stimuli presented near anatomical anchor points like the spine or navel. In their experiments Cholewiak et al. (2004) evaluated conditions for correct localization of seven vibrotactile stimuli that were presented to various locations on the torso. Since their tactors as well as their experimental settings were identical to ours, we can directly compare the two studies. In their case, localization of the seven tactor sites on the front or back of the torso was more accurate than localization of the sites on the left or right side of the torso. At the navel and spine anchor points, performance was near perfect. Van Erp (2007) also demonstrated that spatial resolution for horizontally oriented arrays (subjects had to indicate if the second of two successively presented vibratory stimuli is located left or right from the first) is higher at the midline of the torso (1-2 cm) than at the side of the torso (3-4 cm). He explains the midline effect by the fact that cutaneous areas at or adjacent to the trunk midline are represented bilaterally in the first and second somatiosensory cortex.

A possible explanation for the similarity between the localization and discrimination experiments might be that during the discrimination experiment the subjects are looking for clues to discriminate between successive and saltatory stimulation. In the front and back condition, the navel and spine, respectively, serve as tactor sites and are stimulated once, when all tactors are stimulated successively, but are skipped, when the saltatory pattern is presented (see Figure 12.2). Since the navel and spine can be localized very well**,** subjects might realize that in one pattern the navel is stimulated (successive activation) whereas in the other pattern (saltatory stimulation) the navel is skipped.

We also know that two-point discrimination is enhanced when the two stimuli cross the body-midline, since there are few bilateral receptive fields (Fuchs & Brown, 1984). Although we present our stimuli successively–not simultaneously, as the two-point discrimination paradigm requires−, this finding may also add to the observation, that subjects detect differences in successively and saltatory presented patterns better when they straddle the body midline.

Discrimination was also found to be superior when the body-midline (navel) served as a tactor site (with navel position: Front) compared to when it fell between two tactor sites (Span navel positions: Navel between 3& 4 and navel between 4&5). One might expect that saltation should be better in the with navel condition rather than in the span-navel condition (because of the completion across the midline), so it should be more similar to the successive pattern. But again, note, that in the position front, the navel is only stimulated in the successively presented pattern, but skipped in the saltatory pattern. It is possible that we would have obtained a different result if we would have rotated the array slightly so that the navel would have been stimulated in the successive <u>and</u> in the saltatory pattern, allowing the stimulus at the navel "to bridge the neurological gap" (Tan, Lim, & Traylor, 2000; p. 1111) at the body-midline in the saltatory pattern.

Again, we find an analogy between our results and those of Cholewiak et al. (2004): They rotated their arrays containing 6 or 8 equally spaced tactors around the torso so that tactors fell 1) on either side of the navel or spine, or 2) on the navel and spine. Overall localization performance in condition 1) was poorer compared to that in condition 2), when the navel and spine served as tactor sites. Our results were similar in that we could also show that discrimination performance drops when the 7-tactor array spans the navel.

When we compare the results of this experiment to the results of Experiment 2–where we used a 12-tactor array that circled the whole torso–we can show that the shorter 7-tactor array only leads to better discrimination when it was placed on the front or back of the torso.

The localization results of Cholewiak et al. (2004) are identical to our discrimination findings between different patterns of tactile movement: Discriminability improves when the 7-tactor array is placed on the front or back of the torso compared to the 12-tactor array that spans the whole torso. No statistical significant difference can be found when the 7-tactor array is worn in the left-right orientation compared to the 12-tactor array. In the 7-tactor bilateral (front/back) array three tactor sites serve as anchor points: The start and endpoint of the array as well as the body midline (navel or spine), which might increase the discrimination performance in comparison to the 12-tactor array where the larger number of tactors increases the cognitive load and there is only one distinct endpoint (see also Cholewiak & Collins' 2000 discussion about anatomical anchor points).

To summarize, one might assume, that anatomical anchor points might attract subjects' attention and enable them to discriminate different stimulus patterns better. Thus subjects' selective attention–which is known to influence point localization, or the perceived position of the mislocalized stimulus during saltation (Kilgard & Merzenich, 1995)–might have an impact on the perception of similarity or dissimilarity of different stimulus patterns

Effect of temporal stimulus parameters Although discriminability between different stimulus patterns–one successive, one saltatory–is poor for short SDs and increases for longer SDs, this trend is not statistically significant. ISI has no effect on discriminability, too. Our data suggest that, when we meet the temporal criteria needed for producing apparent movement (long SDs), successive and saltatory stimulation produce discriminable percepts of movement. Although these optimal temporal conditions don't vary fundamentally with the location of the array on the body, there are some minor variations (see Figure 12.7: Effect of SD on discriminability is higher for the array position front where the navel serves as tactor site as for the positions span navel; see also Figure 12.8: Discriminability for bilaterally presented patterns is better than for unilaterally presented patterns, this difference is more distinct for shorter and medium SDs). To my knowledge no publication has ever examined the optimal temporal conditions for apparent movement when it crosses the body midline. Our data indicate that optimal temporal conditions for apparent movement might differ for unilateral and bilateral stimulation, as well as for arrays using anatomical anchor points like the navel as stimulus site or not. Another experimental design–such as judging the quality of apparent movement for uni- and bilateral stimulation–might bring more clarity to this question.

13. General summary and discussion

When a visually moving grating is divided by a gap, subjects perceive the grating continuing through the gap, indicating that a neural filling-in process must have occurred. Meng, Remus, and Tong (2005) demonstrated that there is enhanced activity in early visual areas, which represent the gap region, independent of subjects' attention, and reason that the filling-in process during such visual illusions occurs automatically. Their findings are supported by the study of Larsen et al. (2006): They showed that the pattern of activity in primary visual cortex (area V1), is similar for real and apparent motion; during apparent motion, the gaps between activated sites are filled-in with cortical activation. Chen et al. (2003) and Blankenburg et al. (2006) proved in the tactile sense, that illusory stimuli produced by funneling or saltation are topographically represented in somatosensory cortex.

We assume that motion produced by successive activation and saltation requires similar cortical "filling-in" of the "silent" sites in-between the activated tactors, since illusory stimuli are perceived at sites in-between the physical location of the stimuli. That saltation and successive activation can produce equal sensations of movement, has been demonstrated in the tactile sense (Cholewiak & Collins, 2000; Geldard, 1975) and the auditory sense (e.g. Kidd & Hogben, 2004), provided that appropriate stimulus timing parameters are chosen.

In our experiments, we explored the conditions for which successive *and* saltatory motion produce the same percepts of motion and thus initiate the same cortical integration or "filling in" process. Different spatio-temporal vibratory patterns (successively activated and saltatory) supposed to induce apparent motion were judged by different qualities of motion to explore possible rating differences (Experiment 1). In a second experiment, stimulus patterns had to be discriminated, and subjects had to decide, which pattern felt "best", i.e. for which pattern the integration process was more successful. Finally we examined whether patterns crossing the body-midline, and patterns presented on one body-half were similarly integrated.

Effect of ISI/SD The qualities straightness and smoothness are rated higher for shorter ISIs, spatial distribution and length are barely affected by ISI (Experiment 1). With only two exceptions (250 Hz, length, 12 tactors and 80 Hz straightness, 8 tactors), the effect of ISI on subjects' judgments is the same for both stimulus patterns (successively activated and saltatory). ISI has no effect on discriminability or preference for one stimulus pattern (Experiment 2), and this is true for a 12 –tactor array that covers the whole circumference of the waist (Experiment 2), as well as for an array half as long and for all positionings of the shorter 7-tactor array, which was either unilaterally or bilaterally placed on the torso (Experiment 3).

We can conclude therefore, that over the ISI range tested in our experiment (~10-130 ms) both patterns are integrated similarly. Perhaps at larger values we would have found effects of ISI (see Experiment 3: At ISI>100 ms discriminability starts to improve). It is possible that at higher ISIs, the single stimuli in the patterns start being segregated and differences between the patterns are more easily detected.

Our findings are in line with the neural network model of Wiemer et al. (1998, 2000): Stimuli following closely in time (ISI<300 ms) are expected to belong together, therefore they should be presented close together in cortex (see also Gardner & Constanzo, 1980c, who state that the perception of stimuli are influenced by preceding stimuli). In our experiments ISI was always smaller than the critical limit of 300 ms, therefore it is not surprising that both stimulus patterns are integrated into similar percepts of continuous movement, which are difficult to differentiate.

In Wiemer's model, the effect of SD on the integration of spatio-temporal stimuli is not discussed. Nor is an interaction between SD and ISI considered. We know from the literature that tactile apparent movement is affected by SD as well as by an interaction between SD and ISI. To my knowledge only one study on saltation has ever varied SD systematically: Cholewiak and Collins (2000) found two main effects on the perception of movement generated by saltatory stimulus patterns on the back: Saltatory patterns appeared longer and less straight for increasing SD (SDs between 4 and 140 ms were used). The same effect was found for successively activated patterns. There was no clear effect of SD on discriminability.

In our experiments, the effect of SD was stronger for saltatory patterns, which was unexpected. Saltatory patterns appear to be straighter, smoother and more equally distributed with shorter SD. Apparent movement was mostly unaffected by SD. There was an interaction between SD and ISI, such that for shorter SDs, judgments appear to be largely uninfluenced by ISI, whereas for longer SDs, stimuli feel more evenly distributed for longer ISIs, which was only significant for 250 Hz patterns (Experiment 1). For short SDs, discriminability between successively activated and saltatory patterns seems poorer, although this trend is not statistically significant. Additionally, preference for saltatory patterns is higher for short SDs, when both patterns have to be compared in a forced-choice paradigm, but again this trend failed to be statistically significant (Experiment 2). The same dependency of SD on discriminability was found for the shorter array and for unilateral as well as for bilateral placement of the array (Experiment 3). It seems that short SDs enhance the integration of stimuli, especially for saltatory patterns. It is possible that with longer SDs, subjects' ability to spatially resolve the stimulus patterns enhances and enables them to perceive when saltatory patterns are presented, single sites are activated twice.

Effect of number of stimuli We assumed that the spatial relatedness (that is spatial proximity) of stimuli enhances their cortical integration, thus we expected that increasing the number of stimulus sites (from 8 to 12) within an array of fixed length, thus decreasing the distance between activated sites will lead to better quality judgments (Experiment 1). The distance between activated tactors varied between 6- 9 cm for the 12 tactor array and 9-15 cm for the 8 tactors array (depending on a subject's waist circumference). Thus we exceed the static two-point threshold (as a psychophysical measure of spatial resolution) which is about 35 mm on the belly and 40 mm on the back (Martin & Jessell, 1993), and which is even lower, when the two touch stimuli are presented successively (Greenspan & Bolanowski, 1996).

While the number of tactors had no influence on the quality judgments of successively activated patterns, in most cases, saltatory patterns containing 12 tactors produce better quality judgments than saltatory patterns containing 8 tactors. It seems that we have exceeded the minimum number of tactors which is needed to produce stable quality judgments for successively activated patterns. But for saltatory patterns the inter-tactor distance (confounded with the number of tactors), is still crucial for the range tested here, i.e. temporal resolution is still affected. With only 8 tactors, subjects more likely recognize that stimuli are bundled at certain locations in the saltatory pattern.

According to Cholewiak (1979) and Sherrick and Cholewiak (1986), increasing the number of vibrators (while the intensity of vibration is held constant), results in an increase of the sensory magnitude (vibrotactile loudness) in direct proportion. This effect is not altered by changing the inter-vibrator distance at least in the range 1.5-10.5 cm. Using more tactors (12 instead of 8) might have had the secondary effect of increasing magnitude, which might have also affected quality judgments.

As a second spatial parameter we varied stimulus width, by placing three tactors at each of the 8 or 12 sites in a column, one above the other. We assume that three simultaneously applied stimuli produce a single sensation located under the middle stimulator, which is more intense than the sensation produced by a single stimulator alone (a phenomenon called funneling; see e.g. Békésy, 1958 or Gardner & Constanzo, 1980b). In the first and second experiment we tested if this funneled sensation (called "wider" stimulus) affects quality judgments or discriminability.

We generally found that the effects of stimulus width were a function of the number of tactors that were involved: Simulated movement produced by a 24-tactor array (three rows of 8 tactors) produced fewer significant effects than simulated movement produced by a 36-tactor array (three rows of 12 tactors). Wide stimuli are mostly perceived as less straight, less smooth, more evenly distributed and longer than the narrow stimuli. In most cases the effect is the same for the two different stimulus patterns (successively and saltatory).

Although there is a tendency for wider stimuli to produce more similar percepts of movement, we found only one significant result: Wider 80 Hz different pairs were less often discriminated correctly. Stimulus width has no significant influence on subjects' preference for one stimulus pattern. It seems that the use of the more dense array (wider stimuli) enhances the integration of stimuli, letting them "meld together" more easily.

Effect of vibration frequency Since previous studies have shown that vibration frequency has only a minor effect on apparent motion (Sherrick, 1968a) or the saltatory illusion (Cholewiak (reported by Geldard, 1982)), we did not expect to find any significant differences in our measures of quality of movement (Experiment 1) nor in discrimination performance (Experiment 2). But, contrary to our expectations, vibration frequency did affect the perception of the different qualities of movement: 80 Hz stimuli are perceived to be less straight, less smooth, more equally distributed in space and longer than 250 Hz stimuli. The effect of frequency was generally the same for both stimulus patterns (successively activated and saltatory). We explain these differences by appealing to Békésy's (1967) observation, that there is an increase in lateral spread of travelling waves produced by vibratory stimuli with decreasing frequency. Since surface waves produced by 80 Hz stimuli travel further over the skin, 80 Hz patterns might feel longer, because it is more likely that they activate distant receptors. They might also feel more equally distributed, as single stimuli "meld together". At the same time 80 Hz patterns are perceived as less straight, since they are not as spatially defined as 250 Hz stimuli and start to diverge from a straight path.

In the second experiment (part 1: "same-different") we found that 250 Hz patterns feel significantly more alike than 80 Hz patterns, whereas vibration frequency had no effect on subjects' preference for one stimulus pattern (part 2: "which is best"). It seems that spatial resolution and therefore discriminability is better for low-frequency stimuli, which might be explained by the different populations of mechanoreceptors that are activated by the two vibration frequencies and their ability to resolve fine spatial detail. More experiments like the one from Bensmaia et al. (2006), who measured spatial resolution via gap detection and found a decrease with increasing vibration frequency over the range of 5-80 Hz), need to be done on that issue, since the two standard measures of tactile acuity, two-point threshold and localization error (which are both unaffected by frequency; see Greenspan & Bolanowski, 1996), are not sufficient to study spatial resolution (Johnson, van Boven & Hsaio, 1994). Especially for hairy skin where "the relationship between hairy skin afferent fibers and tactile perception is still largely unknown" (Greenspan & Bolanowski, 1996, p. 43) more information is needed.

Effect of repetitive stimulation Repetitive spatiotemporal stimulation induces changes in the cortical topography in area SI. These changes in turn are correlated to changes in perception (see e.g. Stolle, 2003). We therefore asked if discriminability is affected by repetitive stimulation (Experiment 2). According to Stolle (2003) the size of the stimulated area decreases in perception after repeated stimulation. In addition, a decrease in point localization was observed with repetitive stimulation, due to an integration of the stimulated areas and a fusion of the representational cortical areas, whereas for *simultaneously* presented stimuli, discriminability increases (Pleger et al., 2001; Stolle, 2003). Braun et al. (2000) found, when fingers are stimulated in a fixed order (like in our experiment), the distance between the cortical representations of these fingers decreased. We therefore hypothesized that temporal resolution between *successive* stimuli might decrease with time (due to a fusion of stimulated areas, decreased point localization); and thus disciriminability should be impaired with stimulus repetition. Although we observed a marginal trend in the expected direction (2-3% more "same" answers in the second run, when different stimulus patterns had to be compared) the result was not statistically significant.

In most studies in the literature the fingers (or arm) were used as test site. Since fingers are extensively used (and moved) for daily tasks, it seems advantageous that plastic changes would occur quickly in order to adapt to the demands of specific stimulation and tasks. It is possible that on the torso, which was the test site in our experiments, more stimulus repetitions are required for plastic changes to occur, since for this body site which is rarely used to explore the environment, adaptation processes may take more time. Future studies might clarify the question if the time course of cortical reorganisation related to spatio-temporal stimulation varies with body site.

Effect of attention Attention alters the perceived location of the mislocalized stimulus in saltation (Kilgard and Merzenich, 1995). Also, cortical representations can shift corresponding to the locus of attention (Braun et al., 2001; Noppeney et al., 1999). Such shifts of activation due to selective attention occur within minutes (Iguchi, Hoshi, & Hashimoto, 2001).

In our second experiment we varied the response paradigm to evaluate if a shift of attention affects subjects' responses. Subjects had to distinguish between two stimulus patterns–either indicating whether pairs of patterns were the same or different, or deciding which of the two patterns was best in terms of straight, smooth, and evenly distributed motion. Although subjects perceived different stimulus patterns (one successively activated, the other one saltatory) as being the same in more than 65% of the trials, they preferred the successively activated pattern over the saltatory pattern in nearly 70% of the trials. It seems that by drawing subjects' attention towards specific features of the spatio-temporal stimulus patterns, they are able to make distinctions between the patterns, indicating possible shifts of cortical activation due to selective attention.

Integration of stimuli presented on both body halves Geldard (1982) demonstrated that saltatory areas are truncated at the body midline: When the two generating stimulators are placed on either side of the body-midline, no saltation occurs. However Eimer et al. (2005) provided evidence that a stimulus presented on one body-half can be attracted by a subsequent stimulus presented on the other body-half. Auditory saltation travels the body-midline (however at lower ISIs), in touch and in vision, it does not (Phillips & Hall, 2001).

Sherrick (1968b) found that apparent haptic movement qualitatively declined (more partial movement was observed), when stimuli were presented bilaterally (on both forearms), but the relation between SD and ISOI remained constant, compared to unilateral stimulation. In the auditory sense, apparent motion is vivid when it crosses the body-midline (Strybel et al., 1989), also in vision (Naikar & Corballis, 1996).

In our third experiment we used a 7-tactor array that spans half of the subjects' waist and varied the starting location of this array, so that either only one body-half was stimulated or the array crossed the body-midline, activating both body-halves. We expected that illusory movement generated by successively and saltatory stimulus patterns shouldn't stop at the body-midline since the cortex integrates perceptions from the two body-sites into an integral whole, and thus subjects' ability to discriminate between the two stimulus patterns should not differ for unilateral (array placed on one body-site) and bilateral (array crosses body-midline) presentation.

We found that discrimination performance is better for bilateral than for unilateral stimulation. Thus, when successively activated and saltatory stimulus patterns both travel the body-midline, the percepts they evoke seem to be degraded, which increases subjects' ability to distinguish between the patterns. It has to be noted however, that in more than 60% of the trials, subjects could not differentiate between both patterns correctly, which is better than chance. Discrimination performance for unilaterally-presented patterns differs by only approximately 7% from discrimination performance for bilaterally presented patterns (when only different pairs are considered).

To summarize, although crossing the body-midline seems to impair illusory percepts of motion produced by successively and saltatory patterns, both patterns are still indiscriminable in the majority of cases, indicating, that integration of spatio-temporal stimuli occurred over the body-midline. This finding is in line with Eimer et al.'s (2005) result, that temporally related stimuli attract each other over the body-midline, although the magnitude of attraction might differ for unilateral and bilateral presentation.

Other psychophysical findings also support the notion that spatially and/or temporally-related tactile stimuli are integrated over both body-halves:

- Masking also occurs, when stimuli are presented to different body halves (Sherrick & Cholewiak, 1986), indicating that stimuli presented on both body-halves perceptually interact.
- Enhancement and suppression effects (a conditioning stimulus enhances the sensation magnitude of a test stimulus when ISI ranges between 100 and 500 ms and suppresses sensation magnitude at very short ISIs < 100 ms), can not only be observed when both stimuli are presented unilaterally, but also occur when stimuli are presented on contralateral sides (Gescheider & Verrillo, 1982).

- Stimuli simultaneously presented at multiple sites produce a more intense tactile perception localized to only one site of stimulation–a phenomenon called funneling (see Greenspan & Bolanowski, 1996, p.53; compare also: Békésy, 1958, 1967; Gardner & Constanco, 1980b,c; Gardner & Spencer, 1972)–even when stimuli are widely spread or bilaterally presented.

All these findings suggest that the integration of spatio-temporal stimuli does not happen peripherally, but must require some degree of central involvement. The question remains if the temporal conditions for the integration of stimuli differs, when they are presented unilaterally and bilaterally.

Geffen et al. (1996) demonstrated that bimanual simultaneity thresholds are higher than unimanual simultaneity thresholds (minimum ISI at which the observer can perceive that two stimuli have occurred separately). Such judgments, of whether two stimuli are presented successively rather than simultaneously, are based upon the detection of inferred motion: If no motion is detected, then a judgment of simultaneity is made. In the bimanual condition, thresholds are assumed to be higher due to interhemispheric transmission time: The time needed to cross hemispheres increases the ISI required for subjects to perceive the two stimuli separately.

Visual inspection of Figure 12.6 (Effect of ISI on the percentage of "same" answers for the different positions of the 7-tactor array), shows that for unilateral presentation (positions right and left) discriminability increases (fewer "same" judgments for different stimulus patterns) for ISI>64 ms. For bilateral presentation (positions front and back), this increase is barely noticeable, probably occurring only at higher ISIs. Thus, it seems that larger ISIs are required for bilateral patterns to be spatially resolved and discriminated correctly, which is in line with Geffen et al.'s (1996) finding.

Variability in subjects' performance and correlation with vibratory threshold In all our experiments, we found large variations in subjects performance: Their quality judgments of simulated movement (Experiment 1) showed large interindividual differences as well as their ability to discriminate between tactile stimulus patterns (Experiments 2 and 3). One could hypothesize, that some subjects are more "sensitive" (and thus have lower vibration thresholds) to tactile stimulation than others.

Large individual differences exist in the ability to perform tactile pattern perceptions tasks, even for simple tasks, as reported by Cholewiak and Collins (1997; see also Cholewiak, Sherrick, & Collins, 1992): Discrimination performance between the letters X and O, presented on the OPTACON ranged between about 50-90 %, after subjects had some training in identifying the patterns. When performance was poor in the identification task, it was also poor in a discrimination and masking task. No correlation between vibratory threshold measure and performance was found. Similarly, when vibrotactile thresholds are measured over a relatively homogeneous population of college students, the range is found to be as much as 20 dB (a 10-fold difference) between the least and most sensitive subjects (Cholewiak, Sherrick & Collins, 1992; Fig 52-2).

In Experiment 2 we measured discrimination performance: The percentage of correct discriminations varied between 50 and 75 % in the 80 Hz group, and between 51 and 84 % in the 250 Hz group (note: Cholewiak & Collins, 1997, used a corrected-percent-correct value that minimizes the effects of response biases, but this value only differed by 2% from percent correct obtained from the raw data). Since our discrimination task is supposedly more complex than that of Cholewiak and Collins (1997), the maximum percentage of correct answers is lower in our experiment. But similar to their study, in our study, threshold does not correlate with discrimination performance (in our experiments, two sessions were conducted, in the beginning of each session vibratory threshold was measured; for details see corresponding chapter; correlations were calculated between threshold and percent correct discriminations: 80 Hz: session 1: Pearson correlation r=.05; session 2: r=-.04; 250 Hz: session1: r=-.08; session 2: r=-.23; although there is a tendency that subjects with lower thresholds obtain more correct answers, this trend is far from being significant). In an attempt to find subject characteristics contributing to successful pattern perception Cholewiak et al. (1992) discovered that neither gender nor handedness could predict pattern-perception performance, only a measure of imagery (geometric puzzle that had to be fit together) correlated with pattern perception.

