The interaction of speed and time in biasing the perception of dynamically changing visual inputs

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The perception of the duration of a visual stimulus is a very peculiar sensory experience built without dedicated sensors. Perhaps due to this distinctiveness, duration perception is often influenced by stimulus sensory features such as speed, temporal frequency, or stimulus contrast. For instance, stimulus speed is known to distort temporal judgments, with faster stimuli being perceived as lasting longer compared to static or slow-moving ones. In this study, we explored whether this effect depends on stimulus configuration and persists when salient sensory cues at interval onset and offset are available to solve the temporal task ("filled" vs. "flanked" condition). Additionally, given the strong link between speed and time, we wonder whether stimulus duration can affect speed judgments. To answer these questions, we ran two distinct experiments in which healthy volunteers discriminated either the duration or the speed of noisy incoherent random dot kinematograms whose duration and speed were manipulated orthogonally. The results of both experiments revealed that perceived duration was biased by the stimulus speed, as expected, and that this effect persisted across stimulus configurations. Moreover, we found that the duration of the stimulus influenced the perception of speed, albeit to a lesser degree. These findings emphasize the significance of sensory input integration and the temporal structure of stimuli in shaping both duration and speed perception.

Introduction

The perception of time in the subsecond scale is modulated by a variety of nontemporal factors. In the visual modality, features such as contrast (Benton & Redfern, 2016) and size (Xuan, Zhang, He, & Chen, 2007; Bratzke, 2024) affect the perceived duration of stimuli. Similarly, motion has been repeatedly found to induce temporal illusions, with faster-moving stimuli being perceived to last longer than slower or static ones (Brown, 1995; Kanai, Paffen, Hogendoorn, & Verstraten 2006; Kaneko & Murakami, 2009; Binetti, Lecce, & Doricchi, 2012). This phenomenon is known as time dilation, and it has been linked to different aspects of stimulus motion; specifically, Kanai et al. (2006) isolated different components of motion (namely, speed, motion coherence, spatial frequency, and temporal frequency) and found that the magnitude of time dilation effects could be ascribed to temporal frequency rather than other motion components. A similar study by Kaneko (2009) tested time dilation in both discrimination and reproduction tasks; results showed that time dilation was mainly linked to stimulus velocity (the ratio between temporal frequency and spatial frequency). Authors attributed the time dilation effect to the activity of neurons in V5/MT, which are highly sensitive to motion direction and tuned for speed (Perrone & Thiele, 2001; Priebe, Cassanello, & Lisberger, 2003). While the results of these two studies can be ascribed to the adoption of different types of visual stimuli (expanding grating vs. Gabor patches), both converge on the idea that temporal processing relies on modality-specific mechanisms. Transcranial magnetic stimulation (TMS) studies have indeed shown the causal involvement not only of primary visual cortex but also of extrastriate area V5/MT, the motion-sensitive area, in the duration discrimination of visual stimuli (Bueti, Bahrami, & Walsh, 2008; Salvioni, Murray, Kalmbach, & Bueti, 2013). Salvioni (2013) has shown, for example, that V5/MT is causally involved in both the encoding and the working memory retention of visual duration and that the TMS effects were specific to time processing, leaving nontemporal aspects of stimuli unaffected. Similarly, Bueti, Bahrami, and Walsh (2008) showed the involvement of V5/MT in the visual but not the auditory duration discrimination of both static and moving stimuli.

Time dilation induced by stimulus dynamics has also been reported in the tactile modality (Tomassini, Gori, Burr, Sandini, & Morrone, 2011;

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Toso, Fassihi, Paz, Pulecchi, & Diamond, 2021). In Toso et al. (2021), for example, the authors investigated how the perceived duration of a tactile vibration is influenced by its intensity, defined as the speed of a vibrating probe applied to the fingertip (in humans) or whiskers (in rats). In different tasks and across different species, results showed that the stronger the stimulus intensity the longer the perceived duration and vice versa (i.e., the longer the time, the stronger the perceived intensity). Toso et al. (2021) proposed a leaky integrator model as a unified mechanism for the encoding of both stimulus duration and intensity. The model assumes that the perception of both duration and intensity results from the leaky integration of sensory neurons' activity. The authors tested this hypothesis and used neural spike trains from primary vibrissal somatosensory cortex of rats to feed the model. Using distinct temporal integration parameters for duration and speed, they were able to successfully retrieve the perceptual bias from neural data.

If time perception is a function of sensory input integration, as proposed by Toso et al. (2021), one question that arises concerns the conditions leading to the integration process. Does this integration occur whenever there is a sensory stimulus dynamically changing over time? And what would happen if a more salient source of information, such as sharp stimulus onset and offset, became available? Would the bias remain? This question was already addressed in the tactile modality: Reinartz et al. (2021) demonstrated that when the onset and offset of a tactile stimulus are made more salient by amplifying the initial and final moments of a vibration, the influence of stimulus intensity on perceived duration disappears. These results suggest that clear temporal markers can shift the brain's strategy for estimating duration, from one that depends on continuous sensory integration to one that tracks duration, relying on a signal other than sensory input. A second important question concerns the directionality of the bias induced by stimulus dynamics (in vision, specifically, motion speed) on temporal judgments. While many studies have shown how speed or temporal frequency affects duration perception (Kanai et al., 2006; Kaneko & Murakami, 2009; Johnston, Arnold, & Nishida, 2006), not many studies have investigated the reverse effect, namely, how stimulus duration influences the processing of speed. In the visual modality, as far as we know, there is a single study that looked at the role of total stimulus duration on speed judgment. This study did not identify any effect of duration on speed discrimination thresholds (McKee, 1981). To characterize the relationship between duration and speed processing in the visual modality, we asked whether these two features influence each other in a symmetrical fashion.

