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Detection, Discrimination, and Sensation of Visceral Stimuli

Laboratory for Clinical Psychophysiology

Nr. 30

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1 Introduction

Afferent signals from the viscera are presented to the central nervous system at several morphological and functional levels producing physiological responses, overt behaviour, and verbally reported subjective sensations and perceptions. Interoceptively elicited events extend

(1) from visceral and autonomic reflexes (*cf.*, Ádám, 1967; Jänig, 1990; Zenker & Neuhuber, 1994) to cortical evoked responses of the somatosensory cortex and orbitofrontal and insular areas (Cechetto & Saper, 1987; 1990) on the *neurophysiological side*;

(2) and from mere changes of mood or activation (*e.g.*, Belyaeva, 1991; Kukorelli & Juhász, 1976, 1983; Kukorelli, Juhász & Ádám, 1983; Ádám, Preisich, Kukorelli & Kelemen, 1965) over involuntary discriminative behaviour (Slucki, Ádám & Porter, 1965; Slucki, McCoy & Porter, 1969) of which the subjects is largely unaware (Ádám, 1978; Hefferline & Perera, 1963) and vague, diffuse "feelings in the guts" (*cf.*, Cervero, 1988; Zimmerman, 1990) to distinctly sensed, localized, and identified visceral perceptions projected to specified parts of body schema (*cf.*, Hansen & Schliack, 1962) on the *psychological side*.

Various biological and psychological functions are thus served by these different types of afferent messages from the viscera. Studies on visceral perception, therefore, must specify the level at which the visceral afferent signal is supposed to be effective on the CNS, and which aspect of behaviour is to reflect this effect (*cf.*, Pennebaker & Hoover, 1984). Otherwise, non-perceptual impacts on the organism such as visceral or viscero-somatic reflexes, their secondary perceptual representation, preconscious behavioural discrimination at molar levels, and conscious sensation of the afferent message from the viscus will be hopelessly confounded. Verbal reports and ratings depending on clearcut conscious sensations are not sufficient to record the various types of behaviourally effective visceral messages. In fact, most of the visceral afferent signals, *e.g.*, those controlling feeding behaviour and food selection, generally are not consciously perceived until direct appetitive and consummative decisions are called for (*cf.*, Pudel & Westenhoefer, 1991). Interoceptive signals resulting in moderate changes of activation or mood are not detected consciously at all (Ádám, 1967; Ádám, Preisich, Kukorelli & Kelemen, 1965).

Consequently, it is a central task of human interoception research to develop methods which operationalize those earlier stages of processing visceral signals not clearly represented at the subjective level. Classical methods of "subjective" psychophysics are not suitable for this purpose, neither are conventional types of signal detection based paradigms which rely on ratings of subjective intensity and confidence. This is particularly due to the fact that persons do not learn basic calibration of their perceptual responses to interoceptive stimuli so that "... [they] differ tremendously in their use of self-report scales. Whereas some tend to use only the bottom half of the scale, others may use only the middle or top portions" (Pennebaker, 1982: 61). Behavioural discrimination tests must be constructed to allow subjects to respond to diffuse or even preconscious perceptual traces which are not sufficient for sensation report. For this purpose a whole body of methods is available from cognitive and neuropsychological research on preconscious processing in perception and memory (*e.g.* Dixon, 1981; Libet, 1985; McCarthy & Warrington, 1990; Weiskrantz, 1980; 1986) as well as from behavioural studies on animal perception. The latter approach includes operant discrimination tests such as adaptive methods of threshold determination for animals created by Blough (1966; Blough & Blough, 1977) who modified an older routine developed by Békésy (1947).

In the domain of vision perceptual capacities without awareness of the subjects ("blind-sight") have repeatedly been demonstrated. Patients with occipital lesions have been shown to be capable of localizing and discriminating stimuli presented to the perimetric blind hemifield above chance level. Moreover, Zihl has demonstrated the importance of output channels for the examination of residual capacities (Zihl, 1980; Zihl & Cramon, 1980). His hemianoptic patients were instructed to tell if a spot of light had been presented within defined temporal intervals (1) by closing their eye lids, (2) by pressing a key and (3) by verbal report, respectively. On the first condition, stimulus occurence could be correctly discriminated distinctly above chance level. Performance deteriorated when key pressing was required. Verbal reports, however, were not correlated to stimulus events.

On principle, we can distinguish four stages of perceptual processing by the type of information extracted from the interoceptive signal: event *detection, localisation, graduation* (intensity evaluation) and *identification* (*cf., Table 1*). These stages have already been separated by well-defined tasks in exteroception research. They should be found in the field of interoception as well if interoception is to represent a mode of perception in its own right.

The *first two stages (detection, localization)* can be operationalized by classical stimulus discrimination tasks (S_0 / $\neg S_0$ and S_1 / S_2) using forced choice conditions. In forced choice tasks the subject is explicitly encouraged to guess in the absence of subjective sensations, and additional ratings for intensity of sensation and confidence in guessing are provided for comparison. The *latter two stages (graduation, identification)* require reliable ordering by stimulus magnitude (intensity distinctions) and, finally, labelling of stimulus kind (mode and quality distinctions etc.). Within this framework preconscious detection ("perception without awareness") is operationalized by successful, *i.e.* better than chance discrimination of stimuli at intensity levels subjectively rated zero intensity (not perceived).

Table 1: Processing stages of perceptual signals

Process	Task information extracted *
Detection	Has a (relevant) event happened?
Localisation	Where is it? (internal, external, somatic; spatial data; body-part/visceral organ)
Graduation	How big (strong, intense) is it?
Identification	What (how) is it (like)? (sensory quality, object/visceral event identity

* See text for illustration by exteroceptive example (vision).

The *first question* to be answered, then, is whether this kind of discrimination can be shown to occur and to be dissociated from sensation. This question is addressed in the present article. The *second question* is whether different stimulation sites can be discriminated at preconscious level. The relation between discrimination and sensation when subjects have to locate an interoceptive event has been studied using a three-balloon probe (Erasmus, Sarno & Hölzl, 1993). Colonic distension was presented in both intervals (A, B). Subjects were instructed to decide whether the two stimuli in interval A and B came from the same or two different locations 14 cm apart. An external somatosensory stimulus serving as control was applied via a flat balloon on the lower left abdomen. Results showed that discrimination between two balloon locations occurs only at stimulus magnitudes sufficient to produce conscious sensations. Absolute discriminations of distensions of either of the balloons could still be achieved at considerable lower magnitudes which produced subjective sensations only infrequently. The external stimulus could also be discriminated at these low intensities. This finding indicates that the extero-interoceptive discrimination task is functionally equivalent to absolute interoceptive discrimination ("detection"), thus localisation of interoceptive stimuli being different from exteroceptive localisation. The latter is possible at a preconscious level with stimulus magnitudes not sufficient for conscious sensation and for intensity distinction ("graduation").