It is also possible that the large individual variations are due to differences in subjects' perceptual maps of their waistline (perceptual maps are subjectively perceived somatotopic maps of stimulation, as described by Trojan et al., 2006). Trojan et al. (2006) asked subjects to perform a localization task, using a CO_2 laser and found that the perceptual space was either expanded or reduced or dislocated in one or the other direction. Thus, maybe differences in body perception (that can be psychophysically measured as perceptual maps)–e.g. if subjects consider themselves as being overweight–account for the large individual variations. Recently Schaefer, Flor, Heinze, and Rotte (2007) have demonstrated that changes in the perception of body size (in this study the use of an artificial hand elicited the illusory feeling of an elongated arm) lead to dynamic changes in SI (reduced representational distances of two finger digits of the elongated arm that were stimulated with pneumatically driven tactors). That such bodily illusions in turn affect tactile perception was shown by de Vignemont, Ehrsson, and Haggard (2005): Creating the illusion of an elongated finger caused an increase in length judgments of two simultaneously applied tactile stimuli. The authors reason that "tactile perception of an external stimulus is mediated by the proprioceptive representation if the body part that is touched" (de Vignemont, 2005; p. 1286). Disturbances of the body image also occur, when afferent input increases: Perceived size of the thumb increased after electrical stimulation (Gandevia & Phegan, 1999). Factors like differences in individual body maps and elongated peripheral stimulation might have affected our results.

Conclusions In our experiments we generated illusory movement with a vibrotactile array around the torso, using two stimulus patterns: Saltation and successive activation. Both patterns are indiscriminable–indicating that a similar cortical filling-in process occurred–at short SDs. ISI does not affect discriminability, at least in range that we tested (~10-130 ms). Short inter-stimulus distances improve the integration of saltatory patterns. Our results are in line with neural network models (Wiemer et al., 1998, 2000), stating that temporal and spatial relatedness of stimuli, lead to an integration of cortical representations. Although adaptive changes in somatosensory cortex can occur within minutes with repetitive spatio-temporal stimulation (e.g. Stolle, 2003), we didn't find an effect of repeated stimulation on discriminability, probably because on lesser innervated and lesser used body-sites like the trunk, the temporal course of plastic changes is longer.

As a result of our experiments, we assume that spatio-temporal integration requires the involvement of higher cortical areas (SII), where the somatotopy is less fine-grained (e.g. the second and fifth finger of the right hand have overlapping representational areas, in contrast to SI; see Ruben et al., 2001)–which might explain the poor discriminability between successively and saltatory patterns–and the contralateral as well as the ipsilateral body sites are somatotopically represented (which would explain findings of Experiment 3: For bilateral stimulation the percentage of incorrect responses exceeded 60%, which is significantly more than chance). Although the filling-in process that produces illusory percepts of motion or the saltatory illusion seems to occur in early cortices (Blankenburg et al., 2006; Larsen et al., 2006), the computation of the path of motion apparently involves higher-level cortical areas.

Our experiments might also shed further light on cutaneous spatial resolution. Johnson et al. (1994): "… other methods [than two-point threshold] based on the identification of many complex spatial forms have several desirable properties for the measurement of spatial resolution" (p. 400), as the large number of stimuli forces subjects to focus on the spatial structure of the neural image, not on nonspatial cues.

Our results extend the findings of Cholewiak and Collins (2000) who examined different body sites (finger, forearm, and back) using the same experimental design as we did in Experiments 1 and 2. Yet, a notable difference between the two studies is that their arrays always had distinctive endpoint, being constructed of a linear array of 7 tactors, while ours often involved circular arrays that surrounded the abdomen. Although the effect of the timing parameters on the quality judgments and discriminability differed slightly in their and our experiment, both studies indicate a strong equivalence of the percepts evoked by successive and saltatory stimulation within the spatio-temporal parameters examined.

From the perspective of application, our findings may contribute to the design of tactile torso displays like TSAS (see Chapter 1). The spatio-temporal parameters used in our study were found to be feasible for generating vectors on the skin, that can be used, for example, to indicate direction of motion. The saltatory illusion can also be advantageous in this respect, as fewer activated sites and thus fewer tactors–producing savings in costs and weight–are needed to generate vibrotactile lines.

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Annex A
Voluntary Consent Form

Appendix A. SAMPLE OF CONSENT DOCUMENT(S) AND PRIVACY ACT STATEMENT USED

Localization of vibrotactile Stimuli on the trunk.

VOLUNTARY CONSENT TO PARTICIPATE

1. I am being asked to volunteer to participate in a research study titled, "Perception of vibrotactile Stimuli/' The purpose of this study is to explore the best way to present spatial patterns to the skin by testing my ability to identify the locations, quality, and direction of movement of points of Vibration on my torso. I am being asked to participate for a total of l hour per day over a 4-day period. During my participation in this study, I will be involved in the following procedures or tests:
   * I will be asked to familiarize myself with the keyboards that will be used in some of the studies to follow, by pressing a randomly ordered series of keys in response to oral or visual instructions. This will take about 5 minutes.
   * Initially I will feel several series of vibrations presented to a number of locations on the trunk of my body with tactile arrays, and will be asked in each series to indicate if they all feel about the same. The researchers can then increase or decrease the intensities of notable locations so they all feel about the same. All of the vibrators will be varied in intensity Steps above this level to make sure that l can. feel all of the sites. The intensity of each Vibration will approximate that produced by a vibrating pager. This procedure will take at most 5 minutes.
   * In two sessions, I will serve in a number of trials in which I will be presented with bursts of Vibration at two locations on my torso and will be asked to indicate the locations of those by pressing the appropriate keys on the special keyboard. In one Session there will be several (as many as nine) blocks of trials, separated by rest periods, where we will vary aspects of the experiment like the position of the array of vibrators on my torso (low, around my waist, or at positions higher on my chest). There may be as many as 100 trials in a block, but a single whole series should take less then 30 minutes.
   * In the final two sessions, I will be presented with multiple bursts of Vibration on my torso over several sites in the array (a "pattern"). Each trial will consist of one or two patterns to be judged or compared. [n one session I will be asked to judge the direction, rate, or quality of the resulting Sensation of movement of those bursts when only one pattern is presented, by pressing the appropriate key on a keyboard. In the other session I will be asked to compare the two patterns presented in a trial, judging whether they were the same or different, or which was best. In one session there will be several (as many as nine) blocks of trials, separated by rest periods. There may be as many as 100 trials in a block, but the whole series of blocks should take less then 30 minutes in each of these final two sessions.
   * At the end of each session, I will be given the opportunity to ask any questions that might have come up during my lest series. This procedure will take as much time as I need.

2. The investigators believe that there will be no risks or discomforts to me resulting from the mechanical Stimulation of the skin in this study.

3. The benefits to me from participating in this research will be a greater appreciation of the use of the skin as an alternative communication modality, particularly as it is used by persons who are deaf or blind. The potential benefits include the possible improvements in aviation safety that might someday benefit all members of the aerospace community, as well as the improvement in our basic understanding of the Operation of the sense of touch, an underappreciated and poorly-studied sensory modality.

4. My privacy will be ensured during and after the study. The researchers will assign a code to my data. This will be the only identifying entry on any of my research records. A cross-reference between my name and my code will be maintained under lock by the research staff. It will be decoded only if to do so would benefit me or enhance the scientific value of the data.

5. If I have questions about this study, I should contact the following individuals:
   a. For questions about research (scientific) aspects l can contact Dr. Roger Cholewiak at 609-258-5277, Ms.**Anja Schwab,** at 850-452-9294, or **CAPT Angus Rupert** at 850-452-4496. b. For questions about medical aspects, injury, or any health or safety questions I have about participation in this study, I can contact **LT Merrill Rice MC USN** at 850-452-3287 x 1168, Medical monitor. c. For questions about the ethical aspects of this study, my rights as a volunteer, or any problem related to protection of research volunteers, I can contact the Principal Investigators or Leonard A. Temme, Ph.D., Chair, Committee for the Protection of Human Subjects at 850-452-3287 ext. 1128.

6. My participation in this study is completely voluntary. I may discontinue my participation in this study at any time. If I choose to discontinue, there will be no penalty, and I will not lose any benefits to which I am otherwise entitled.

7. No risks are anticipated for this protocol.

8. My participation in this study may be ended before the expected number of sessions by the researchers or the medical monitor without my consent. This could occur, for example, because of equipment malfunction. If this happens, there will be no penalty, and I will not lose any benefit to which I am otherwise entitled.

9. There are no costs to me that may result from my voluntary participation in this study.

10. If I decide to withdraw from participation in this study, it is requested that I inform **Ms.** Anja **Schwab** at the Tactile Research Lab (850-452-9294) of my wishes. I understand I may discontinue participation in this study at any time, without penalty.

11. New findings developed during the course of the research that might affect my willingness to continue participation will be provided to me.

12. Official government agencies, such as the Department of Defense and the U.S. Navy, may have a need to inspect the research records from this study, including mine, to fulfill their responsibilities.

13. I have received a Statement informing me about the provisions of the Privacy Act.

14. I have been informed that **Ms. Anja** Schwab is responsible for storage of my consent form and the research records related to my participation in this study. These records will be stored in locked files in the Tactile Research Lab building in 1811 of the Naval Aerospace Medical Research Laboratory in Pensacola, Florida.

15. I have been given an opportunity to ask questions about this study and its related procedures and risks, as well as any of the other information contained in this consent form. All of my questions have been answered to my satisfaction. By my signature below, I give my voluntary informed consent to participate in the research as it has been explained to me, and I acknowledge receipt of two copies of this form, one for my medical records and one for my own personal records.

Volunteer Date (DD/MM/YY)

Witness Date (DD/MM/YY)

Investigator Date (DD/MM/YY)

Annex B

Medical Questionnaire

NAMRL Tactile Research Laboratory
Medical History Questionnaire

This survey was designed to obtain information about our research participants prior to their serving in our studies. We need the medical information to help us interpret your results. ALL data collected in this laboratory is kept confidential.

Name: ______________________________ Date: ____________

Sex (circle one): M / F

Address: ______________________________ Date of Birth: __________

______________________________ Age: __________

______________________________ Initials: ____/____/____

Daytime Phone Number: ____________________ Handedness: L / R

Measurements

Lower Circumference: _______ cm

Upper Circumference: _______ cm

Low
Rostral-Caudal: _______ cm
Lateral: _______ cm

High
Rostral-Caudal: _______ cm
Lateral: _______ cm

Your Initials ___/___/___

NAMRL Tactile Research Laboratory
Medical History Questionnaire

1. Have you had any of the following conditions that affected your arms, wrist, hands, or fingers?
If yes, please indicate how much the condition interferes with your activities now and which side:
0= Not at all 1 = A little 3 = A great deal L = Left Side R = Right Side

		If yes, please circle
Skin disorders (e.g., pressure sores, severe burns)	No / Yes	0 1 2 L R
Peripheral neuropathy	No / Yes	0 1 2 L R
Carpal Tunnel Syndrome	No / Yes	0 1 2 L R
Broken/injured (indicate: left arm, wrist, hand, or fingers)	No / Yes	0 1 2 L R
Cuts requiring sutures (indicate: left arm, wrist, hand, or fingers)	No / Yes	0 1 2 L R
Pinched Nerve	No / Yes	0 1 2 L R
Hand-Arm Vibration Syndrome or Vibration White Finger	No / Yes	0 1 2 L R

Other: ______________________________

2. Have you experienced any numbness, tingling, or pain in your extremities, particularly in your hands and fingers that has not been explained by any of the above conditions? No / Yes

If yes, please explain what body part(s) are affected and to what extent: ________________

3. Are you currently taking any medication that might affect your motor coordination, particularly use of your arms, hands, or fingers? No / Yes

If yes, please list below:

Medication Name	Reason Taken

4. Is there anything else (injuries, illnesses) that might affect your ability to use your arms, hands, or fingers? No / Yes

If yes, please explain what body part(s) are affected and to what extent: ________________

Your Initials ____/____/____

5. How "dexterous" or "good with your hands" do you consider yourself?

Below Average		Average		Above Average
1	2	3	4	5

6. For each of the following activities, indicate which hand you prefer to use:

Writing	Left Hand	Either Hand	Right Hand
Strike a Match	Left Hand	Either Hand	Right Hand
Drawing	Left Hand	Either Hand	Right Hand
Throwing a Ball	Left Hand	Either Hand	Right Hand
Hold Toothbrush	Left Hand	Either Hand	Right Hand
Hold Spoon	Left Hand	Either Hand	Right Hand
Hold Comb/Brush	Left Hand	Either Hand	Right Hand
Use Hammer	Left Hand	Either Hand	Right Hand
Use Scissors	Left Hand	Either Hand	Right Hand
Cut with Knife	Left Hand	Either Hand	Right Hand

Annex C

Quality descriptions

Length

How much surface area does the line cover along the length of the belt?

Shortest Line									Longest Line
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Long lines will start at the navel, go around your torso and probably travel over your navel,

whereas **short** lines may end before the navel is reached.

Straightness

Does the movement feel like it would go in a straight line around the torso?

Not straight									Straight line
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Not straight means the movement zigzags or bends or strays to one side or another

or the movement stays internally straight but does not end at the same position where it started.

Straight means the movement travels in a straight line around the torso and ends at the same position where it started.

Spatial distribution

Do the bursts feel equally distant from one another or do they seem to be irregularly distributed?

Poor spatial distribution									Equal spatial distribution
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10

Poor spatial distribution means that the bursts feel bunched up or the distances between the bursts vary. .. … . . .. .. …

Equally spatial distribution means that the bursts spread out evenly.

. . . .

Smoothness

Is the movement fluid, continuous or do the bursts feel like isolated events?

Not smooth									Smooth movement
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Not smooth means the movement feels like distinct taps in different locations; the movement feels choppy or coarse.

Smooth means the movement feels like an unitary event; the movement feels fluid and continuous.

Annex D

Experimenter Script for Pilot Study 1: Direction discrimination

Purpose
This test will help us to evaluate how well people can determine the direction of "flo" of the vibrotactile stimuli on the torso (in a clockwise or counter-clockwise direction). I will place a belt with 36 vibrating motors (called "tactors") around you; only the middle row with 12 tactors will be activated during this experiment.

Ultimately, we are hoping that this experiment will tell us what tactile cues may help in preventing spatial disorientation and motion sickness in pilots. Throughout the entire experiment, we will be testing different modalities – direction, smoothness, length etc. Today, direction will be tested.

First, I need you to change into a **t-shirt** for the testing. This is important, because we cannot fairly compare the results if our participants are wearing different types of clothing. This is a newly cleaned t-shirt that we will keep in the lab for testing you.

Now, I need to **measure your waist** and I will **mark your naval** by drawing a line on the t-shirt.

Then I would like to collect some basic information from you. I would like you to read and sign the **consent-form** and then to fill out the **Medical Questionnaire**.

Meanwhile: Put tactors on belt.

Place belt on participant.

I've placed a belt containing 36 tactors around you. The tactors vibrate much like a pager motor. When all of the tactors activate around your body, do the best you can to hit the key corresponding to the direction of movement as quickly and as accurately as possible. (#1 = clockwise and #2 = counter-clockwise)

We will now go through the **instruction phase** together:

First, I want to tell you that, throughout the test, you will get no feedback as to whether your answer was correct or incorrect.

Now, if you look on the visual display, you will read "**Rotating Tactors**". Here, you will have the opportunity to feel the sensation of the tactors. If you press the "Align " button, each tactor will activate in a circle around your torso. Please repeat the "Rotating Tactors" two more times.

Next, you will read "**Threshold Measure**" on the display screen. This is a measure to determine your individual threshold – or point where you can just feel all of the tactors. After we determine that point, we will increase the intensity by 10% to ensure that you will be able to feel all of the tactors activate during the test.

In order to determine your threshold, push the "Align" button and all of the tactors will activate in a circle around your torso. Each time you push this button, the intensity will decrease. When you cannot feel any one tactor, push the "#1" key to lock in your threshold. If you cannot feel any one tactor on the first attempt, let me know and I will increase the intensity. Also, please inform me of the tactor which you did not feel first.

Now the display will read "Block 1." Press the "Align" button and the display will read "direction," press the "Align" button again and the display will read "ready." Your next keystroke, the "Align" button, will activate the system. The tactors will activate around your body either in a clockwise or counter-clockwise direction. When you determine which direction they moved press the corresponding key (#1=clockwise, #2 = counter-clockwise). After you answer, press the "Align" button to get the next stimuli. You control when the stimuli are presented by pressing the align key. There is no time limit to this test.

Today's test will consist of 2 blocks of trials. Each block of trial will consist of 98 stimuli. You can take a brief break in between the blocks if you wish. To start the next block of trials, hit the "Align" button again.

Do you have **any questions**?

Headphones!

Annex E

Experimenter Script for Pilot Study 2: Different modes of saltation

Purpose
In this experiment, you will receive two sets of stimuli and be asked to determine "which is best." This will be judged by pressing a button on the keyboard (#1 for the first set of stimuli and #2 for the second set of stimuli). There are no correct or incorrect responses simply because you are rating which of these two patterns feels best to you. This test will help us to evaluate the optimal parameters to present vibrotactile flo over the torso.

First, I need you to change into a **t-shirt** for the testing. This is important, because we cannot fairly compare the results if our participants are wearing different types of clothing. This is a freshly cleaned t-shirt that we will keep in the lab for testing you.

Now, I need to **measure your waist** and I will **mark your naval** on the t-shirt.

Then I would like to collect some basic information from you. I would like you to read and sign the **consent-form** and then to fill out the **Medical Questionnaire**.

Meanwhile: Put tactors on belt.

Place belt on participant.

I've placed a belt containing 36 tactors around you. For today's experiment, only the middle row of 12 tactors will activate. The tactors vibrate much like a pager motor

We will now go through the **instruction phase** together:

At first, you will read "**Rotating Tactors**" on the display.

If you press the "Align " button, the display will read '1 ready'. Press the "Align" button again and the tactors will activate in a circle around your torso. This process will be repeated two more times.

Now the display will read **"Threshold Measure."** This is a measure to determine your individual threshold – or point where you can just feel all of the tactors. After we determine that point, we will increase the intensity 10 times to ensure you will be able to feel all of the tactors activate during the experiment.

In order to determine your threshold, push the "Align" button and all of the tactors will activate in a circle around your torso. Each time you push this button, the intensity will decrease. When you cannot feel any one tactor, push the "#1" key to lock in your threshold. If you cannot feel any one tactor on the first attempt, let me know and I will increase the intensity. Also, please inform me of the tactor that you did not feel first.

Now the display will read "Block 1." Press the "Align" button and the display will read "ready." Your next keystroke, the "Align" button, will activate the system. During the experiment, you will be presented with two sets of stimuli. Each set will go around your torso. After the first set of stimuli is presented, there will be a brief break and then the second will automatically begin. After the second set was presented, you will answer "which is best" by pressing either #1 for the first set of stimuli or #2 for the second set of stimuli. Again, there is no right or wrong answer and no feedback will be given. We are interested in determining which set of stimuli you perceive to be the best. By "which is best," we mean what set feels overall better. Guidelines to determine this include: which line felt straighter, smoother, or equally distributed in both space and time. All patterns will vary in terms of how long the burst lasts and the time in between bursts.

After you answer, press the "Align" button to get the next stimuli. You control when the stimuli are presented by pressing the align key.

Today's test will consist of 3 blocks of trials. Each block of trials will consist of 98 stimuli. You can take a brief break in between the blocks if you wish. To start the next block of trials, hit the "Align" button again.

Do you have **any questions**?

Headphones!

WHICH IS BEST?

Which line felt:

- Straighter
- Smoother
- Equally distributed in both space & time

Annex F

Experimenter Script for Experiment 1: Quality judgments

In this experiment, you will be presented with a single pattern of stimuli and be asked to make judgments on certain characteristics of the pattern based on how it feels on your torso. The specific qualities you will be asked to judge are smoothness, straightness, length and spatial distribution. You will make your decision by pressing a button on the keyboard (#1 =least/not to #10= most). There are no correct or incorrect responses simply because you are rating how these patterns feel to you. This test will help us to evaluate the optimal parameters to present vibrotactile flo over the torso.

First, I need you to change into a **t-shirt** for the testing. This is important, because we cannot fairly compare the results if our participants are wearing different types of clothing. This is a freshly cleaned t-shirt that we will keep in the lab for testing you.

Now, I need to **measure your waist** and I will **mark your naval** on the t-shirt.

Then I would like to collect some basic information from you. I would like you to read and sign the **consent-form** and then to fill out the **Medical Questionnaire**.

Meanwhile: Put tactors on belt.

Place belt on participant.

I've placed a belt containing 36 (24) tactors around you. For today's experiment, only the middle row of 12/8 tactors (or all 36/24 tactors) will activate. When the tactors activate they vibrate like a pager motor or cell phone.

You are asked to come back three more times because there are four different conditions we would like to measure. The four conditions are: 1 row with 12 tactors, 3 rows with 36 tactors, 1 row with 8 tactors, and 3 rows with 24 tactors.

We will now go through the **instruction phase** together:

At first, you will read "**Rotating Tactors**" on the display.

If you press the "Align " button, the display will read '1 ready'. Press the "Align" button again and the tactors will activate in a circle around your torso. There will be 8/12 positions that activate. Count them as they go along to ensure you can feel a tactor activate at every position. This process will be repeated two more times.

Now the display will read **"Threshold Measure."** This is a measure to determine your individual threshold – or point where you can just feel all of the tactors. After we determine that point, we will increase the intensity by 10 times to ensure you will be able to feel all of the tactors activate during the experiment.

In order to determine your threshold, push the "Align" button and all of the tactors will activate in a circle around your torso. Each time you push this button, the intensity will decrease. When you cannot feel any one tactor, push the "#1" key to lock in your threshold. If you cannot feel any one tactor on the first attempt, let me know and I will increase the intensity. Also, please inform me of the tactor that you did not feel first.

Now you will feel three stimuli samples similar to the patterns you will receive in the experiment. During the experiment, all of the patterns will vary in terms of how long the burst lasts and the time in between bursts. The sample patterns will be fast, medium, and slow in terms of stimulus duration around the torso. Press the "Align" button and you will read **"Flo Samples"** on the display. Press the "align" button again and you will read "Fast Ready." Your next press of the "align" button will produce the fast sample pattern. Now the display reads "Medium Ready." Press the align button again to receive the medium pattern. Now the display reads "Slow Ready." Press the "align" button to receive the slow pattern.

Now the display will read "Block 1." Press the "Align" button and the first quality you will judge will appear on the visual display. Press the "align" button again and read "ready." Your next keystroke, the "Align" button, will activate the system.

During the experiment, you will be presented with patterns of stimuli around your torso. After the pattern is presented, you will judge its quality by pressing number 1 through 10 on the keyboard (#1 representing the least/not to #10 representing the most). Again, there is no right or wrong answer and no feedback will be given. We are interested in determining how you perceive the quality of the pattern.

After you answer, press the "Align" button to get the next stimuli. You control when the stimuli are presented by pressing the align key.

The four qualities you will be asked to judge are length, straightness, smoothness and spatial distribution. The blocks will be given in a random order during the test.

You can use the following criteria for your judgments:

Length: How much surface area does the line cover along the length of the array? This may vary depending on the time of the bursts and burst durations. You may perceive the length as being a complete circle, a little shorter than a circle, or a little longer than a circle as though the stimuli overshoots its origin at your navel. To indicate the shortest line possible press #1. To indicate the longest single circuit possible press #9, while if there is an overshoot press #10. You may find that many of your judgments will fall somewhere in the middle. If that is the case, press a number correlating to your judgment from 2 to 8.

Straightness: Does the line feel straight? Does the line zigzag at all? Does it bend over? Does the line stray to one side or another? To indicate the straightest line press #10. To indicate the least straight line press #1. Again, if you judge the straightness of the line to fall somewhere in the middle, press the correlating number between 2 & 9.