In order to answer these questions, we used a temporal discrimination task where we asked participants to discriminate the duration of pairs of

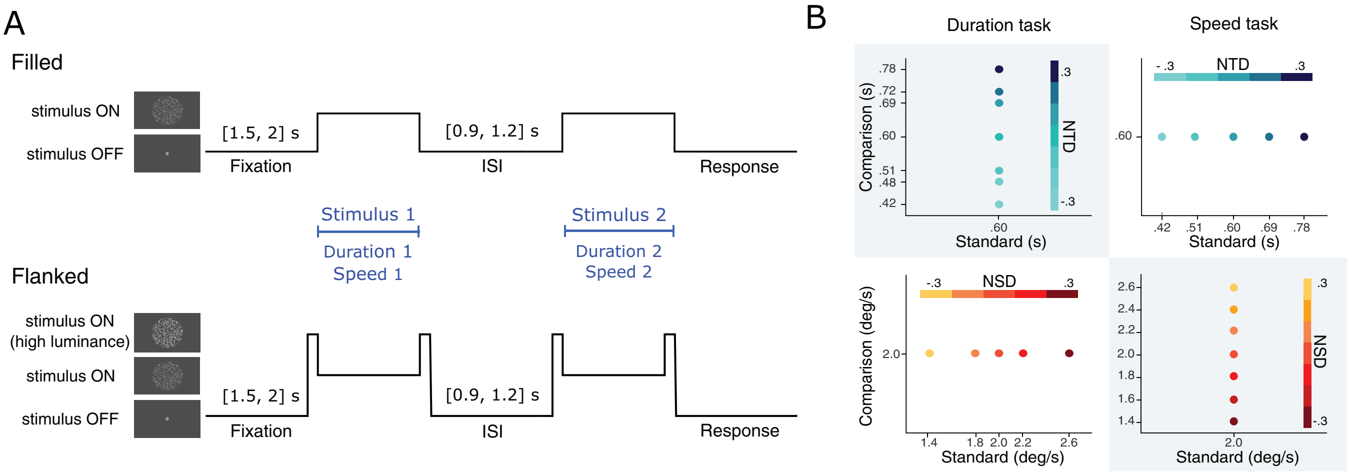

Figure 1. Experimental design. (A) Schematic representation of a trial in each stimulus condition. In each trial, participants were shown two stimuli in a row; participants had to judge which stimulus was longer/faster. (B) Manipulation of stimulus features across tasks. Each subplot represents one combination of task (*columns*) and feature (*rows*). Gray areas highlight the manipulation of the task-relevant feature. The x-axis shows the feature values of the standard stimulus, and the y-axis shows the feature values of the comparison stimulus. Each point thus represents a standard-comparison combination. In the time discrimination task (*left column*), the standard stimulus had a fixed duration and variable speed, while the comparison stimulus had a variable duration and fixed speed. In the speed discrimination task (*right column*), the standard stimulus had a variable duration and fixed speed; the comparison stimulus had a variable speed and fixed duration. Color bars indicate normalized values for each feature; blue shades represent the normalized temporal difference (NTD), while red shades represent the normalized speed difference (NSD). The task-relevant normalized index was computed as follows: (Comparison – Standard)/Standard. The normalized index for the task-irrelevant feature was instead computed as follows: (Standard – Comparison)/Comparison.

visual stimuli. We used random dot kinematograms varying orthogonally in both speed and display time (i.e., duration), and in different blocks of trials, we manipulated the stimulus configuration. In filled blocks, durations consisted of a continuous stream of sensory input; in flanked blocks instead, the filled stimuli were marked at their onset and offset by transient and salient changes of luminance (Figure 1A). Notably, both filled and flanked stimuli consisted of a continuous sensory input, but flanked stimuli had more salient temporal markers. With this manipulation, we aimed to test whether increasing the salience of temporal boundaries could promote a timing strategy more typically associated with empty intervals (which consist only of temporal markers), even though the interval itself remains filled. We hypothesized that the speed-induced time dilation effect would be measured in the filled but not in the flanked condition. However, we expected flankers to have no effect on speed judgments, as in our design, speed discrimination required temporal integration over several frames, making boundary markers irrelevant for solving the speed task. When testing the counterpart of time dilation, namely, the duration-induced distortion of speed perception, we had to consider the different information processing time course of the manipulated features (as discussed in Togoli, Fornaciai, & Bueti, 2021). In fact, the duration of a sensory event is only available at its disappearance, while speed of a moving object can be estimated almost immediately. In an attempt to match the information processing time courses of speed and duration, we introduced a noise component into the motion of the dots. By making the perception of speed more discontinuous, we aimed to encourage participants to estimate speed by averaging information over time. We hypothesized that we would not only replicate the speed-induced time dilation effect but also reveal its counterpart, namely, an effect of stimulus duration on speed judgments. As will be shown, this approach revealed an asymmetry between time dilation and speed dilation. This finding motivated a second experiment employing a narrower range of durations, designed to test whether a closer alignment in temporal availability of information could enhance the influence of duration on speed judgments.

Methods

Twenty-one healthy participants took part in each experiment (10 females in Experiment 1, 12 females in Experiment 2). Participants' ages ranged from 19 to 39 years (mean: 25, *SD*: 4), and they had normal or corrected-to-normal visual acuity. All participants gave their written informed consent and received monetary compensation for their participation. The study was approved by the ethics committee at the International School for Advanced Studies (SISSA), protocol nr. 11772-III/13.

Apparatus and stimuli

Experiments were conducted in a darkened room, using a BenQ XL2731-B monitor with a screen refresh rate of 144 Hz (screen resolution was 1,920 × 1,080 pixels). During the experiment, participants sat at a 57-cm distance from the computer screen with their head on a chin rest. The stimuli, random dot kinematograms consisting of 640 moving dots presented within a 4^{circ} circular aperture at the center of the screen, were generated in MATLAB R2019b using the Psychophysics Toolbox extensions (Kleiner et al., 2007). The initial position of each dot was randomly determined in polar coordinates. From this initial position, the dots' location in Cartesian coordinates was updated over time based on specific speed and motion direction. Each dot moved along a random trajectory, and thus, there was no coherent motion direction at the global level. At each frame, each dot position was updated along the x- and y-axes according to the following equations:

$$x_t = x_{t-1} + v + n \quad (1)$$

$$y_t = y_{t-1} + v + n \quad (2)$$

where t is the current time point, v is a fixed quantity along a fixed trajectory, and n is a random noise component, a value extracted from a Gaussian distribution. The noise component was added to the stimulus dynamics to better align the information-processing time course of speed and duration. Duration, in fact, becomes only available at stimulus offset, while speed can be determined by one position update only (i.e., two frames). The motion randomness also made the dots' path less predictable. Furthermore, dots' positions could be reset if they moved out of the circular aperture. Density checks were performed at each position update to ensure that the distribution of dots remained consistent across annular sectors. Adjustments could be made if certain areas became too sparse or too dense. When a sector became more dense than others (e.g., due to random motion accumulation), exceeding dots were removed and redistributed to sparser sectors to avoid visible clustering. These changes affected only a small subset of dots (approximately 4% of exceeding dots per frame) and occurred continuously, making them imperceptible to participants. In the filled condition, dots were presented against a gray background with a contrast of 27% (Michelson's contrast). In the flanked condition, five additional frames were added at the beginning and end of the stimulus. These extra frames were presented with a greater luminance compared to the remaining frames of the stimulus, that is, 52% Michelson's contrast with respect to the background and 29% with respect to the rest of the stimulus (Figure 1A).