The *third question* concerns the distinction between different stimulus modalities or channels, particularly, between mechanoreceptive somatosensory (haptic) and visceral stimulation on preconscious compared to conscious (sensation) level (Erasmus, Neidig, Möltner & Hölzl, 1993; Neidig, Erasmus, Möltner & Hölzl, 1993; Neidig, 1994). From the results of the study reported above it may be concluded that discrimination of somatosensory from interoceptive stimulus channels is a basic function which requires but stimulus magnitudes usually insufficient to elicit conscious sensations. This discrimination task, therefore, cannot have required clear "identification" of the stimulus with quality and form distinctions etc. Obviously, other tasks have to be designed which require explicit extraction of qualitative information from the afferent signal. Whether this is possible at all is still an open question. Paradigms suitable for testing the assumption are not readily available at present. However, more specific tests on somato-visceral stimulus differenciation and interaction have been constructed which have some bearing on the issue of interoceptive stimulus identification. In our laboratory, for instance, masking of interoceptive by somatosensory stimuli was investigated in a recent study using a two-interval forced choice procedure similar to the one described above (Neidig, 1994; Neidig et al., 1993). In lieu of single stimuli in the intervals A and B overlapping combinations of intero- and exteroceptive stimuli had to be discriminated from isolated presentations in both channels. In this task detection thresholds for combined stimuli were *above* those for isolated stimuli in separate channels. However, when task requirements were altered from extero-interoceptive discrimination to detection of any event (interoceptive, exteroceptive or extero-interoceptive combinations) detection thresholds were clearly *below* single channel thresholds (Erasmus et al., 1993; Neidig, 1994). Distinction between somatosensory and visceral channels, therefore, is no simple matter of defining afferent visceral signals (the "distal" stimulus). What is extracted from the afferent messages as "proximal" stimulus (behaviourally relevant information or subjectively available sensation) seems to depend on the task setting which is solely defined in psychological terms.

The situation is even more complicated by unknown dynamics of the output side of sensation report. Individuals may not only differ in the mode of connecting the "distal stimulus" (distension volume) to the "proximal stimulus" (sensation) but also in the mode of connecting sensation to report. This situation cannot be sufficiently accounted for by different "response criteria" or "bias" in the sense of signal detection theory in every single case. For instance, individuals may not only vary quantitatively in threshold criteria for specified rating categories but also qualitatively in their rating dynamics such as setting a cut-off point to mark the onset of intensity-dependent rating.

In a way similar to the studies outlined above the present investigation uses a forced choice method as behavioural parameter of stimulus discrimination which is not necessarily paralleled by subjective experience. Because of the diffuse, ill-defined phenomenal properties of visceral sensations it is assumed that persons are capable of behaviourally responding to interoceptive signals without awareness of the stimulus. The study employs an adaptive up-down tracking of threshold determination which is a modification of sequential methods described by Wetherill, Chen & Vasudeva (1966). Preliminary reports on interoceptive staircase tracking procedures have previously been published

(Kratzmair, Erasmus, Hölzl & Hartl, 1987; Hölzl, Erasmus & Kratzmair, 1989; Hölzl, Püll, Erasmus & Kratzmair, 1988; Hölzl, Püll, Samay & Erasmus, 1990).

Several questions concerning the relationship between stimulus parameters, behavioural stimulus discrimination and subjective sensation are addressed. In the first place, it is the issue of whether interoceptive stimuli too small to produce subjective perceptions can be correcty discriminated in behaviour. If so there is a dissociation of sensory capacities well known from exteroceptive examinations (*e.g.* McCarthy & Warrington, 1990). Behavioural discrimination thresholds are directly made commensurable with conventional "subjective" thresholds of sensation by means of an adapted SDT-model. Second, the relation between the stimulus parameters volume and increase in pressure, respectively, and behavioural discrimination is investigated since little is known of the effective stimulus in intraluminal distension of the colon. Third, the relationship between stimulus magnitude and subjectively perceived intensity (ordered rating categories) is studied to reveal the subjective use of response categories available. Use of categories dependent on stimulus magnitude would indicate a graduating process.

2 Method

2.1 Subjects

2.1.1 Criteria of selection and recruitment

Ss have been selected using the following criteria of exclusion:

- Organic and functional gastrointestinal diseases (checked by an inventory of bodily complaints; *cf.,* Kröger, 1986; test of hidden blood in the stools using Haemoccult™; digital examination of the anorectal channel);
- Presence of pain outside the gastrointestinal tract (inventory of bodily complaints; *cf.,* Kröger, 1986);
- Neurological diseases and diabetes mellitus (medical examination);
- Psychiatric disorders, substance abuse, use of psychoactive drugs, psychotherapy (medical examination; psychological interview);
- Use of analgesics (medical examination; psychological interview).

Ss were recruited by means of advertisements in local journals and notices on black boards in the Max-Planck-Institute for Psychiatry (Munich) and at the University of Munich. Each person interested in participation was given a date in the laboratory for being informed about the conduct of the experiment and getting familiar with the laboratory setting. For each experimental hour a fee of DM 30.- was paid to the Ss.

2.1.2 Study sample

Fourty-eight persons (29 men and 19 women), mean age 30.6 yrs (range 19-71) served as Ss. The majority of the Ss, namely 22, passed through four runs of threshold determination. 10 Ss went through two runs, 7 Ss through 6 runs, and 4 Ss through 3 runs. One S passed through 1, 7 and 8 runs, respectively. Altogehter, the sample includes 188 tracking runs of threshold determination.