Smoothness: Does the line feel smooth? Is the line movement smooth or choppy? Some lines may feel like distinct taps in different locations (coarse), while others seem to be a unitary event (smooth). To indicate a smooth movement press #10. To indicate a choppy movement press #1. If you judge the smoothness in between press the correlating number from 2 to 9.

Spatial Distribution: Does the line feel well distributed spatially? Do the taps seem to be equally distant from one another spatially? Do the lines seem to be bunched up at certain locations? To indicate equal spatial distribution press #10. To indicate poor spatial distribution press #1. If you judge the spatial distribution to fall somewhere in the middle, press the correlating number from 2 to 9.

You can refer to the paper in front of you during the experiment for a more descriptive definition of the quality you are being asked to judge.

Today's test will consist of 4 blocks of trials, each consisting of 98 stimuli. In each of the four blocks, you will be asked to judge a different quality. The quality that you are asked to judge will always appear on the visual display before you make your decision. You can take a brief break in between the blocks if you wish. To start the next block of trials, hit the "Align" button again.

Do you have **any questions**?

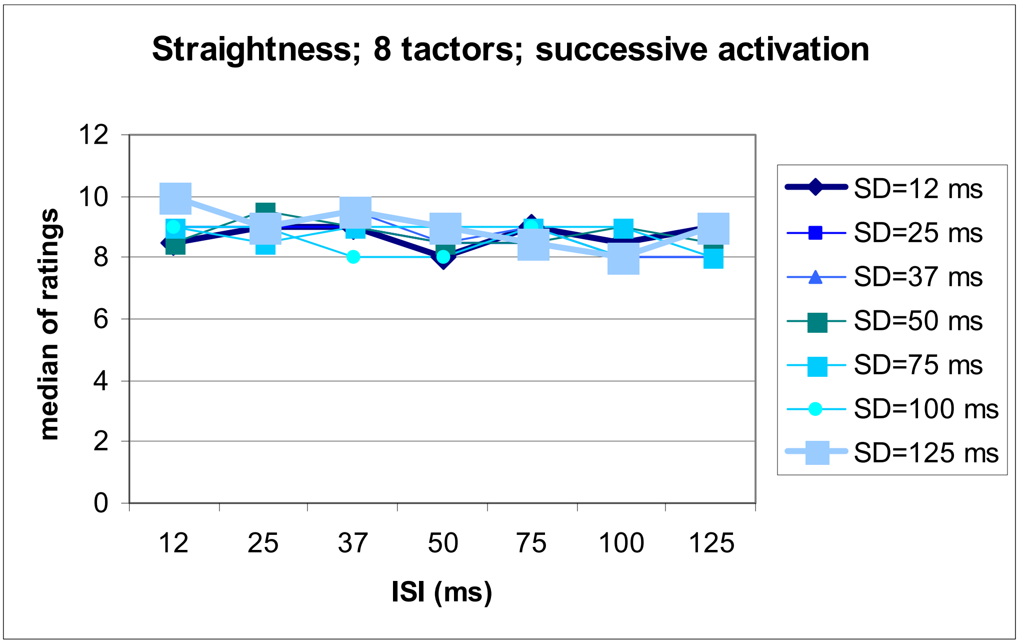
Headphones!

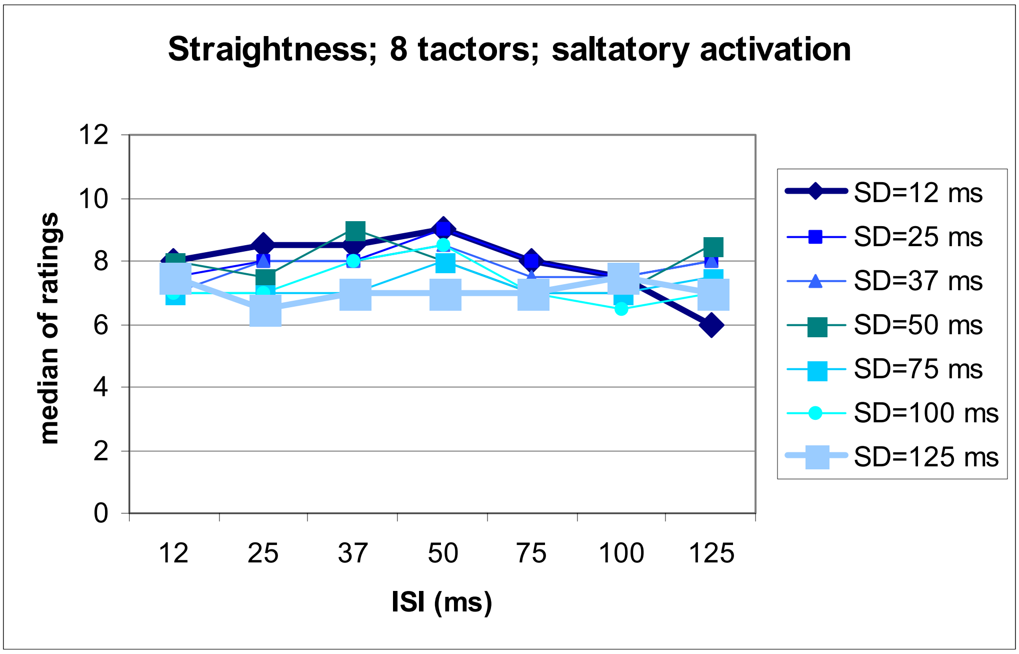
Annex G

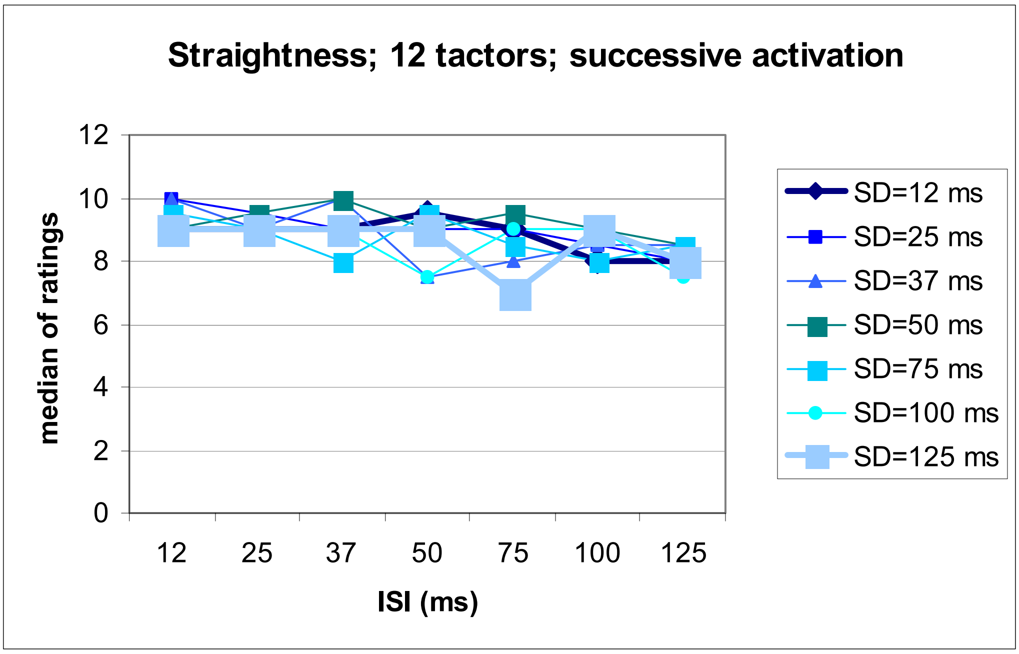
Median ratings for the different levels of SD dependent on ISI

Quality Straightness

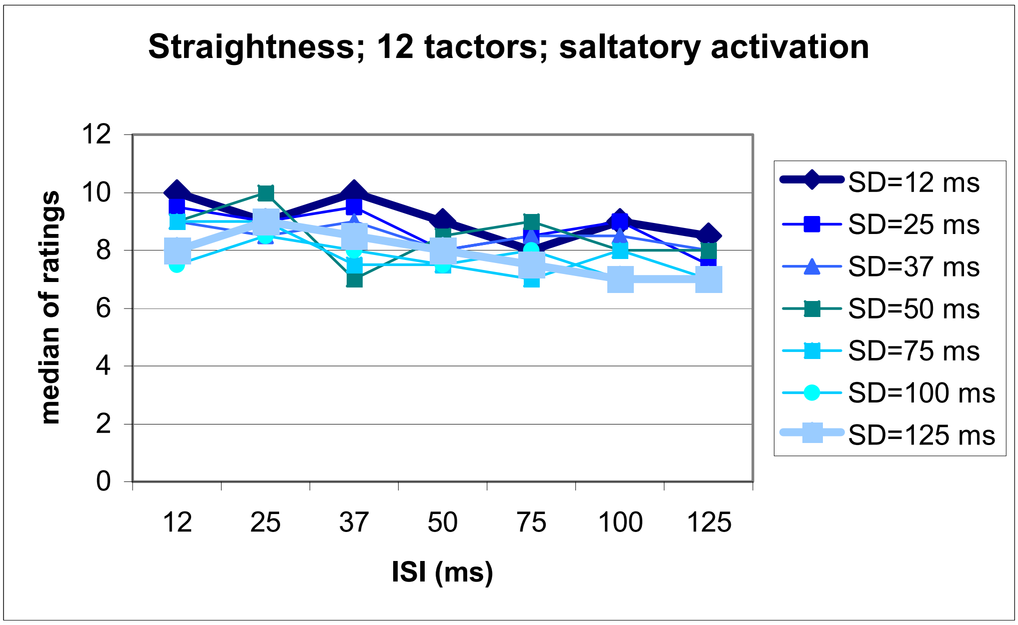
80 Hz





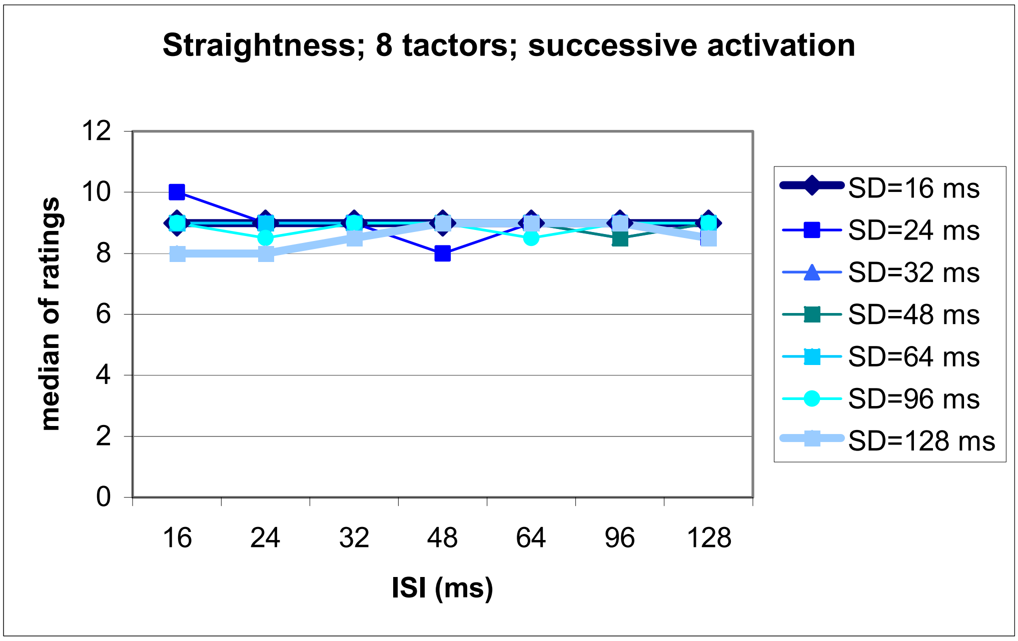


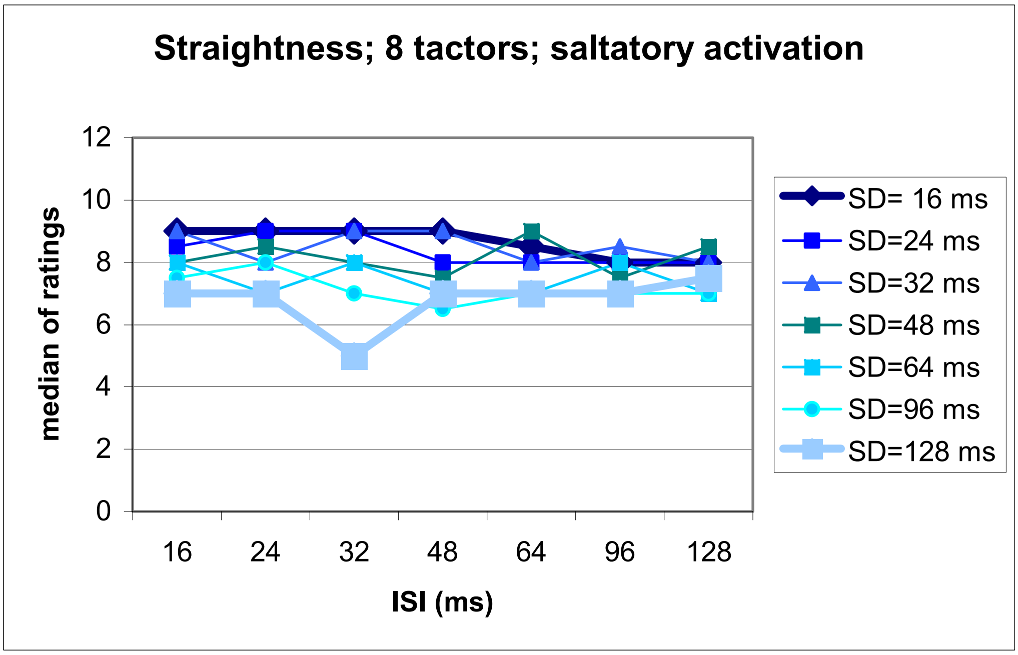
Straightness; 12 tactors; successive activation
median of ratings
12
10
8
6
4
2
0
12
25
37
50
75
100
125
ISI (ms)
SD=12 ms
SD=25 ms
SD=37 ms
SD=50 ms
SD=75 ms
SD=100 ms
SD=125 ms

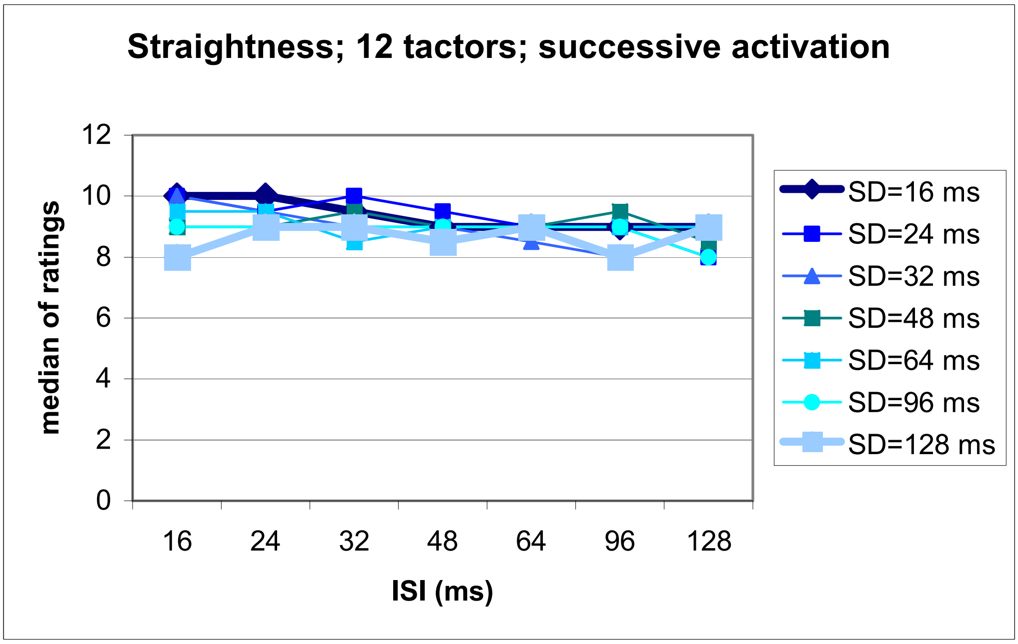


Straightness; 12 tactors; saltatory activation
median of ratings
12
10
8
6
4
2
0
12
25
37
50
75
100
125
ISI (ms)
SD=12 ms
SD=25 ms
SD=37 ms
SD=50 ms
SD=75 ms
SD=100 ms
SD=125 ms

<u>250 Hz</u>


Straightness; 8 tactors; successive activation
median of ratings
12
10
8
6
4
2
0
16
24
32
48
64
96
128
ISI (ms)
SD=16 ms
SD=24 ms
SD=32 ms
SD=48 ms
SD=64 ms
SD=96 ms
SD=128 ms


Straightness; 8 tactors; saltatory activation
median of ratings
12
10
8
6
4
2
0
16
24
32
48
64
96
128
ISI (ms)
SD= 16 ms
SD=24 ms
SD=32 ms
SD=48 ms
SD=64 ms
SD=96 ms
SD=128 ms



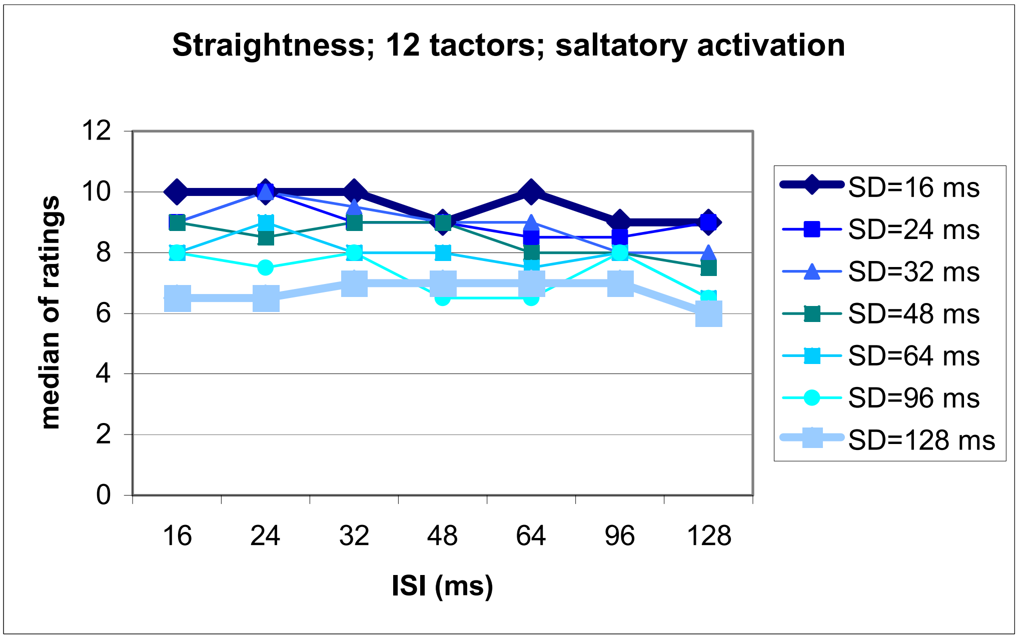
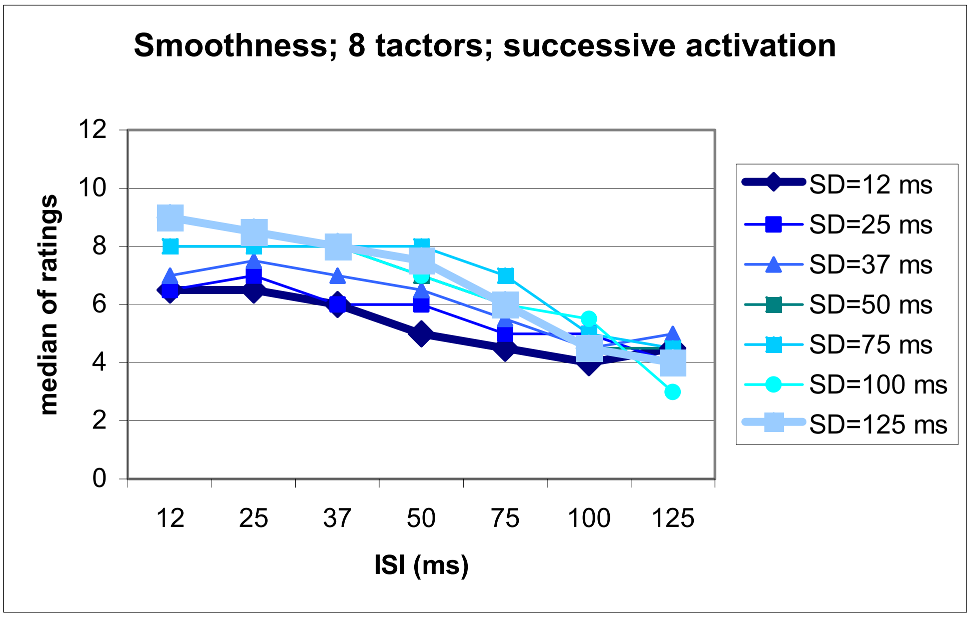
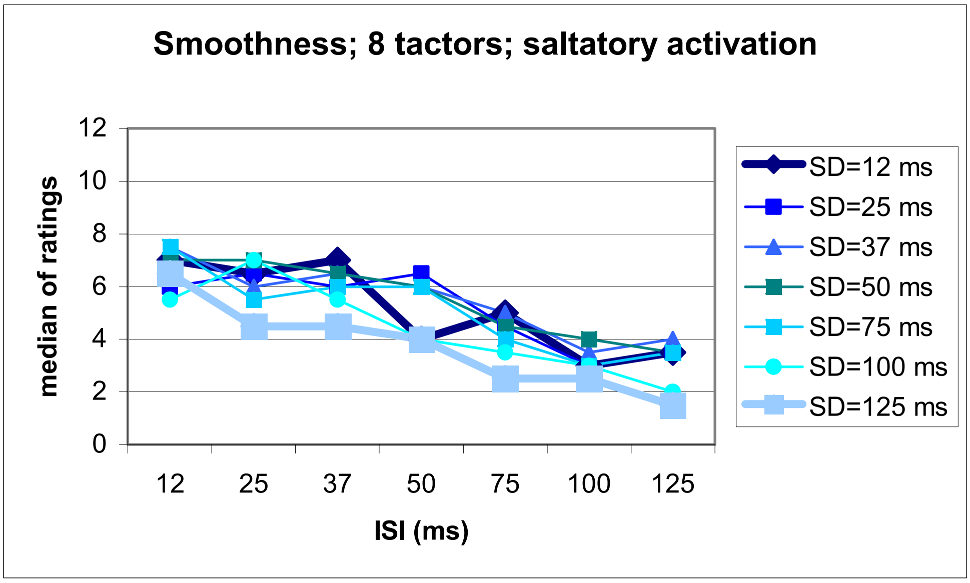


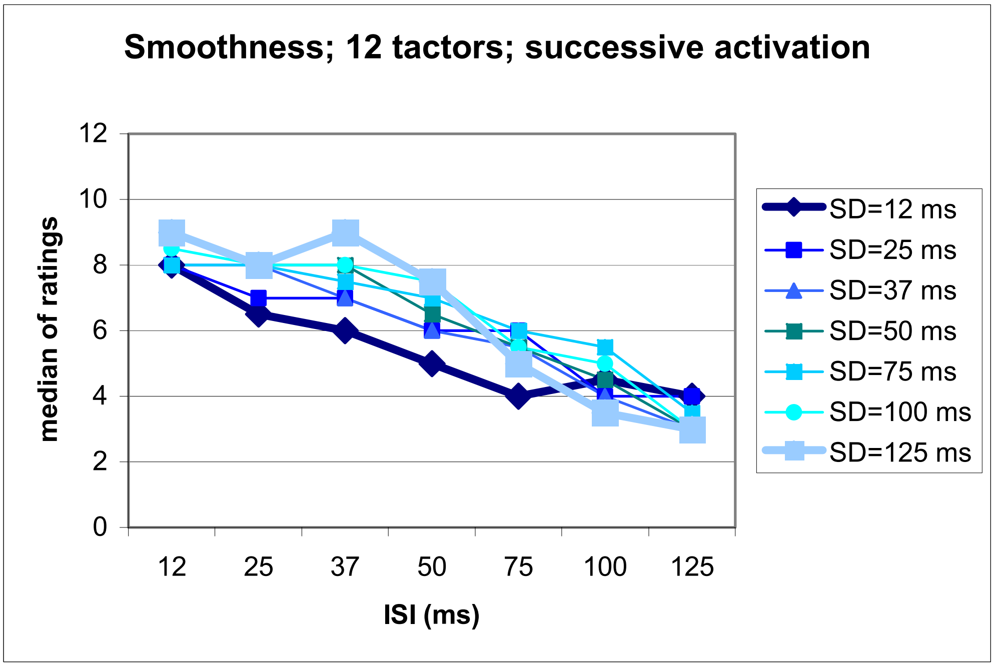
Figure G-1: Median ratings (over 20 subjects in the 80 Hz group, and over 28 subjects in the 250 Hz group) on a 10-point scale dependent on SD and ISI for the quality straightness. Displayed are the values for successively activated and saltatory stimulus patterns and for either 8 or 12 tactors. The lighter the line, the higher SD.