Participants were tested in a duration-discrimination task and in a speed-discrimination task. In each task, speed and duration were orthogonally manipulated: The task-relevant feature was held constant in the standard stimulus and varied in the comparison stimulus, while the task-irrelevant feature was held constant in the comparison stimuli and varied in the standard stimulus (Figure 1B). The presentation order of standard and comparison stimulus was randomized. In the duration task, the standard was 0.6 s in duration and varied in speed (1.4, 1.8, 2, 2.2, 2.6 deg/s). The comparison stimulus instead was fixed in speed (2 deg/s) and varied in duration (0.42, 0.48, 0.51, 0.60, 0.69, 0.72, 0.78 s, in Experiment 1). In the speed task, the standard stimulus was fixed in speed (2 deg/s) and varied in duration (0.42, 0.51, 0.60, 0.69, 0.78 s in Experiment 1); the comparison stimulus had a fixed duration (0.6 s) and varied in speed (1.4, 1.6, 1.8, 2, 2.2, 2.4, 2.6 deg/s). In Experiment 2, speed values were identical to Experiment 1, but a different range of durations was used. The standard stimulus in the duration task lasted 0.4 s, and the comparison could take one of seven possible values (0.28, 0.32, 0.34, 0.4, 0.46, 0.48, 0.52 s); in the speed task, the comparison stimulus was fixed in duration (0.4 s), and the standard could take one of five possible values (0.28, 0.34, 0.4, 0.46, 0.52 s).

Procedure

In each trial, participants were presented with a pair of stimuli in sequence. In the duration discrimination task, participants had to judge which stimulus of the pair lasted longer by pressing the left (for Stimulus 1) or right (for Stimulus 2) arrow key on the computer keyboard. The same trial structure and response modality was used in the speed discrimination task, where participants had to judge which stimulus of the pair had faster moving dots. The different tasks (speed and duration) and stimulus types (filled and flanked) were tested in different blocks of trials, resulting in four experimental conditions (2 stimulus types × 2 tasks). Participants completed each condition twice, for a total of eight blocks. Each block consisted of 140 trials, and the order of the blocks was randomized across participants. Stimuli were presented consecutively with an interstimulus interval (ISI) ranging between 0.9 and 1.2 s. The intertrial interval (ITI) ranged from 1.5 to 2 s.

Data analysis

Performance accuracy was computed as the proportion of correct responses within each block. To analyze participants' performance, we computed the relative frequencies of responding "comparison > standard," pooling trials of blocks belonging to the same experimental condition (i.e., same stimulus type, same task, and same level of the task-irrelevant feature), yielding eight trials for each unique combination of factors for each participant. Therefore, each psychometric function was fitted on 56 trials. We fitted these values with psychometric curves using a generalized linear model with a binomial distribution and a logit link function (implemented using the `fitglm` function in MATLAB R2019B). It is worth emphasizing here that the relatively low number of trials (i.e., eight) per data point (i.e., for each unique combination of task, stimulus type, task-relevant and task-irrelevant feature) in the psychometric functions represents a limitation of our experimental design. While this approach allowed us to maintain a manageable session length given the factorial structure of the experiment, it likely introduced additional variability in the parameter estimates and reduced the precision of the fits. Future studies could address this by increasing the number of trials per condition or simplifying the design to allow for more repetitions per data point, thereby improving the reliability of the psychometric measures.

Individual just noticeable differences (JND) and point of subjective equalities (PSE) values were extracted as measures of interest. JND was computed as half the difference between the 75% and 25% thresholds of the fitted psychometric function; PSE was computed as the 50% threshold of the function. All statistical analyses were run on R (version 4.3.3). Outlier removal was performed based on JND values and applied to each specific combination of subject, task, and stimulus type. Outliers were identified using the interquartile range (IQR) method, applied only to the right tail of the distribution. Specifically, data points exceeding the third quartile (Q3) plus 1.5 times the IQR were excluded. Accuracy, JND, and PSE scores were analyzed with linear mixed-effect models (LMEs; Bates, Mächler, Bolker, & Walker, 2015). The degrees of freedom were estimated with Satterthwaite's method. Model estimates were then analyzed with ANOVA using the Kenward–Roger method for degrees of freedom estimation. In cases where `lmer` models failed to converge or resulted in singular fits (i.e., variance estimates near zero for random effects), we refit the models using the `lme` and `anova.lme` functions from the `nlme` package. We report partial eta squared (η_p^2) effect sizes using the `effectsize` package. For post hoc tests, estimated marginal means and estimated marginal trends were computed and compared using the `emmeans` package (Lenth, 2021). Specifically, we estimated simple slopes using the `emtrends` and tested them with the `test` function. By default, these tests are based on *t*-ratios with Satterthwaite/Kenward–Roger degrees of freedom.

The primary dependent variable was the PSE, which reflects perceptual bias, as our focus was on measuring distortions induced by task-irrelevant features on the judgment of task-relevant features. To this end, individual PSEs were extracted for each level of the task-irrelevant feature and analyzed separately for each task (duration, speed) and experiment with an LME model. The model comprised stimulus type (filled, flanked) and task-irrelevant feature (duration in speed task and speed in duration task) as fixed effects and subjects as random effect (formula: $PSE \sim stimulustype*irrelevantfeature + (1|subjectID)$). To contrast the magnitude of effects of the task-irrelevant feature on PSEs across tasks, we fitted a linear mixed-effect regression to PSE values from both tasks using task-irrelevant feature and task type as fixed predictors; subjects were included as a random intercept factor (formula: $PSE \sim task*irrelevantfeature + (1|subjectID)$). In addition, we analyzed JNDs as a control measure to verify that task difficulty and perceptual sensitivity were comparable across conditions, thereby ensuring that any observed PSE shifts could not be attributed to differences in sensitivity. On JND values, we performed an LME model with task type and the task-irrelevant feature as predictors (formula: $JND \sim task*stimulustype*irrelevantfeature + (1|subjectID)$. To be able to compare the effects of task-relevant and task-irrelevant stimulus features across tasks, for each task, we computed two normalized indices, one for the task-relevant and the other one for the task-irrelevant stimulus feature. Thus, for each pair of stimuli in a trial, we computed a normalized temporal difference (NTD) and a normalized speed difference (NSD). The task-relevant normalized index was computed as follows: (Comparison – Standard)/Standard. The normalized index for the task-irrelevant feature was instead computed as follows: (Standard – Comparison)/Comparison. In the duration task, positive NSD values correspond to faster speed, while in the speed task, positive NTD values correspond to longer durations.

