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Effect of motion coherence on time perception relates to perceived speed

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Running Head: Motion coherence and time perception

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Abstract

The present study examined the effect of coherence of moving visual objects on time perception. Participants observed stimuli composed of four line segments moving behind or in front of occluders. The line segments appeared to move either coherently as a diamond outline or incoherently, depending on the occlusion. Results from the temporal bisection task indicated that the duration of the coherently moving stimulus was perceived longer or shorter compared to the duration of the incoherently moving stimulus depending on the stimulus configurations. The speed comparison task revealed that the trend of the difference in perceived speed between the coherent and incoherent motions in each stimulus configuration was consistent with that of the difference in perceived duration between them. These results demonstrate the effect of motion coherence on perceived duration, and that this effect may be mediated by changes in perceived speed. Our finding provides evidence supporting the involvement of global motion processing in time perception.

Keywords: global motion processing, time perception, coherence, temporal bisection, perceived speed

1. Introduction

Time perception refers to the ability to estimate the duration and timing of events. This ability is crucial for the fulfillment of various activities (Buhusi & Meck, 2005) and for coping with a dynamic environment. In particular, temporal processing within the range of tens to hundreds of milliseconds is critical for sensory processing and motor control (Mauk & Buonomano, 2004). While temporal processing is essential to our daily lives, time perception is susceptible to non-temporal processing and duration judgment is often distorted (Fraisse, 1984). Previous studies have revealed an interesting relationship between the stimulus intensity and the perceived duration of stimulus presentation. Specifically, the perceived duration of stimuli is longer as their size (Ono & Kawahara, 2007; Thomas & Cantor, 1975), number (Mo, 1975; Xuan, Zhang, He, & Chen, 2007), or luminance (Matthews, Stewart, & Wearden, 2011; Xuan et al., 2007) increases. These findings suggest that temporal processing is associated with non-temporal processing, though the critical stage is highly controversial.

Visual motion processing is also known to influence time perception. Previous studies have shown that the perceived duration of moving stimuli is longer than that of stationary stimuli, and perceived duration increases with speed (or temporal frequency) (Beckmann & Young, 2009; Brown, 1995; Kanai, Paffen, Hogendoorn, & Verstraten, 2006; Kaneko & Murakami, 2009; Yamamoto & Miura, 2012a). These results suggest that motion-processing areas are involved in temporal processing. It is generally accepted that visual motion is hierarchically processed in multiple stages in the dorsal pathway, and different stages contribute to the processing of local and global motion information (Adelson & Movshon, 1982; Amano, Edwards, Badcock, & Nishida, 2009; Movshon, Adelson, Gizzi, & Newsome, 1985; Snowden &

Verstraten, 1999). Based on this, Kanai et al. (2006) manipulated speed and motion coherence of random dots independently to examine whether global motion information plays a role in time perception. Their experiment only indicated a speed-related effect with motion coherence showing no influence on perceived duration. This suggests that early motion processing stages, which are specialized for local motion processing, are critical for motion-induced time distortion. In contrast, more recent studies have suggested the importance of later motion processing stages on motion-induced time distortion (Au, Ono, & Watanabe, 2012; Kaneko & Murakami, 2009; Yamamoto & Miura, 2012a). For example, Yamamoto and Miura (2012a) used plaid pattern motion composed of two drifting gratings with differing orientations. They found that manipulating the pattern's coherent global motion speed influenced perceived duration. Their results suggest that motion information is involved in time perception after the process of motion integration.

Although both of the aforementioned studies [Kanai et al. (2006) and Yamamoto and Miura (2012a)] focused on the relationship between global motion processing and time perception, the conclusions were not consistent between them. One possible reason for this discrepancy is that the influence of motion coherence was diminished by changes in the other features (e.g., dot proximity or direction distribution) of the random-dot pattern used in Kanai et al. (2006). If this is the case, the effect of motion coherence should be analyzed using more controlled stimulus configurations. Another possibility is that different motion components included in the plaid pattern contributed to the influence of global motion observed in Yamamoto and Miura (2012a). The plaid pattern is composed of spatially overlapped gratings and contains second-order motion components, which were suggested to influence plaid motion perception (Cox & Derrington, 1994; Nishida, 2011; Wilson & Kim, 1994; Wilson, Ferrera, & Yo, 1992). If the duration distortion was caused by the additional motion components, it should not have an effect when the coherent stimulus does not include spatial overlap of local motion signals.