Quality Smoothness

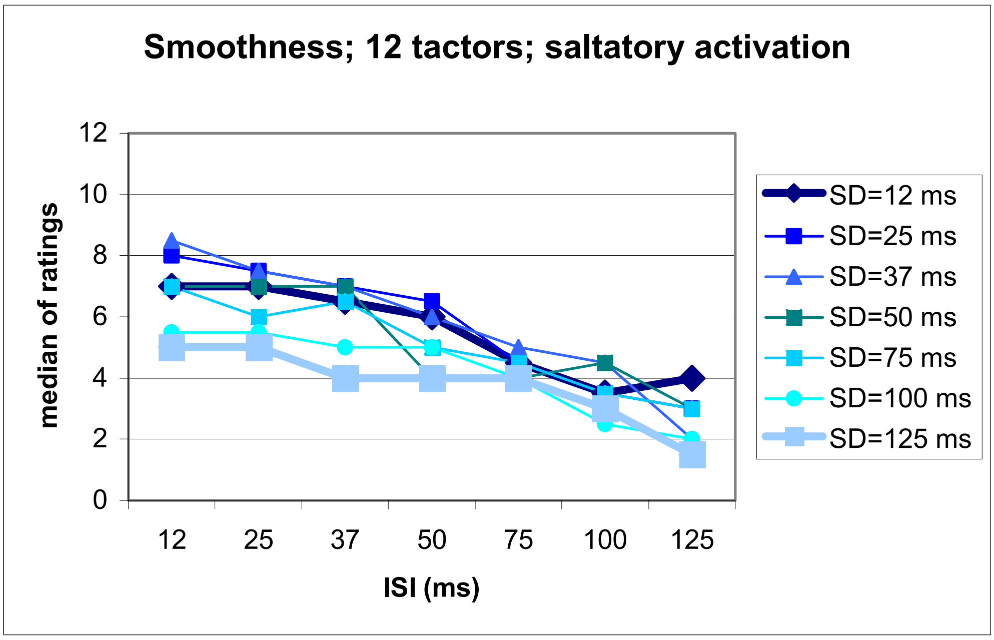
80 Hz





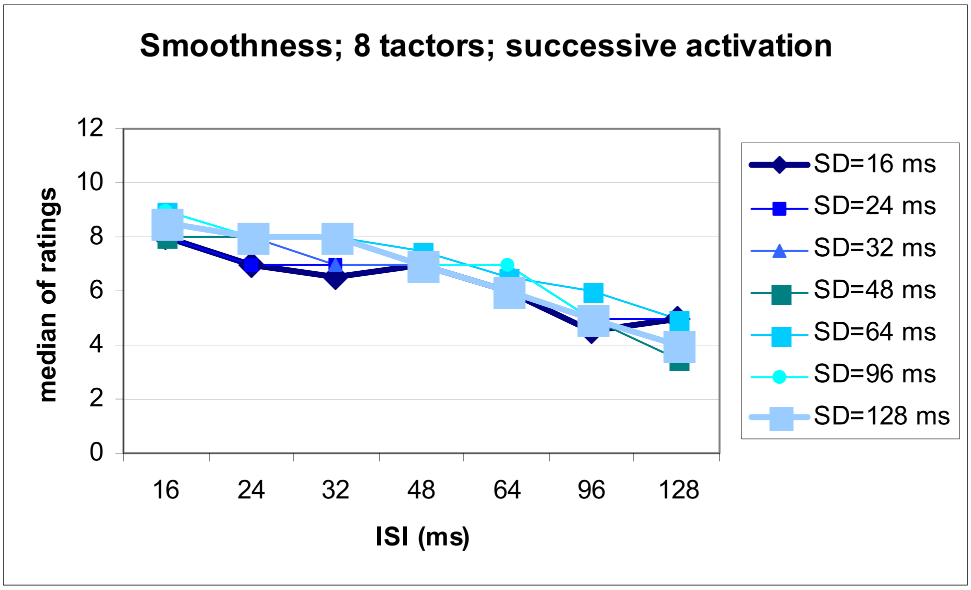


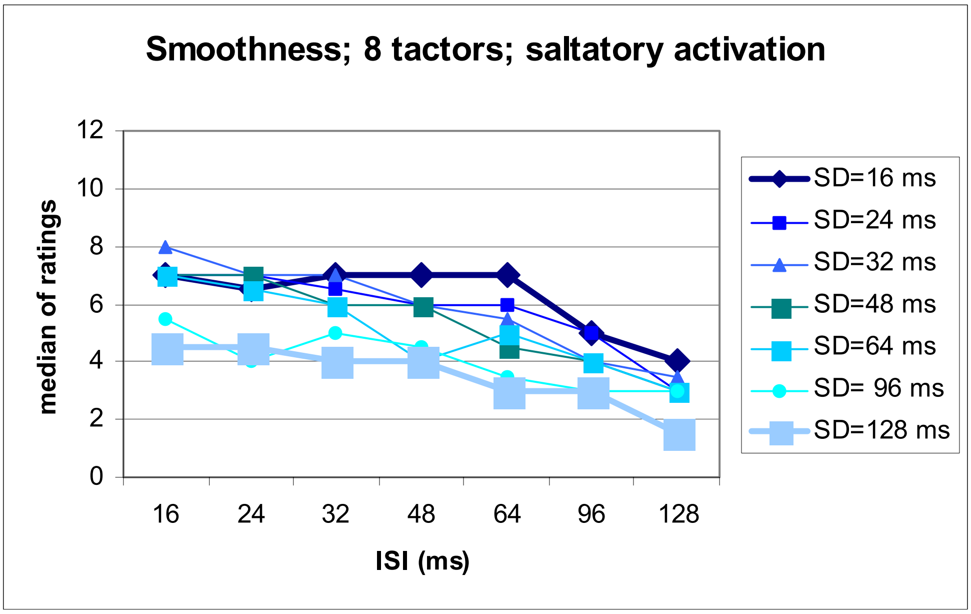
Smoothness; 12 tactors; successive activation
median of ratings
12
10
8
6
4
2
0
12
25
37
50
75
100
125
ISI (ms)
SD=12 ms
SD=25 ms
SD=37 ms
SD=50 ms
SD=75 ms
SD=100 ms
SD=125 ms



Smoothness; 12 tactors; saltatory activation
median of ratings
12
10
8
6
4
2
0
12
25
37
50
75
100
125
ISI (ms)
SD=12 ms
SD=25 ms
SD=37 ms
SD=50 ms
SD=75 ms
SD=100 ms
SD=125 ms

250 Hz


Smoothness; 8 tactors; successive activation
median of ratings
12
10
8
6
4
2
0
16
24
32
48
64
96
128
ISI (ms)
SD=16 ms
SD=24 ms
SD=32 ms
SD=48 ms
SD=64 ms
SD=96 ms
SD=128 ms


Smoothness; 8 tactors; saltatory activation
median of ratings
12
10
8
6
4
2
0
16
24
32
48
64
96
128
ISI (ms)
SD=16 ms
SD=24 ms
SD=32 ms
SD=48 ms
SD=64 ms
SD= 96 ms
SD=128 ms

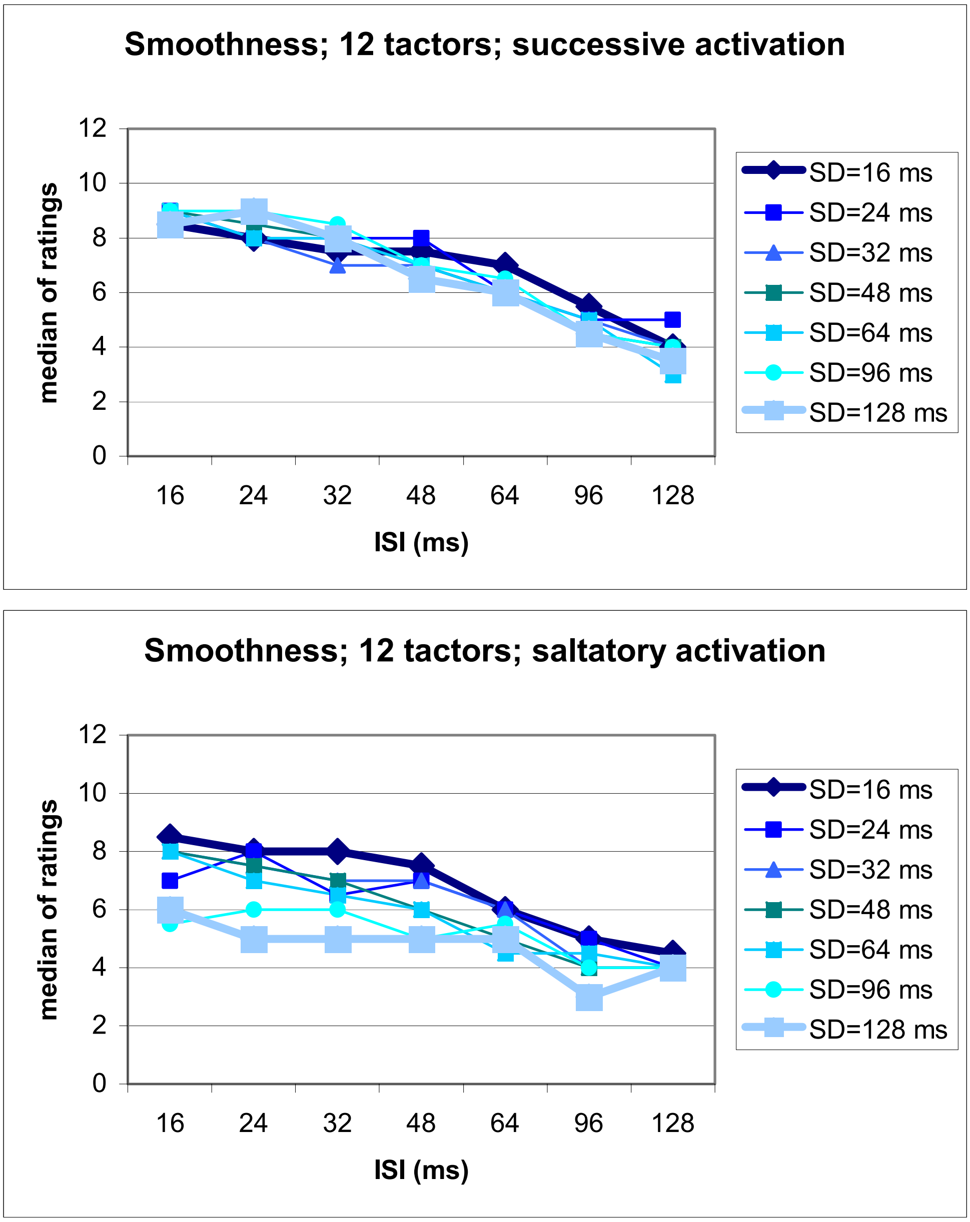
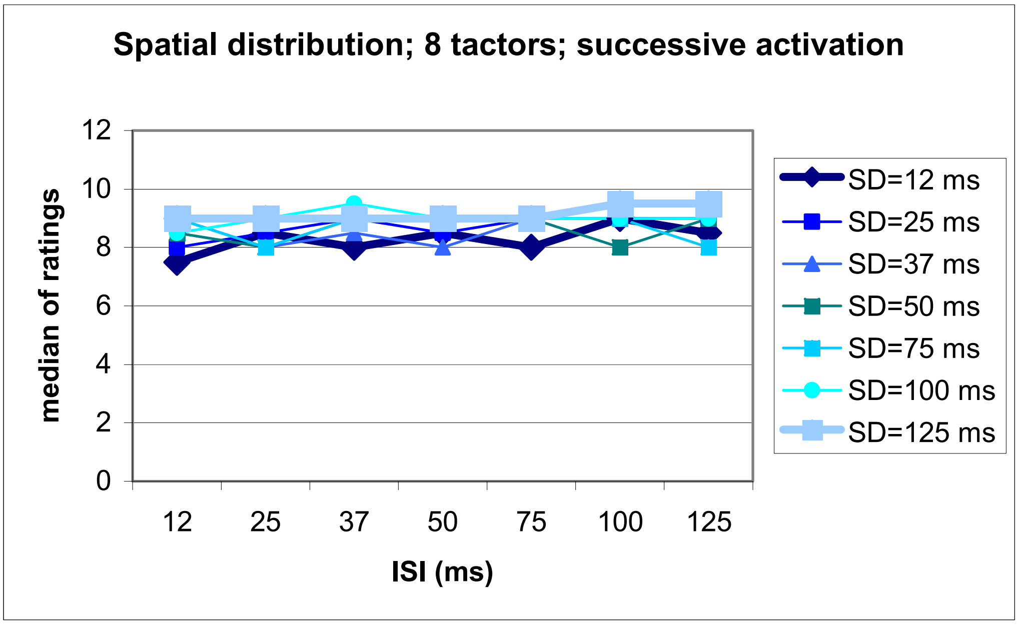
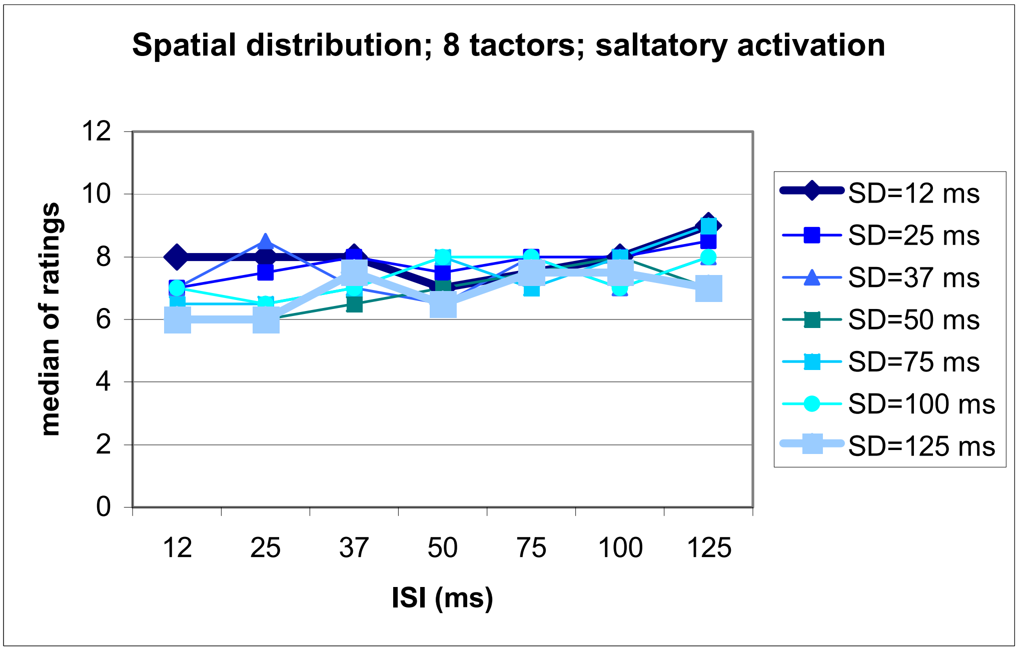


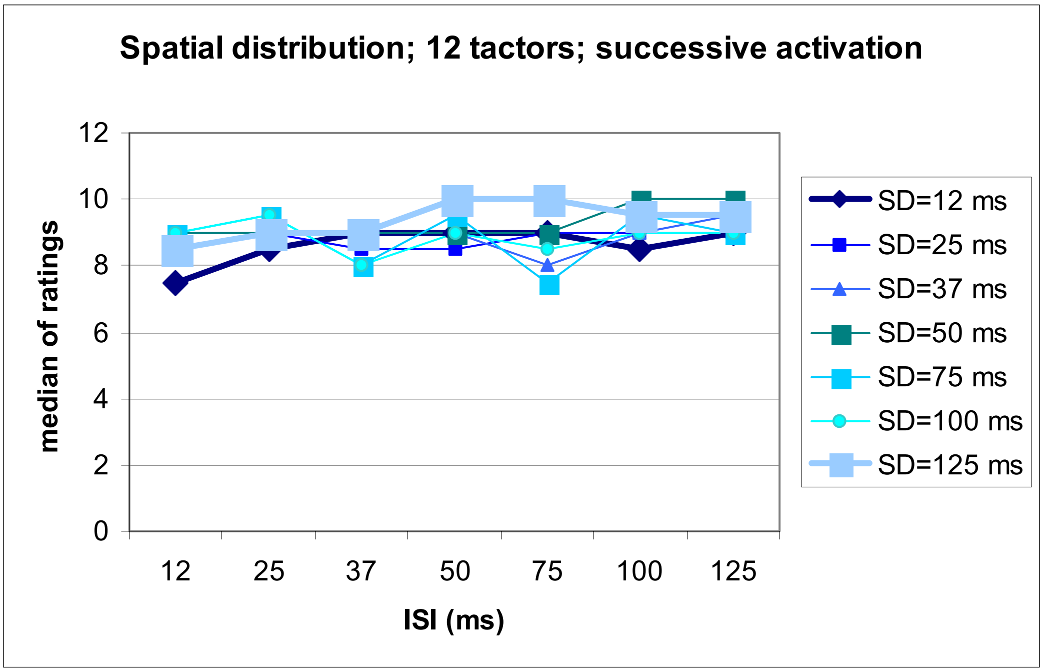
Figure G-2: Median ratings (over 20 subjects in the 80 Hz group, and over 28 subjects in the 250 Hz group) on a 10-point scale dependent on SD and ISI for the quality smoothness. Displayed are the values for successively activated and saltatory stimulus patterns and for either 8 or 12 tactors. The lighter the line, the higher SD.

Quality Spatial distribution

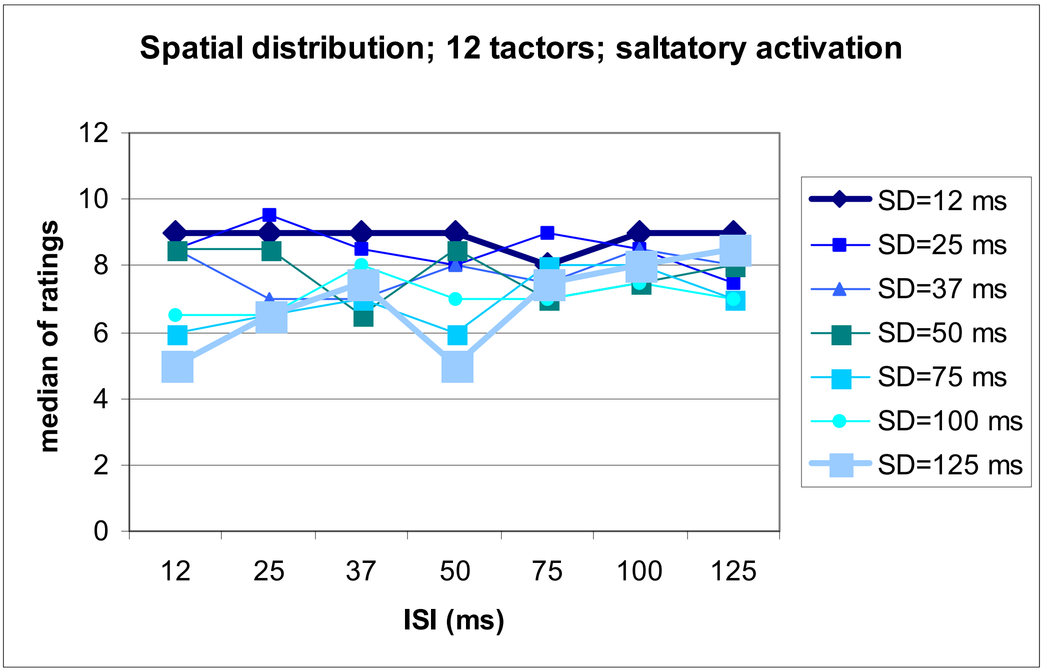
80 Hz





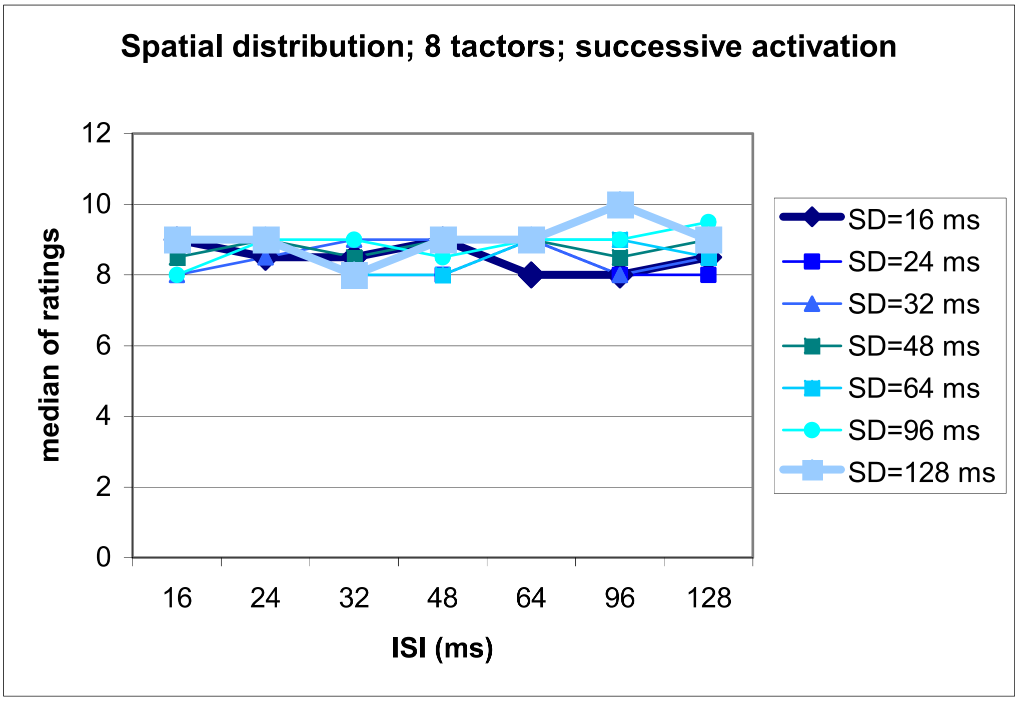


Spatial distribution; 12 tactors; successive activation
median of ratings
12
10
8
6
4
2
0
12
25
37
50
75
100
125
ISI (ms)
SD=12 ms
SD=25 ms
SD=37 ms
SD=50 ms
SD=75 ms
SD=100 ms
SD=125 ms