2.2 Apparatus

Intraluminal stimuli were applied by distension of a balloon mounted on a flexible colon probe (14 mm external diameter). The stimulating device consisted of a simplified modification of the probe described in Erasmus, Püll, Kratzmair & Hölzl (1994) with a calibrated silcolatex balloon of flat pressure-volume characteristic and suitable transducers and amplifiers for manometric recording. Balloon properties for reproducible stimulation of specified volume and pressure values with valid recordings of bowel responses were achieved by mounting the balloon pipe in pre-stretched condition and individual calibration of diameter-filling functions. Thereby, an adequate correction of pressure-volume readings with specified balloon diameters as well as flat and specified pressure-volume characteristics over a wide range of distension volumes are ensured. In a distance of 40 mm to the tip the probe is surrounded by the balloon made of silcolatex. The wall of the balloon tube is fixed at both ends on the carrier tube resulting in a fixed length of 40 mm. By virtue of its flexibility the probe can be inserted without causing pain to the Ss. Depth of insertion can be monitored by means of lines painted on the probe.

The pumping system consists of a syringe-type pump driven by a stepping motor with programmable control unit. It allows of pumping volumes up to 500 ml with a resolution of 0.1 ml. Speed is adjustable from 0 to 50 ml/s in steps of 0.1 ml/s. For phasic stimulation employed in threshold tracking a volume rate of 50 ml/s was used. The predistension of the balloon before the experimental runs was done at a 0.1 ml/s speed. The apparatus is described in more detail in Erasmus et al. (1994).

2.3 Procedure

2.3.1 Subject preparation

On a previous appointment Ss were extensively informed about the conduct of the experiment. Before leaving they were handed three Haemoccult™ test-envelopes. These stool tests were to be applied on three consecutive days before the session. If one of these tests was positive additional sigmoidoscopy was performed. In case of pathological findings the session was cancelled. Ss obtained two ampullas of a mild enema (sodium mono-/dihydrogenphosphat, Fresenius™, 260 ml in toto) with which they should evacuate the distal colon in the morning of the experimental session. Along with detailed instructions on meal restrictions (last meal not later than 6 p.m., no heavy fatty food, no gas producing food such as beans, onions etc. the day before) this preparation sufficed to reduce faeces in the distal colon to a degree commensurate with practicable probe insertion and good recordings. In a few cases only an additional enema (max. 130 ml) was necessary immediately before threshold determination.

Ss were instructed about potential risks of probe application, which consist in injury of the bowel wall solely in case of serious preexisting damage, and gave their informed consent. After these preparatory steps the colon probe was rectally inserted using smoothing gel. Depth of insertion was monitored with the aid of lines painted on the probe. Therefore, direct sonographic or X-ray control was not required. Insertion was finished when the balloon was positioned in the mid sigmoid, tip 35 cm, balloon 30 cm from the anal verge. In previous tests this procedure proved to be entirely safe owing to the relative large diameter (14 mm) with rounded tip and semi-flexibility of the probe. Curling back was prevented by reason of residual stiffness due to a multi-lumen core (*cf.,* Erasmus et al., 1994). Throughout the entire experimental session Ss were in supine position on the study couch.

2.3.2 Stimulus definition

Phasic mechanical stimuli were applied to the colon wall by inflating the balloon through a PVC tube inside the probe. The balloon was distended with precise amounts of air. Stimulus consisted of increase in volume which was added to a predistension volume (socket) of 10 and 60 ml, respectively. Dwell time of the stimulus was constantly 6 s, volume rate 50 ml/s and rise time, depending on volume, 0.2-0.9 s. A specially developed software enabled the experimenter to precisely apply stimuli as well as to record intraluminal pressure and Ss' responses.

2.3.3 Experimental design and procedure

Adaptive up-down threshold tracking

An adaptive up-down tracking (staircase method) of threshold determination was used to reduce the number of stimuli necessary and to maximize the number of near-threshold stimuli. In particular, it was a modification of sequential techniques described by Wetherill (Wetherill, & Levitt, 1965; Wetherill, Chen & Vasudeva, 1966). With this variant of a transformed up-down method (*cf.*, Levitt, 1970) stimulus magnitude (volume) was controlled by the Ss' behavioural 2AFC responses in one or several preceding trials. In case of correct (*C*) responses stimulus magnitude was decreased, in case of false (*F*) responses it was increased. To be exact, after response sequences of *C, CCC, CCFC*, respectively, volume was decreased whereas after sequences of *F, CF, CCFF*, respectively, volume was increased by steps of equal size. In series of trials sufficiently long this algorithm is expected to converge to the 70.7% point of the psychometric function which marks discriminative capacities distinctly above mere guessing probability.

In adaptive tracking procedures the choice of step size is of crucial importance (*cf.*, Falmagne, 1985). Choosing too large a step size, on the one hand, stimuli are unprecisely placed relative to target probability. On the other hand, choosing it too small too large a number of trials are required to obtain target probability (point of convergence). The initial 3 to 5 trials of each session, therefore, started with a large step size from above-threshold volumes ("lock-in series"). This minor modification of the algorithm is supposed to direct stimulus magnitude to the near-threshold range. If there was a false response in trial 3 or 4 lock-in series was finished. For the subsequent runs of 30 trials each a smaller step size was chosen in order to more precisely adjust stimulus volume to target probability. Apart from a test for determination of visceral pain threshold (GDT: graded distension test; *cf.,* Erasmus, Sarno & Hölzl, 1993; Hölzl, Erasmus, Kröger, Whitehead & Ottenjann, 1994a,b; Kröger, Hölzl & Löffler, 1987) each session included two runs (of 30 trials each) of up-down tracking. The first tracking run was executed on a predistension volume (socket) of 10 ml, the second on a predistion of 60 ml. A schematic representation of the experimental design is given in *Figure 1*.

