Does speed equal distance over duration in perception?

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If the perceived speed of a moving object equals perceived distance traveled in perceived duration, speed perception should inherit distance illusions, unless they elicit *proportional* duration illusions. Three experiments systematically evaluated whether an object appears to move faster (a) along subjectively longer horizontal lines (Müller-Lyer distance illusion) and (b) around subjectively larger circles (Ebbinghaus size illusion). The predicted Müller-Lyer and Ebbinghaus speed illusions were consistently absent across absolute (Experiments 1a–b), binary comparative (Experiments 2a–b), and ternary comparative judgments (Experiments 3a–b), providing converging evidence against the hypothesis that illusory distance increments produce illusory speed increments. This could be reconciled with the notion that speed equals distance over duration in perception if distance illusions induce proportional duration illusions through space–time interference, thereby preserving the perceived distance/duration ratio. The spatial Müller-Lyer and Ebbinghaus illusions were accompanied by directionally aligned temporal illusions in absolute (Experiments 4a–b) and binary comparative judgments (Experiments 5a–b). However, Experiments 5a–b indicated that the duration illusions were not proportional to the distance illusions and therefore insufficient to explain the absence of cross-dimensional illusion carry-over from distance to speed. Together, these findings cast doubt on whether speed equals distance over duration in perception.

Keywords: speed perception, Müller-Lyer illusion, Ebbinghaus illusion, space–time interference

Public significance statement: When we see something move, we may judge its speed by determining how far it has traveled and how long the movement lasted. Across five experiments using well-known visual illusions, we tested whether this intuitive rule holds in perception. Importantly, increases in apparent movement distance were not accompanied by corresponding increases in apparent movement speed. These findings suggest that perceived speed is not derived from perceived distance and time.

Introduction

Galileo Galilei defined the average speed of a moving object as the ratio of the distance traveled to the time of transit: $v = s/t$. This kinematic speed definition implies $s = v \cdot t$ and $t = s/v$. Since speed is derived from the fundamental quantities of distance and duration, each of the three physical quantities can be inferred from the other two. Does the human visual system preserve this interdependence, so that perceived speed equals the ratio of perceived distance and perceived travel time (termed *distance/duration rule* henceforth)? This fundamental question—whether distance, duration, and speed are integral (versus separable) perceptual dimensions, as predicted by the distance/duration rule—has rarely been asked, let alone clearly answered. The present study begins to fill this gap by systematically testing whether illusions in perceived movement distance carry over to speed perception (Experiments 1–3) and whether this potential distance–speed transfer is offset by space–time interference (Experiments 4–5).

Few previous studies evaluated whether speed perception adheres to the distance/duration rule. Some studies used psychophysical scaling to quantify the relation between judg-

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ments of distance, duration, and speed (Algom & Cohen-Raz, 1984; Brown, 1931a; Mashhour, 1964, 1981; Rachlin, 1966; Svenson, 1970). For example, Rachlin (1966) revealed that magnitude estimates of linear and circular motion speed can be predicted from distance and duration estimates via $\hat{v} = k(\hat{s}/\hat{t})^{0.8}$, where k is a scaling constant. Other studies supported the hypothesis based on the distance/duration rule that speed estimates should increase more steeply with greater physical distance as physical duration decreases (Algom & Cohen-Raz, 1984, 1987). However, instead of such an interactive pattern, Wilkening (1981) found additive effects of physical distance and duration in adults and 10-year-old children, suggesting a subtractive distance–duration rule ($\hat{v} = \hat{s} - \hat{t}$), and only a main effect of physical distance in 5-year-old children, which even suggests a distance-only rule ($\hat{v} = \hat{s}$). Analogously, the question arises as to whether apparent motion speed follows the distance/duration rule, as hypothesized by DeSilva (1928). Carlson (1978) observed that the apparent motion between successive light flashes separated by a constant physical distance was judged to be slower when the physical inter-stimulus interval (ISI) was longer, and interpreted this as evidence for a distance/duration rule (see also Lappin et al., 1975). Taken together, these previous studies investigated how judgments of one perceptual dimension (e.g., speed) are influenced by *physical* variations in another dimension (e.g., distance or duration), which reveals little about whether and how the three perceptual dimensions are functionally related (e.g., whether and how speed perception is informed by distance and duration perception).

If speed perception adheres to the distance/duration rule, increases in perceived distance and decreases in perceived duration should both increase perceived speed. The hypothesized perceptual transfer from distance and duration to speed can be tested by manipulating distance or duration perception and measuring whether the induced distance or duration illusions also turn into speed illusions. Whether illusory distance increments lead to illusory speed increments can be tested by exploiting classic geometric configurations that induce distance illusions, such as Müller–Lyer and Ebbinghaus figures. Specifically, a dot traveling along the horizontal line of a Müller-Lyer figure should appear to move faster when inward (versus outward) pointing arrowheads cause the traveled distance (horizontal line length) to appear longer. Analogously, a dot traveling around the central circle of an Ebbinghaus figure should appear to move faster when small (versus large) inducer circles cause the traveled distance to appear longer.

Empirical data relevant to the predicted Müller–Lyer and Ebbinghaus speed illusions are scarce and mixed. To our knowledge, speed perception has not yet been investigated in Müller-Lyer figures and only rarely in Ebbinghaus figures (Pavlova & Sokolov, 2000; Szego & Rutherford, 2007). Broadly in line with the distance/duration rule, Szego and Rutherford (2007, Experiment 2) found that a majority of observers (68%) judged a dot traversing a subjectively larger central circle as moving faster in most trials than a dot traversing a subjectively smaller central circle. However, no analysis based on quantitative measures of the individual preferences was reported. The binary judgments between physically identical speeds may also have been relatively susceptible to response biases near subjective equality. Interestingly, Pavlova and Sokolov (2000) reported the opposite pattern in a similar configuration, indicating that movements over subjectively longer distances appear *slower*. Taken together, it remains unclear whether speed perception is sensitive to distance illusions in the direction expected based on the distance/duration rule.

There is also an important caveat to the prediction of the distance/duration rule that movements over subjectively longer distances appear faster: This tendency can be counteracted by two well-supported phenomena—*velocity transposition* and *space–time interference*. Velocity transposition reflects that the perceived speed of a moving object depends on how large this object appears relative to the size of its spatial reference frame (Brown, 1931b). Accordingly, objects appear to move more slowly when they are embedded in a larger spatial reference frame. This contextual scaling can establish approximate constancy of perceived speed against changes in viewing distance (e.g., Brown, 1931b; Wallach, 1931) and has been demonstrated repeatedly (e.g., Epstein, 1978; Sokolov et al., 1997). Interestingly, Rock et al. (1968) also found that approximate speed constancy breaks down when binocular depth cues are eliminated. This indicates that approximate speed constancy depends on both size scaling (i.e., velocity transposition) and distance scaling (but see also Zohary & Sittig, 1993).

The counterintuitive finding by Pavlova and Sokolov (2000) might suggest that velocity transposition leads to the perception of slower movement speeds over subjectively longer distances if the traveled line becomes the spatial reference frame due to the absence of a broader background structure. For example, if the Müller-Lyer figure is presented in isolation against a uniform background, observers may align their spatial reference frame to the apparent length of the horizontal line. In this case, an illusorily long line would induce a larger spatial reference frame and could thus result in a lower perceived speed due to velocity transposition. Therefore, unlike previous studies (Pavlova & Sokolov, 2000; Szego & Rutherford, 2007), all experiments reported below embedded the moving dot and the Müller-Lyer or Ebbinghaus figure in a constant spatial frame to minimize velocity-transposition confounds. Indeed, pilot experimentation hinted at slower perceived movement speeds over subjectively longer distances without a constant spatial frame (consistent with Pavlova & Sokolov, 2000), but no such tendency when a constant spatial frame was added.

Even when potential velocity-transposition confounds are

controlled, distance illusions do not necessarily imply speed illusions under the distance/duration rule. Instead, the presence of a distance illusion is compatible with the absence of a speed illusion if the distance illusion is accompanied by a proportional duration illusion, such that the ratio of perceived distance and duration remains invariant. Qualitatively in line with this idea is the robust finding that physically larger objects are judged to endure longer (e.g., Bottini & Casasanto, 2013; Casasanto & Boroditsky, 2008; Mo & Michalski, 1972; Riemer et al., 2026; Thomas & Cantor, 1975; Whitaker et al., 2024; for a review, see Riemer & Cai, 2024). More importantly, there is also evidence that distance illusions carry over to duration perception—both for Müller-Lyer (Bratzke, 2024; Lebensfeld & Wapner, 1968) and Ebbinghaus figures (Bratzke, 2024; Bratzke et al., 2024; Ono & Kawahara, 2007). These intriguing findings suggest that spatial extensions are accompanied by temporal extensions in perception, which would weaken the transfer of distance illusions to speed perception under the assumption of a distance/duration rule. However, the Müller-Lyer and Ebbinghaus speed illusions are only predicted to disappear completely if the distance illusions and their accompanying duration illusions are *proportional*. Whether the Müller-Lyer and Ebbinghaus distance and duration illusions are proportional is an open empirical question addressed in the present study.

Five experiments systematically evaluate whether speed perception adheres to the distance/duration rule. Experiments 1–3 test the prediction that illusory increases in perceived movement distance should lead to illusory increases in perceived speed using absolute judgments (Experiment 1), binary comparative judgments (Experiment 2), and ternary comparative judgments (Experiment 3). Experiments 4–5 test whether distance illusions are accompanied by proportional duration illusions. We first test a necessary condition for this auxiliary assumption—directional alignment of distance and duration illusions—using absolute judgments (Experiment 4) and then provide a more direct test of proportionality using binary comparative judgments (Experiment 5). Each experiment is performed with the Müller-Lyer illusion (Experiments 1–5a) and the Ebbinghaus illusion (Experiments 1–5b).