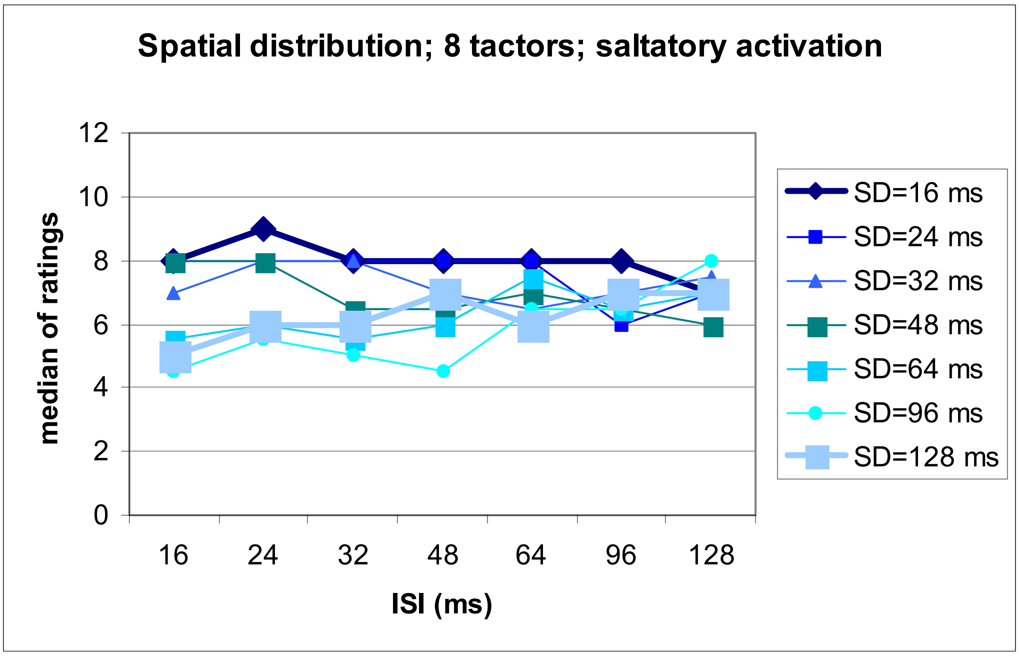


Spatial distribution; 12 tactors; saltatory activation
median of ratings
12
10
8
6
4
2
0
12
25
37
50
75
100
125
ISI (ms)
SD=12 ms
SD=25 ms
SD=37 ms
SD=50 ms
SD=75 ms
SD=100 ms
SD=125 ms

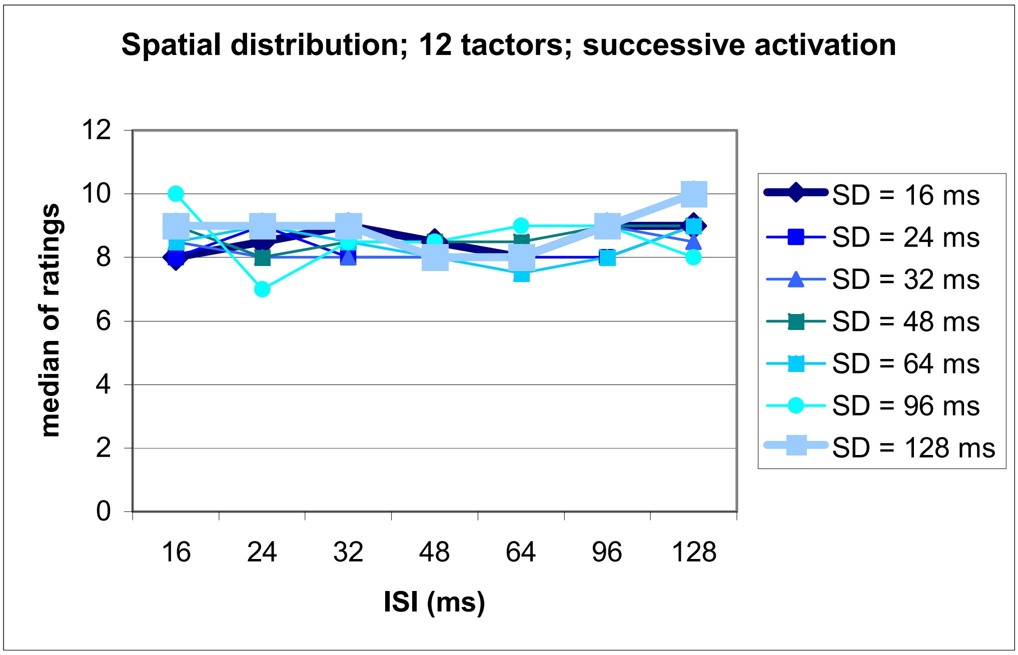
250 Hz



Spatial distribution; 8 tactors; successive activation
median of ratings
12
10
8
6
4
2
0
16
24
32
48
64
96
128
ISI (ms)
SD=16 ms
SD=24 ms
SD=32 ms
SD=48 ms
SD=64 ms
SD=96 ms
SD=128 ms



Spatial distribution; 8 tactors; saltatory activation
median of ratings
12
10
8
6
4
2
0
16
24
32
48
64
96
128
ISI (ms)
SD=16 ms
SD=24 ms
SD=32 ms
SD=48 ms
SD=64 ms
SD=96 ms
SD=128 ms



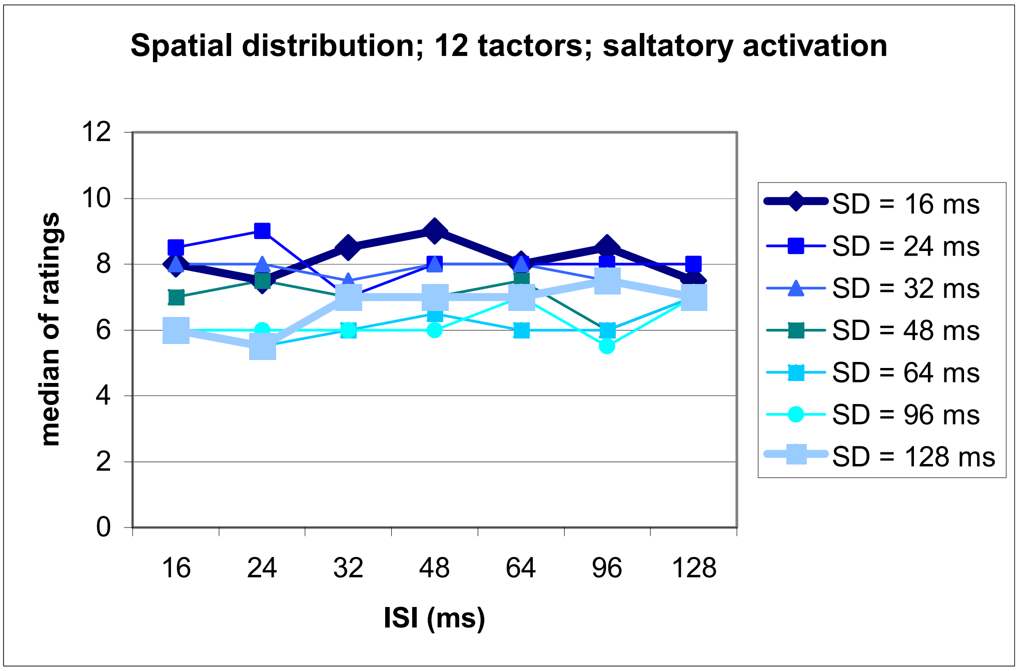
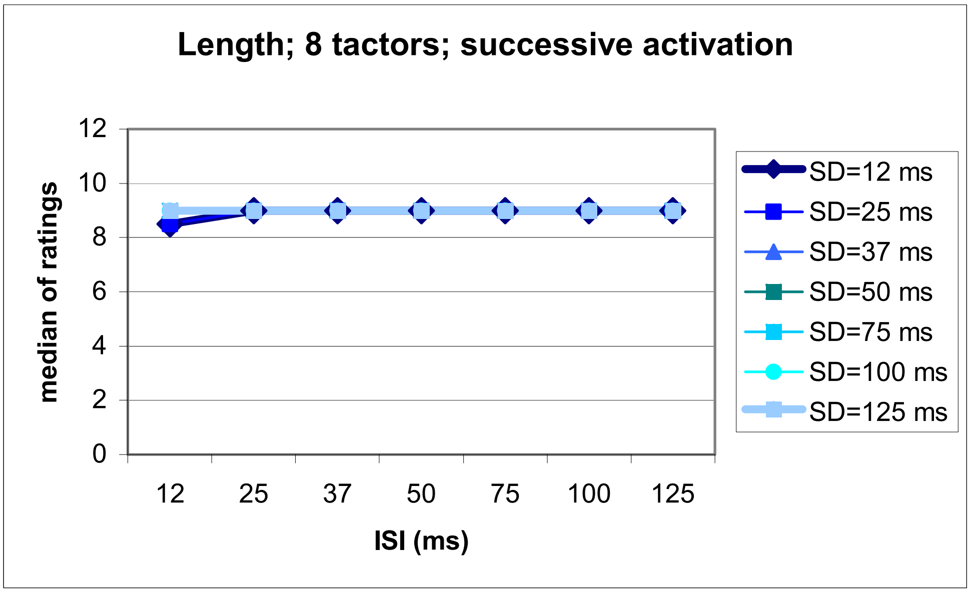
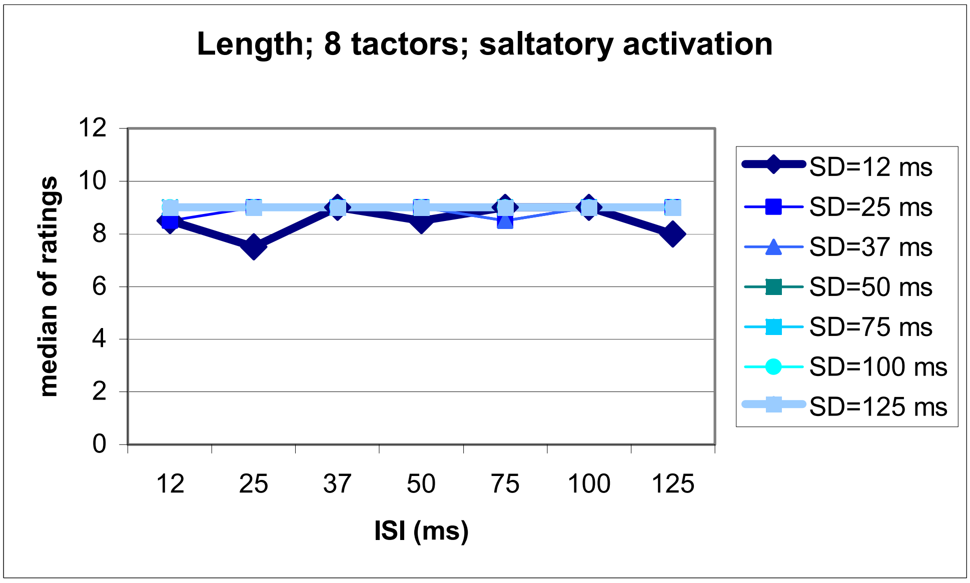


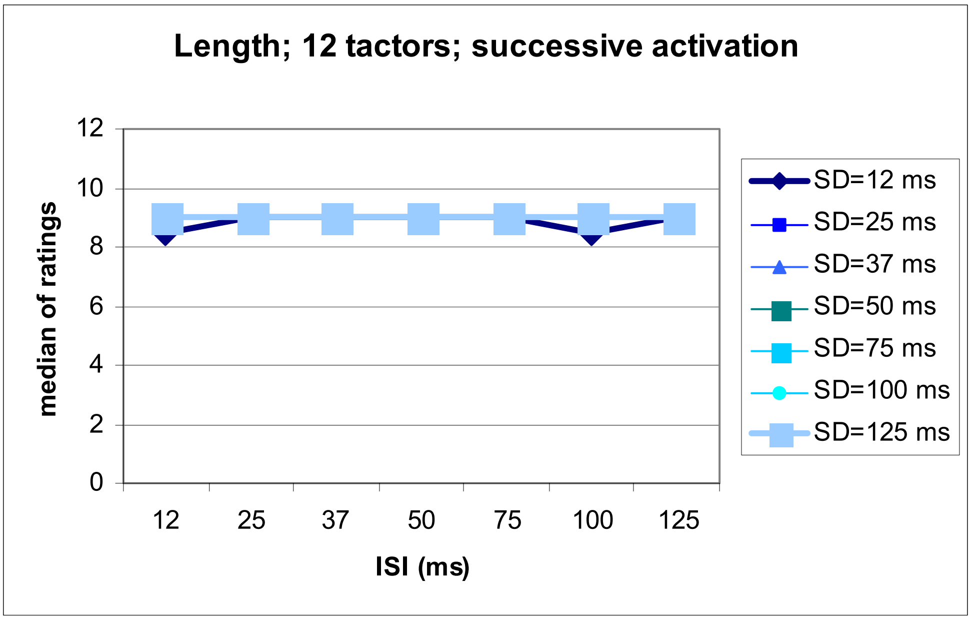
Figure G-3: Median ratings (over 20 subjects in the 80 Hz group, and over 28 subjects in the 250 Hz group) on a 10-point scale dependent on SD and ISI for the quality spatial distribution. Displayed are the values for successively activated and saltatory stimulus patterns and for either 8 or 12 tactors. The lighter the line, the higher SD.

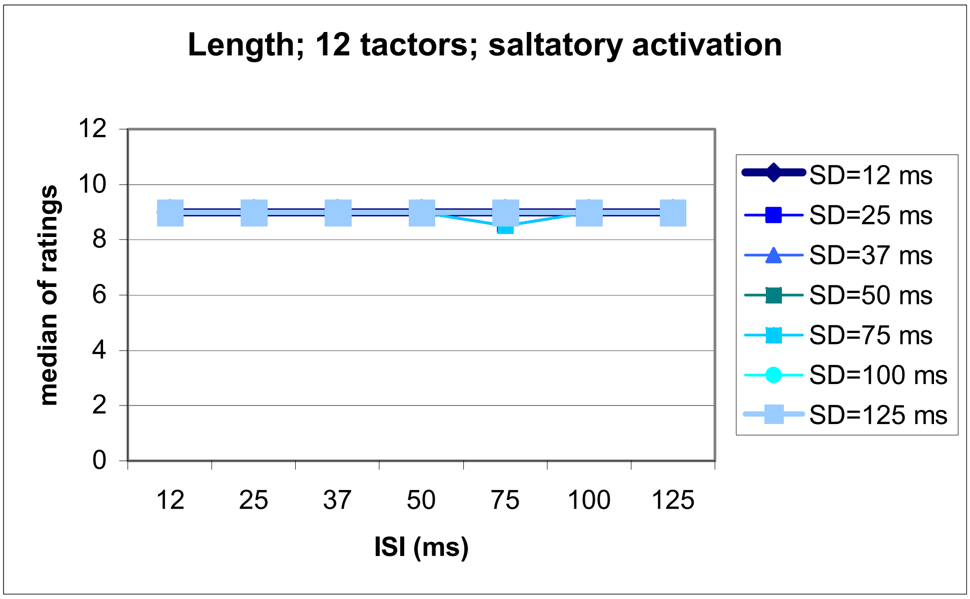
Quality Length

80 Hz

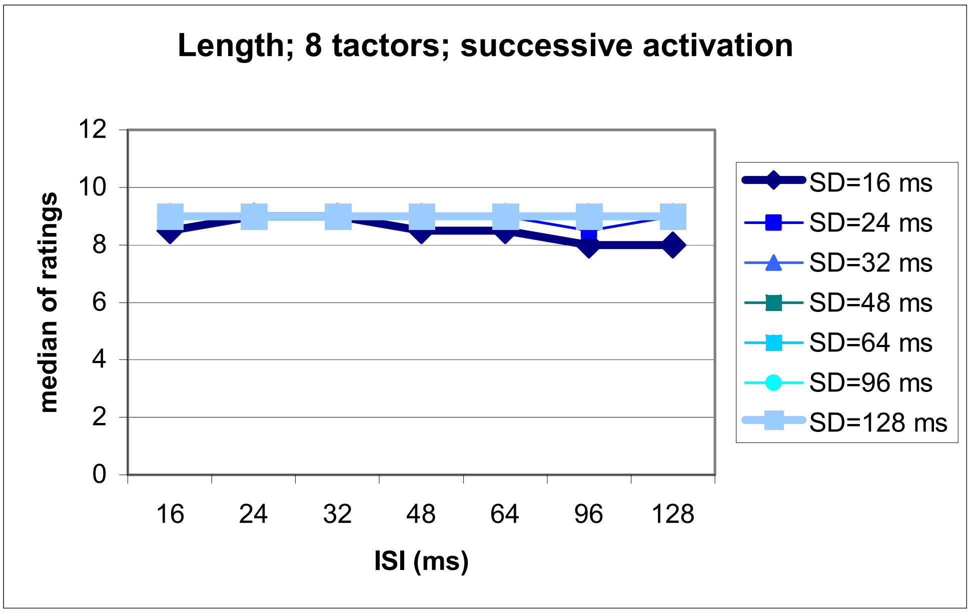




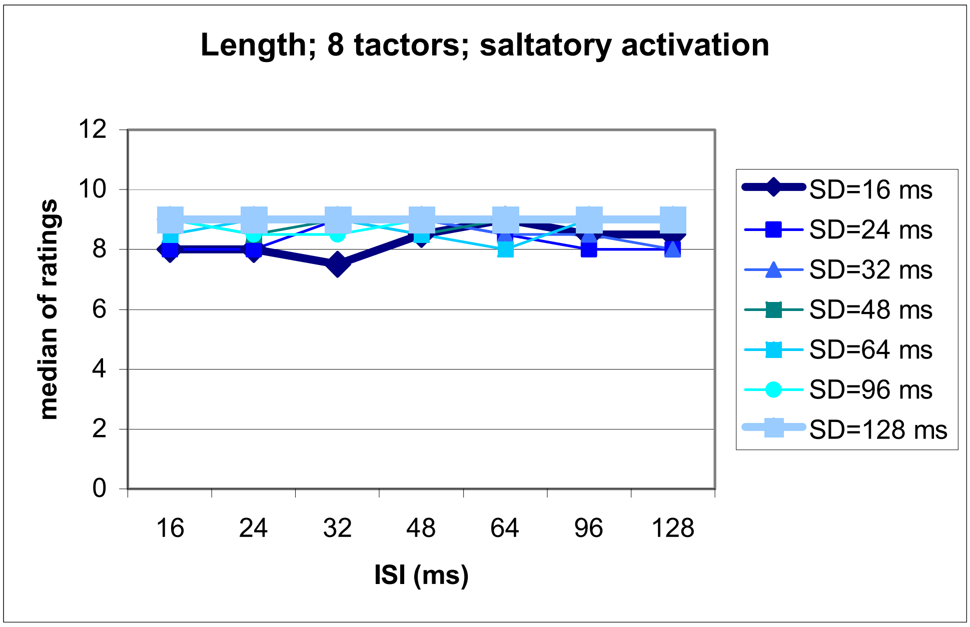

Length; 12 tactors; successive activation
median of ratings
12
10
8
6
4
2
0
12
25
37
50
75
100
125
ISI (ms)
SD=12 ms
SD=25 ms
SD=37 ms
SD=50 ms
SD=75 ms
SD=100 ms
SD=125 ms


Length; 12 tactors; saltatory activation
median of ratings
12
10
8
6
4
2
0
12
25
37
50
75
100
125
ISI (ms)
SD=12 ms
SD=25 ms
SD=37 ms
SD=50 ms
SD=75 ms
SD=100 ms
SD=125 ms

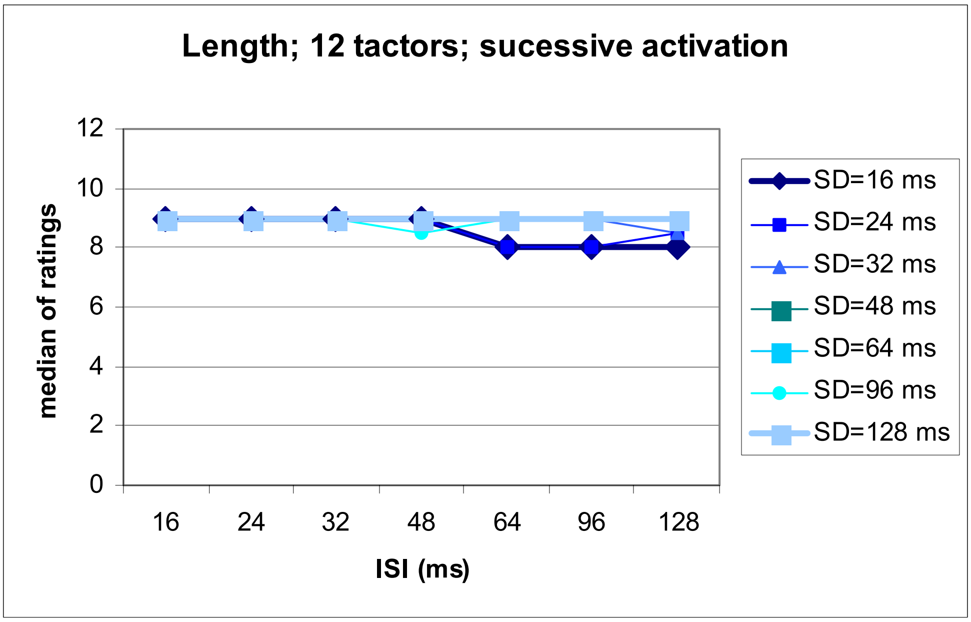
<u>250 Hz</u>



Length; 8 tactors; successive activation
median of ratings
12
10
8
6
4
2
0
16
24
32
48
64
96
128
ISI (ms)
SD=16 ms
SD=24 ms
SD=32 ms
SD=48 ms
SD=64 ms
SD=96 ms
SD=128 ms



Length; 8 tactors; saltatory activation
median of ratings
12
10
8
6
4
2
0
16
24
32
48
64
96
128
ISI (ms)
SD=16 ms
SD=24 ms
SD=32 ms
SD=48 ms
SD=64 ms
SD=96 ms
SD=128 ms



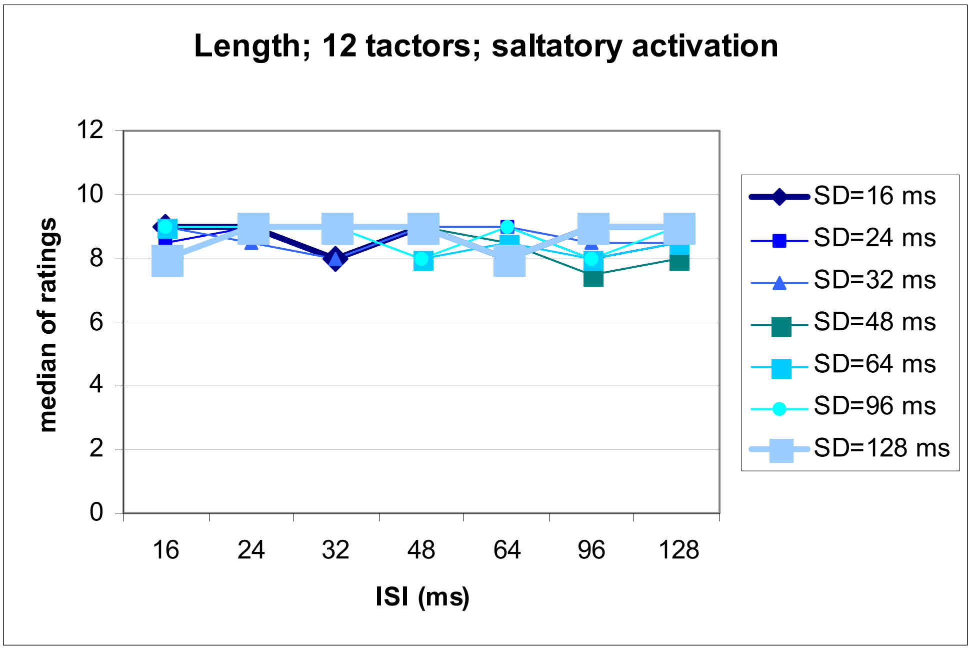


Figure G-4: Median ratings (over 20 subjects in the 80 Hz group, and over 28 subjects in the 250 Hz group) on a 10-point scale dependent on SD and ISI for the quality length. Displayed are the values for successively activated and saltatory stimulus patterns and for either 8 or 12 tactors. The lighter the line, the higher SD.