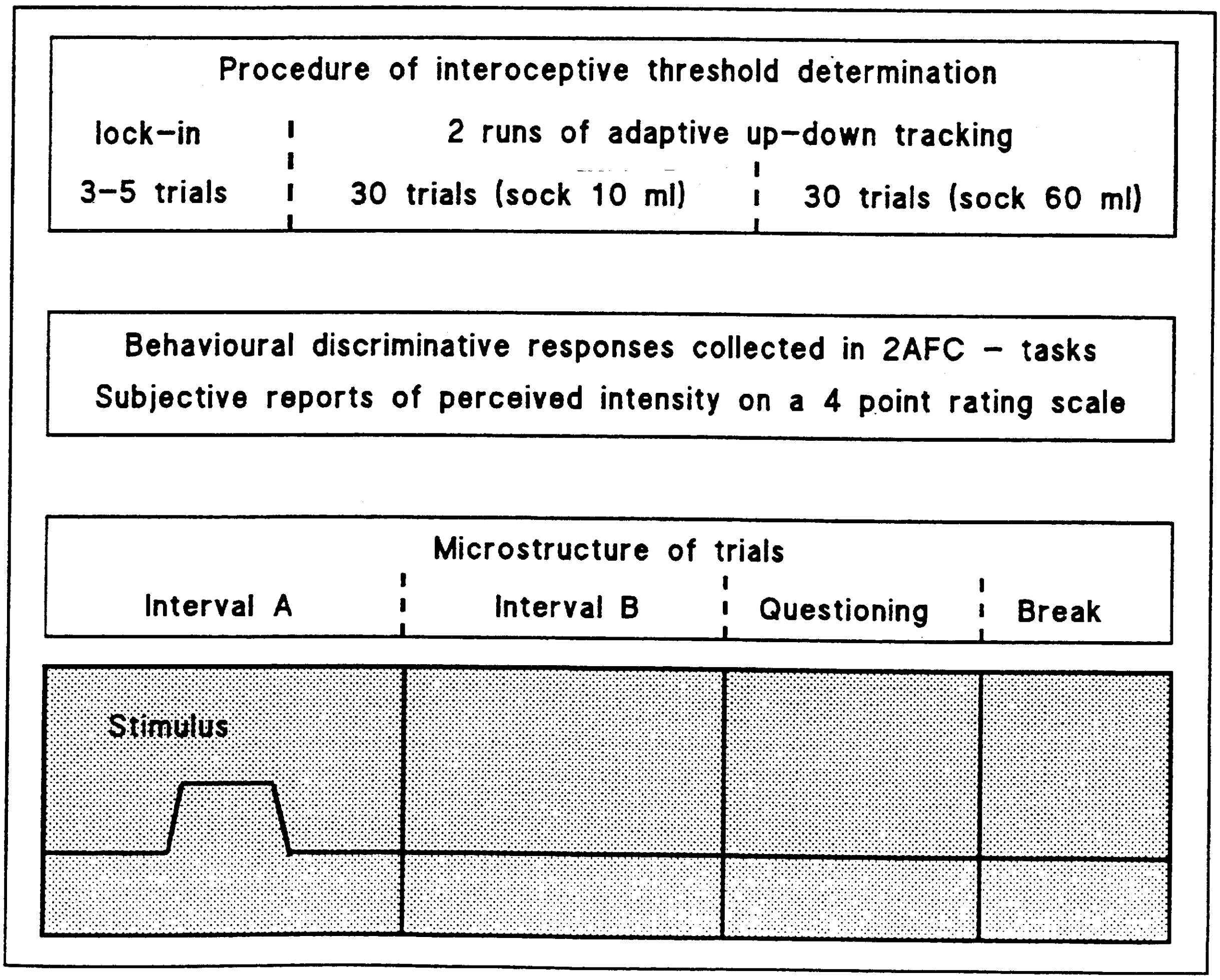

Figure 1: Schematic representation of experimental design.

Trial structure

Ss were presented with two temporal intervals (A,B) by means of acoustic and optical signals (*cf. Figure 1*). The stimulus was applied in one of these intervals, either in interval A or B. After these two intervals Ss had to decide in which of them stimulus had occured (2AFC task) and to rate intensity of subjective sensation on a four-point scale. Responses were followed by a short break before onset of the subsequent trial.

Instruction and psychological task

As outlined above, the perceptual test consisted of a 2AFC task with subsequent four-point verbal ratings of intensity of sensation. Therefore, Ss were asked to make an effort to perceive distension stimuli in the lower bowel segments during the two intervals A and B. After completion of interval B Ss had to decide in which of the intervals given the stimulus had occured. They were explicitly encouraged to guess in the absence of subjective sensations. Ss gave both behavioural and subjective responses in a special response box using their right hand. In particular, following questions (incl. response options) have been presented on the subject screen:

In which of the intervals has the stimulus occurred?
Interval A - Interval B

How have you perceived the stimulus?
nothing (1) - just (2) - distinctly (3) - strongly (4)

2.4 Data analysis

2.4.1 Cumulative functions of subjective intensity responses

In order to investigate the relations between conscious perception of interoceptive stimuli and stimulus magnitude Ss' responses actually should reflect differences in stimulus magnitude. For this purpose, cumulative response frequencies of given stimulus quantities are plotted against volume. If, in an extreme case, response categories are independent from stimulus magnitude the curves are congruent; otherwise they are shifted against each other on the abscissa. In the case of several categories employed it can be decided whether, *e.g.*, the response categories 1 ("nothing perceived") and 2 ("just perceived") are equivalent with regard to stimulus magnitude but both differing from response category "distinctly perceived".

2.4.2 Relations between physical parameters and behavioural responses

Little is known of the physiological mechanisms responsible for the perception of mechanical intracolonic stimuli. Therefore, analysis commences comparing the correlations between volume and hit rate, increase in pressure and hit rate, respectively. For every single run consisting of 30 trials coefficients of correlation (*Kendall*'s τ) and of partial correlation (*Kendall*'s partial τ) have been calculated. In the next step an analysis of the parameters resulting from a total of 188 runs was carried out.

As empirical hit rates depending on stimulus magnitude do not increase continuously in a monotonous mode the underlying psychometric function must be estimated. For this purpose an isotonic regression of hit rate on stimulus magnitude has been performed. Isotonic regression merely presumes a *(weak) monotonous* correlation between the dependent and independent variable. Apart from that, it does not implicate assumptions on the shape of the psychometric function (as, *e.g.*, the logistic function does). In analogy, an estimation of the psychometric function is performed for the dichotomized rating responses using isotonic regression on the assumption of monotonous relations.

The comparison of both curves allows of a preliminary answer to the question of whether behavioural (hit rates) and subjective (intensity ratings) responses increase in the same range of stimulus magnitude or whether they show different dose response characteristics. The latter case would suggest a dissociation between behavioural discrimination (detection) and conscious perception.

2.4.3 Do categories discriminate ?

The model assumes that subjects actually graduate the "internal" signals using all categories available. This assumption can be contrasted by a model according to which given categories are equivalent; *e.g.,* below a fixed cut-off point the subjects respond pressing key 2 ("just perceived") with a probability of 40%, above the cut-off point they will always press key 3 ("distinctly perceived"). *Table 2* summarizes several possible models for three response categories in the normal distribution model. Rating categories 3 and 4 have been pooled because of low frequency of category 4.