Experiments 1a–b: Absolute speed judgments

Experiments 1a and 1b provide a first test of the predicted Müller-Lyer and Ebbinghaus speed illusions. Similar to several previous studies on space–time interference (e.g., Bratzke, 2024; Bratzke & Ulrich, 2025; Ono & Kawahara, 2007), observers gave absolute judgments of the speed of a single stimulus to investigate distortions in speed perception without requiring bias-prone comparisons between stimuli. A wide range of physical speeds (three physical distances × three physical durations) was explored to accommodate the possibility that the functional relation between distance, duration, and speed perception depends on physical parameters (e.g., Jagorska & Riemer, 2024).

Method

Transparency and openness

All experiments were preregistered. Data were collected in 2024 and 2025. Raw data, analysis scripts, experimental scripts, and preregistrations are available at https://osf.io/7km3r (Kelber et al., 2026). We document how we determined our sample size as well as all data exclusions, manipulations, and measures.

Observers

Two separate samples of 30 observers completed a single half-hour session (Experiment 1a: 16 women, 27 right-handers, mean age: 28 years, age range: 18–60 years; Experiment 1b: 18 women, 26 right-handers, mean age: 24 years, age range: 18–59 years). Given a standard 5% significance level, this sample size ensured a statistical power of above 95% for a repeated-measures analysis of variance (ANOVA) F-test to detect an effect size of $\eta_p^2 = .15$, which was observed by Bratzke (2024) and Bratzke et al. (2024) for the influence of the distance illusions on perceived duration (calculated with G*Power, Version 3.1.9.4; Faul et al., 2007). All observers in this and the following experiments reported normal or corrected-to-normal visual acuity, provided informed consent prior to the experiment, and could receive course credit or financial reimbursement (12 € per hour). The experiments were approved by the institutional ethics committee at the University of Tübingen.

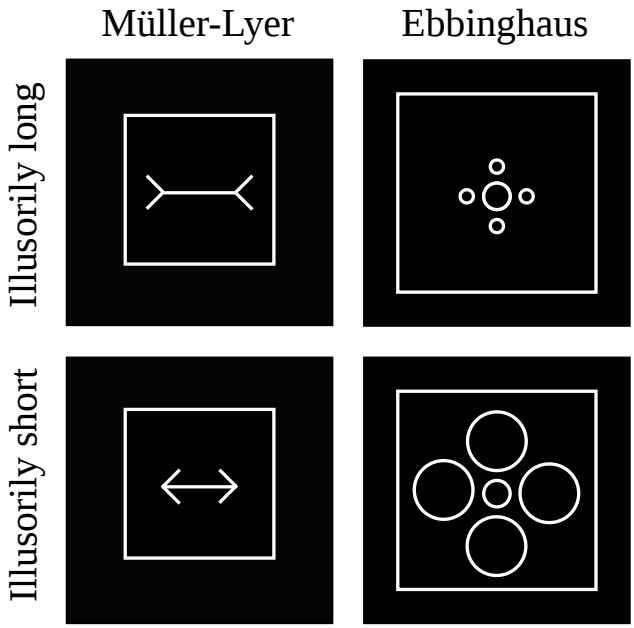
Apparatus and stimuli

Stimulus presentation and response recording were controlled by custom `Python` scripts based on the `PsychoPy` library (Peirce et al., 2019). In Experiment 1a, the stimuli were presented on a 60 Hz monitor (1,920 × 1,080 pixels, 14 in.) and viewed from about 60 cm in a quiet environment. In Experiment 1b, the stimuli were also presented on a 60 Hz monitor (1,920 × 1,080 pixels, 24 in.) and viewed from a chinrest (distance: 60 cm) in a dimly lit chamber.

In Experiment 1a, the centrally presented Müller-Lyer figure (see Figure 1, left) comprised a horizontal line (length: 4, 6, or 8°) and two fins (length: 1°) at each end. The arrowheads pointed outward (acute angle of 45°) in the "illusorily short" conditions, and inward (obtuse angle of 135°; shown in Figure 1) in the "illusorily long" conditions. In Experiment 1b, the centrally presented Ebbinghaus figure (see Figure 1, right) comprised a central circle (circumference: 4, 6, or 8°) and four inducer circles, each presented with an edge-to-edge distance of 1° to the central circle. The circumference of the inducer circles was twice the circumfer-

Figure 1

Illustration of the Müller-Lyer and Ebbinghaus figures used in the experiments (not to scale)



ence of the central circle in the "illusorily short" conditions, and half of its circumference in the "illusorily long" conditions. In each trial, a dot (diameter: 0.3°) moved once from left to right on the horizontal line of the Müller-Lyer figure (Experiment 1a), or once clockwise around the central circle of the Ebbinghaus figure, starting from the leftmost point (Experiment 1b). The movement duration was 300, 400, or 500 ms. All stimuli were displayed in white against a black background inside a square with a white outline (side length: 12° for the Müller-Lyer figure, and 16° for the Ebbinghaus figure). This constant spatial frame was used to minimize velocity-transposition confounds.

The speed of the moving dot was rated on a slider scale from 0 (slow) to 100 (fast), as illustrated in Figure 2. A red slider could be placed and moved on the scale with the mouse. As soon as the mouse was released, the number corresponding to the current slider position was displayed. The absolute judgment was confirmed by pressing the space bar on the keyboard.

Procedure

Figure 2 illustrates the trial course. The dot first appeared at its initial position for 500 ms, followed by another 500 ms at this position together with the Müller-Lyer figure (Experiment 1a) or the Ebbinghaus figure (Experiment 1b). The dot then moved for 300, 400, or 500 ms. After that, the slider scale was shown until the absolute judgment was confirmed, which finally initiated an inter-trial interval (ITI) of 1,000 ms (blank screen).

Physical distance (4, 6, or 8°), physical duration (300, 400, or 500 ms), and "illusory distance" (short or long) were manipulated orthogonally in each block. Each of the $3 \times 3 \times 2 = 18$ trial types was repeated twice per block. The resulting 36 trials per block were presented in random order. A session comprised eight blocks of speed judgments.

In a final block, observers were instructed to rate the distance of the horizontal line (Experiment 1a) or the size of the central circle (Experiment 1b) from 0 (short/small) to 100 (long/large). To this end, each Müller-Lyer/Ebbinghaus figure (three physical distances/sizes × two illusory distances/sizes) was presented for 1,000 ms in one trial, and the slider scale was used to provide an absolute distance/size judgment.

Analysis

The observers' mean absolute speed judgments were submitted to a three-way ANOVA with the within-subjects factors *physical distance* (4, 6, or 8°), *physical duration* (300, 400, or 500 ms), and *illusory distance* (short or long), separately for Experiments 1a and 1b. Likewise, the mean absolute distance/size judgments were submitted to two-way ANOVAs with the within-subjects factors *physical distance/size* (4, 6, or 8°) and *illusory distance/size* (short/small or long/large). The *p*-values were Greenhouse-Geisser corrected if a significant Mauchly test indicated a violation of sphericity.

Results

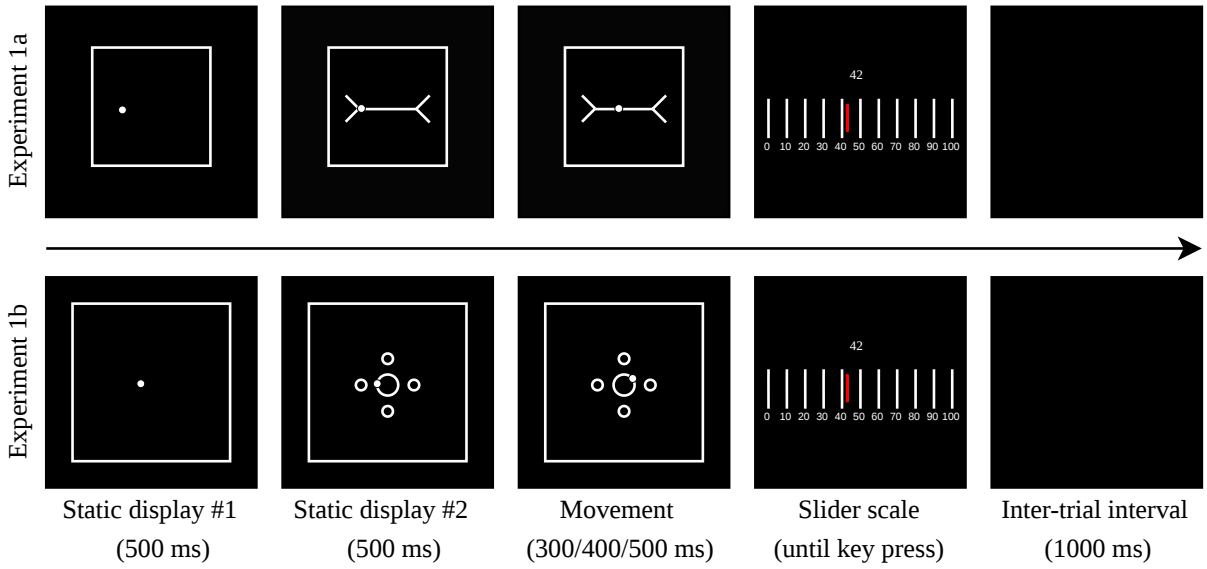
Müller-Lyer illusion (Experiment 1a)

Distance judgments. Significant main effects of *physical distance*, $F(2, 58) = 145.82$, $p < .001$, $\eta_p^2 = .83$, and *illusory distance*, $F(1, 29) = 25.59$, $p < .001$, $\eta_p^2 = .47$, reflect that mean distance judgments increased with physical line length (4°: 35.3, 6°: 49.0, 8°: 62.2) and illusory line length (short: 46.5, long: 51.2). Our stimulus material thus elicited the Müller-Lyer distance illusion. Figure 3 illustrates that this spatial illusion was present across all physical distances. The interaction was not significant, $F(2, 58) = 1.15$, $p = .312$, $\eta_p^2 = .04$.