Annex H

Effect of vibration frequency on qualitative judgments

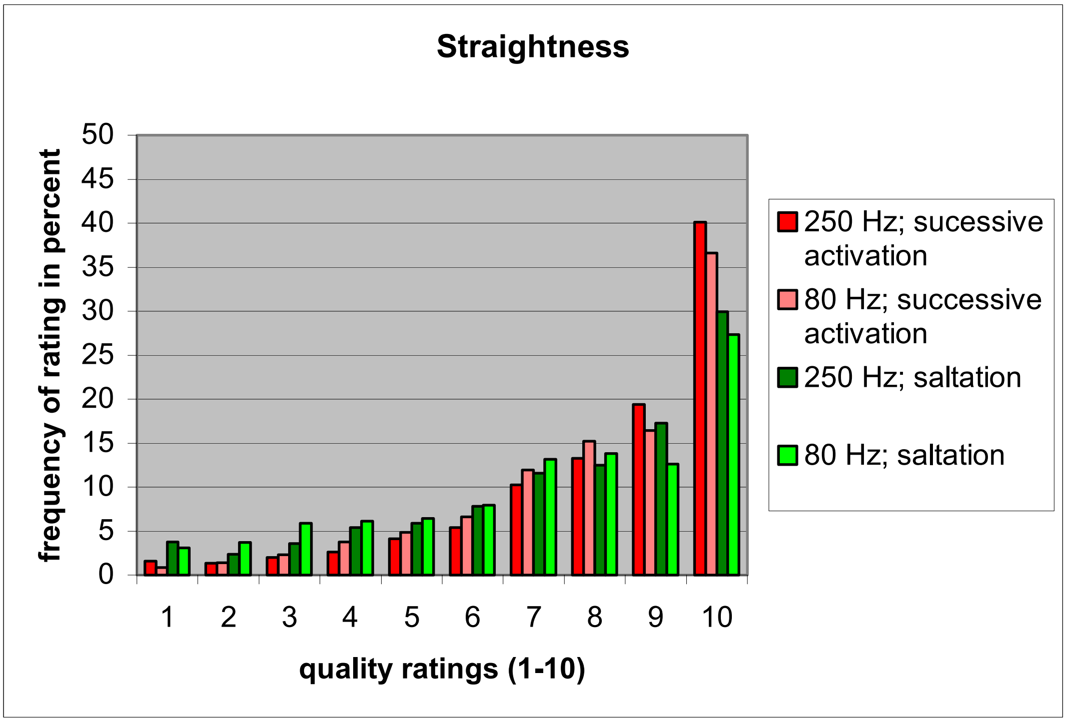


Figure H-1: Quality judgments on the 10-point scale for the quality straightness dependent on vibration frequency (80 and 250 Hz) and stimulus pattern (successively activated or saltatory).

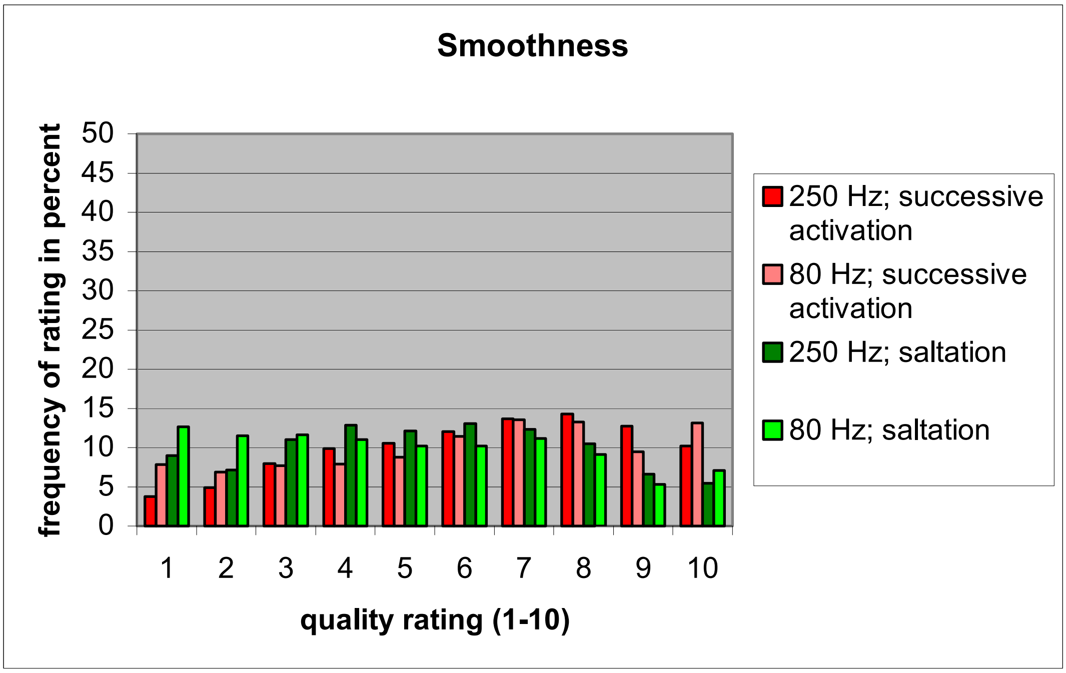


Figure H-2: Quality judgments on the 10-point scale for the quality smoothness dependent on vibration frequency (80 and 250 Hz) and stimulus pattern (successively activated or saltatory).

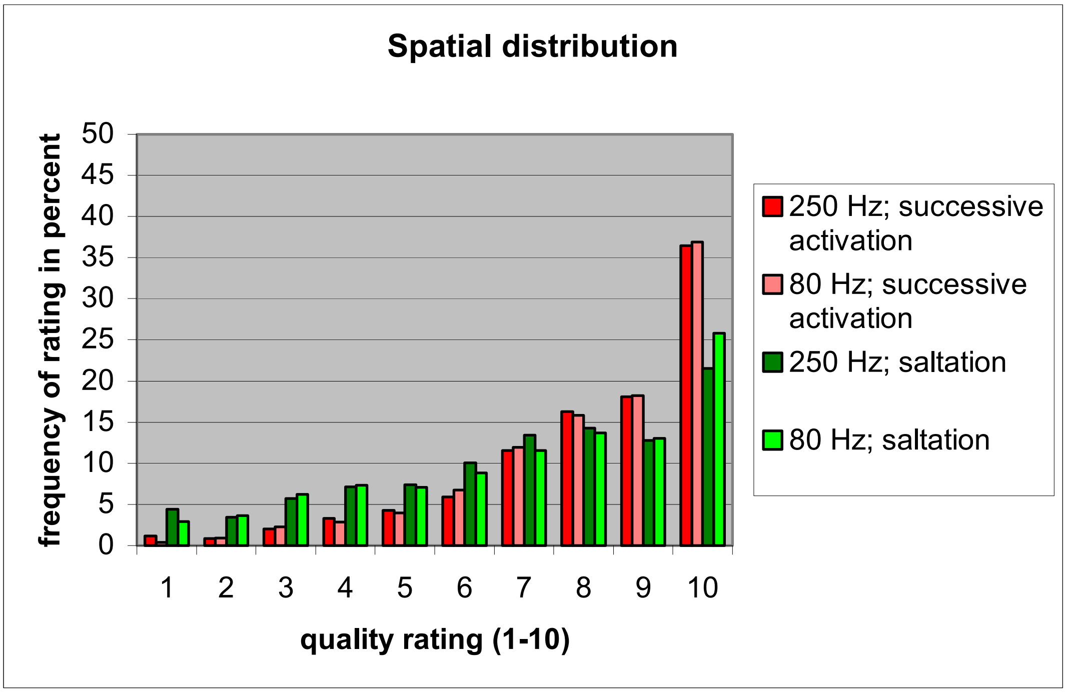


Figure H-3: Quality judgments on the 10-point scale for the quality spatial distribution dependent on vibration frequency (80 and 250 Hz) and stimulus pattern (successively activated or saltatory).

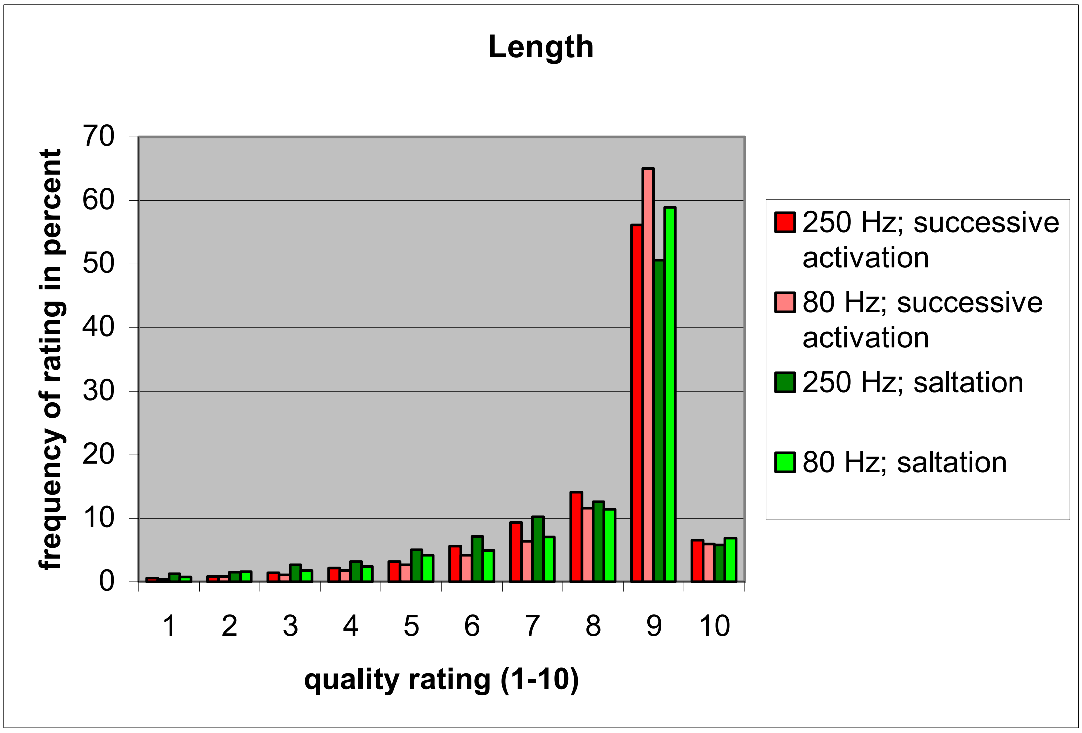


Figure H-4: Quality judgments on the 10-point scale for the quality length dependent on vibration frequency (80 and 250 Hz) and stimulus pattern (successively activated or saltatory).

Annex I

Experimenter Script for Experiment 2 (Part 1): Same/different discrimination

In this experiment, you will receive two sets of stimuli and be asked to determine whether they were the "Same or Different" from one another. You will make your judgment by pressing a button on the keyboard (S if both lines are the Same or D if both lines are Different). This test will help us to evaluate the optimal parameters to present vibrotactile flo over the torso.

*First, I need you to change into a **t-shirt** for the testing. This is important, because we cannot fairly compare the results if our participants are wearing different types of clothing. This is a freshly cleaned t-shirt that we will keep in the lab for testing you.*

*Now, I need to **measure your waist** and I will **mark your naval** on the t-shirt.*

*Then I would like to collect some basic information from you. I would like you to read and sign the **consent-form** and then to fill out the **Medical Questionnaire**.*

Meanwhile: Put tactors on belt.
Place belt on participant.

I've placed a belt containing 36 tactors around you. Either only the middle row, or all three rows will be activated. When the tactors activate they vibrate like a pager motor or cell phone. The only difference between today and tomorrow's session is the number of activated tactors.

We will now go through the **instruction phase** together:

At first, you will read "**Rotating Tactors**" on the display.

If you press the "Align " button, the display will read '1 ready'. Press the "Align" button again and the tactors will activate in a circle around your torso. There will be 12 tactors (columns of tactors) that activate. Count them as they go along to ensure you can feel a tactor activate at every position. This process will be repeated two more times.

Now the display will read **"Threshold Measure."** This is a measure to determine your individual threshold – or point where you can just feel all of the tactors activate. After we determine that point, we will increase the intensity by 10 times to ensure you will be able to feel all of the tactors activate during the experiment.

In order to determine your threshold, push the “Align” button and all of the tactors will activate in a circle around your torso. Each time you push this button, the intensity will decrease. As the pattern goes from tactor site to tactor site, count them off in your head so you can tell me which one disappeared first. If you cannot fell all tactors on the first attempt, let me know and I will increase the intensity. You are asked to wear the headphones for this section of the experiment. (headphones, subject presses “S” when threshold is reached).

The display will reads “Test Series”, press the Align button and the display will read “Block 1.” Press the “Align” button and “same/different” will appear on the visual display. Press the “Align” button again and read “Ready.” Your next keystroke, the “Align” button, will activate the system.

During the experiment, you will be presented with two sets of stimuli around your torso. After the first set of stimuli is presented, there will be a brief break and then the second will automatically begin. After the second set is presented, you will answer “Same or Different” by pressing either the “S” button for Same or the “D” button for Different. No feedback will be given throughout the test.

After you answer, press the “Align” button to get the next stimuli. You control when the stimuli are presented by pressing the align key.

Today’s test will consist of 4 blocks of trials, each consisting of 98 sets of stimuli. You will perform the same task in all of the blocks.

You can take a brief break in between the blocks if you wish. To start the next block of trials, hit the “Align” button again.

Do you have **any questions**?

Headphones!

Annex K

Experimenter Script for Experiment 2 (Part 2): Which is best

Purpose
In this experiment, you will receive two sets of stimuli and be asked to determine "**which is best.**" This will be judged by pressing a button on the keyboard (#1 for the first set of stimuli and #2 for the second set of stimuli). There are no correct or incorrect responses simply because you are rating which of these two patterns feels best to you. This test will help us to evaluate the optimal parameters to present vibrotactile flo over the torso.

First, I need you to change into a **t-shirt** for the testing. This is important, because we cannot fairly compare the results if our participants are wearing different types of clothing. This is a freshly cleaned t-shirt that we will keep in the lab for testing you.

Now, I need to **measure your waist** and I will **mark your naval** on the t-shirt.

Then I would like to collect some basic information from you. I would like you to read and sign the **consent-form** and then to fill out the **Medical Questionnaire**.

Meanwhile: Put tactors on belt.

Place belt on participant.

I've placed a belt containing 36 tactors around you. For the first part of today's experiment, only the middle row of 12 (all 36 tactors) will activate. During the second part of today's experiment the middle row of 12 (all 36) tactors will activate. When the tactors activate they vibrate much like a pager motor

We will now go through the **instruction phase** together:

At first, you will read "**Rotating Tactors**" on the display.

If you press the "Align " button, the display will read '**1 ready**'. The next time you press the "Align" button the tactors will activate in a circle around your torso. The intention of this display is to give you an opportunity to experience what the tactors feel like, and to make sure that all 12 sites can be felt. This process will be repeated two more times.

Now the display will read **"Threshold Measure."** This is a measure to determine your individual threshold – or point where you can just feel all of the tactors. After we determine that point, we will increase the intensity by a factor of

10 to ensure you will be able to feel all of the tactors activate during the experiment.

In order to determine your threshold, push the “Align” button and all of the tactors will activate in a circle around your torso. Each time you push this button, the intensity will decrease. As the pattern goes from tactor site to tactor site, count them off from 1 through 12 so you can tell me which one disappears first. Let me know the first time you cannot feel any one tactor and we will lock your threshold in at that level *(this is done by pressing the #1 button).* Also, please inform me of which tactor it was that you did not feel. If you cannot feel any one tactor on the first attempt, let me know and I will increase the overall intensity.

Now the display will read “**Test Series**.” Press the ‘Align” button and the display will read “**Block 1**.” Press the “Align” button again and the display will read “**which is best**”. Press the “Align” button one more time and the display will read “**ready**.” Your next keystroke on the “Align” button will activate the system to present you with a stimulus trial consisting of the pair of patterns.

During the experiment, you will be presented with two sets of stimuli around your torso. After the first set of stimuli is presented, there will be a brief break and then the second will automatically begin. After the second set is presented, you will answer “**which is best**” by pressing either #1 for the first set of stimuli or #2 for the second set of stimuli. Again, there are no right or wrong answers and no feedback will be given. We are interested in determining which set of stimuli you <u>perceive</u> to be the best.

By “**which is best**,” we mean what set felt overall better. Guidelines to determine this include: which line felt straighter, smoother, or had sites that felt equally distributed in both space and time. All patterns will vary in terms of how long the burst lasts and the time in between bursts.

After you answer, press the “Align” button to get the next stimulus. Again, when you see “**ready**,” your next keystroke will activate the system to present you with a stimulus trial. You always control when the stimuli are presented by pressing the align key until you see “**ready**,” preparing you for your next trial.

Today’s test will have 2 sessions, each consisting of two blocks of trials. Each block of trials will have of 98 sets of stimuli. When the second block has been completed I will remove the belt so you can take a break. After the break, we will begin the second part of today’s experiment. The total test time is approximately 1 hour.

Do you have **any questions**?

Headphones!

WHICH IS BEST?

Which line felt:

- Straighter
- Smoother
- Equally distributed in both space & time

Annex L

Experiment 2: Effect of SD on subjects' discrimination performance

Table L-1: Effect of SD on discrimination performance (here: number of "same" answers), tested with χ^2-Tests

250 Hz

Subject (initials)	Same patterns	Different patterns
WK	$\chi^2_{(.01;6;n=373)}=0.29$	$\chi^2_{(.01;6;n=250)}=33.08$
AW	$\chi^2_{(.01;6;n=271)}=3.29$	$\chi^2_{(.01;6;n=240)}=4.18$
LM	$\chi^2_{(.01;6;n=305)}=1.19$	$\chi^2_{(.01;6;n=270)}=11.73$
KP	$\chi^2_{(.01;6;n=361)}=0.96$	$\chi^2_{(.01;6;n=315)}=0.29$
TC	$\chi^2_{(.01;6;n=248)}=4.96$	$\chi^2_{(.01;6;n=192)}=6.26$
JL	$\chi^2_{(.01;6;n=327)}=5.17$	$\chi^2_{(.01;6;n=87)}=69.49$
KH	$\chi^2_{(.01;6;n=339)}=2.22$	$\chi^2_{(.01;6;n=279)}=9.05$
NS	$\chi^2_{(.01;6;n=381)}=0.07$	$\chi^2_{(.01;6;n=300)}=20.93$
JM	$\chi^2_{(.01;6;n=381)}=0.14$	$\chi^2_{(.01;6;n=342)}=5.01$
WG	$\chi^2_{(.01;6;n=321)}=1.46$	$\chi^2_{(.01;6;n=295)}=0.97$
DC	$\chi^2_{(.01;6;n=371)}=0.49$	$\chi^2_{(.01;6;n=260)}=37.72$
JC	$\chi^2_{(.01;6;n=363)}=1.21$	$\chi^2_{(.01;6;n=299)}=19.84$
OC	$\chi^2_{(.01;6;n=243)}=4.94$	$\chi^2_{(.01;6;n=176)}=8.70$
AC	$\chi^2_{(.01;6;n=368)}=0.45$	$\chi^2_{(.01;6;n=278)}=27.53$
RG	$\chi^2_{(.01;6;n=342)}=0.47$	$\chi^2_{(.01;6;n=301)}=1.53$
RL	$\chi^2_{(.01;6;n=377)}=0.50$	$\chi^2_{(.01;6;n=313)}=17.70$
SS	$\chi^2_{(.01;6;n=346)}=0.40$	$\chi^2_{(.01;6;n=297)}=1.27$
VW	$\chi^2_{(.01;6;n=361)}=1.16$	$\chi^2_{(.01;6;n=298)}=3.14$

80 Hz

Subject (initials)	Same patterns	Different patterns
KB	$\chi^2_{(.01;6;n=311)}=1.75$	$\chi^2_{(.01;6;n=287)}=6.34$
EH	$\chi^2_{(.01;6;n=361)}=0.69$	$\chi^2_{(.01;6;n=332)}=3.41$
RM	$\chi^2_{(.01;6;n=345)}=0.39$	$\chi^2_{(.01;6;n=314)}=0.69$
AS	$\chi^2_{(.01;6;n=305)}=0.68$	$\chi^2_{(.01;6;n=245)}=4.69$
AL	$\chi^2_{(.01;6;n=265)}=2.51$	$\chi^2_{(.01;6;n=174)}=15.80$
JW	$\chi^2_{(.01;6;n=275)}=1.41$	$\chi^2_{(.01;6;n=243)}=2.75$
RS	$\chi^2_{(.01;6;n=285)}=2.59$	$\chi^2_{(.01;6;n=228)}=20.93$
BP	$\chi^2_{(.01;6;n=276)}=2.68$	$\chi^2_{(.01;6;n=189)}=25.04$
DB	$\chi^2_{(.01;6;n=266)}=5.47$	$\chi^2_{(.01;6;n=218)}=24.24$
JK	$\chi^2_{(.01;6;n=304)}=1.38$	$\chi^2_{(.01;6;n=271)}=2.05$
NK	$\chi^2_{(.01;6;n=355)}=1.80$	$\chi^2_{(.01;6;n=338)}=1.27$
CA	$\chi^2_{(.01;6;n=298)}=3.80$	$\chi^2_{(.01;6;n=133)}=10.84$
MB	$\chi^2_{(.01;6;n=379)}=0.20$	$\chi^2_{(.01;6;n=340)}=0.49$
BW	$\chi^2_{(.01;6;n=313)}=1.33$	$\chi^2_{(.01;6;n=296)}=1.64$
DH	$\chi^2_{(.01;6;n=303)}=2.48$	$\chi^2_{(.01;6;n=270)}=4.66$
KH	$\chi^2_{(.01;6;n=334)}=2.42$	$\chi^2_{(.01;6;n=182)}=83.69$
LB	$\chi^2_{(.01;6;n=330)}=0.99$	$\chi^2_{(.01;6;n=295)}=2.16$
JG	$\chi^2_{(.01;6;n=359)}=0.38$	$\chi^2_{(.01;6;n=330)}=6.76$
JP	$\chi^2_{(.01;6;n=238)}=2.71$	$\chi^2_{(.01;6;n=221)}=8.48$

Note: Separate χ^2-Tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with SD. Each subject completed 392 trials with same patterns and 392 trials with different patterns. n is the number of "same" answers. χ^2-values that exceed the critical level of χ^2=16.81 (α=.01, df=6) are graphically highlighted. In those cases SD had a significant effect on discriminability. The first table shows the results for the 250 Hz group, the second table for the 80 Hz group.

For seven out of 18 subjects in the 250 Hz group, and for four out of 19 subjects in the 80 Hz group the number of "same" answers varied significantly for different pairs as a function of SD. The raw data indicate that the number of "same" responses (these are incorrect responses to different pairs) decreases with increasing SD.