2.4.4 Quantitative analysis by means of a SDT model

In addition to direct comparison of the psychometric functions determined by the data a model based on SDT approach was developed for quantitative analysis. This model permits a stochastically founded decision on the question of which categories have been used for graduation. The model includes SDT-analogous measures for the *behavioural discrimination* in the 2AFC task as well as *criterion measures* for the *intensity ratings* (subjective perception of stimuli). For model derivation and description see *Appendix*.

Table 2: Graduation models

Rating category of simulus perceived	not	just	distinctly
Graduation using *three* categories	1	2	3
Graduation using *two* categories Combining 1 ("not") and 2 ("just")	1	2	3
Graduation using *two* categories Combining 2 ("just") and 3 ("distincly")	1	2	3
No graduation	1	2	3

3 Results

3.1 Correlations between physical parameters and behavioural responses

Correlation (*Kendall's* tau) between hit rate and volume ($\tau_{v,h}$) is higher than correlation between hit rate and volume increase ($\tau_{\Delta p,h}$) in 142 of 188 runs (*cf. Table 3*). The sample median of $\tau_{v,h}$ of 0.464 is significantly higher than the sample median of $\tau_{\Delta p,h}$ of 0.333 ($p < .0001$; *Wilcoxon* matched pairs rank sum test). Hence, for the purpose of psychophysical analysis, balloon volume turns out to be the more adequate parameter than increase in pressure. After partialling out volume, however, correlation between hit rate and pressure does not entirely collapse (*Kendall's* partial tau). It is true that partial correlations $\tau_{\Delta p,h.v}$ are generally low (median = 0.097) but significantly different from zero ($p < .0001$; *Wilcoxon* matched pairs rank sum test).

According to tendency, the results for the ratings of subjective intensity are similar although they are obviously less pronounced. In analogy to hit rates the correlations of intensity rating with volume($\tau_{v,I}$) are higher than the correlations of intensity and pressure increase ($\tau_{\Delta p,I}$), yet the difference is not significant ($p = .10$; *Wilcoxon* matched pairs rank sum test). Likewise, partial correlations are positive more often than negative ($p = .0001$; *Wilcoxon* matched pairs rank sum test).

Table 3: Correlations between stimulus parameters and responses

	M	*SD*	*Q1*	*Md*	*Q3*
$\tau_{\Delta p,v}$	.520	.363	.365	.619	.778
$\tau_{v,h}$	.465	.262	.290	.464	.644
$\tau_{\Delta p,h}$	.284	.287	.106	.333	.479
$\tau_{v,h.\Delta p}$	.313	.278	.093	.300	.493
$\tau_{\Delta p,h.v}$	.109	.238	-.041	.097	.250
$\tau_{v,I}$	.249	.347	.000	.258	.503
$\tau_{\Delta p,I}$	.206	.297	.000	.225	.398
$\tau_{v,I.\Delta p}$	.134	.294	-.069	.082	.338
$\tau_{\Delta p,I.v}$	.102	.248	-.041	.090	.236

τ Kendall's tau; M mean; *SD* standard deviation; *Q1* 1st quartile; *Md* median; *Q3* 3rd quartile; *Max* maximum; v volume; Δp increase in pressure; h hit rate; I subjective rating of intensity.

3.2 Dose-response curves

A smaller proportion of the Ss (about one third) show a sensation characteristic flatter than their corresponding discrimination curve. This finding might be interpreted as evidence of a leaner criterion of the forced choice response (sensu signal detection theory). It is yet inconclusive regarding a different processing stage of discrimination as compared to reportable sensation or even an indication of "interoception without awareness". However, a considerable proportion of the Ss (up to two thirds) show psychometric curves for discrimination and sensation which are qualitatively different. The initial part of the curve rises to a medium level of correct detection which prevails over a large range of stimulus intensity indicating a basic "detection" process not depending on magnitude until magnitudes are sufficiently high to give rise to conscious sensation. In this higher stimulus range discrimination and sensation tasks tap the same intensity-dependent process, *i.e.* graduation.

3.3 SDT analysis

3.3.1 Frequency of graduation models and use of categories

Graduation is analysed by means of volume-intensity characteristics. *Table 4* represents the number of runs revealing a particular use of categories (*rows*) and the number of runs covering a particular range of categories (*columns*). In 37 of 188 (19.7%) runs only, Ss show complete graduation in so far as the three volume-intensity characteristics are distinctly separated (model 1/2/3). A total of 102 (54.3%) runs display a dichotomic response pattern according to which two rating categories are equivalent. Among these runs, in the great bulk of cases change of category occurs between step 1 and 2 which represents 87 of 188 (43.1%) runs in all (model 1/23). By comparison, transition of category between rating step 2 and 3 can be observed in 15 runs (15.4%) only (model 12/3).

In 78 of 188 (41.5%) runs all three steps of subjective intensity were used. In 102 (54.2%) runs two steps were used. In 8 (4.3%) runs Ss confined themselves to only one step thus showing no graduation at all. *Column 1,2,3* of *Table 4* contains those 78 runs which permit non-trivial decisions on graduation models. In 37 of 78 (47.4%) runs Ss display intensity-dependent graduation according to model 1/2/3. In a total of 33 runs (42.3%) Ss' ratings of intensity show a dichotomic pattern two rating steps being equivalent with regard to volume. In the greater proportion of these runs change of category occurs between step 1 and 2 representing 21 of 78 (26.9%) runs in all (model 1/23). Transition between step 2 and 3 can be observed in 12 runs (15.4%) only (model 12/3). 8 of 78 runs (10.3%) with all categories used do not show any kind of graduation at all (model 123).

Table 4: Graduation models and use of categories

Model	1	2	1,2	2,3	1,2,3	
	Categories actually used					
123	6	2	29	4	8	49
12/3				3	12	15
1/23			66		21	87
1/2/3					37	37
	6	2	95	7	78	188

The entries in the table represent absolute frequency of runs.

3.3.2 SDT parameters and interoceptive thresholds

"Classical" subjective threshold (18.6 ± 14.4 ml) is above 70.1%-threshold of behavioural discrimination (17.1 ± 14.3 ml) if *ι* > 0.6055 (*cf. Table 5* and *Appendix*). In 81 runs ranked subjective threshold is above behavioural threshold, in 49 below, and in 9 cases ranks are tied. This difference is secured by *Wilcoxon* matched pairs rank sum test on a very high level of significance ($p < .0001$).