Speed judgments. Significant main effects of *physical distance* (4°: 46.7, 6°: 56.9, 8°: 64.4), $F(2, 58) = 173.49$, $p < .001$, $\eta_p^2 = .86$, and *physical duration* (300 ms: 66.1, 400 ms: 54.7, 500 ms: 47.2), $F(2, 58) = 204.28$, $p < .001$, $\eta_p^2 = .88$, confirmed that observers were sensitive to the physical speed manipulations. However, importantly, the main effect of *illusory distance* was not significant, $F(1, 29) = 1.46$, $p = .237$, $\eta_p^2 = .05$, reflecting statistically indistinguishable mean speed judgments for illusorily short lines (outward-pointing arrowheads; 56.2) and illusorily long lines (inward-pointing arrowheads; 55.8). Figure 4 reveals that this difference in judged speed was not significant or in the unexpected

Figure 2

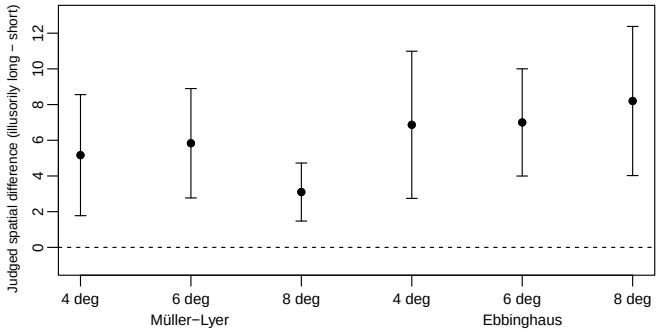
Illustration of the trial course in Experiments 1a–b (not to scale)



Note. The depicted movement distances are illusorily long.

Figure 3

Müller-Lyer distance illusion and Ebbinghaus size illusion as a function of physical distance/size in Experiments 1a–b



Note. Black points are means across observers and error bars are 95% confidence intervals.

direction across all physical conditions. No interaction was significant (all *p*s > .081).

Ebbinghaus illusion (Experiment 1b)

Size judgments. Significant main effects of *physical size*, $F(2, 58) = 98.61$, $p < .001$, $\eta_p^2 = .77$, and *illusory size*, $F(1, 29) = 35.41$, $p < .001$, $\eta_p^2 = .55$, reflect that mean size judgments increased with physical central circle size (4°: 32.3, 6°: 44.9, 8°: 58.2) and illusory central circle size (small: 41.4, large: 48.8). Our stimulus material thus elicited the Ebbinghaus size illusion. Figure 3 illustrates that this spatial illusion was present across all physical sizes. The interaction was not significant, $F(2, 58) = 0.16$, $p = .777$, $\eta_p^2 = .01$.

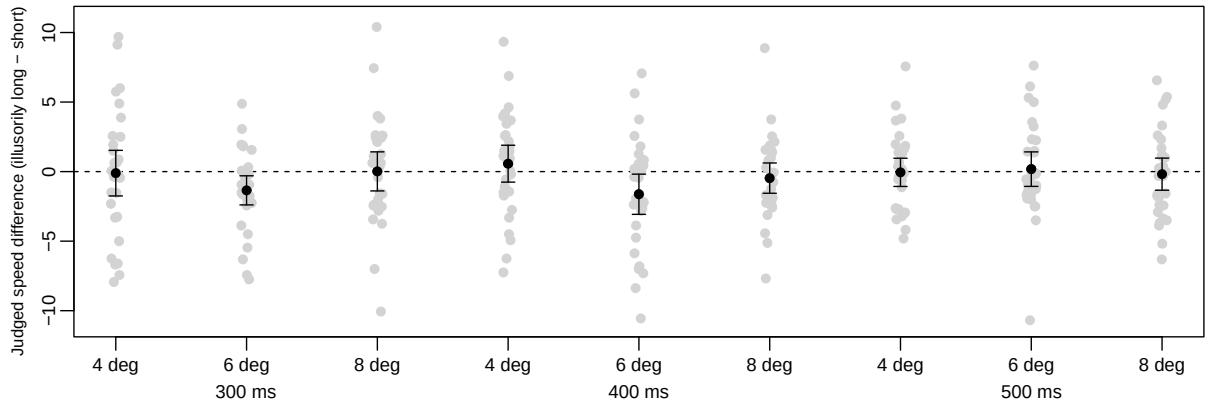
Speed judgments. Significant main effects of *physical distance* (4°: 51.6, 6°: 59.9, 8°: 66.9), $F(2, 58) = 105.02$, $p < .001$, $\eta_p^2 = .78$, and *physical duration* (300 ms: 72.5, 400 ms: 58.4, 500 ms: 47.5), $F(2, 58) = 201.15$, $p < .001$, $\eta_p^2 = .87$, confirmed that observers were sensitive to the physical speed manipulations. However, importantly, the main effect of *illusory distance* was not significant, $F(1, 29) = 0.01$, $p = .918$, $\eta_p^2 < .01$, reflecting statistically indistinguishable mean speed judgments for illusorily small central circles (large inducer circles; 59.5) and illusorily large central circles (small inducer circles; 59.4). Figure 5 reveals that this difference in judged speed was not significant across all physical conditions. The interaction between *physical distance* and *physical duration*, $F(4, 116) = 3.38$, $p = .012$, $\eta_p^2 = .10$, reflects that mean speed judgments were least sensitive to physical distance when the physical duration was shortest. No other interaction was significant (all *p*s > .117).

Discussion

Contrary to the distance/duration rule, the spatial Müller-Lyer and Ebbinghaus illusions were not accompanied by the predicted speed illusions in Experiments 1a–b. One possible explanation for this outcome is that absolute judgments were insensitive to small differences in perceived movement speed

Figure 4

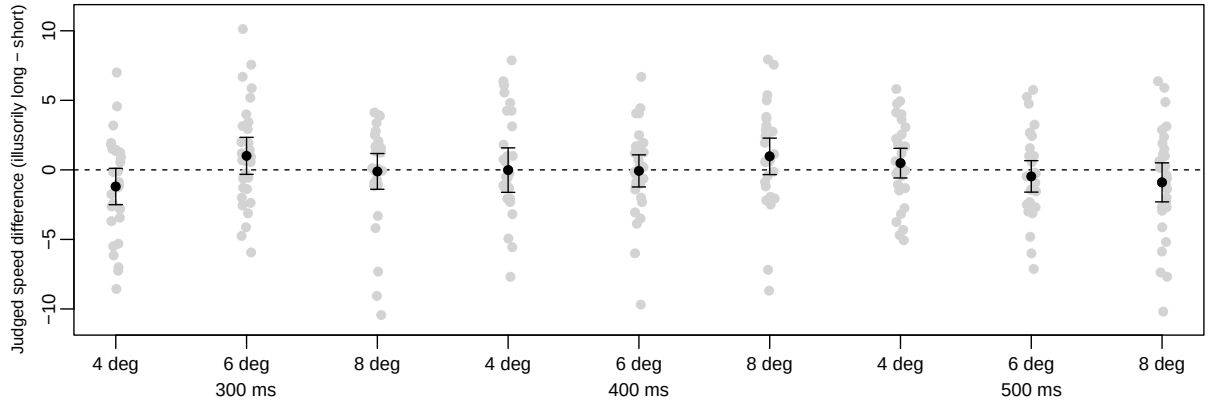
Difference in judged speed over illusorily long versus short distances induced by Müller-Lyer figures as a function of physical distance and duration in Experiment 1a



Note. Black points are means across observers, gray points are individual values, and error bars are 95% confidence intervals.

Figure 5

Difference in judged speed over illusorily long versus short distances induced by Ebbinghaus figures as a function of physical distance and duration in Experiment 1b



Note. Black points are means across observers, gray points are individual values, and error bars are 95% confidence intervals. One individual outlier is not shown (−13.7; 4 deg and 400 ms) but was included in the statistical analysis.

over illusorily short and long distances. This is conceivable because observers may rely on a limited set of particularly informative cues when making absolute speed judgments, such as the registered physical distance and duration levels and the registered speed difference between previous and current trials, especially given the large trial-by-trial variation in physical distance and duration in Experiments 1a–b. However, in this case, direct comparisons between two movements over an illusorily short versus long distance should uncover the predicted Müller-Lyer and Ebbinghaus speed illusions.

Experiments 2a–b: Binary comparative speed judgments

Experiments 2a–b conceptually replicated Experiments 1a–b with binary comparative (instead of absolute) speed judgments to reveal potential speed illusions in direct stimulus comparisons and quantify them via the point of subjective equality (PSE).

Method

Observers

Thirty observers (24 women, 29 right-handers, mean age: 22 years, age range: 18–34 years) completed Experiments 2a and 2b in two separate one-hour sessions.

Apparatus and stimuli

The stimuli were presented on a 60 Hz monitor (2,560 × 1,440 pixels, 27 in.) and viewed from a distance of about 60 cm in a quiet environment. In a two-alternative forced-choice task, two movements were presented sequentially in each trial, the first serving as the standard and the second as the comparison. Observers judged whether the first (standard) or second (comparison) movement appeared faster. The standard and comparison movements covered the same physical distance (both 4° or both 8°), but the standard (comparison) movement was illusorily short (long) or vice versa. Whereas the standard movement duration was fixed (300 or 500 ms), the comparison movement duration was determined by an adaptive-staircase procedure.