Results

Experiment 1

In the first experiment, we aimed to evaluate (a) the role of speed in duration perception and the role of duration in speed perception, and (b) the influence of sharp onset/offset signals on the biases caused by speed and time in duration and speed judgments, respectively. Overall, participants successfully performed the two tasks in both conditions. In the duration task, mean accuracy was 75.2% ± 4.6% (mean ± standard deviation) in the filled condition and 76.8% ± 4.4% in the flanked condition; in the speed task, mean accuracy was 75.1% ± 4.8% in the filled condition and 74.5% ± 7.1% in the flanked condition. No significant differences were observed in accuracy between tasks ($F(1, 60) = 0.004$, $p = 0.949$, $\eta_p^2 < .001$) and stimulus conditions ($F(1, 60) = 0.904$, $p = 0.345$, $\eta_p^2 = 0.01$). Data cleaning based on JND outliers resulted in the removal of 5.71% of data points. The group-averaged psychometric curves for the different tasks and stimulus types are shown in Figure 2. For the duration discrimination task, Type III ANOVA on model estimates (marginal $R2 = 0.34$, conditional $R2 = 0.38$) indicated a statistically significant main effect of the task-irrelevant feature (motion speed, $F(1, 172.41) = 69.59$, $p < 0.001$, $\eta_p^2 = 0.30$). Higher levels of speed were associated with higher PSE values ($t(173) = 10.12$, $p < 0.0001$), indicating an overestimation of duration for the faster speed levels (Figure 3A). A trend toward significance for the interaction between speed and stimulus type was also found ($F(1, 71.21) = 2.94$, $p = 0.09$, $\eta_p^2 = 0.02$, Figure 3B, C). For the speed discrimination task, as the `lmer` model failed to converge due to singular random effects, results are reported from the `lme` model, which converged successfully. The ANOVA on model estimates (marginal $R2 = 0.07$, conditional $R2$: 0.07) revealed a main effect of the task-irrelevant feature (stimulus duration, $F(1, 178) = 7.67$, $p = 0.006$, $\eta_p^2 = 0.04$), so that longer standard stimulus durations were associated with larger PSE ($t(178) = 3.736$, $p = 0.0003$, Figure 3A). In other words, the longer the stimulus duration, the faster the perceived speed. No main effect of stimulus type or interaction effect between the two predictors reached significance (Figure 3B, C). Results from Experiment 1 are displayed in Figure 3, and model estimates are displayed in Table 1.

This first set of results showed that both speed and time, when task-irrelevant, were able to bias duration and speed judgments. When checking for the differences in the magnitude of these effects across tasks, model estimates (marginal $R2 = 0.28$, conditional $R2 = 0.29$) showed a significant main effect of the task-irrelevant feature ($F(1, 184.80) = 65.98$, $p < 0.0001$, $\eta_p^2 = 0.26$), as well as a significant interaction between task-irrelevant feature and task type ($F(1, 184.44) = 9.77$, $p < 0.001$, $\eta_p^2 = 0.05$), suggesting a differential effect of the task-irrelevant feature on the two tasks. Pairwise comparisons of estimated marginal trends showed indeed that the magnitude of the bias induced by speed on duration

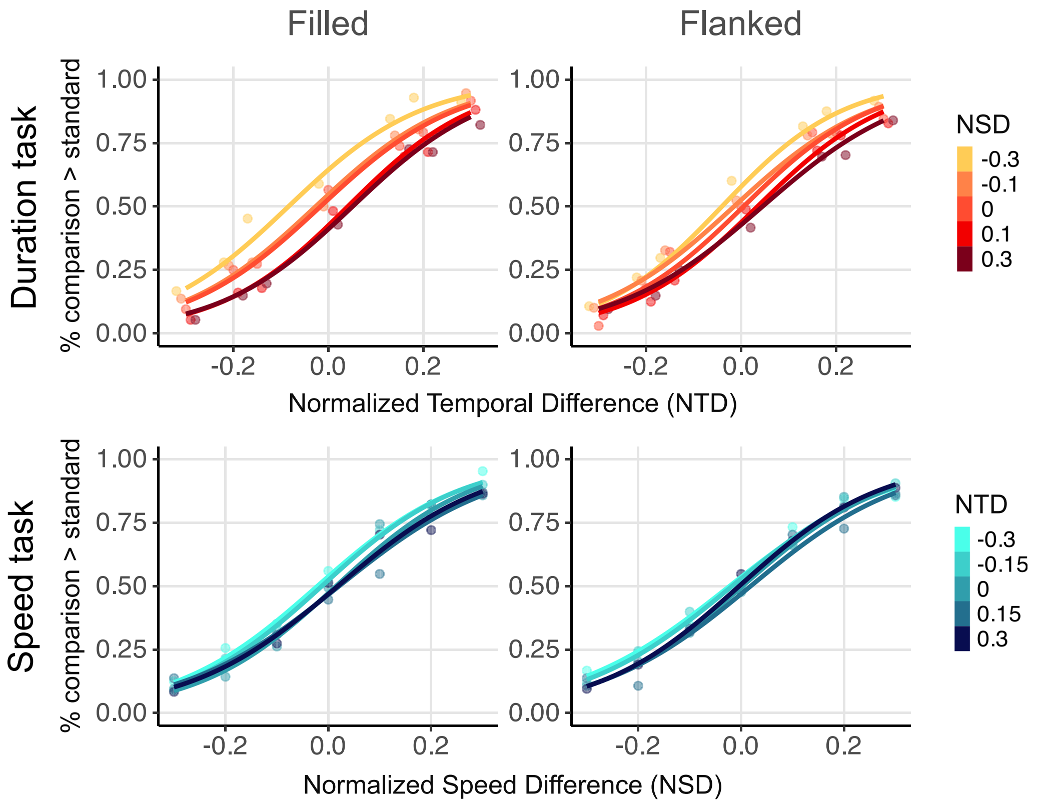

Figure 2. Psychometric curves obtained by averaging responses across subjects in Experiment 1 (for visualization purposes only). Results are divided by task (rows) and stimulus type (columns). The normalized speed difference (NSD) in the duration task and the normalized time difference (NTD) in the speed task were calculated as follows: (Standard – Comparison)/Comparison. In contrast, NTD and NSD in the duration and speed task, respectively, were computed as follows: (Comparison – Standard)/Standard Curves are color coded as a function of the task-irrelevant feature.