Table 5: SDT parameters and interoceptive thresholds

	M	*SD*	*Q1*	*Md*	*Q3*	*n*
d'	0.011	0.008	0.004	0.009	0.015	188
ι	0.963	0.833	0.361	0.883	1.506	139
TB	17.1	14.3	6.3	11.1	24.3	139
TS	18.6	14.4	7.6	13.3	24.3	139

d' SDT analogous measure of behavioural discrimination; *ι* measure of subjective intensity ratings; TB behavioural threshold (ml); TS subjective threshold (ml); M mean; *SD* standard deviation; *Q1* 1st quartile; *Md* median; *Q3* 3rd quartile; *n* frequency of runs.

4 Discussion

Relations between the behavioural parameter of discrimination (hit proportions) and volume turned out to be stronger than relations between hit proportions and increase in pressure. This finding shows that volume is the stimulus more effective on discriminative behaviour. As to the adequate simulus dimension of intraluminal distension, it has to be considered that this finding may be explained by the mechanism of the adaptive technique employed accoring to which discriminative behaviour directly controlled stimulus intensity in terms of volume instead of increase in pressure.

In 42% of experimental runs only, at least three rating categories of subjective intensity were used. In the majority of runs (54%) only two categories of intensity rating were used. Those runs in which the whole range of subjective intensity was covered are more instructive with respect to the graduation models assumed. Only in less than half of them (47%) complete graduation can be observed with all categories used depending on stimulus volume (model 1/2/3). A total of 42% of runs display a dichotomic pattern of responding with two rating steps being equivalent. In the greater proportion of these runs (27%) transition of categories occurs between step 1 and 2 (model 1/23). Any kind of graduation was absent 10% of the runs only (model 123).

A smaller proportion of the Ss showed sensation characteristics flatter than their corresponding discrimination curves. This might reflect a leaner criterion (in the sense of signal detection theory) of the forced choice response and is not conclusive with repect to a different processing stage for discrimination as compared to reportable sensation or even an indication of "interoception without awareness". However, a considerable proportion, up to two thirds of the Ss produced qualitatively different psychometric curves for discrimination and sensation. The initial part of the curve rose to a medium level of correct detection which prevailed over a large range of intensities, indicating a basic "detection" process which is independent of stimulus quantity (intensity) until quantities are sufficiently high to allow of conscious sensation. In this higher stimulus range discrimination and sensation tasks tap the same intensity-dependent process, *i.e.,* graduation. The 2AFC task of temporal discrimination in interoception thus can be said to push two distinguishable sensory processes depending on stimulus intensity. This finding is in line with results from exteroceptive studies on "implicit vision" or "seeing without awareness" (*e.g.* Weiskrantz, 1986).

To summarize, in perception of phasic gastrointestinal distension, at least two stages of interoceptive processing are suggested by the relations between behavioural performance of discrimination and subjective sensation characteristics. At low intensities simple *detection* of the interoceptive event is accomplished which is independent of stimulus quantity over a wide range of volumes. At higher intensity volume-dependent sensation and detection ratios can be established indicating that *graduation* has set in. Graduating processes cannot be observed below a level of conscious visceral sensation. Since not all Ss showed this two-stage pattern of processing criteria of changing from mere detection to graduation with sensation must vary from individual to individual. This is possibly due to idiosyncratic perceptual sets which have not been well controlled by the experimental procedure.

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6 Appendix: Derivation of SDT-models

6.1 SDT-model 1: single stimulus and 2-alternative forced-choice tasks

6.1.1 Modelling hit proportion

Corresponding to standard SDT model setup let U_n and U_s be random variables that denote the "activation" set off by the noise-interval and the signal-interval, respectively. Subjects are assumed to make a correct interval choice for any realisation of $U_s > U_n$.

Furthermore, let u_n and u_s denote the distributional densities of U_n und U_s, respectively. We can thus define H to be the distribution function of $U_s - U_n$ with density h, where

$$h(x) = \int_{-\infty}^{\infty} u_s(x+t)u_n(t)dt$$

The hit proportion in 2AFC-tasks, then, is given by

$$P(U_s > U_n) = P(U_s - U_n > 0) = \int_0^{\infty} h(t)dt$$

6.1.2 Modelling intensity ratings

Suppose that, for rating tasks, response categories k_0 to $k_{\max}$ are available. In the model, any rating of intensity is based on a distribution function I with density i, representing an "internal signal" triggered by the physical stimulus applied. The probability of selecting category k in response is given by

$$P(\text{intensity} = k) = \int_{\iota_k}^{\iota_{k+1}} i(x)dx = I(\iota_{k+1}) - I(\iota_k)$$

where all $\iota_i \in \Re \cup \{-\infty, +\infty\}$ satisfy

$$-\infty = \iota_0 \leq \ldots \leq \iota_k \leq \iota_{k+1} \leq \ldots \iota_{k_{\max}+1} = +\infty$$

The following assumption will then relate hit proportion to intensity rating:

Intensity rating is based on the signal which dictates interval decision, that is $\max(U_n, U_s)$. *Decision behaviour* in a 2AFC task with three categories available ("not felt", "just felt", "distinctly felt") is thus determined by the signal u_A "received" in interval A and signal u_B "received" in interval B:

Table *A.1*: Model 1: response determination in a 2AFC-task

signal-relation	selected interval	relation signal/criterion	intensity rated
$u_A > u_B$	A	$u_A < \iota_1$	not
		$\iota_1 < u_A < \iota_2$	just
		$\iota_2 < u_A$	distinctly
$u_A < u_B$	B	$u_B < \iota_1$	not
		$\iota_1 < u_B < \iota_2$	just
		$\iota_2 < u_B$	distinctly

The distribution function of $\tilde{U} := \max(U_s, U_n)$ takes the form

$$\tilde{U}(x) = P(\max(U_s, U_n) < x) = P(U_s < x)P(U_n < x) = U_s(x)U_n(x)$$

Writing $I = \tilde{U}$ with density $i = \tilde{u}$ leads to

$$P(\text{Intensity} = k) = \int_{\iota_k}^{\iota_{k+1}} \tilde{u}(x)dx = \tilde{U}(\iota_{k+1}) - \tilde{U}(\iota_k)$$

6.1.3 Normal distribution model

Let U_s und U_n obey a normal distribution rule with mean 0 (μ) and standard deviation of 1. Distributions forming the above models can then be rewritten as

$$\begin{aligned} U_s(x) &= \Phi_{\mu,1}(x) \\ U_n(x) &= \Phi_{0,1}(x) \\ H(x) &= \Phi_{\mu,\sqrt{2}}(x) \\ \tilde{U}(x) &= \Phi_{\mu,1}(x)\Phi_{0,1}(x) \end{aligned}$$

Note that the mean μ of the signal distribution corresponds to the parameter d' in classical SDT-modelling.