Procedure

The PSE was estimated using the weighted up-down adaptive-staircase procedure (Kaernbach, 1991). Specifically, for each experimental condition, two separate staircases targeted the points $X_{.25}$ and $X_{.75}$ of the psychometric function representing the probability of judging the comparison speed (second stimulus) as faster than the standard speed (first stimulus) as a function of the comparison speed. Thus, $X_{.25}$ and $X_{.75}$ reflect the comparison speeds judged to be faster than the standard speed with probabilities of 25% and 75%. The staircase targeting $X_{.25}$ (lower run) started with a comparison speed of two-thirds of the standard speed, which was increased by one step after responding "standard faster" and decreased by three steps after responding "comparison faster". The staircase targeting $X_{.75}$ (upper run) started with a comparison speed of four-thirds of the standard speed, which was increased by three steps after responding "standard faster" and decreased by one step after responding "comparison faster". Comparison speed was increased (decreased) by decreasing (increasing) the movement duration, with a single step size of 17 ms.

Two adaptive staircases with 40 trials each were administered for each of the eight experimental conditions (two physical standard distances × two physical standard durations × two illusory standard distances). All 16 staircases were intermixed. Each session comprised 640 trials (separated in 16 blocks with 40 trials each). The Müller-Lyer figure (Experiment 2a) and the Ebbinghaus figure (Experiment 2b) were used in two sessions on separate days, with session order counterbalanced across observers.

Each trial started with the Müller-Lyer/Ebbinghaus figure (500 ms), followed by the standard movement (300 or 500 ms), a blank screen (ISI; 500 ms), the Müller-Lyer/Ebbinghaus figure (500 ms), the comparison movement (variable duration), the prompt "1 or 2 faster?" (until response), and another blank screen (ITI; 1,000 ms). The dot onsets coincided with the movement onsets.

Analysis

The estimates $\hat{X}_{.25}$ and $\hat{X}_{.75}$ were obtained by averaging the reversals in each staircase, and a PSE estimate (i.e., $\hat{X}_{.50}$) was then obtained by averaging $\hat{X}_{.25}$ and $\hat{X}_{.75}$. We did not estimate $X_{.50}$ directly to move the staircases away from the guessing regime and thereby reduce the contribution of response bias if standard and comparison speeds were indiscriminable. The resulting PSE estimates were submitted to three-way ANOVAs with the within-subjects factors *physical standard distance* (4 or 8°), *physical standard duration* (300 or 500 ms), and *illusory standard distance* (short or long).

Results

Figure 6 presents the speed PSE differences observed in Experiments 2a–b.

Müller-Lyer illusion (Experiment 2a)

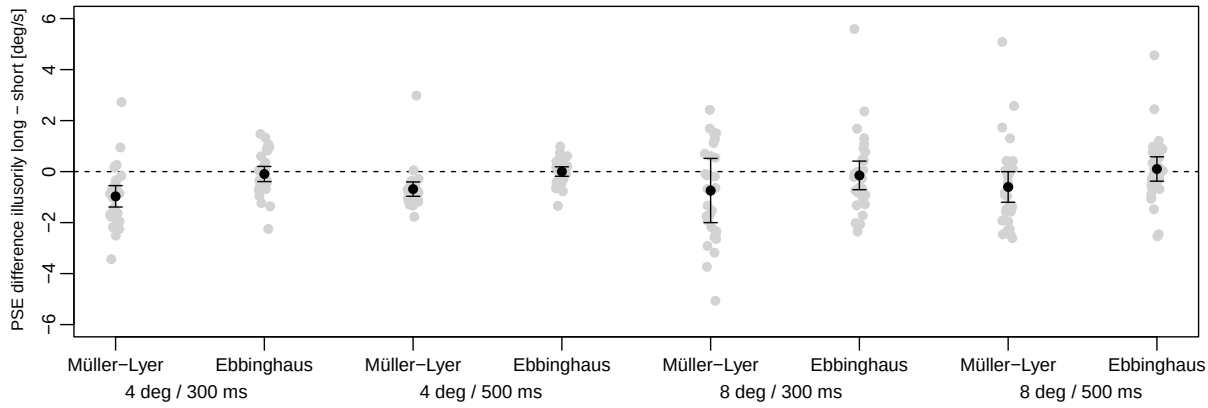
Significant main effects of *physical standard distance*, $F(1, 29) = 1949.50$, $p < .001$, $\eta_p^2 = .99$, and *physical standard duration*, $F(1, 29) = 492.22$, $p < .001$, $\eta_p^2 = .94$, on the PSE reflect that comparison speed had to be increased to match higher standard distance (4°: 10.1 deg/s, 8°: 18.5 deg/s) but decreased to match higher standard duration (300 ms: 17.1 deg/s, 500 ms: 11.5 deg/s). These factors also interacted, $F(1, 29) = 156.20$, $p < .001$, $\eta_p^2 = .84$, reflecting that the mean speed PSE was less sensitive to the physical standard distance when the physical standard duration was shorter. The main effect of *illusory standard distance* was significant, $F(1, 29) = 7.46$, $p = .011$, $\eta_p^2 = .20$. However, unexpectedly, this effect reflects that a *lower* comparison speed was needed to match the standard speed over illusorily long (13.9 deg/s) versus short distance (14.7 deg/s). No other effect was significant (all ps > .444).

Ebbinghaus illusion (Experiment 2b)

The mean speed PSE was again significantly shaped by *physical standard distance* (4°: 10.0 deg/s, 8°: 18.8 deg/s), $F(1, 29) = 3335.91$, $p < .001$, $\eta_p^2 = .99$, and *physical standard duration* (300 ms: 16.9 deg/s, 500 ms: 11.8 deg/s), $F(1, 29) = 396.55$, $p < .001$, $\eta_p^2 = .93$. The interaction of these factors, $F(1, 29) = 195.42$, $p < .001$, $\eta_p^2 = .87$, again reflects a weaker influence of physical standard distance for the shorter physical standard duration. Importantly, the main effect of *illusory standard distance* was not significant, $F(1, 29) = 0.06$, $p = .806$, $\eta_p^2 < .01$, reflecting that the mean comparison speeds needed to match the standard speed over illusorily short and long distances (both 14.4 deg/s) are statistically indistinguishable. In addition, no other effect was significant (all ps > .273).

Figure 6

Differences in speed PSEs over illusorily long versus short distances induced by Müller-Lyer and Ebbinghaus figures in Experiments 2a–b



Note. Black points are means across observers, gray points are individual values, and error bars are 95% confidence intervals. Two individual outliers are not shown (−9.4 and 12.9 deg/s; both in the condition with the Müller-Lyer illusion, 8 deg distance, and 300 ms duration) but were included in the statistical analysis.

Discussion

Contrary to the prediction of the distance/duration rule, movements over illusorily long distances were not judged as significantly faster than movements over illusorily short distances in Experiments 2a–b. In contrast to the null effect with the Ebbinghaus illusion, the Müller-Lyer illusion even produced a small but significant effect in the opposite direction, which may indicate residual velocity-transposition confounds in this configuration. Binary comparative judgments thus also did not reveal the predicted Müller-Lyer and Ebbinghaus speed illusions.

Our final methodological concern was that binary comparisons ("first or second speed faster?") force observers to guess when uncertain about which movement was faster. Although the staircases in Experiments 2a–b targeted the points $X_{.25}$ and $X_{.75}$ of the psychometric function (instead of $X_{.50}$) to reduce the frequency of guessing, speed differences were still hard to discriminate in many trials. This makes PSE differences in binary comparative judgments bias-prone because the PSE can be shifted by the tendency to report the movement over the illusorily short/long distance as faster in the case of perceptual indiscriminability (e.g., Kelber & Ulrich, 2025b). Such response biases can be minimized by allowing observers to report that the perceived speeds were identical as a third choice option (for a different approach, see Meyerhoff et al., 2023). This ternary response format has proven informative in several psychophysical domains, such as temporal-order judgment (García-Pérez & Alcalá-Quintana, 2012a; Kelber & Ulrich, 2024, 2026; Sternberg et al., 2026; Ulrich, 1987), duration discrimination (García-Pérez, 2014; Rammsayer & Ulrich, 2001), and contrast discrimination (Alcalá-Quintana & García-Pérez, 2011; García-Pérez & Alcalá-Quintana, 2013).

Experiments 3a–b: Ternary comparative speed judgments

Experiments 3a–b conceptually replicated Experiments 2a–b with ternary (instead of binary) comparative speed judgments to minimize potential biases of the PSE due to guessing tendencies when the movement speeds over illusorily short versus long distances are perceptually indiscriminable.

Method

Observers

Thirty observers (19 women, 28 right-handers, mean age: 25 years, age range: 19–37 years) completed Experiments 3a and 3b in two separate 1.5-hour sessions.

Apparatus and stimuli

All stimuli were presented on a 120 Hz monitor (1,920 × 1,080 pixels, 24 in.) and viewed from a chinrest (distance: 53 cm) in a dimly lit booth. Both standard and comparison movements covered a physical distance of 6°, but the standard (comparison) distance was illusorily short (long) or vice versa. The standard movement duration was 400 ms, and the comparison movement ranged from 300 to 600 ms (nine levels: 300, 317, 342, 367, 400, 433, 483, 533, and 600 ms). As a result, the standard speed was 15 deg/s, and the comparison speed ranged from 10 to 20 deg/s in steps of about 1.25 deg/s. The physical speed difference thus varied between −5 and 5 deg/s.

Observers judged whether the first (standard) or second (comparison) movement appeared faster, or whether their perceived speeds were identical. Responses were given with a button box, where the left button indicated "first faster", the central button "same speed", and the right button "second faster". Stickers with the symbols "1", "=", and "2" were affixed to the left, central, and right button, respectively, to provide an intuitive stimulus-response mapping and thus minimize response errors (see García-Pérez & Alcalá-Quintana, 2012b; Kelber & Ulrich, 2025a).

Procedure

The trial course was analogous to Experiments 2a–b. Each of the 18 trial types (two illusory standard distances × nine physical comparison durations) was presented three times in each block. The resulting 54 trials per block were presented in random order. Each of the two sessions per observer comprised 20 blocks (i.e., $20 \times 3 = 60$ trials per condition, and $20 \times 54 = 1{,}080$ trials per session).