judgments was greater than the bias of time on speed judgments (time – speed: $t(184) = 3.13$, $p = 0.002$, Figure 6). Although the expected behavioral differences were at the PSE level, we also checked participants' JND performance. Results showed no significant effect (see Supplementary Table S1), indicating that sensitivity was comparable across tasks and robust to the manipulations of the task-irrelevant feature and stimulus configuration (Supplementary Figure S1A). The results of the first experiment confirmed that speed influenced duration judgments as expected. This bias persisted even when more perceptually salient visual inputs (i.e., flanked condition) were available to solve the task. Surprisingly, the duration of a visual input also influenced speed judgments. This effect was independent of stimulus configuration (flanked vs. filled) and was smaller in magnitude compared to the speed-induced bias on duration judgments. If the perception of speed and time in our experiment results from the integration of dynamically changing sensory inputs, a possible explanation for this asymmetry could lie in the different integration windows required to perceive speed versus duration, with speed likely requiring a faster integration time. To test this possibility, we conducted a second experiment, identical to Experiment 1, but with a shorter duration range (see Methods). With these shorter presentation times, we expected to observe a symmetrical bias of duration on speed and vice versa.

Experiment 2

In this second experiment, the duration range tested spanned from 0.28 to 0.52 s, whereas speed values were identical to Experiment 1. In Experiment 2, we conducted an identical set of analyses on both JND (Supplementary Figure S1B) and PSE data (Figure 5). Group-averaged psychometric curves for Experiment 2 are reported in Figure 4. Overall accuracy scores showed that participants successfully performed the two tasks. The mean accuracy in the duration task was 73% ± 5.2% in the filled condition and 71.1% ± 5.7% in the flanked condition. In the speed task, accuracy was 75.5% ± 4.5% in the filled condition and 73.3% ± 5.6% in the flanked condition. No significant effects of stimulus

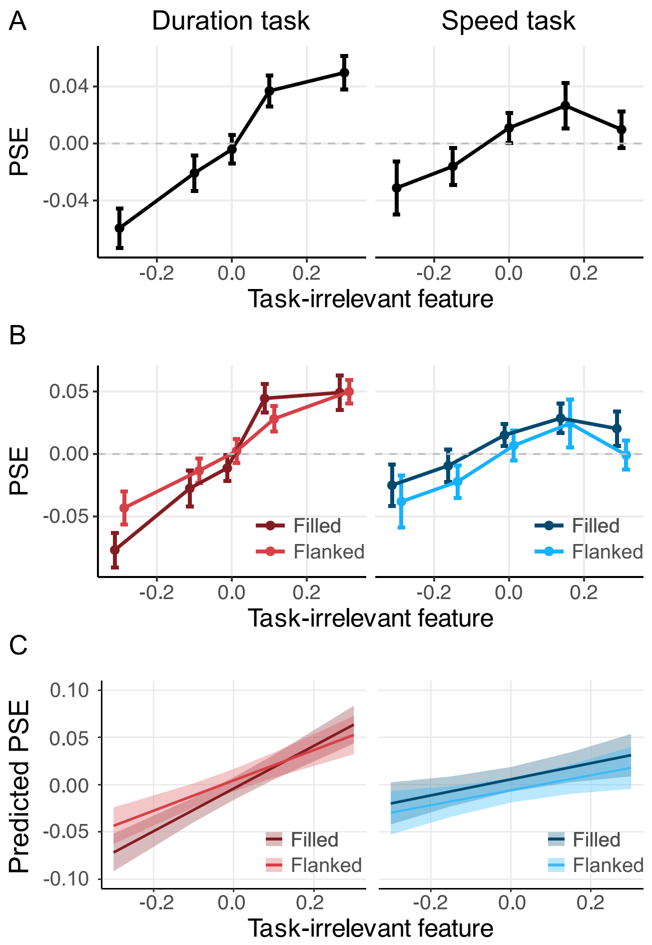

Figure 3. Results on PSE values in Experiment 1. Each dot represents the mean PSE value, with error bars denoting the standard error of the mean (SEM). The x-axis displays values of the task-irrelevant feature for each condition. The left column refers to the duration discrimination task, while the right column refers to the speed discrimination task. (A) PSE values are averaged and plotted by task. (B) Values are divided by stimulus type and task to examine differences by visual configuration. (C) Estimated marginal trends for the effect of the task-irrelevant feature on PSE values, with shaded areas indicating the 95% confidence interval for each condition.

conditions ($F(1, 60) = 1.809$, $p = 0.184$, $\eta_p^2 = 0.03$) on accuracy were found, but results showed a trend toward significance for the effect of task ($F(1, 60) = 3.074$, $p = 0.084$, $\eta_p^2 = 0.05$), suggesting an increased difficulty for participants in discriminating durations.

Cleaning based on JND scores resulted in the removal of 7.86% of data points. In the duration discrimination task, fitting the model with `lmer` failed to converge and produced a singular random-effects structure; therefore, we report the results obtained with `lme`, which provided stable estimates. The results (marginal $R2 = 0.07$, conditional $R2 = 0.07$) revealed a main effect of speed (i.e., the task-irrelevant feature, $F(1, 166) = 7.755$, $p = 0.006$, $\eta_p^2 = 0.04$, Figure 5A) in the same direction—although smaller in magnitude—as the effect found in Experiment 1. Estimated marginal trends for speed, collapsed across all other factors, showed in fact an effect, that is, faster speed led to longer perceived duration ($t(166) = 2.990$, $p = 0.003$). Results also showed a significant main effect of stimulus type ($F(1, 166) = 4.125$, $p = 0.044$, $\eta_p^2 = 0.02$, Figure 5B), so that PSEs in the filled condition were lower than in the flanked condition ($t(166) = -0.02$, $p = 0.043$). The results of the speed discrimination task (marginal $R2 = 0.02$, conditional $R2 = 0.03$) showed a trend toward significance for the effect of the task-irrelevant feature ($F(1, 172.91) = 3.71$, $p = 0.056$, $\eta_p^2 = 0.02$). Durations tended to bias speed judgments, although differently from our prediction, the magnitude of this effect was similar to that of Experiment 1 (Figure 6). Model estimates referring to Experiment 2 are reported in Table 2. Additionally, we compared the effect of the task-irrelevant feature across the two tasks (speed vs. duration). The ANOVA on model estimates (marginal $R2 = 0.03$, conditional $R2 = 0.03$) showed a main effect of the task-irrelevant feature ($F(1, 362) = 10.547$, $p = 0.001$, $\eta_p^2 = 0.03$) but no interaction with the task, suggesting an equivalent effect of speed and time on, respectively, duration and speed judgments ($F(1, 362) = 1.683$, $p = 0.195$, $\eta_p^2 = 0.004$). The main effects of the task-irrelevant feature in Experiment 2 are shown in Figure 5.