6.2 SDT-model 2: various stimulus magnitudes

6.2.1 Modelling hit proportion

This model may be extended to cover different stimulus magnitudes simply by entering the corresponding signal distributions U_{s_i}. Generally, one will assume that different U_{s_i} can be described by a particular functional relation f; using above results and assuming normality it takes the form

$$U_{s_i} = \Phi_{d'f(s_i),1}$$

with s_i as stimulus magnitude. Entering $s = 0$ directly gives the noise signal. If f is reduced to the identity function it is clear that discrimination becomes a linear function of stimulus magnitude. f may also take the form of a power function $f(s) = s^c$ with parameter c to be estimated.

6.2.2 Estimation of d' with $f(s)$ given

In the normal distribution model, hit proportion is given by

$$t_s(d') = 1/2(1 + \text{erf}(d' f(s)/2))$$

A maximum likelihood estimation of d' is given by

$$\ell(d') = \sum_s n_s^+ \log(t_s(d')) + n_s^- \log(1 - t_s(d'))$$

where n_s^+ denotes the number of hits corresponding to a SDT-stimulus s and n_s^- the denotes the number of misses.

6.2.3 Model including intensity ratings

Extending the above model in order to account for intensity rating leads to the maximum likelihood function

$$\ell(d', \iota_1, \ldots, \iota_{k_{max}}) = \sum_i \left\{ \begin{array}{ll} \log(t_{s_i}(d')) & \text{case hit} \\ \log(1 - t_{s_i}(d')) & \text{case miss} \end{array} \right\} + \log(I_{s_i}(\iota_{k_i+1} - I_{s_i}(\iota_{k_i})$$

with i indicating trial number, s_i and k_i denoting stimulus magnitude and response category of this particular trial, respectively. Note that in the model for intensity rating (section 6.1.2.) I is also dependent on parameter d'.

6.3 The discriminative power of categories

All models c.a. assume that subjects are in fact making use of *all* categories available when graduating their "internal" signal. Nevertheless it is entirely possible that certain categories are treated equivalently; e.g.. subjects' response behaviour may be led by a fixed cut-off *below which* there is a chance of 60% for "not felt" and a chance of 40% for "just felt" and *above which* the answer will *always* be "distinctly felt". Considering three categories actually at the subjects' disposal, it is still possible to construct a model by combining categories "not felt" and "just felt" into one single category. Alternatively a model may be considered that entirely dispenses with graduation-by-categorization. The following table summarizes all options given three categories and a normal distribution model:

Table *A.2*: Models for three categories

response	"not felt"	"just felt"	"distinctly felt"
graduation by 3 categories			
	$\tilde{U}_{d's}(\iota_1)$	$\tilde{U}_{d's}(\iota_2) - \tilde{U}_{d's}(\iota_1)$	$1 - \tilde{U}_{d's}(\iota_2)$
graduation by 2 categories (collapsing "not" und "just")			
	$(1-p)\,\tilde{U}_{d's}(\iota_2)$	$p\,\tilde{U}_{d's}(\iota_2)$	$1 - \tilde{U}_{d's}(\iota_2)$
graduation by 2 categories (collapsing "just" und "distinct")			
	$\tilde{U}_{d's}(\iota_1)$	$(1-p)\,(1 - \tilde{U}_{d's}(\iota_1))$	$p\,(1 - \tilde{U}_{d's}(\iota_1))$
no graduation			
	p_1	p_2	p_3

When fitting a model to real data, the relative merits of each model can be easily evaluated by likelihood ratio methods.

6.4 Worked example: normal distribution model for three response categories

In this section model parameters are estimated for three selected data sets obtained in the study outlined in this report. In the first examples, categories reflect differences in balloon distension by varying *volume* (see figure below: Run 2, ◇ representing "not", △ "just" and ▽ "distinctly felt"). Quantitative analysis gives the maximum likelihood estimate for the model in question (⇒). In the second example (run 23) categories 1 and 2 are treated equivalently, but quantitative analysis shows the same results. No graduation can be found in example 3 (Run 22). Example 4 demonstrates a case of less distinct usage of categories: the discriminative power of category 1 is clearly seen whereas categories 2 and 3 enable discrimination at relatively high volume only (note that "distinctly felt" was twice responded at relatively low volume). The maximum-likelihood criterion, though, indicates that a model using all of three response categories should be preferred to the model combining categories 2 & 3. It must be pointed out that – in the figure refered to – all points of the cumulated frequency function graph *not* conforming to the model reflect but one observation.

Table A.3: Worked examples: maximum likelihood model identification

	ℓ	$m \cdot 100$	ι_1	ι_2
Run 2				
⇒	47.447	0.333	0.431	1.907
	47.643	0.296		1.869
	47.630	0.292	0.401	
	47.890			
Run 23				
	45.804	0.595	0.656	2.194
⇒	45.754	0.611		2.209
	45.995	0.545	0.627	
	46.024			
Run 22				
	48.446	1.298	0.841	1.878
	48.329	1.329		1.899
	48.477	1.295	0.841	
⇒	48.311			
Run 1				
⇒	47.690	0.452	.365	1.721
	48.090	0.416		1.672
	47.763	0.455	0.367	
	48.304			

6.5 Behavioural vs. subjective thresholds

The measure of threshold in forced-choice-procedures is usually taken to be the point corresponding to the 75%-ordinate of the psychometric function, thus representing the stimulus magnitude which results in a hit proportion of 75%. In the present context let this measure denote the *behavioural threshold* S_b. Then

$$1/2(1 + \mathrm{erf}(d' S_b/2)) = 3/4$$

and solved for S_b

$$S_b = \frac{2}{d'}\mathrm{erf}^{-1}(1/2) \approx \frac{0.95387}{d'}$$

Consider that subjective categories of intensity have been fixed using the methods elicited in the previous section and graduation of stimuli is is taking place accordingly (that is, "not felt" vs. "just felt" or "just felt" and "distinctly felt"). Then the proportion of responses indicating a *higher* category given a stimulus magnitude of 0 can be calculated as

$$1 - \frac{1}{4}\left[\mathrm{erf}\left(\frac{\iota}{\sqrt{2}}\right) + 1\right]^2$$