Analysis

The PSE was estimated separately for illusorily short and long standard distances, using a parametric and a non-parametric approach to determine the robustness of our inferences.

For the parametric PSE estimation, we developed a speed-indiscriminability (SPIN) model based on the following three assumptions: First, the perceived speed difference between standard s and comparison c, $\mathbf{\Delta v} = \mathbf{v}_c - \mathbf{v}_s$, can be decomposed into the sum of the true (recovered physical) speed difference, Δv_Φ, and the illusory (psychologically introduced) speed difference, $\mathbf{\Delta v}_\Psi$. Thus, $\mathbf{\Delta v} = \Delta v_\Phi + \mathbf{\Delta v}_\Psi$. Second, the illusory speed difference is subject to trial-by-trial variability due to neural noise. For convenience, the illusory speed difference is modeled as a normally distributed random variable, $\mathbf{\Delta v}_\Psi \sim N(\mu, \sigma^2)$. Third, the perceived speed difference $\mathbf{\Delta v}$ is only considered reliable by the observer if it reaches a constant boundary b (i.e., criterion or threshold). Thus, given a ternary response format, s is reported to be faster than c if $\mathbf{\Delta v} \leq -b$, c is reported to be faster than s if $\mathbf{\Delta v} \geq b$, and the speeds of s and c are reported to be identical if $-b < \mathbf{\Delta v} < b$. Closed-form expressions of the response probabilities predicted by the SPIN model are derived in the Appendix.

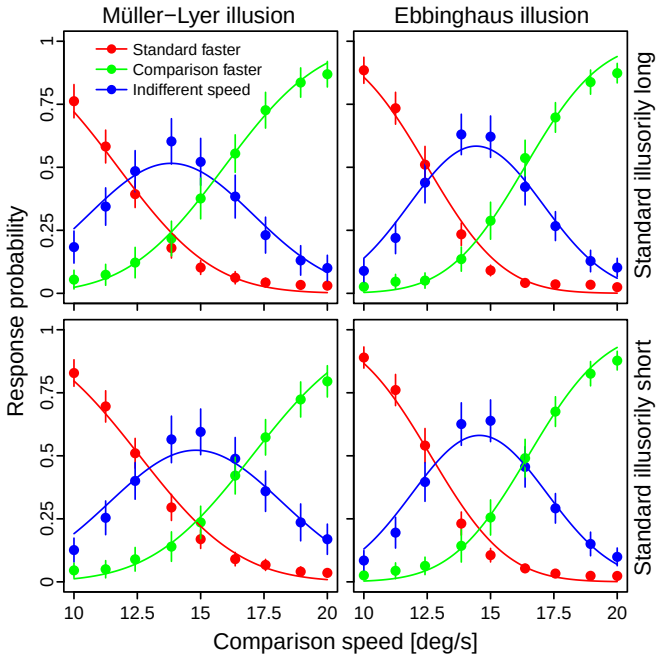
Taken together, the SPIN model comprises the free parameters μ, σ, and b, where PSE $= s - \mu$. The SPIN model was fitted to the individual data by minimizing the likelihood-ratio goodness-of-fit statistic G^2 using the numerical search algorithm `L-BFGS-B`. This algorithm searched the three-dimensional parameter space ($\mu = [-10,\ 10]$, $\sigma = [0,\ 10]$, $b = [0,\ 10]$), starting from the initial position ($\mu = 0$, $\sigma = 1$, $b = 2$), with all values in deg/s.

For the non-parametric PSE estimation, we applied the modified Spearman-Kärber method (Kärber, 1931; Spearman, 1908; Sternberg et al., 1982). This method has been described in detail elsewhere (Miller & Ulrich, 2001; Ulrich & Miller, 2004). Here we considered the two psychometric functions generated by the ternary response format: the left function including "same" judgments, $F_\mathrm{L} = P(\text{"}c\text{ faster" or "same"} \mid c)$, and the right function excluding "same" judgments, $F_\mathrm{R} = P(\text{"}c\text{ faster"} \mid c)$. We then used the Spearman-Kärber method to estimate the expected values of the random variables associated with F_L and F_R, and averaged these two values to arrive at the PSE. The Spearman-Kärber method does not rest on distributional assumptions but only requires that the true psychometric functions increase monotonically from 0 to 1. Therefore, the observed individual psychometric functions were monotonized (Ayer et al., 1955), when necessary, and assumed to reach 0 and 1 at the extreme physical speed differences of −7 and 7 deg/s (i.e., comparison speeds of 8 and 22 deg/s) outside the tested range of physical speed differences between −5 and 5 deg/s (i.e., comparison speeds between 10 and 20 deg/s).

The parametric and non-parametric PSE estimates were submitted to separate one-way ANOVAs with the within-subjects factor *illusory standard distance* (short or long).

Figure 7

Group-level psychometric functions observed in Experiments 3a–b and fitted by the SPIN model



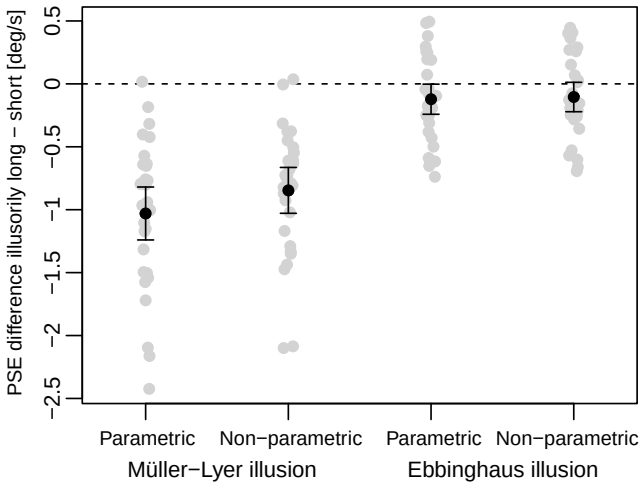
Note. Error bars reflect 95% confidence intervals. As the standard speed was 15 deg/s, the x-axis can also be represented as the physical speed difference between comparison and standard, ranging from −5 to 5 deg/s.

Results

Figure 7 summarizes the fits of the SPIN model to the observed psychometric functions. Chi-square goodness-of-fit tests revealed non-significant deviations between observed and fitted individual data in 94 of 120 cases (30 observers × two illusions × two illusory standard distances). Visual inspection of the significant misfits (21.7%) did not hint at systematic or consistent patterns of the model–data mismatch but rather at noisy psychometric functions for some observers. Figure 8 visualizes the estimated speed PSE differences, revealing a close agreement between the parametric approach (SPIN model) and the non-parametric approach (Spearman-Kärber method).

Figure 8

Differences in speed PSEs over illusorily long versus short distances induced by Müller-Lyer and Ebbinghaus figures in Experiments 3a–b



Note. Black points are means across observers, gray points are individual values, and error bars are 95% confidence intervals.

Müller-Lyer illusion (Experiment 3a)

According to the parametric PSE estimates, a significantly *lower* comparison speed was needed to match the standard speed over illusorily long (13.7 deg/s) versus short distance (14.8 deg/s), $F(1, 29) = 92.14$, $p < .001$, $\eta_p^2 = .76$. The same pattern was found in the non-parametric PSE estimates (illusorily short: 14.8 deg/s, illusorily long: 14.0 deg/s), $F(1, 29) = 82.88$, $p < .001$, $\eta_p^2 = .74$.

Ebbinghaus illusion (Experiment 3b)

The parametric PSE estimates revealed a numerically—but not significantly—lower comparison speed needed to match the standard speed over illusorily long (14.4 deg/s) versus short distance (14.5 deg/s), $F(1, 29) = 3.99$, $p = .055$, $\eta_p^2 = .12$. The same pattern was found in the non-parametric PSE estimates (illusorily short: 14.6 deg/s, illusorily long: 14.5 deg/s), $F(1, 29) = 3.07$, $p = .090$, $\eta_p^2 = .10$.

Discussion

Even when minimizing potential guessing biases by using a ternary response format in Experiments 3a–b, the predicted Müller-Lyer and Ebbinghaus speed illusions did not materialize. Instead, we found a reverse effect for the Müller-Lyer illusion (faster perceived movement speed over apparently shorter lines), replicating the pattern in Experiment 2. This may indicate that, unlike absolute judgments, comparative judgments were sensitive to residual influences of velocity transposition in Müller-Lyer figures.[1] However, irrespective of whether there is no perceived speed difference or whether it goes in the unexpected direction, Experiments 1–3 provide consistent evidence against the predicted Müller-Lyer and Ebbinghaus speed illusions across absolute, binary comparative, and ternary comparative judgments.

Does this robust outcome imply that speed perception violates the distance/duration rule or that the predictions rest on an invalid auxiliary assumption? A critical question is whether the Müller-Lyer and Ebbinghaus distance illusions are accompanied by *proportional* duration illusions due to space–time interference (e.g., Bratzke, 2024; Ono & Kawahara, 2007), as this would eliminate perceived speed differences given the distance/duration rule. Experiments 4–5 evaluated whether the distance/duration rule can be rescued by this proportionality explanation.

Experiments 4a–b: Absolute judgments of distance, duration, and speed

Experiments 4a–b used absolute judgments to test whether the Müller-Lyer and Ebbinghaus distance illusions are accompanied by duration illusions in the direction expected based on space–time interference. Accordingly, transits of moving dots over illusorily longer distances should appear to last longer. This would conceptually replicate previous findings (e.g., Bratzke, 2024; Ono & Kawahara, 2007) and extend this line of evidence for space–time interference to our dynamic stimuli. Importantly, the directional alignment

[1] Why might velocity transposition lead to lower perceived speeds over illusory longer distances in Müller-Lyer figures, but not in Ebbinghaus figures? One speculative possibility is that different aspects of the Müller-Lyer and Ebbinghaus figures influenced the extent of the spatial reference frame. In Müller-Lyer figures, the apparent length of the horizontal line may have dominated this reference frame, potentially leading to slower perceived motion over illusorily longer distances. In Ebbinghaus figures, by contrast, an analogous influence of the apparent central circle size on the reference frame might have been counteracted by an opponent influence of the inducer circle size.

of distance and duration illusions is a necessary but insufficient condition for their proportionality, as required to reconcile the distance/duration rule with absent speed illusions. Although Experiments 4a–b thus cannot establish the proportionality of distance and duration illusions, it can falsify proportionality by evaluating a necessary condition.