Concerning JND, the ANOVA performed on model parameters (marginal $R2 = 0.10$, conditional $R2 = 0.26$) showed a main effect of task ($F(1, 358.53) = 13.350$, $p < .001$, $\eta_p^2 = 0.04$). The pairwise comparison of model estimates showed that JND values were higher (i.e., sensitivity was lower) in the duration compared to the speed discrimination task (time – speed: $t(358) = 6.072$, $p < 0.0001$). Additionally, stimulus type significantly affected JND ($F(1, 358.54) = 11.18$, $p = 0.001$, $\eta_p^2 = 0.03$); the contrast of the estimated marginal means showed that JND was higher (sensitivity was lower) in the flanked compared to the filled condition (filled-flanked: $t(358) = -3.830$, $p = 0.0002$). Although not conclusive, the results of Experiment 2 indicate an effect of speed on duration judgments and a marginally significant effect of time on speed judgments. Reducing the overall presentation times of the stimuli did not amplify the effect of duration on speed judgments; this effect was indeed comparable across the two experiments (see Figure 6, blue lines). In contrast, the effect of speed on duration judgments in Experiment 2 appears to be smaller in magnitude (see Figure 6, red lines).

Predictor	Estimates	Std. error	*df*	*t* value	*p* value
Duration task					
Intercept	−0.004	0.006	51.008	−0.670	0.5056
Irrelevant feature	0.226	0.027	172.571	8.348	<**0.001**
Stimulus type	0.009	0.008	171.235	1.139	0.256
Irrelevant feature: Stimulus type	−0.065	0.038	171.382	−1.715	0.088
Marginal *R*2/conditional *R*2	0.34/0.38				
Speed task					
Intercept	0.006	0.007	178	0.861	0.390
Irrelevant feature	0.085	0.031	178	2.769	**0.006**
Stimulus type	−0.012	0.009	178	−1.234	0.219
Irrelevant feature: Stimulus type	−0.006	0.044	178	−0.134	0.893
Marginal *R*2/conditional *R*2	0.07/0.07				

Table 1. LME model estimates for PSE values in Experiment 1. The table reports fixed-effect estimates, standard error, degrees of freedom, *t* values, and *p* values for each predictor. The bold font highlights significant effects ($p < 0.05$).

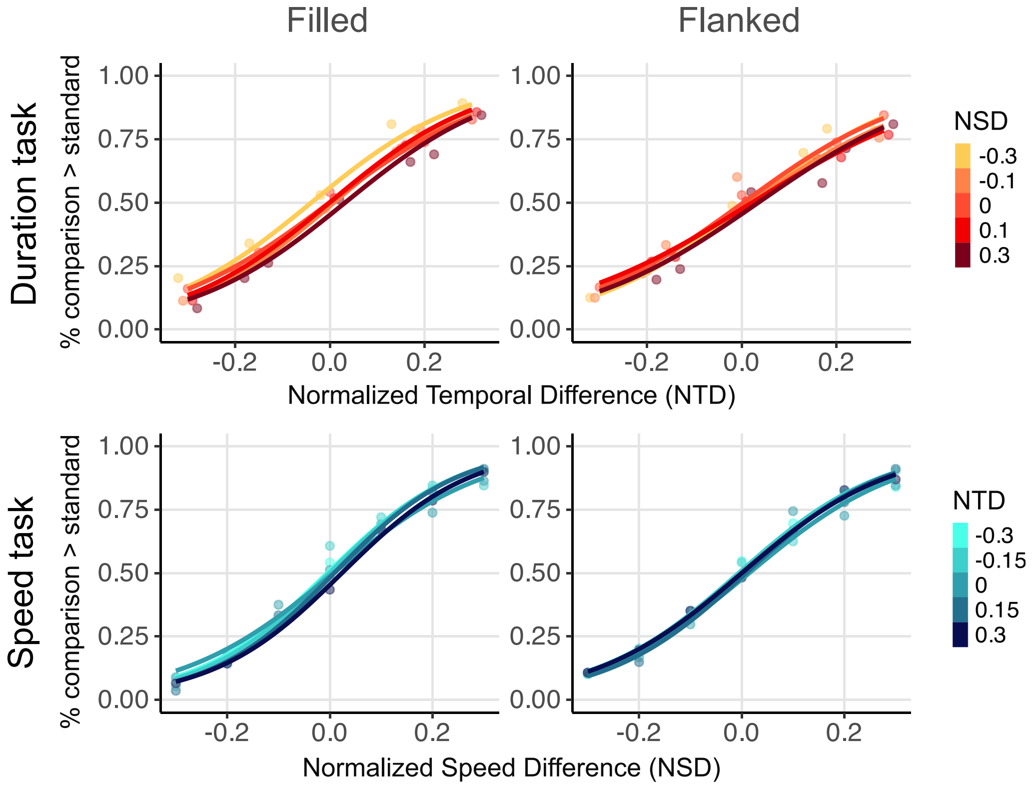

Figure 4. Grand average psychometric curves from Experiment 2. Results are divided by task (*rows*), stimulus type (*columns*), and level of the task-irrelevant feature (*color-coded*).