The *subjective threshold* is to be estimated at the stimulus magnitude for which the proportion of responses indicating higher categories is placed exactly between the hit proportion at stimulus magnitude 0 and 100%. If at stimulus magnitude 0, for example, 20% of all responses indicate a higher category, then the subjective threshold is to be estimated at the stimulus magnitude X *given which in 60% of all trials responses indicating a higher category are obtained.* Then it is true that

$$1 - \frac{1}{4}\left[\operatorname{erf}\left(\frac{\iota - d'\,S_s}{\sqrt{2}}\right) + 1\right]\left[\operatorname{erf}\left(\frac{\iota}{\sqrt{2}}\right) + 1\right] = \frac{1}{2}\left(1 + 1 - \frac{1}{4}\left[\operatorname{erf}\left(\frac{\iota}{\sqrt{2}}\right) + 1\right]^2\right)$$

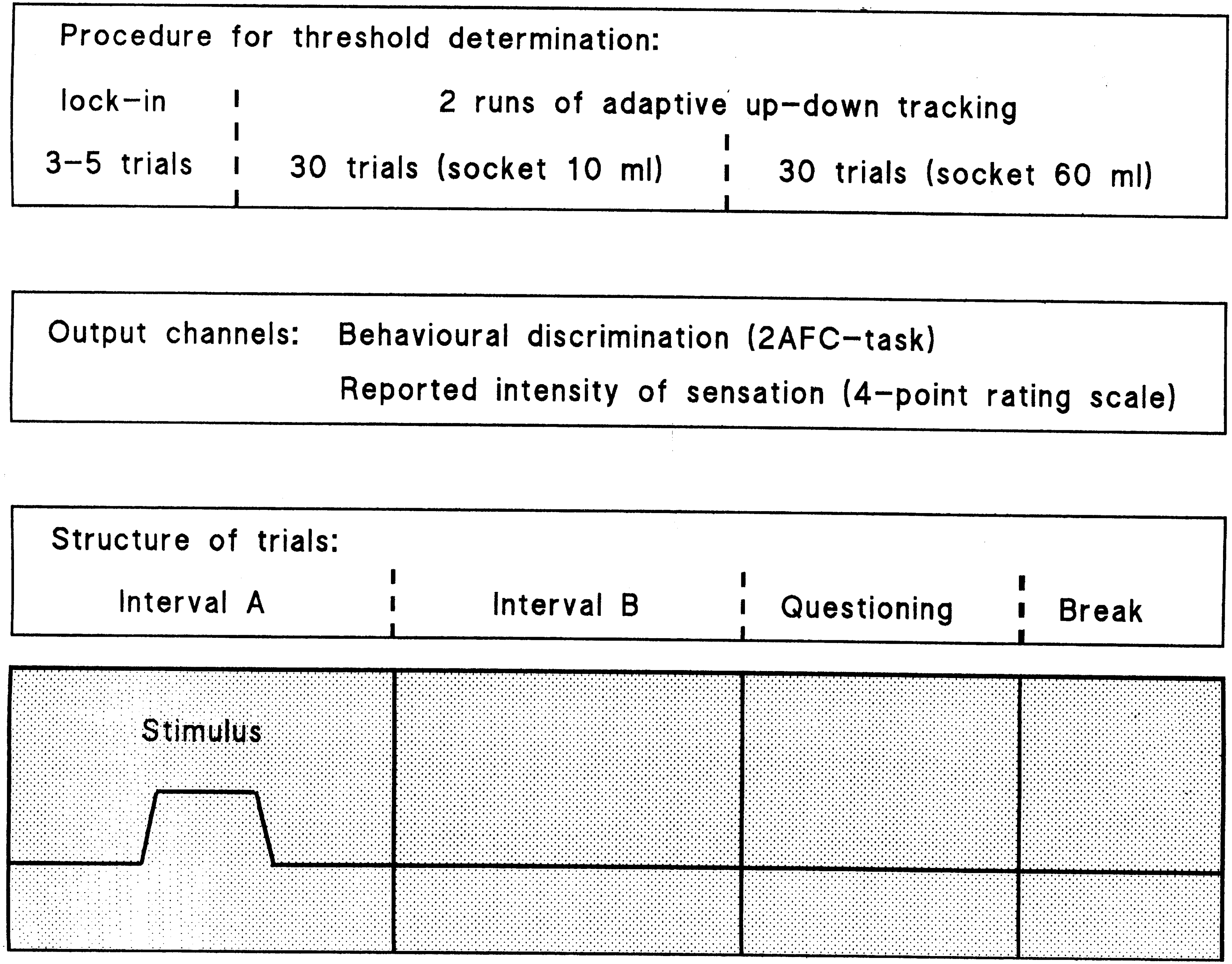
which simplifies to

$$\operatorname{erf}\left(\frac{\iota}{\sqrt{2}}\right) = 2\operatorname{erf}\left(\frac{\iota - d'S_s}{\sqrt{2}}\right) + 1$$

The proportion of responses indicating a higher category of rated intensity in the *behavioural* context is given by

$$\begin{aligned} 1 - \frac{1}{4}\left[\operatorname{erf}\left(\frac{\iota - m\,S_b}{\sqrt{2}}\right) + 1\right]\left[\operatorname{erf}\left(\frac{\iota}{\sqrt{2}}\right) + 1\right] \\ \approx 1 - \frac{1}{4}\left[\operatorname{erf}\left(\frac{\iota - 0.95387}{\sqrt{2}}\right) + 1\right]\left[\operatorname{erf}\left(\frac{\iota}{\sqrt{2}}\right) + 1\right] \end{aligned}$$

This expression is monotonically decreasing with ι and is less than S_s **iff** $\iota > 0.605538$, that is, the subjective threshold S_s is greater than its behavioural counterpart **iff** ι is greater than a given value.


Procedure for threshold determination:
lock-in
2 runs of adaptive up-down tracking
3-5 trials
30 trials (socket 10 ml)
30 trials (socket 60 ml)
Output channels:
Behavioural discrimination (2AFC-task)
Reported intensity of sensation (4-point rating scale)
Structure of trials:
Interval A
Interval B
Questioning
Break
Stimulus