Besides distance and duration, observers also rated speed to confirm that absolute speed judgments reveal null effects of illusory distance (as in Experiments 1a–b). Five movement distances were fully crossed with five movement durations in each task to create a broad and apparently continuous stimulus space. This design also allowed us to examine whether the lack of speed illusions observed in Experiments 1a–b extends to a wider range of physical movement conditions. Each observer gave absolute judgments of distance, duration, and speed in separate experimental parts to avoid biases due to strategic responding.

Method

Observers

Thirty observers (25 women, 27 right-handers, mean age: 27 years, age range: 20–44 years) completed Experiments 4a and 4b in two separate 1.5-hour sessions. One observer misunderstood the task instructions, as became apparent during later interactions with the experimenter. The data from this observer were therefore excluded from all analyses. Including these data led to the same statistical inferences.

Apparatus and stimuli

Each trial involved a single movement of a dot along the horizontal line of the Müller-Lyer figure (Experiment 4a) or around the central circle of the Ebbinghaus figure (Experiment 4b). Physical distance (4, 5, 6, 7, or 8°), physical duration (300, 350, 400, 450, or 500 ms), and illusory distance (short or long) were varied within each block. Observers used the same slider scale (0–100) to rate movement distance, duration, and speed.

Procedure

The trial course was analogous to Experiments 1a–b. Every observer completed two sessions (Müller-Lyer and Ebbinghaus illusions), each consisting of three parts (distance, duration, and speed judgment), with five 50-trial blocks per part (five physical distances × five physical durations × two illusory distances). The order of sessions and parts was counterbalanced across observers.

Analysis

The mean distance, duration, and speed judgments were submitted to separate ANOVAs with the three within-subjects factors *physical distance*, *physical duration*, and *illusory distance*.

Results

Figure 9 reveals that, collapsed across all physical conditions, significant Müller-Lyer and Ebbinghaus distance illusions were accompanied by significant duration illusions, whereas there were again no significant speed illusions. Including the factors *physical distance* and *physical duration* in the ANOVAs led to the same picture (see details below).

Müller-Lyer illusion (Experiment 4a)

Distance judgments. Significant main effects of *physical distance*, $F(4, 112) = 702.03$, $p < .001$, $\eta_p^2 = .96$, and *illusory distance*, $F(1, 28) = 332.08$, $p < .001$, $\eta_p^2 = .92$, reflect that mean distance judgments increased with physical line length (4°: 31.1, 5°: 44.7, 6°: 56.4, 7°: 67.6, 8°: 77.6) and illusory line length (short: 47.3, long: 63.6). No other effect was significant (all ps > .083).

Duration judgments. Significant main effects of *physical duration*, $F(4, 112) = 116.26$, $p < .001$, $\eta_p^2 = .81$ and *illusory distance*, $F(1, 28) = 28.80$, $p < .001$, $\eta_p^2 = .51$, reflect that mean duration judgments increased with physical travel time (300 ms: 33.1, 350 ms: 40.2, 400 ms: 46.9, 450 ms: 53.2, 500 ms: 58.6) and illusory line length (short: 44.1, long: 48.7). Unexpectedly, the main effect of *physical distance*, $F(4, 112) = 7.82$, $p = .005$, $\eta_p^2 = .22$, reflects that mean duration judgments decreased with physical line length (4°: 49.6, 5°: 48.6, 6°: 47.4, 7°: 44.2, 8°: 42.2). The interaction between *physical duration* and *physical distance*, $F(16, 448) = 2.73$, $p < .001$, $\eta_p^2 = .09$, reflects that mean duration judgments were least sensitive to physical duration for the shortest physical distance. No other interaction was significant (all ps > .083).

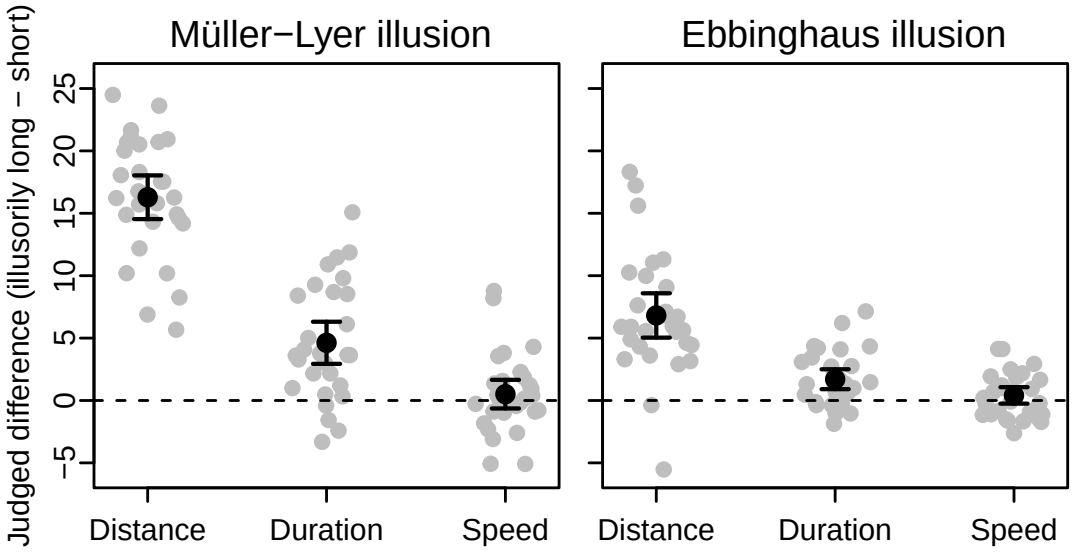
Speed judgments. As expected, significant main effects of *physical distance*, $F(4, 112) = 391.46$, $p < .001$, $\eta_p^2 = .93$, and *physical duration*, $F(4, 112) = 245.35$, $p < .001$, $\eta_p^2 = .90$, reflect that mean speed judgments increased with physical line length (4°: 40.1, 5°: 49.5, 6°: 58.1, 7°: 64.8, 8°: 69.8) and decreased with physical travel time (300 ms: 72.0, 350 ms: 64.0, 400 ms: 55.4, 450 ms: 48.5, 500 ms: 42.6). Replicating Experiment 1a, the main effect of *illusory distance* on mean speed judgments was not significant (illusorily short: 56.2, illusorily long: 56.7), $F(1, 28) = 0.75$, $p = .394$, $\eta_p^2 = .03$. No interaction was significant (all ps > .054).

Ebbinghaus illusion (Experiment 4b)

Distance judgments. Significant main effects of *physical distance*, $F(4, 112) = 483.40$, $p < .001$, $\eta_p^2 = .95$, and *illusory distance*, $F(1, 28) = 56.51$, $p < .001$, $\eta_p^2 = .67$, reflect that mean distance judgments increased with physical central

Figure 9

Judged differences in perceived distance, duration, and speed between illusorily long and short distances induced by the Müller-Lyer and Ebbinghaus figures in Experiments 4a–b



Note. Black points are means across observers, gray points are individual data, and error bars are 95% confidence intervals. The depicted values are averages across all 25 physical conditions.

circle size (4°: 17.5, 5°: 29.7, 6°: 42.4, 7°: 55.0, 8°: 67.5) and illusory central circle size (short: 39.0, long: 45.8). The main effect of *physical duration* also reached significance (300 ms: 42.0, 350 ms: 42.7, 400 ms: 42.3, 450 ms: 42.3, 500 ms: 42.9), $F(4, 112) = 2.56$, $p = .043$, $\eta_p^2 = .08$. The interaction between *physical distance* and *illusory distance*, $F(4, 112) = 24.83$, $p < .001$, $\eta_p^2 = .47$, indicates that the spatial Ebbinghaus illusion observed in absolute judgments increases with physical central circle size (4°: 2.6, 5°: 4.1, 6°: 7.5, 7°: 9.3, 8°: 10.7). No other interaction was significant (all ps > .363).

Duration judgments. Significant main effects of *physical duration*, $F(4, 112) = 83.16$, $p < .001$, $\eta_p^2 = .75$, *physical distance*, $F(4, 112) = 4.49$, $p = .036$, $\eta_p^2 = .14$, and *illusory distance*, $F(1, 28) = 17.51$, $p < .001$, $\eta_p^2 = .38$, reflect that mean duration judgments increased with physical travel time (300 ms: 27.2, 350 ms: 34.6, 400 ms: 42.8, 450 ms: 50.7, 500 ms: 56.9), physical central circle size (4°: 38.9, 5°: 41.3, 6°: 42.6, 7°: 44.3, 8°: 45.1) and illusory central circle size (short: 41.6, long: 43.3). The interaction between *physical distance* and *illusory distance* also reached significance, $F(4, 112) = 2.51$, $p = .046$, $\eta_p^2 = .08$, suggesting that the temporal Ebbinghaus illusion in absolute judgments varies across the physical central circle sizes (4°: 0.7, 5°: 0.7, 6°: 2.7, 7°: 2.9, 8°: 1.6). No other interaction was significant (all ps > .341).