Annex M

Experiment 2: Effect of ISI on subjects' discrimination performance

Table M-1: Effect of ISI on discrimination performance (here: "same" answers), tested with χ^2-Tests

250 Hz

Subject (initials)	Same patterns	Different patterns
WK	$\chi^2_{(.01;6;n=373)}$=0.29	$\chi^2_{(.01;6;n=250)}$=15.78
AW	$\chi^2_{(.01;6;n=271)}$=1.02	$\chi^2_{(.01;6;n=240)}$=2.21
LM	$\chi^2_{(.01;6;n=305)}$=1.55	$\chi^2_{(.01;6;n=270)}$=2.90
KP	$\chi^2_{(.01;6;n=361)}$=0.73	$\chi^2_{(.01;6;n=315)}$=1.69
TC	$\chi^2_{(.01;6;n=248)}$=3.60	$\chi^2_{(.01;6;n=192)}$=1.89
JL	$\chi^2_{(.01;6;n=327)}$=1.19	$\chi^2_{(.01;6;n=87)}$=10.28
KH	$\chi^2_{(.01;6;n=339)}$=2.31	$\chi^2_{(.01;6;n=279)}$=2.18
NS	$\chi^2_{(.01;6;n=381)}$=0.10	$\chi^2_{(.01;6;n=300)}$=0.40
JM	$\chi^2_{(.01;6;n=381)}$=0.25	$\chi^2_{(.01;6;n=342)}$=1.12
WG	$\chi^2_{(.01;6;n=321)}$=1.02	$\chi^2_{(.01;6;n=295)}$=5.86
DC	$\chi^2_{(.01;6;n=371)}$=0.15	$\chi^2_{(.01;6;n=260)}$=6.48
JC	$\chi^2_{(.01;6;n=363)}$=0.63	$\chi^2_{(.01;6;n=299)}$=0.69
OC	$\chi^2_{(.01;6;n=243)}$=3.33	$\chi^2_{(.01;6;n=176)}$=8.70
AC	$\chi^2_{(.01;6;n=368)}$=0.22	$\chi^2_{(.01;6;n=278)}$=2.10
RG	$\chi^2_{(.01;6;n=342)}$=0.26	$\chi^2_{(.01;6;n=301)}$=1.72
RL	$\chi^2_{(.01;6;n=377)}$=0.28	$\chi^2_{(.01;6;n=313)}$=2.63
SS	$\chi^2_{(.01;6;n=346)}$=1.09	$\chi^2_{(.01;6;n=297)}$=9.56
VW	$\chi^2_{(.01;6;n=361)}$=1.55	$\chi^2_{(.01;6;n=298)}$=11.46

80 Hz

Subject (initials)	Same patterns	Different patterns
KB	$\chi^2_{(.01;6;n=311)}=1.57$	$\chi^2_{(.01;6;n=287)}=1.07$
EH	$\chi^2_{(.01;6;n=361)}=0.93$	$\chi^2_{(.01;6;n=332)}=0.42$
RM	$\chi^2_{(.01;6;n=345)}=0.72$	$\chi^2_{(.01;6;n=314)}=0.42$
AS	$\chi^2_{(.01;6;n=305)}=3.57$	$\chi^2_{(.01;6;n=245)}=8.97$
AL	$\chi^2_{(.01;6;n=265)}=1.55$	$\chi^2_{(.01;6;n=174)}=7.03$
JW	$\chi^2_{(.01;6;n=275)}=2.33$	$\chi^2_{(.01;6;n=243)}=9.20$
RS	$\chi^2_{(.01;6;n=285)}=2.93$	$\chi^2_{(.01;6;n=228)}=1.04$
BP	$\chi^2_{(.01;6;n=276)}=1.16$	$\chi^2_{(.01;6;n=189)}=3.11$
DB	$\chi^2_{(.01;6;n=266)}=1.58$	$\chi^2_{(.01;6;n=218)}=6.39$
JK	$\chi^2_{(.01;6;n=304)}=2.30$	$\chi^2_{(.01;6;n=271)}=7.48$
NK	$\chi^2_{(.01;6;n=355)}=0.82$	$\chi^2_{(.01;6;n=338)}=0.65$
CA	$\chi^2_{(.01;6;n=298)}=5.96$	$\chi^2_{(.01;6;n=133)}=5.05$
MB	$\chi^2_{(.01;6;n=379)}=0.24$	$\chi^2_{(.01;6;n=340)}=0.78$
BW	$\chi^2_{(.01;6;n=313)}=1.42$	$\chi^2_{(.01;6;n=296)}=1.50$
DH	$\chi^2_{(.01;6;n=303)}=4.98$	$\chi^2_{(.01;6;n=270)}=4.97$
KH	$\chi^2_{(.01;6;n=334)}=1.29$	$\chi^2_{(.01;6;n=182)}=5.92$
LB	$\chi^2_{(.01;6;n=330)}=0.48$	$\chi^2_{(.01;6;n=295)}=2.39$
JG	$\chi^2_{(.01;6;n=359)}=0.14$	$\chi^2_{(.01;6;n=330)}=2.44$
JP	$\chi^2_{(.01;6;n=238)}=5.35$	$\chi^2_{(.01;6;n=221)}=1.76$

Note: Separate χ^2-Tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with ISI. Each subject completed 392 trials with same patterns and 392 trials with different patterns. n is the number of "same" answers. The first table shows the results for the 250 Hz group, the second table for the 80 Hz group. None of the calculated χ^2-values exceeds the critical level of $\chi^2=16.81$ ($\alpha=.01$, df=6). Thus, no subject showed a significant variation in its number of "same" responses as a function of ISI.

Annex N

Experiment 2 – Part 2 (Which is best): Subjects' preference for one stimulus pattern

Table N-1: Preference for one stimulus pattern (either successively activated and saltatory) in a paired-comparison paradigm, tested with χ^2-Tests

250 Hz

Subject (initials)	Results χ^2-Tests	
RG	$\chi^2_{(.01;1;n=392)}=6.38$	
BM	$\chi^2_{(.01;1;n=392)}=90.16$	
JC	$\chi^2_{(.01;1;n=392)}=96.01$	
RD	$\chi^2_{(.01;1;n=392)}=82.65$	
BB	$\chi^2_{(.01;1;n=392)}=82.65$	
GA	$\chi^2_{(.01;1;n=392)}=130.30$	
DD	$\chi^2_{(.01;1;n=392)}=65.31$	Prefers saltatory patterns
RB	$\chi^2_{(.01;1;n=392)}=8.00$	
DG	$\chi^2_{(.01;1;n=392)}=84.50$	
MG	$\chi^2_{(.01;1;n=392)}=11.11$	
GR	$\chi^2_{(.01;1;n=392)}=110.37$	
MB	$\chi^2_{(.01;1;n=392)}=104.09$	
AB	$\chi^2_{(.01;1;n=392)}=16.33$	
JA	$\chi^2_{(.01;1;n=392)}=106.16$	
AA	$\chi^2_{(.01;1;n=392)}=185.97$	
LA	$\chi^2_{(.01;1;n=392)}=27.59$	
NB	$\chi^2_{(.01;1;n=392)}=106.16$	
DB	$\chi^2_{(.01;1;n=392)}=214.54$	
EB	$\chi^2_{(.01;1;n=392)}=19.76$	
WC	$\chi^2_{(.01;1;n=392)}=72.00$	

<u>80 Hz</u>

Subject (initials)	Results χ^2-Tests	
JT	$\chi^2_{(.01;1;n=392)}=191.52$	
JH	$\chi^2_{(.01;1;n=392)}=1.72$	
SS	$\chi^2_{(.01;1;n=392)}=47.18$	
JW	$\chi^2_{(.01;1;n=392)}=4.50$	
MS	$\chi^2_{(.01;1;n=392)}=13.97$	
IC	$\chi^2_{(.01;1;n=392)}=191.52$	
RW	$\chi^2_{(.01;1;n=392)}=169.81$	
CW	$\chi^2_{(.01;1;n=392)}=94.04$	
OH	$\chi^2_{(.01;1;n=392)}=48.58$	
BS	$\chi^2_{(.01;1;n=392)}=51.44$	
CS	$\chi^2_{(.01;1;n=392)}=15.52$	
CL	$\chi^2_{(.01;1;n=392)}=19.76$	
KB	$\chi^2_{(.01;1;n=392)}=29.76$	
PM	$\chi^2_{(.01;1;n=392)}=35.52$	
JB	$\chi^2_{(.01;1;n=392)}=151.86$	
DS	$\chi^2_{(.01;1;n=392)}=0.00$	
SM	$\chi^2_{(.01;1;n=392)}=79.02$	
CC	$\chi^2_{(.01;1;n=392)}=50.00$	
VO	$\chi^2_{(.01;1;n=392)}=16.33$	
KF	$\chi^2_{(.01;1;n=392)}=96.01$	

Note: Subjects had to decide which of two patterns was best in terms of straightness, smoothness, and spatial distribution. Separate χ^2-tests for each subject have been carried out to test if the frequency of preference is equally distributed over both patterns. Each subject completed 392 trials. The first table shows the results for the 250 Hz group, the second table for the 80 Hz group. χ^2-values that exceed the critical level of $\chi^2=6.64$ ($\alpha=.01$, df=1) are graphically highlighted. In those cases, subjects preferred the successively activated over the saltatory patterns with one exception: Subject DD in the 250 Hz group preferred the saltatory patterns significantly more often. Besides, nearly all of the subjects preferred the successively activated patterns significantly more often.

Annex O

Experiment 2 – Part 2 (Which is best): Effect of SD on subjects' preference for one stimulus pattern

Table O-1: Effect of SD on subjects' preference for saltatory stimulus patterns, tested with χ^2-Tests

250 Hz		80 Hz	
Subject (initials)	Results χ^2-Tests	Subject (initials)	Results χ^2-Tests
RG	$\chi^2_{(.01;6;n=171)}=4.25$	JT	$\chi^2_{(.01;6;n=59)}=49.56$
BM	$\chi^2_{(.01;6;n=102)}=41.98$	JH	$\chi^2_{(.01;6;n=183)}=22.52$
JC	$\chi^2_{(.01;6;n=99)}=41.21$	SS	$\chi^2_{(.01;6;n=128)}=25.45$
RD	$\chi^2_{(.01;6;n=106)}=33.47$	JW	$\chi^2_{(.01;6;n=175)}=3.12$
BB	$\chi^2_{(.01;6;n=106)}=10.09$	MS	$\chi^2_{(.01;6;n=159)}=7.02$
GA	$\chi^2_{(.01;6;n=83)}=54.05$	IC	$\chi^2_{(.01;6;n=59)}=13.97$
DD	$\chi^2_{(.01;6;n=276)}=1.06$	RW	$\chi^2_{(.01;6;n=67)}=35.91$
RB	$\chi^2_{(.01;6;n=168)}=8.17$	CW	$\chi^2_{(.01;6;n=100)}=12.42$
DG	$\chi^2_{(.01;6;n=105)}=14.00$	OH	$\chi^2_{(.01;6;n=127)}=15.70$
MG	$\chi^2_{(.01;6;n=163)}=7.19$	BS	$\chi^2_{(.01;6;n=125)}=7.67$
GR	$\chi^2_{(.01;6;n=92)}=41.00$	CS	$\chi^2_{(.01;6;n=157)}=13.01$
MB	$\chi^2_{(.01;6;n=95)}=14.13$	CL	$\chi^2_{(.01;6;n=152)}=7.99$
AB	$\chi^2_{(.01;6;n=156)}=2.67$	KB	$\chi^2_{(.01;6;n=142)}=18.51$
JA	$\chi^2_{(.01;6;n=94)}=19.94$	PM	$\chi^2_{(.01;6;n=137)}=2.64$
AA	$\chi^2_{(.01;6;n=61)}=14.62$	JB	$\chi^2_{(.01;6;n=74)}=43.86$
LA	$\chi^2_{(.01;6;n=144)}=4.26$	DS	$\chi^2_{(.01;6;n=196)}=6.21$
NB	$\chi^2_{(.01;6;n=94)}=15.62$	SM	$\chi^2_{(.01;6;n=108)}=8.54$
DB	$\chi^2_{(.01;6;n=51)}=24.90$	CC	$\chi^2_{(.01;6;n=126)}=19.33$
EB	$\chi^2_{(.01;6;n=152)}=16.83$	VO	$\chi^2_{(.01;6;n=156)}=19.72$
WC	$\chi^2_{(.01;6;n=112)}=31.63$	KF	$\chi^2_{(.01;6;n=99)}=31.74$

Note: Subjects had to decide which of two patterns was best in terms of straightness, smoothness, and spatial distribution. Separate χ^2-tests for each subject have been carried out to test if the frequency of preference for a saltatory pattern in a paired-comparison paradigm varies with SD. Each subject completed 392 trials. n is the number trials where subjects preferred the saltatory over the successively activated pattern. χ^2-values that exceed the critical level of χ^2=16.81 (α=.01, df=6) are graphically highlighted. In those cases SD had a significant effect on preference. The first two columns show the results for the 250 Hz group, the third and fourth column for the 80 Hz group.

For nine out of 20 subjects in the 250 Hz and in the 80 Hz group the preference for saltatory patterns varied significantly as a function of SD. The raw data indicate, that preference increased with decreasing SD.

Annex P

Experiment 2 – Part 2 (Which is best): Effect of ISI on subjects' preference for one stimulus pattern

Table P-1: Effect of ISI on subjects' preference for saltatory stimulus patterns, tested with χ^2-Tests

250 Hz		**80 Hz**	
Subject (initials)	Results χ^2-Tests	Subject (initials)	Results χ^2-Tests
RG	$\chi^2_{(.01;6;n=171)}=4.00$	JT	$\chi^2_{(.01;6;n=59)}=5.19$
BM	$\chi^2_{(.01;6;n=102)}=17.41$	JH	$\chi^2_{(.01;6;n=183)}=2.86$
JC	$\chi^2_{(.01;6;n=99)}=6.71$	SS	$\chi^2_{(.01;6;n=128)}=2.70$
RD	$\chi^2_{(.01;6;n=106)}=5.60$	JW	$\chi^2_{(.01;6;n=175)}=1.12$
BB	$\chi^2_{(.01;6;n=106)}=8.11$	MS	$\chi^2_{(.01;6;n=159)}=4.11$
GA	$\chi^2_{(.01;6;n=83)}=17.28$	IC	$\chi^2_{(.01;6;n=59)}=2.58$
DD	$\chi^2_{(.01;6;n=276)}=3.80$	RW	$\chi^2_{(.01;6;n=67)}=8.54$
RB	$\chi^2_{(.01;6;n=168)}=1.75$	CW	$\chi^2_{(.01;6;n=100)}=2.76$
DG	$\chi^2_{(.01;6;n=105)}=0.80$	OH	$\chi^2_{(.01;6;n=127)}=7.98$
MG	$\chi^2_{(.01;6;n=163)}=2.21$	BS	$\chi^2_{(.01;6;n=125)}=5.09$
GR	$\chi^2_{(.01;6;n=92)}=5.09$	CS	$\chi^2_{(.01;6;n=157)}=6.05$
MB	$\chi^2_{(.01;6;n=95)}=3.07$	CL	$\chi^2_{(.01;6;n=152)}=5.41$
AB	$\chi^2_{(.01;6;n=156)}=3.21$	KB	$\chi^2_{(.01;6;n=142)}=3.52$
JA	$\chi^2_{(.01;6;n=94)}=14.87$	PM	$\chi^2_{(.01;6;n=137)}=6.32$
AA	$\chi^2_{(.01;6;n=61)}=1.08$	JB	$\chi^2_{(.01;6;n=74)}=11.70$
LA	$\chi^2_{(.01;6;n=144)}=5.04$	DS	$\chi^2_{(.01;6;n=196)}=4.57$
NB	$\chi^2_{(.01;6;n=94)}=3.85$	SM	$\chi^2_{(.01;6;n=108)}=1.67$
DB	$\chi^2_{(.01;6;n=51)}=3.49$	CC	$\chi^2_{(.01;6;n=126)}=10.00$
EB	$\chi^2_{(.01;6;n=152)}=2.18$	VO	$\chi^2_{(.01;6;n=156)}=2.13$
WC	$\chi^2_{(.01;6;n=112)}=3.75$	KF	$\chi^2_{(.01;6;n=99)}=6.14$

Note: Subjects had to decide which of two patterns was best in terms of straightness, smoothness, and spatial distribution. Separate χ^2-tests for each subject have been carried out to test if the frequency of preference for a saltatory pattern in a paired-comparison paradigm varies with ISI. Each subject completed 392 trials. n is the number trials where subjects preferred the saltatory over the successively activated pattern. χ^2-values that exceed the critical level of χ^2=16.81 (α=.01, df=6) are graphically highlighted. In those cases ISI had a significant effect on preference. The first two columns show the results for the 250 Hz group, the third and fourth column for the 80 Hz group.

For two out of 20 subjects in the 250 Hz the preference for saltatory patterns varied significantly as a function of ISI: The preference for saltatory patterns increased with shorter ISI. In the 80 Hz group no χ^2-value reached statistical significance.

Annex Q

Experimenter Script for Experiment 3: Same/different discriminations with 7-tactor arrays on different positions

In this experiment, you will receive two sets of stimuli and be asked to determine whether they were the "Same or Different" from one another. You will make your judgment by pressing a button on the keyboard (S if both lines are the Same or D if both lines are Different). This test will help us to evaluate the optimal parameters to present vibrotactile flo over the torso.

*First, I need you to change into a **t-shirt** for the testing. This is important, because we cannot fairly compare the results if our participants are wearing different types of clothing. This is a freshly cleaned t-shirt that we will keep in the lab for testing you.*

*Now, I need to **measure your waist** and I will **mark your naval** on the t-shirt.*

*Then I would like to collect some basic information from you. I would like you to read and sign the **consent-form** and then to fill out the **Medical Questionnaire**.*

Meanwhile: Put tactors on belt.
Place belt on participant.

I've placed a belt containing 7 tactors around you. When the tactors activate they vibrate like a pager motor or cell phone. The only difference between today and tomorrow's session is the position of the tactors. Tomorrow the belt will be positioned so that the tactors are on your (right, left, front, back) side.

We will now go through the **instruction phase** together:

At first, you will read "**Rotating Tactors**" on the display.

If you press the "Align " button, the display will read '1 ready'. Press the "Align" button again and the tactors will activate in a circle around your torso. There will be 7 tactors that activate. Count them as they go along to ensure you can feel a tactor activate at every position. This process will be repeated two more times.

Now the display will read **"Threshold Measure."** This is a measure to determine your individual threshold – or point where you can <u>just</u> feel all of the tactors activate. After we determine that point, we will increase the intensity by 10 times to ensure you will be able to feel all of the tactors activate during the experiment.

In order to determine your threshold, push the “Align” button and all of the tactors will activate in a circle around your torso. Each time you push this button, the intensity will decrease. As the pattern goes from tactor site to tactor site, count them off in your head from 1 to 7 so you can tell me which one disappeared first. If you cannot fell all 7 tactors on the first attempt, let me know and I will increase the intensity. You are asked to wear the headphones for this section of the experiment. (headphones, subject presses “S” when threshold is reached).

The display will reads “Test Series”, press the Align button and the display will read “Block 1.” Press the “Align” button and “same/different” will appear on the visual display. Press the “Align” button again and read “Ready.” Your next keystroke, the “Align” button, will activate the system.

During the experiment, you will be presented with two sets of stimuli around your torso. After the first set of stimuli is presented, there will be a brief break and then the second will automatically begin. After the second set is presented, you will answer “Same or Different” by pressing either the “S” button for Same or the “D” button for Different. No feedback will be given throughout the test.

After you answer, press the “Align” button to get the next stimuli. You control when the stimuli are presented by pressing the align key.

Today’s test will consist of 4 blocks of trials, each consisting of 98 sets of stimuli. You will perform the same task in all of the blocks.

You can take a brief break in between the blocks if you wish. To start the next block of trials, hit the “Align” button again.

Do you have **any questions**?

Headphones!

Annex R

Experiment 3: Effect of SD on subjects' discrimination performance depending on different placements of a 7-tactor array on the torso

Table R-1: Effect of SD on the number of "same" answers for same and different pairs for the position front

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
RM	$\chi^2_{(.01;6;n=173)}=2.00$	$\chi^2_{(.01;6;n=134)}=14.57$
MQ	$\chi^2_{(.01;6;n=192)}=0.06$	$\chi^2_{(.01;6;n=189)}=0.22$
BN	$\chi^2_{(.01;6;n=169)}=1.11$	$\chi^2_{(.01;6;n=100)}=24.18$
NR	$\chi^2_{(.01;6;n=155)}=1.57$	$\chi^2_{(.01;6;n=84)}=29.67$
CR	$\chi^2_{(.01;6;n=139)}=5.28$	$\chi^2_{(.01;6;n=81)}=16.05$
PO	$\chi^2_{(.01;6;n=150)}=1.39$	$\chi^2_{(.01;6;n=112)}=12.50$
AC	$\chi^2_{(.01;6;n=189)}=0.07$	$\chi^2_{(.01;6;n=135)}=15.01$
BP	$\chi^2_{(.01;6;n=156)}=0.60$	$\chi^2_{(.01;6;n=80)}=29.90$
RS	$\chi^2_{(.01;6;n=156)}=3.12$	$\chi^2_{(.01;6;n=121)}=8.07$
RV	$\chi^2_{(.01;6;n=180)}=0.76$	$\chi^2_{(.01;6;n=151)}=10.46$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with SD. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the front of the torso. n is the number of "same" answers. χ^2-values that exceed the critical level of χ^2=16.81 (α=.01, df=6) are graphically highlighted. In those cases SD had a significant effect on discriminability. For three out of 10 subjects the number of "same" answers varied significantly for different pairs as a function of SD for the position front. The number of "same" responses (incorrect responses to different pairs) increased with decreasing SD. SD had no effect on the number of "same" responses for same pairs.

Table R-2: **E**ffect of SD on the number of “same” answers for same and different pairs for the position back

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
JV	$\chi^2_{(.01;6;n=189)}=0.30$	$\chi^2_{(.01;6;n=179)}=1.94$
SW	$\chi^2_{(.01;6;n=162)}=0.64$	$\chi^2_{(.01;6;n=68)}=8.59$
WM	$\chi^2_{(.01;6;n=180)}=0.52$	$\chi^2_{(.01;6;n=56)}=54.75$
TB	$\chi^2_{(.01;6;n=153)}=0.77$	$\chi^2_{(.01;6;n=137)}=1.21$
KK	$\chi^2_{(.01;6;n=184)}=0.51$	$\chi^2_{(.01;6;n=166)}=0.99$
AA	$\chi^2_{(.01;6;n=190)}=0.11$	$\chi^2_{(.01;6;n=77)}=11.27$
BF	$\chi^2_{(.01;6;n=171)}=0.48$	$\chi^2_{(.01;6;n=116)}=16.40$
CH	$\chi^2_{(.01;6;n=182)}=0.38$	$\chi^2_{(.01;6;n=64)}=30.50$
MW	$\chi^2_{(.01;6;n=191)}=0.20$	$\chi^2_{(.01;6;n=152)}=12.32$
TM	$\chi^2_{(.01;6;n=194)}=0.05$	$\chi^2_{(.01;6;n=192)}=0.06$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of “same” answers varies with SD. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the back of the torso. n is the number of “same” answers. χ^2-values that exceed the critical level of χ^2=16.81 (α=.01, df=6) are graphically highlighted. In those cases SD had a significant effect on discriminability. For two out of 10 subjects the number of “same” answers varied significantly for different pairs as a function of SD for the position back. The number of “same” responses (incorrect responses to different pairs) increased with decreasing SD. SD had no effect on the number of “same” responses for same pairs.