Discussion

This study investigated two central aspects of visual temporal perception: (1) the mutual influence of stimulus duration and motion speed and (2) the role of stimulus configuration in duration processing. To address the former point, we orthogonally manipulated stimulus duration and motion speed and assessed whether participants' performance on duration and speed discrimination tasks would be biased by the task-irrelevant feature. To address the second point, we examined whether this mutual influence—particularly the well-documented speed-induced time dilation effect (Kanai et al., 2006)—was modulated by stimulus structure. Specifically, we used the presence and strength of this bias as an index of sensory evidence integration, which has been proposed as a core mechanism in the

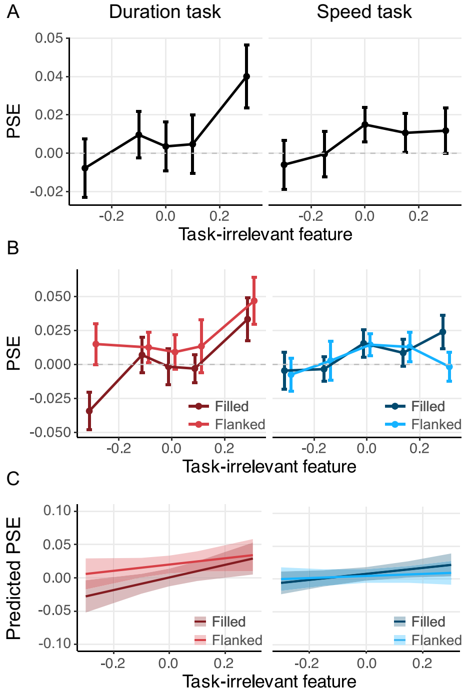

Figure 5. Effect of the task-irrelevant feature across tasks and stimuli in Experiment 2. PSE values averaged across subjects, plotted according to the task-irrelevant feature and divided by task; error bars indicate the standard error. Line plots in the bottom row represent the estimated marginal trend for the effect of the irrelevant feature on PSE; shaded areas represent the 95% confidence interval.

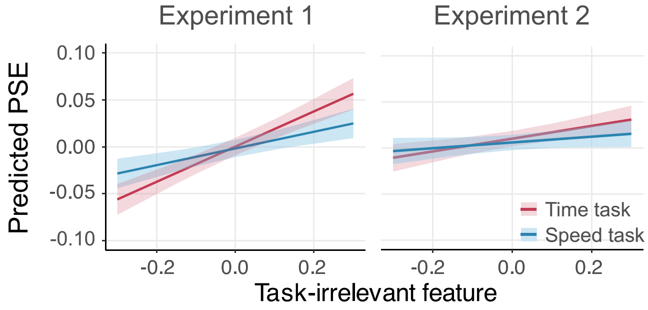

Figure 6. Model estimates for the effect of the task-irrelevant feature on PSE across tasks in Experiment 1 (*left*) and Experiment 2 (*right*). Shaded areas indicate the 95% confidence interval for each condition.

perception of filled intervals (Toso et al., 2021). By comparing filled versus flanked stimulus configurations, we tested whether increasing the salience of onset and offset markers reduces the reliance on sensory integration in duration judgments. Theoretically, observers can accurately judge the duration of an interval even when the only available sensory information is its onset and offset markers, as shown by previous studies on “empty intervals” (Grondin, 1993). However, timing mechanisms often capitalize on sensory information provided *throughout* an interval, as shown by the dependence of perceived duration on basic stimulus features (Thomas & Cantor, 1976; Eagleman, 2008; Terao, Watanabe, Yagi, & Nishida, 2008; Benton & Redfern, 2016). Here, we increased the salience of stimulus onset and offset to investigate whether observers would integrate the sensory input unfolding during the interval or rely on an alternative timing mechanism (as they do for the processing of empty intervals). In line with this idea, in the tactile modality, Reinartz et al. (2021) found that the bias induced by stimulus vibration intensity on duration

Predictor	Estimates	Std. error	*df*	*t* value	*p* value
Duration task					
Intercept	0.001	0.007	166	0.082	0.935
Irrelevant feature	0.095	0.034	166	2.785	**0.006**
Stimulus type	0.019	0.01	166	2.031	**0.044**
Irrelevant feature: Stimulus type	−0.048	0.047	166	−1.005	0.316
N subjID	21				
Observations	190				
Marginal *R*2/conditional *R*2	0.067/0.067				
Speed task					
Intercept	0.008	0.005	67.318	1.488	0.141
Irrelevant feature	0.046	0.024	173.474	1.927	0.056
Stimulus type	−0.003	0.007	174.321	−0.438	0.662
Irrelevant feature: Stimulus type	−0.03	0.034	175.163	−0.871	0.385
N subjID	21				
Observations	196				
Marginal *R*2/conditional *R*2	0.021/0.03				

Table 2. LME model estimates for PSE values in Experiment 2. The table reports fixed-effect estimates, standard error, degrees of freedom, *t* values, and *p* values for each predictor. The bold font highlights significant effects ($p < 0.05$).

judgments disappeared when animals received flanked stimuli. This finding suggests that there are two distinct mechanisms for duration processing: one relying on the integration of sensory information over time and one that relies on alternative sources of temporal information.

Results from the duration discrimination task of both experiments showed that the percept of duration was biased by motion speed so that faster stimuli were perceived as longer. This aligns with previous research demonstrating temporal overestimation of faster-moving stimuli compared to slower or stationary ones (Kanai et al., 2006; Kaneko & Murakami, 2009; Tomassini et al., 2011; Binetti, Lecce, & Doricchi, 2012; Bruno, Ayhan, & Johnston, 2015). This time dilation effect has been interpreted within a change-based account of temporal processing, suggesting that the number of events (i.e., changes) occurring during an interval relates to its perceived duration (Brown, 1995; Ahrens & Sahani, 2011; Roseboom et al., 2019).

However, contrary to our initial predictions, we observed time dilation under both stimulus conditions, indicating that flanked stimuli are still timed via a sensory-based mechanism akin to filled stimuli. The robustness of the speed-induced time dilation likely reflects the tight relationship between speed and time processing within the visual system. Area V5/MT, primarily dedicated to motion and speed processing (Priebe, Cassanello, & Lisberger, 2003; Zeki 2015), is also directly implicated in visual temporal computations (Bueti, Bahrami, & Walsh, 2008; Salvioni et al., 2013). As a component of the dorsal visual stream, area V5/MT receives numerous inputs from the magnocellular visual pathway (Zeki, 2015), whose fast response properties make it crucial for detecting motion and rapid visual changes. These response characteristics make area V5/MT well suited for temporal processing (Bruno, Ayhan, & Johnston, 2015). Additionally, it has been shown that adaptation to motion reduces the perceived duration of a subsequent stimulus (Tonoyan, Fornaciai, Parsons, & Bueti, 2022) and that area V5/MT might be the locus of such adaptation effects (Gulhan & Ayhan, 2019). Specifically, time dilation induced by speed might result from the existence of overlapping neuronal populations encoding both speed and duration. If abundant empirical evidences show speed selectivity in V5/MT neurons (Rodman & Albright, 1987; Perrone & Thiele, 2001; Priebe, Cassanello, & Lisberger, 2003; Priebe, Lisberger, & Movshon, 2006; Gaglianese et al., 2023), only more recently, a few studies have identified in human V5/MT neural populations that are selective to both the spatial position and the duration of a visual stimulus or exclusively selective for duration (Hendrikx, Paul, van Ackooij, van der Stoep, & Harvey, 2022; Centanino, Fortunato, & Bueti, 2024). Hence, the intertwining of speed encoding and duration encoding in this area might underlie the robust speed-induced distortions in duration perception.