Speed judgments. As expected, significant main effects of *physical distance*, $F(4, 112) = 74.25$, $p < .001$, $\eta_p^2 = .73$, and *physical duration*, $F(4, 112) = 225.77$, $p < .001$, $\eta_p^2 = .89$, reflect that mean speed judgments increased with physical central circle size (4°: 47.2, 5°: 52.6, 6°: 56.6, 7°: 60.2, 8°: 62.8) and decreased with physical travel time (300 ms: 75.2, 350 ms: 65.9, 400 ms: 55.3, 450 ms: 45.6, 500 ms: 37.5). Replicating Experiment 1b, the main effect of *illusory distance* on mean speed judgments was not significant (illusorily short: 55.7, illusorily long: 56.1), $F(1, 28) = 1.46$, $p = .237$, $\eta_p^2 = .05$. The interaction between *physical distance* and *physical duration*, $F(16, 448) = 5.62$, $p < .001$, $\eta_p^2 = .17$, reflects that the effect of physical central circle size on mean speed judgments varied with physical travel time. No other interaction was significant (all ps > .096).

Discussion

In line with previous findings (Bratzke, 2024; Bratzke et al., 2024; Ono & Kawahara, 2007), the Müller-Lyer and Ebbinghaus distance illusions were accompanied by directionally aligned duration illusions in Experiments 4a–b. Further, absolute judgments again did not reveal speed illusions. This could be reconciled with the distance/duration rule if distance and duration illusions were proportional. The presence of duration illusions for dynamic stimuli moving on Müller-Lyer and Ebbinghaus configurations satisfies a necessary condition for this proportionality explanation. However, the exact coordination functions (Dunn & Anderson, 2026) relating the latent variables of interest (i.e., perceived

distance, duration, and speed) to the observed absolute judgments are unknown (except for monotonicity). Therefore, the data from Experiments 4a–b do not allow for a strong test of proportionality.

Experiments 5a–b: Binary comparative judgments of distance and duration

If the Müller-Lyer and Ebbinghaus distance and duration illusions are proportional, there should be a comparison that matches a given illusorily long standard in both perceived distance and perceived duration. In Experiments 5a–b, we tested this prediction by determining the PSEs for distance and duration discrimination with identical physical stimuli using binary comparative judgments and an adaptive-staircase procedure, standardizing the PSE estimates by the respective physical standard, and examining whether the resulting "illusion factors" are statistically indistinguishable for distance and duration discrimination.

Method

Observers

Thirty-two observers (26 women, 27 right-handers, mean age: 26 years, age range: 18–42 years) completed Experiments 5a–b within a single one-hour session. The sample size was increased from 30 to 32 to counterbalance four sequences of experimental conditions evenly across observers.

Apparatus and stimuli

The standard movement covered a physical distance of 6°, which was illusorily long, in a physical duration of 400 ms. In the distance (duration) discrimination task, the comparison movement distance (duration) was varied using the weighted up-down adaptive-staircase procedure with a single step size of 0.2° (17 ms). The comparison movement distance was illusorily short, and the comparison movement distance (duration) was physically identical to the standard movement distance (duration) in the duration (distance) discrimination task. Two staircases for each experimental condition targeted $X_{.25}$ and $X_{.75}$ (as in Experiments 2a–b). The temporal order of standard and comparison varied randomly across trials, and their spatial positions within a central region were jittered independently in each trial. Observers judged whether the first or the second movement covered a longer distance (distance discrimination) or took longer (duration discrimination).

Procedure

The trial course was analogous to Experiments 2a–b. Four (two stimulus orders × two staircase runs) 40-trial staircases per experimental part were interleaved in four 40-trial blocks. The order of the four experimental parts (two tasks × two illusions) was counterbalanced across observers, with the constraint that the two distance parts and the two duration parts were always completed in direct succession.

Analysis

The PSE estimates ($\hat{X}_{.50} = (\hat{X}_{.25} + \hat{X}_{.75}) / 2$) for distance and duration discrimination were standardized by dividing them by the standard distance and duration, respectively. The resulting illusion factors I were submitted to ANOVAs with the within-subjects factor *dimension* (distance or duration).[2] Additional one-sample t-tests (one-sided) on the illusion factors examined whether the expected distance and duration illusions ($E(I) > 1$) are significant (H_0: $E(I) \leq 1$).

Results

Figure 10 compares the observed illusion factors for distance and duration discrimination.

Müller-Lyer illusion (Experiment 5a)

A significant distance illusion ($M = 1.26$), $t(31) = 22.52$, $p < .001$, $d = 3.98$, was accompanied by a significant duration illusion ($M = 1.09$), $t(31) = 8.62$, $p < .001$, $d = 1.52$. However, the illusion factors differed significantly, $F(1, 31) = 116.19$, $p < .001$, $\eta_p^2 = .79$, suggesting that the Müller-Lyer distance and duration illusions are not proportional.

Ebbinghaus illusion (Experiment 5b)

A significant distance illusion ($M = 1.15$), $t(31) = 9.00$, $p < .001$, $d = 1.59$, was accompanied by a significant duration illusion ($M = 1.03$), $t(31) = 3.25$, $p < .001$, $d = 0.57$. However, the illusion factors differed significantly, $F(1, 31) = 58.79$, $p < .001$, $\eta_p^2 = .65$, suggesting that the Ebbinghaus distance and duration illusions are not proportional.

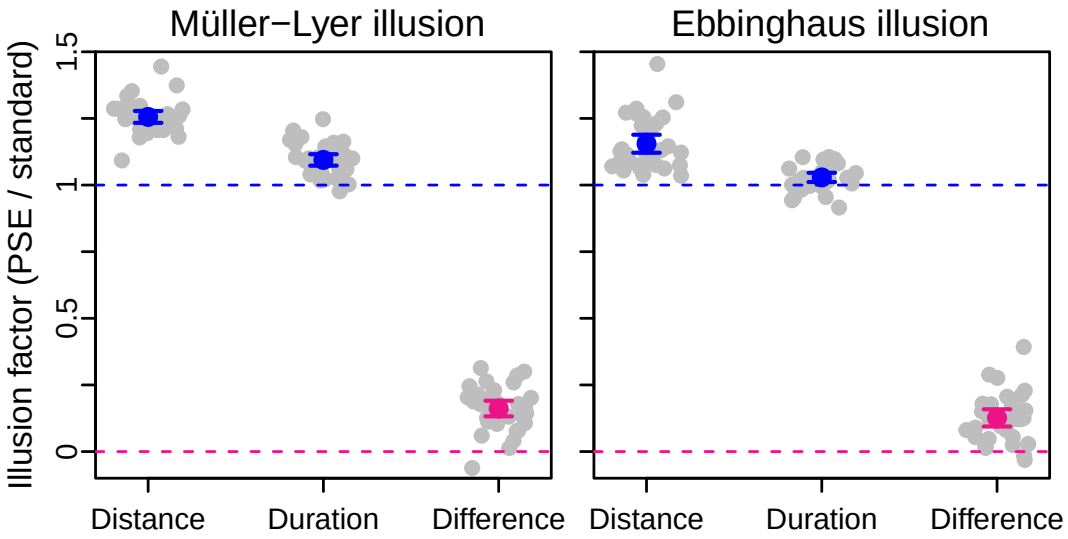
Discussion

Experiments 5a–b indicated that differently extreme comparisons are needed to match the same, illusorily long standard in perceived distance and perceived duration, consistently across Müller-Lyer and Ebbinghaus illusions. This provides evidence against the proportionality of Müller-Lyer and Ebbinghaus distance and duration illusions. It thus seems that although space–time interference would counteract the Müller-Lyer and Ebbinghaus speed illusions predicted by the distance/duration rule, it cannot fully explain their absence

[2] We reached identical statistical decisions about the differences between the illusion factors in distance and duration discrimination when also including the within-subjects factor *stimulus order* (standard or comparison first).

Figure 10

Müller-Lyer and Ebbinghaus distance and duration illusions in Experiments 5a–b



Note. Colored [dark] points are means across observers, gray points are individual values, and error bars are 95% confidence intervals.

(or their reversal in Experiments 2–3a). Therefore, Experiments 5a–b arguably provide the strongest, yet certainly not definitive, evidence to date against the view that speed equals distance over duration in perception.

General discussion

The present study investigated the functional relation between the perceptual dimensions of distance, duration, and speed by testing whether illusions in perceived movement distance carry over to perceived speed—as one would expect if speed perception adheres to the distance/duration rule—and whether the predicted space-to-speed transfer is offset by space–time interference. Three experiments consistently refuted the prediction that movements appear faster along an illusorily longer horizontal line of the Müller-Lyer figure (Experiments 1–3a) or around an illusorily larger central circle of the Ebbinghaus figure (Experiments 1–3b) across a variety of psychophysical judgments (Experiment 1: absolute judgments, Experiment 2: binary comparative judgments, Experiment 3: ternary comparative judgments). Comparative judgments even revealed a reverse tendency for the Müller-Lyer illusion—slower perceived movement speeds over illusorily long distances—rather pointing to velocity transposition (Pavlova & Sokolov, 2000) than to a distance/duration rule.

The absence of the predicted speed illusions can be reconciled with the distance/duration rule if illusions in movement distance are accompanied by proportional illusions in movement duration. Two experiments consistently revealed that distance illusions elicited by Müller-Lyer (Experiments 4–5a) and Ebbinghaus figures (Experiments 4–5b) were accompanied by directionally aligned duration illusions across absolute (Experiment 4) and binary comparative judgments (Experiment 5). This replicates and extends previous findings (Bratzke, 2024; Bratzke et al., 2024; Ono & Kawahara, 2007). However, importantly, the illusions in movement duration did not appear to be proportional to those in movement distance, as Experiment 5 revealed significantly larger illusion factors for distance discrimination than for duration discrimination. Together, the five experiments pose a problem for the intuitive notion that perceived linear or circular movement speed reflects the perceived movement distance traveled in the perceived movement duration.