Table R-3: Effect of SD on the number of "same" answers for same and different pairs for the position left

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
MQ	$\chi^2_{(.01;6;n=184)}=0.21$	$\chi^2_{(.01;6;n=171)}=0.97$
JV	$\chi^2_{(.01;6;n=184)}=0.89$	$\chi^2_{(.01;6;n=159)}=7.28$
NR	$\chi^2_{(.01;6;n=172)}=0.64$	$\chi^2_{(.01;6;n=92)}=25.48$
WM	$\chi^2_{(.01;6;n=185)}=0.82$	$\chi^2_{(.01;6;n=77)}=53.82$
PO	$\chi^2_{(.01;6;n=164)}=2.04$	$\chi^2_{(.01;6;n=110)}=20.58$
KK	$\chi^2_{(.01;6;n=183)}=0.26$	$\chi^2_{(.01;6;n=143)}=5.76$
AC	$\chi^2_{(.01;6;n=180)}=0.37$	$\chi^2_{(.01;6;n=146)}=6.27$
MW	$\chi^2_{(.01;6;n=194)}=0.05$	$\chi^2_{(.01;6;n=146)}=21.90$
RS	$\chi^2_{(.01;6;n=155)}=2.21$	$\chi^2_{(.01;6;n=133)}=10.42$
TM	$\chi^2_{(.01;6;n=187)}=0.43$	$\chi^2_{(.01;6;n=167)}=1.38$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with SD. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the left side of the torso. n is the number of "same" answers. χ^2-values that exceed the critical level of χ^2=16.81 (α=.01, df=6) are graphically highlighted. In those cases SD had a significant effect on discriminability. For four out of 10 subjects the number of "same" answers varied significantly for different pairs as a function of SD for the position left. The number of "same" responses (incorrect responses to different pairs) increased with decreasing SD. SD had no effect on the number of "same" responses for same pairs.

Table R-4: Effect of SD on the number of "same" answers for same and different pairs for the position right

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
RM	$\chi^2_{(.01;6;n=188)}=0.26$	$\chi^2_{(.01;6;n=118)}=20.58$
BN	$\chi^2_{(.01;6;n=188)}=0.40$	$\chi^2_{(.01;6;n=117)}=35.38$
SW	$\chi^2_{(.01;6;n=150)}=2.69$	$\chi^2_{(.01;6;n=135)}=5.05$
CR	$\chi^2_{(.01;6;n=143)}=3.71$	$\chi^2_{(.01;6;n=98)}=8.86$
TB	$\chi^2_{(.01;6;n=164)}=0.93$	$\chi^2_{(.01;6;n=126)}=4.11$
AA	$\chi^2_{(.01;6;n=184)}=0.28$	$\chi^2_{(.01;6;n=143)}=6.94$
BF	$\chi^2_{(.01;6;n=157)}=1.59$	$\chi^2_{(.01;6;n=152)}=2.74$
BP	$\chi^2_{(.01;6;n=171)}=0.73$	$\chi^2_{(.01;6;n=105)}=35.20$
CH	$\chi^2_{(.01;6;n=188)}=0.48$	$\chi^2_{(.01;6;n=168)}=3.42$
RV	$\chi^2_{(.01;6;n=174)}=0.28$	$\chi^2_{(.01;6;n=146)}=4.74$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with SD. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the right side of the torso. n is the number of "same" answers. χ^2-values that exceed the critical level of $\chi^2=16.81$ ($\alpha=.01$, df=6) are graphically highlighted. In those cases SD had a significant effect on discriminability. For three out of 10 subjects the number of "same" answers varied significantly for different pairs as a function of SD for the position right. The number of "same" responses (incorrect responses to different pairs) increased with decreasing SD. SD had no effect on the number of "same" responses for same pairs.

Table R-5: **E**ffect of SD on the number of “same” answers for same and different pairs for the <u>position navel between 3&4</u>

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
JM	$\chi^2_{(.01;6;n=171)}=0.97$	$\chi^2_{(.01;6;n=162)}=1.85$
SO	$\chi^2_{(.01;6;n=183)}=0.42$	$\chi^2_{(.01;6;n=181)}=0.57$
AH	$\chi^2_{(.01;6;n=132)}=3.23$	$\chi^2_{(.01;6;n=101)}=1.23$
DC	$\chi^2_{(.01;6;n=179)}=0.30$	$\chi^2_{(.01;6;n=165)}=3.55$
MG	$\chi^2_{(.01;6;n=161)}=2.43$	$\chi^2_{(.01;6;n=114)}=19.37$
RK	$\chi^2_{(.01;6;n=155)}=1.30$	$\chi^2_{(.01;6;n=122)}=9.62$
DK	$\chi^2_{(.01;6;n=179)}=1.08$	$\chi^2_{(.01;6;n=162)}=0.90$
AT	$\chi^2_{(.01;6;n=187)}=0.28$	$\chi^2_{(.01;6;n=191)}=0.20$
CA	$\chi^2_{(.01;6;n=193)}=0.06$	$\chi^2_{(.01;6;n=146)}=12.70$
CS	$\chi^2_{(.01;6;n=185)}=0.29$	$\chi^2_{(.01;6;n=75)}=37.65$
EF	$\chi^2_{(.01;6;n=183)}=0.57$	$\chi^2_{(.01;6;n=143)}=21.62$
ES	$\chi^2_{(.01;6;n=176)}=1.07$	$\chi^2_{(.01;6;n=81)}=41.98$
FW	$\chi^2_{(.01;6;n=150)}=2.69$	$\chi^2_{(.01;6;n=138)}=2.20$
JC	$\chi^2_{(.01;6;n=157)}=2.75$	$\chi^2_{(.01;6;n=134)}=0.57$
JP	$\chi^2_{(.01;6;n=134)}=2.24$	$\chi^2_{(.01;6;n=115)}=5.46$
MH	$\chi^2_{(.01;6;n=134)}=4.22$	$\chi^2_{(.01;6;n=124)}=4.03$
MM	$\chi^2_{(.01;6;n=155)}=0.49$	$\chi^2_{(.01;6;n=155)}=2.03$
PT	$\chi^2_{(.01;6;n=187)}=0.28$	$\chi^2_{(.01;6;n=171)}=2.77$
ST	$\chi^2_{(.01;6;n=164)}=1.10$	$\chi^2_{(.01;6;n=127)}=1.26$
WJ	$\chi^2_{(.01;6;n=196)}=0.00$	$\chi^2_{(.01;6;n=196)}=0.00$
YS	$\chi^2_{(.01;6;n=156)}=1.50$	$\chi^2_{(.01;6;n=150)}=0.92$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of “same” answers varies with SD. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the front of the torso, so that the navel lay between tactors number three and four. n is the number of “same” answers. χ^2-values that exceed the critical level of χ^2=16.81 (α=.01, df=6) are graphically highlighted. In those cases SD had a significant effect on discriminability. For four out of 21 subjects the number of "same" answers varied significantly for different pairs as a function of SD. The number of "same" responses (incorrect responses to different pairs) increased with decreasing SD. SD had no effect on the number of "same" responses for same pairs.

Table R-6: Effect of SD on the number of "same" answers for same and different pairs for the position navel between 4&5

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
JM	$\chi^2_{(.01;6;n=149)}=4.01$	$\chi^2_{(.01;6;n=78)}=2.41$
SO	$\chi^2_{(.01;6;n=173)}=1.27$	$\chi^2_{(.01;6;n=162)}=4.19$
AH	$\chi^2_{(.01;6;n=144)}=1.64$	$\chi^2_{(.01;6;n=121)}=3.21$
DC	$\chi^2_{(.01;6;n=162)}=1.59$	$\chi^2_{(.01;6;n=152)}=5.50$
MG	$\chi^2_{(.01;6;n=144)}=3.39$	$\chi^2_{(.01;6;n=107)}=11.61$
RK	$\chi^2_{(.01;6;n=141)}=4.71$	$\chi^2_{(.01;6;n=111)}=2.83$
DK	$\chi^2_{(.01;6;n=157)}=2.31$	$\chi^2_{(.01;6;n=141)}=3.91$
AT	$\chi^2_{(.01;6;n=196)}=0.00$	$\chi^2_{(.01;6;n=196)}=0.00$
CA	$\chi^2_{(.01;6;n=180)}=0.60$	$\chi^2_{(.01;6;n=159)}=7.55$
CS	$\chi^2_{(.01;6;n=160)}=1.44$	$\chi^2_{(.01;6;n=83)}=24.53$
EF	$\chi^2_{(.01;6;n=183)}=0.87$	$\chi^2_{(.01;6;n=137)}=21.34$
ES	$\chi^2_{(.01;6;n=178)}=1.25$	$\chi^2_{(.01;6;n=90)}=33.82$
FW	$\chi^2_{(.01;6;n=139)}=4.58$	$\chi^2_{(.01;6;n=139)}=2.76$
JC	$\chi^2_{(.01;6;n=180)}=0.60$	$\chi^2_{(.01;6;n=153)}=5.90$
JP	$\chi^2_{(.01;6;n=148)}=2.69$	$\chi^2_{(.01;6;n=138)}=5.55$
MH	$\chi^2_{(.01;6;n=124)}=5.39$	$\chi^2_{(.01;6;n=104)}=5.85$
MM	$\chi^2_{(.01;6;n=159)}=1.91$	$\chi^2_{(.01;6;n=165)}=1.94$
PT	$\chi^2_{(.01;6;n=167)}=2.38$	$\chi^2_{(.01;6;n=160)}=2.31$
ST	$\chi^2_{(.01;6;n=132)}=1.42$	$\chi^2_{(.01;6;n=70)}=32.80$
WJ	$\chi^2_{(.01;6;n=190)}=0.11$	$\chi^2_{(.01;6;n=142)}=21.17$
YS	$\chi^2_{(.01;6;n=180)}=0.52$	$\chi^2_{(.01;6;n=174)}=0.68$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with SD. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the front of the torso, so that the navel lay between tactors number four and five. n is the number of "same" answers. χ^2-values that exceed the critical level of χ^2=16.81 (α=.01, df=6) are graphically highlighted. In those cases SD had a significant effect on discriminability. For five out of 21 subjects the number of "same" answers varied significantly for different pairs as a function of SD. The number of "same" responses (incorrect responses to different pairs) increased with decreasing SD. SD had no effect on the number of "same" responses for same pairs.

Annex S

Experiment 3: Effect of ISI on subjects' discrimination performance depending on different placements of a 7-tactor array on the torso

Table S-1: Effect of ISI on the number of "same" answers for same and different pairs for the position front

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
RM	$\chi^2_{(.01;6;n=173)}=0.79$	$\chi^2_{(.01;6;n=134)}=1.51$
MQ	$\chi^2_{(.01;6;n=192)}=0.06$	$\chi^2_{(.01;6;n=189)}=0.44$
BN	$\chi^2_{(.01;6;n=169)}=1.20$	$\chi^2_{(.01;6;n=100)}=3.88$
NR	$\chi^2_{(.01;6;n=155)}=1.57$	$\chi^2_{(.01;6;n=84)}=3.33$
CR	$\chi^2_{(.01;6;n=139)}=0.75$	$\chi^2_{(.01;6;n=81)}=1.19$
PO	$\chi^2_{(.01;6;n=150)}=1.39$	$\chi^2_{(.01;6;n=112)}=1.63$
AC	$\chi^2_{(.01;6;n=189)}=0.44$	$\chi^2_{(.01;6;n=135)}=1.21$
BP	$\chi^2_{(.01;6;n=156)}=2.58$	$\chi^2_{(.01;6;n=80)}=4.53$
RS	$\chi^2_{(.01;6;n=156)}=2.49$	$\chi^2_{(.01;6;n=121)}=2.17$
RV	$\chi^2_{(.01;6;n=180)}=0.60$	$\chi^2_{(.01;6;n=151)}=1.01$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with ISI. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the front of the torso. n is the number of "same" answers. None of the χ^2-values exceeded the critical level of $\chi^2=16.81$ ($\alpha=.01$, df=6). Thus ISI had no effect on the number of "same" responses for same and different pairs.

Table S-2: Effect of ISI on the number of “same” answers for same and different pairs for the <u>position back</u>

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
JV	$\chi^2_{(.01;6;n=189)}=0.15$	$\chi^2_{(.01;6;n=179)}=0.46$
SW	$\chi^2_{(.01;6;n=162)}=0.38$	$\chi^2_{(.01;6;n=68)}=2.82$
WM	$\chi^2_{(.01;6;n=180)}=0.37$	$\chi^2_{(.01;6;n=56)}=12.00$
TB	$\chi^2_{(.01;6;n=153)}=1.23$	$\chi^2_{(.01;6;n=137)}=2.34$
KK	$\chi^2_{(.01;6;n=184)}=0.51$	$\chi^2_{(.01;6;n=166)}=0.99$
AA	$\chi^2_{(.01;6;n=190)}=0.11$	$\chi^2_{(.01;6;n=77)}=7.09$
BF	$\chi^2_{(.01;6;n=171)}=0.97$	$\chi^2_{(.01;6;n=116)}=6.38$
CH	$\chi^2_{(.01;6;n=182)}=0.54$	$\chi^2_{(.01;6;n=64)}=4.25$
MW	$\chi^2_{(.01;6;n=191)}=0.13$	$\chi^2_{(.01;6;n=152)}=2.00$
TM	$\chi^2_{(.01;6;n=194)}=0.12$	$\chi^2_{(.01;6;n=192)}=0.06$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of “same” answers varies with ISI. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the back of the torso. n is the number of “same” answers. None of the χ^2-values exceeded the critical level of $\chi^2=16.81$ ($\alpha=.01$, df=6). Thus ISI had no effect on the number of “same” responses for same and different pairs.

Table S-3: Effect of ISI on the number of "same" answers for same and different pairs for the position left

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
MQ	$\chi^2_{(.01;6;n=184)}=0.21$	$\chi^2_{(.01;6;n=171)}=0.23$
JV	$\chi^2_{(.01;6;n=184)}=0.36$	$\chi^2_{(.01;6;n=159)}=2.70$
NR	$\chi^2_{(.01;6;n=172)}=0.72$	$\chi^2_{(.01;6;n=92)}=5.85$
WM	$\chi^2_{(.01;6;n=185)}=0.22$	$\chi^2_{(.01;6;n=77)}=10.36$
PO	$\chi^2_{(.01;6;n=164)}=0.41$	$\chi^2_{(.01;6;n=110)}=2.64$
KK	$\chi^2_{(.01;6;n=183)}=0.19$	$\chi^2_{(.01;6;n=143)}=1.06$
AC	$\chi^2_{(.01;6;n=180)}=0.44$	$\chi^2_{(.01;6;n=146)}=1.10$
MW	$\chi^2_{(.01;6;n=194)}=0.05$	$\chi^2_{(.01;6;n=146)}=2.92$
RS	$\chi^2_{(.01;6;n=155)}=1.12$	$\chi^2_{(.01;6;n=133)}=4.74$
TM	$\chi^2_{(.01;6;n=187)}=0.43$	$\chi^2_{(.01;6;n=167)}=0.87$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with ISI. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the left side of the torso. n is the number of "same" answers. None of the χ^2-values exceeded the critical level of χ^2=16.81 (α=.01, df=6). Thus ISI had no effect on the number of "same" responses for same and different pairs.

Table S-4: Effect of ISI on the number of "same" answers for same and different pairs for the position right

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
RM	$\chi^2_{(.01;6;n=188)}=0.18$	$\chi^2_{(.01;6;n=118)}=9.90$
BN	$\chi^2_{(.01;6;n=188)}=0.26$	$\chi^2_{(.01;6;n=117)}=7.74$
SW	$\chi^2_{(.01;6;n=150)}=1.57$	$\chi^2_{(.01;6;n=135)}=2.67$
CR	$\chi^2_{(.01;6;n=143)}=1.16$	$\chi^2_{(.01;6;n=98)}=1.43$
TB	$\chi^2_{(.01;6;n=164)}=2.38$	$\chi^2_{(.01;6;n=126)}=1.56$
AA	$\chi^2_{(.01;6;n=184)}=0.43$	$\chi^2_{(.01;6;n=143)}=6.06$
BF	$\chi^2_{(.01;6;n=157)}=4.18$	$\chi^2_{(.01;6;n=152)}=3.11$
BP	$\chi^2_{(.01;6;n=171)}=0.32$	$\chi^2_{(.01;6;n=105)}=3.60$
CH	$\chi^2_{(.01;6;n=188)}=0.18$	$\chi^2_{(.01;6;n=168)}=1.08$
RV	$\chi^2_{(.01;6;n=174)}=0.92$	$\chi^2_{(.01;6;n=146)}=3.88$

Note: Separate χ^2-Tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with ISI. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the right side of the torso. n is the number of "same" answers. None of the χ^2-values exceeded the critical level of χ^2=16.81 (α=.01, df=6). Thus ISI had no effect on the number of "same" responses for same and different pairs.

Table S-5: Effect of ISI on the number of "same" answers for same and different pairs for the <u>position navel between 3&4</u>

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
JM	$\chi^2_{(.01;6;n=171)}=0.73$	$\chi^2_{(.01;6;n=162)}=0.47$
SO	$\chi^2_{(.01;6;n=183)}=0.42$	$\chi^2_{(.01;6;n=181)}=0.88$
AH	$\chi^2_{(.01;6;n=132)}=1.95$	$\chi^2_{(.01;6;n=101)}=2.06$
DC	$\chi^2_{(.01;6;n=179)}=0.69$	$\chi^2_{(.01;6;n=165)}=0.67$
MG	$\chi^2_{(.01;6;n=161)}=0.52$	$\chi^2_{(.01;6;n=114)}=3.89$
RK	$\chi^2_{(.01;6;n=155)}=1.39$	$\chi^2_{(.01;6;n=122)}=5.15$
DK	$\chi^2_{(.01;6;n=179)}=0.07$	$\chi^2_{(.01;6;n=162)}=1.51$
AT	$\chi^2_{(.01;6;n=187)}=0.28$	$\chi^2_{(.01;6;n=191)}=0.13$
CA	$\chi^2_{(.01;6;n=193)}=0.06$	$\chi^2_{(.01;6;n=146)}=9.73$
CS	$\chi^2_{(.01;6;n=185)}=0.29$	$\chi^2_{(.01;6;n=75)}=17.68$
EF	$\chi^2_{(.01;6;n=183)}=0.87$	$\chi^2_{(.01;6;n=143)}=7.92$
ES	$\chi^2_{(.01;6;n=176)}=0.83$	$\chi^2_{(.01;6;n=81)}=8.96$
FW	$\chi^2_{(.01;6;n=150)}=2.13$	$\chi^2_{(.01;6;n=138)}=1.29$
JC	$\chi^2_{(.01;6;n=157)}=0.79$	$\chi^2_{(.01;6;n=134)}=2.34$
JP	$\chi^2_{(.01;6;n=134)}=1.40$	$\chi^2_{(.01;6;n=115)}=1.20$
MH	$\chi^2_{(.01;6;n=134)}=3.60$	$\chi^2_{(.01;6;n=124)}=0.98$
MM	$\chi^2_{(.01;6;n=155)}=3.02$	$\chi^2_{(.01;6;n=155)}=1.39$
PT	$\chi^2_{(.01;6;n=187)}=0.28$	$\chi^2_{(.01;6;n=171)}=1.95$
ST	$\chi^2_{(.01;6;n=164)}=0.50$	$\chi^2_{(.01;6;n=127)}=1.37$
WJ	$\chi^2_{(.01;6;n=196)}=0.00$	$\chi^2_{(.01;6;n=196)}=0.00$
YS	$\chi^2_{(.01;6;n=156)}=0.96$	$\chi^2_{(.01;6;n=150)}=2.23$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with ISI. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the front of the torso, so that the navel lay between tactors number three and four. n is the number of "same" answers. The χ^2-value that exceeds the critical level of χ^2=16.81 (α=.01, df=6) is graphically highlighted. In this case ISI had a significant effect on discriminability. For only one out of 21 subjects the number of "same" answers varied significantly for different pairs as a function of ISI. In this case there were more correct discriminations with increasing ISI. ISI had no effect on the number of "same" responses for same pairs.

Table S-6: Effect of ISI on the number of "same" answers for same and different pairs for the position navel between 4&5

Subject (initials)	Results of χ^2-tests	
	Same patterns	Different patterns
JM	$\chi^2_{(.01;6;n=149)}=4.30$	$\chi^2_{(.01;6;n=78)}=18.56$
SO	$\chi^2_{(.01;6;n=173)}=0.62$	$\chi^2_{(.01;6;n=162)}=0.64$
AH	$\chi^2_{(.01;6;n=144)}=2.71$	$\chi^2_{(.01;6;n=121)}=3.67$
DC	$\chi^2_{(.01;6;n=162)}=1.59$	$\chi^2_{(.01;6;n=152)}=1.63$
MG	$\chi^2_{(.01;6;n=144)}=0.67$	$\chi^2_{(.01;6;n=107)}=1.53$
RK	$\chi^2_{(.01;6;n=141)}=4.71$	$\chi^2_{(.01;6;n=111)}=6.61$
DK	$\chi^2_{(.01;6;n=157)}=1.77$	$\chi^2_{(.01;6;n=141)}=1.63$
AT	$\chi^2_{(.01;6;n=196)}=0.00$	$\chi^2_{(.01;6;n=196)}=0.00$
CA	$\chi^2_{(.01;6;n=180)}=0.60$	$\chi^2_{(.01;6;n=159)}=2.62$
CS	$\chi^2_{(.01;6;n=160)}=1.44$	$\chi^2_{(.01;6;n=83)}=19.98$
EF	$\chi^2_{(.01;6;n=183)}=0.72$	$\chi^2_{(.01;6;n=137)}=3.46$
ES	$\chi^2_{(.01;6;n=178)}=0.54$	$\chi^2_{(.01;6;n=90)}=3.80$
FW	$\chi^2_{(.01;6;n=139)}=0.55$	$\chi^2_{(.01;6;n=139)}=1.35$
JC	$\chi^2_{(.01;6;n=180)}=1.69$	$\chi^2_{(.01;6;n=153)}=6.35$
JP	$\chi^2_{(.01;6;n=148)}=2.22$	$\chi^2_{(.01;6;n=138)}=2.61$
MH	$\chi^2_{(.01;6;n=124)}=6.63$	$\chi^2_{(.01;6;n=104)}=5.85$
MM	$\chi^2_{(.01;6;n=159)}=0.50$	$\chi^2_{(.01;6;n=165)}=0.24$
PT	$\chi^2_{(.01;6;n=167)}=1.04$	$\chi^2_{(.01;6;n=160)}=2.75$
ST	$\chi^2_{(.01;6;n=132)}=2.89$	$\chi^2_{(.01;6;n=70)}=5.60$
WJ	$\chi^2_{(.01;6;n=190)}=0.11$	$\chi^2_{(.01;6;n=142)}=1.94$
YS	$\chi^2_{(.01;6;n=180)}=0.52$	$\chi^2_{(.01;6;n=174)}=0.76$

Note: Separate χ^2-tests for each subject and for same pairs (both patterns successively activated or both patterns saltatory) and different pairs (one pattern saltatory, one pattern successively activated) have been carried out to test if the frequency of "same" answers varies with ISI. Each subject completed 196 trials with same patterns and 196 trials with different patterns. The 7-tactor array was placed on the front of the torso, so that the navel lay between tactors number four and five. n is the number of "same" answers. χ^2-values that exceed the critical level of χ^2=16.81 (α=.01, df=6) are graphically highlighted. In those cases ISI had a significant effect on discriminability. For two out of 21 subjects the number of "same" answers varied significantly for different pairs as a function of ISI. The raw data indicate that one subject showed a significant increase and the other one a significant decrease in the number of "same" responses with increasing ISI. ISI had no effect on the number of "same" responses for same pairs.

Affirmation

I hereby affirm that I made this dissertation without illegal assistance. All the resources (literature, equipment, hardware,…) used are indicated and specified in this paper.

This dissertation has never been submitted to another examination authority.

Augsburg, den 02.02.2008 Anja Schwab