An alternative, yet not mutually exclusive, interpretation of this effect comes from the idea that the perceived duration of a stimulus reflects the amount of energy used to encode it, with stimuli that elicit heightened neural responses being overestimated in duration (Eagleman & Pariyadath, 2009). In support of this latest account of the speed-induced duration bias, a few studies have shown that faster perceived speed is linked to higher activity levels in the human MT complex (hMT+; Zacks, Swallow, Vettel, & McAvoy, 2006; Williams & Wright, 2009; Takemura, Ashida, Amano, Kitaoka, & Murakami, 2012). In other words, time dilation induced by motion speed might originate from higher activity rates in area V5/MT.

While numerous studies have demonstrated that temporal processing is affected by the manipulation of visual speed, less research has investigated the reverse effect, namely, how stimulus duration influences the processing of speed. As far as we know, the only study that touched upon this issue found that the total stimulus duration did not affect the sensitivity of velocity discrimination judgments (McKee, 1981). In the present study, we concurrently examined the relationship between the percept of time and the percept of speed by measuring the distortion, not the precision, induced by stimulus duration on speed perception. Results from the speed discrimination task yielded ambiguous findings: Experiment 1 revealed a significant effect of duration on perceived speed, which, however, was not fully replicated in Experiment 2, where the effect of total stimulus duration on speed judgment was only marginally significant.

The reciprocal bias between speed and duration aligns with the functional interconnection between their processing discussed earlier. The magnitude of the perceptual bias was notably greater in the duration task compared to the speed task (see Figure 6), at least in Experiment 1. In Experiment 2, we did not observe an enhancement of the duration-induced speed bias; instead, our manipulation increased the difficulty of the duration discrimination task. In this second experiment, the asymmetry between effects disappeared as the overall magnitude of the speed-induced bias on duration judgments was smaller than in Experiment 1. This reduction was likely due to a general worsening of the discrimination thresholds (i.e., higher JNDs) observed in the duration task compared to the speed task.

An asymmetry of effects between time and other magnitudes (e.g., space and numerosity) has been previously reported and discussed (Casasanto & Boroditsky, 2008; Cappelletti, Freeman, & Cipolotti, 2009). Regarding time and numerosity, for example, Togoli, Fornaciai, and Bueti (2021) showed that a symmetrical effect in magnitude integration can be measured if the time course of each magnitude processing is matched. The fact that, in our study, speed perception was only weakly affected by the temporal dimension of stimuli can be interpreted in light of the existence of specialized neural populations involved in speed perception. These populations, which are tuned to specific combinations of spatial and temporal frequencies (Gaglianese et al., 2023), may render speed perception more robust to distortions induced by other stimulus dimensions. In contrast, the perception of time, which may result from a more complex process of sensory integration (Toso et al., 2021), could be inherently more malleable and susceptible to bias. Another factor contributing to the stronger influence of speed on duration judgments than vice versa lies in the sensory modality used. Vision typically allows for more precise estimates of spatial and motion-related properties than temporal ones (Cai & Connell, 2015; Loeffler, Cañal-Bruland, Schroeger, Tolentino-Castro, & Raab, 2018; Riemer & Cai, 2024) and in vision duration differences may be less perceptible than speed differences; as a result, duration judgments are more susceptible to bias from other factors (e.g., speed). Conversely, speed judgments are more robust, leaving less room for interference from irrelevant features (e.g., duration). This asymmetry might explain why speed influences duration more than the reverse. Nevertheless, a limitation in our design remains: that the time course of time and speed processing was not matched, even after noise injection and decrease of durations used. The introduction of noise injection into the speed component itself might have introduced an additional asymmetry—while time unfolded continuously, speed varied over time. Another factor that might contribute to the asymmetry of effects concerns our choice to interleave the different levels of speed and duration within blocks. This was done to avoid predictability effects and encourage participants to treat all stimuli as originating from a shared distribution. We note, however, that our design does not account for differential central tendency effects for duration and speed. While our interpretation assumes that central tendency similarly affects both task-relevant and task-irrelevant features, future studies might investigate whether and to what extent central tendency contributes to the asymmetry of cross-dimensional interferences between speed and duration. Such asymmetries in stimulus features may underlie the perceptual biases observed in our results.

Finally, our findings are to be considered within a broader literature examining how time and space are interrelated dimensions in perceptual processing. There is a rich body of literature in fact demonstrating the mutual—yet asymmetric—relations between perceived time and perceived space or distance (for a broad scope review, see Robbe, 2023), even when space is only implicit in object nouns of longer objects (Bottini & Casasanto, 2010). Notably, Riemer, Achtzehn, Kuehn, and Wolbers (2022) found mutual but reverse interferences between space and time, namely, that perceived time increased with longer distances, but perceived distances decreased with longer durations. The authors demonstrated that speed-sensitive regions (specifically hMT+) mediate the strength of the former effect, whereas activity in IPS represents the latter. More generally, they argue that cross-dimensional interferences between space and time can be accounted for by the involvement of a speed component, which gives rise to mutual but opposite interference effects. In our design, spatial displacement was minimized as the motion of dots had no coherence and no net drift, and could be described as a Brownian motion-like stimulus. As a result, participants could not infer speed from spatial displacement, and our findings likely reflect the visual system's reliance on speed information even in the absence of explicit spatial cues. This distinction underscores how different stimulus designs can isolate or confound the contributions of time, space, and speed in perceptual judgments. Future studies could test whether the pattern of results reported here also holds in modalities with higher temporal resolution, such as audition. Moreover, to more precisely match sensitivity across different visual features, future work could employ adaptive procedures to equate perceptual ranges on an individual basis while optimizing the number of trials administered.

Conclusions

In this study, we investigated the interaction between stimulus speed and duration in biasing perception. The results of two experiments revealed a robust effect of stimulus speed on duration judgments, with faster speeds leading to longer perceived durations. In contrast, the effect of stimulus duration on speed judgments was smaller in magnitude and less robust. These results emphasize the importance of dynamically varying sensory features in shaping visual perception. Furthermore, they highlight the greater susceptibility of time to perceptual bias.

Keywords: time perception, speed perception, time dilation

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