The consistent findings across five two-part experiments have several important theoretical implications. First, they challenge the simple view that perceived speed is derived from perceived distance and duration. Instead, speed appears to be a more fundamental dimension of perceptual experience in the sense that perceived speed does not seem to be directly related to perceived distance and duration. However, this does not rule out the view that perceived speed is derived from lower-level spatial and temporal representations unaffected by the presented Müller-Lyer and Ebbinghaus configurations. Second, the absence of cross-dimensional illusion carry-over from distance to speed is difficult to reconcile with the idea of a general magnitude-processing system (Walsh, 2003), which should produce bidirectional interference between quantitative perceptual dimensions. Our findings suggest that speed is not processed in such a general magnitude system or that the relevant speed computations in this system

operate on lower-level spatial representations, which are not distorted by geometric configurations inducing distance illusions. Third, although the extreme view that perceived speed corresponds exactly to the ratio of perceived distance to perceived duration seems unrealistic and uncommon, it is notable that observers do not appear to take available distance cues into account when judging speed. This seems difficult to reconcile with the notion of optimal integration of available cues, as exemplified in Bayesian ideal-observer models of speed perception (e.g., Stocker & Simoncelli, 2006; Weiss et al., 2002). Fourth, the finding that the perception of speed—unlike duration—does not take into account higher-level distance information appears consistent with low-level explanations of speed perception, as exemplified in motion-energy models (e.g., Adelson & Bergen, 1985).

Motion-energy models translate sequences of retinal images into local velocity signals, which are likely unaffected by the more global spatial appearance evoked by Müller-Lyer and Ebbinghaus figures. Such accounts of speed perception contrast conceptually with context-dependent scaling accounts based on velocity transposition (Brown, 1931b; Pavlova & Sokolov, 2000) and raise a fundamental question: does the visual system track average or instantaneous speed? Whereas average speed reflects the total movement distance traveled in the total movement duration, instantaneous speed reflects the limit of average speed as the movement duration approaches zero. The distinction may appear irrelevant at constant speed, since the average and instantaneous speeds are then numerically identical. However, if the visual system measures speed locally (representing instantaneous speed) rather than globally (representing average speed), spatial distortions might be less impactful when they emerge only in more global perceptual representations. In this view, our findings rather suggest that perceived speed reflects local, moment-to-moment measurements of instantaneous speed. Of course, these interpretations should be treated with some caution, as the generalizability of our findings to other experimental methods and samples remains an open empirical question. At the same time, we are not aware of any a priori reasons why the conclusions about the fundamental perceptual processes under investigation should be restricted to the convenience samples tested here.

Our investigation deliberately refrained from presupposing specific mechanisms underlying the induced spatial illusions and instead focused on a systematic analysis of cross-dimensional transfer under a hypothetical distance/duration rule. Future studies may benefit from linking questions of cross-dimensional transfer more explicitly with theoretical accounts of within-dimensional illusions, such as the perspective theory proposed by Gregory (1963). This theory assumes that although visual stimuli are presented in the same frontoparallel plane at a fixed distance from the observer, they are perceived as parts of 3D space by default. To achieve size constancy, the perceived size (or length) s of visual elements (such as the line segments in the Müller-Lyer figure and the circles in the Ebbinghaus figure) follows the product of retinal size (visual angle α) and apparent distance d from the observer.[3] Thus, geometric configurations may produce illusions in s by eliciting differences in d. Müller-Lyer-like configurations in everyday life (see, e.g., Gregory, 1968, Figure 9) suggest that inward-pointing (versus outward-pointing) arrowheads make the horizontal line in the Müller-Lyer figure appear further away (i.e., d is larger for inward-pointing arrowheads than for outward-pointing arrowheads). Accordingly, the spatial Müller-Lyer illusion may partially arise from a 3D interpretation and a size-constancy mechanism (but see also Amir & Firestone, 2025; Carrasco et al., 1986; Morgan et al., 1990).

If we further assume that speed perception adheres to the distance/duration rule, differences in apparent viewing distance d should lead to speed illusions (1) irrespective of retinal size α and (2) unless they are offset by matching differences in perceived duration t. Regarding the first implication, Experiments 1, 2, and 4 consistently revealed that the differences in judged speed between illusory and long movement distances were not significantly modulated by physical size/length manipulations (see Figures 4, 5, and 6). Moreover, the second implication appears to conflict with Experiment 5, which demonstrates that the temporal illusions accompanying the spatial Müller-Lyer and Ebbinghaus illusions are too weak to account for the absence of the predicted speed illusions under the distance/duration rule.

More generally, substantial evidence suggests that the spatial Müller-Lyer and Ebbinghaus illusions involve lower-level processes and thus cannot be fully explained by the higher-level processes proposed in Gregory's perspective theory. For example, empirical support for the centroid explanation of the Müller-Lyer illusion (e.g., Morgan et al., 1990) indicates that the direction of the fins biases the perceived location of the line end points via spatial pooling of neighboring signals (see also Carrasco et al., 1986). The likely contribution of such lower-level processes to the spatial Müller-Lyer and Ebbinghaus illusions further strengthens the case against a distance/duration rule in speed perception.

In summary, we posed the question whether speed equals distance over duration in perception, proposed a framework to answer this question by investigating the cross-dimensional carry-over of perceptual illusions, and conducted five experiments that together challenge the distance/duration rule. Future studies may extend the investigation to other illusions (such as the vertical–horizontal illusion and the Delboeuf illusion), other judgments (such as reproduction, as often used in research on space–time interference; e.g., Bottini and Casasanto, 2010; Bratzke, 2024;

[3] Note that d refers to the viewing distance here, not to the (movement) distance referred to elsewhere in the manuscript.

Casasanto and Boroditsky, 2008; Ono and Kawahara, 2007), and more realistic virtual-reality environments (e.g., Bogon et al., 2024, 2025; Jagorska et al., 2026). It might also be informative to let observers judge perceived distance, duration, and speed jointly within the same trial. A parallel line of research may create duration illusions (such as using oddballs or repetitive stimuli; e.g., Ono & Kitazawa, 2010, 2011) and examine whether illusory increases in perceived movement duration lead to illusory decreases in perceived movement speed, as predicted by the distance/duration rule (for some considerations about the relation between perceived duration and speed, see Brown, 1931a; Riemer & Cai, 2024; Riemer et al., 2026). The logic applied here also raises a variety of further research questions, such as whether illusory increases in perceived speed increase perceived distance and decrease perceived duration (see, e.g., Plastira et al., 2026; von Sobbe et al., 2021). Thus, the stage is set for a systematic evaluation of the integrality and separability of the perceptual dimensions of distance, duration, and speed.

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Appendix
Speed-indiscriminability (SPIN) model

The SPIN model posits that observers perceive two stimuli as having the same speed if the registered speed difference falls into an indiscriminability interval. Assume that two successive stimuli move with physical speeds of $v_{\Phi,1}$ and $v_{\Phi,2}$. Our sensory systems may not preserve $v_{\Phi,1}$ and $v_{\Phi,2}$ accurately and precisely, which means that noisy psychological errors $\mathbf{v}_{\Psi,1}$ and $\mathbf{v}_{\Psi,2}$ are added. Further, the comparator of the perceived speed magnitudes may operate with limited resolution, thus producing an indiscriminability interval. Let the physical speed difference $\Delta v_\Phi = v_{\Phi,1} - v_{\Phi,2}$ and the added psychological speed difference $\mathbf{\Delta v}_\Psi = \mathbf{v}_{\Psi,1} - \mathbf{v}_{\Psi,2}$. For convenience, we assume that the psychological speed difference follows a normal distribution, $\mathbf{\Delta v}_\Psi \sim N(\mu, \sigma^2)$, and that the indiscriminability interval is constant and symmetric around the point of numerical equality of the perceived speed magnitudes (i.e., limited by two fixed boundaries/criteria b and $-b$). In this three-parameter observer model, the PSE is $s - \mu$ (where s is the standard speed), and $\mu \neq 0$ deg/s reflects a time-order error (e.g., Hellström, 1985).

The three perceptual states hypothesized by the SPIN model correspond to the choice options in a ternary response format: "first stimulus faster" (i.e., "$v_1 > v_2$"), "same speed" (i.e., "$v_1 = v_2$"), and "second stimulus faster" (i.e., "$v_1 < v_2$"). The SPIN model predicts that the psychometric functions in the ternary-response task are

$$\begin{aligned} P(\text{“}v_1 > v_2\text{”} \mid \Delta v_\Phi) &= P(\mathbf{\Delta v_\Psi} + \Delta v_\Phi \leq -b) \\ &= P(\mathbf{\Delta v_\Psi} \leq -b - \Delta v_\Phi) \\ &= F_{\mathbf{\Delta v_\Psi}}(-b - \Delta v_\Phi), \end{aligned} \tag{A1}$$

$$\begin{aligned} P(\text{“}v_1 = v_2\text{”} \mid \Delta v_\Phi) &= P(-b < \mathbf{\Delta v_\Psi} + \Delta v_\Phi < b) \\ &= P(-b - \Delta v_\Phi < \mathbf{\Delta v_\Psi} < b - \Delta v_\Phi) \\ &= F_{\mathbf{\Delta v_\Psi}}(b - \Delta v_\Phi) - F_{\mathbf{\Delta v_\Psi}}(-b - \Delta v_\Phi), \end{aligned} \tag{A2}$$

$$\begin{aligned} P(\text{“}v_1 < v_2\text{”} \mid \Delta v_\Phi) &= P(\mathbf{\Delta v_\Psi} + \Delta v_\Phi \geq b) \\ &= P(\mathbf{\Delta v_\Psi} \geq b - \Delta v_\Phi) \\ &= 1 - P(\mathbf{\Delta v_\Psi} < b - \Delta v_\Phi) \\ &= 1 - F_{\mathbf{\Delta v_\Psi}}(b - \Delta v_\Phi). \end{aligned} \tag{A3}$$