To address the above uncertainty, our study examined whether the coherence of spatially segregated moving objects influences perceived duration. To achieve this, we used a translating diamond stimulus (Lorenceau & Shiffrar, 1992; McDermott, Weiss, & Adelson, 2001; Murray, Kersten, Olshausen, Schrater, & Woods, 2002) where a diamond outline translates along a circular trajectory with its corners occluded. Although the diamond outline is partially occluded and is thus separated into four line segments, the stimulus is generally perceived as a diamond translating behind the occluders. However, if the occluders are blended into the background and become invisible, the four line segments are perceived to move incoherently in directions orthogonal to their orientation. This is because the motion of the line segments is ambiguous as a result of the aperture problem. Perceptual completion of the diamond outline behind the visible occluders can solve this ambiguity (McDermott et al., 2001).

The present study used a similar stimulus composed of four line segments located behind or in front of visible occluders to eliminate the effect of occluder visibility on perceived time. Figure 1 shows examples of the stimulus displays. Although the line segments physically move in directions orthogonal to their orientation, the stimulus is generally perceived as a diamond translating along a circular trajectory when the corners are behind the occluders (Figure 1A). Conversely, the stimulus is perceived as four moving line segments if completion is prevented by the inversion of the overlapping order (Figure 1B). We used these stimuli because they

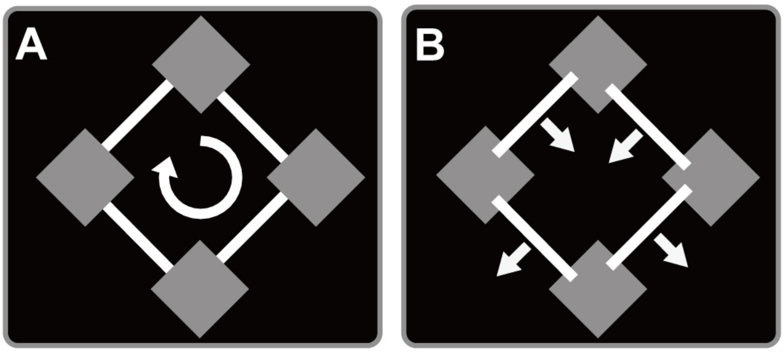

Figure 1. Schematic illustration of the (A) coherent and (B) incoherent stimuli used in Experiment 1. The arrows represent the perceived motion direction of the stimuli.

do not have spatial overlap of local motion signals, and there is little difference in low-level visual features between the coherent and incoherent stimuli.

We first compared the perceived duration of the coherent and incoherent stimuli using two different stimulus configurations, and then performed a speed discrimination task to assess whether the difference in perceived duration can be attributed to the difference in perceived speed. The perceived duration of stimulus presentation was measured using the temporal bisection task (Gil & Droit-Volet, 2009; Wearden, 1996; Yamamoto & Miura, 2012b). In this task, participants were initially trained to correctly categorize two standard durations as ‘‘short’’ or ‘‘long’’ (0.4 and 1.0 s, respectively). The coherent and incoherent stimuli were then presented with seven probe durations. Participants were asked to judge whether the duration of each stimulus was more similar to the long or short standard duration.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Twelve paid volunteers (4 men and 8 women, age: 20.8 ± 1.4 years) participated in the experiment. One of them was excluded from the data because of poor performance (i.e., Weber ratio of above 0.2). All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. All provided written informed consent. This study was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1.2. Apparatus

The stimuli were presented on a 22-inch gamma-corrected CRT monitor with a resolution of 1,280 × 800 pixels and a refresh rate of 100 Hz, controlled by an Apple Macintosh computer. A chin rest restrained the participants' head movements at a viewing distance of 57 cm from the display. The stimuli were generated using Matlab (The MathWorks, Natick, MA, USA) with the Psychtoolbox extension (Brainard, 1997; Pelli, 1997).

2.1.3. Stimuli

The stimuli were composed of four white line segments moving behind (coherent stimulus) or in front of (incoherent stimulus) four gray occluders (3.7 deg × 3.7 deg). They were presented on a black background. The line segments (0.3 deg in width and 4.0 deg in length) were tilted at 45° to the left or right and arranged to form a virtual diamond subtending 8.5 deg × 8.5 deg. Each line segment moved sinusoidally in a direction orthogonal to its orientation within a spatial interval of 1.3 deg at a mean speed of 3.1 deg/s, whereas the virtual diamond moved along a circular path at a constant speed of 4.8 deg/s. The starting position and moving direction of the line segments were randomized in each trial.

2.1.4. Procedure

The experiment was conducted in a darkened room. Before launching the main experiment, we presented the coherent and incoherent stimuli to participants and asked them to judge whether the stimuli moved along a circular or a linear path. We confirmed that all participants correctly judged the motion direction of each stimulus. This means that the coherent and incoherent stimuli were indeed perceived as moving coherently and incoherently, respectively.

The experiment consisted of two phases, a training phase and a test phase. In the training phase, only the occluders were presented in the center of the display with two standard durations (0.4 or 1.0 s) after a 1-s central fixation. The fixation was continuously present during the stimulus presentation. Participants were asked to categorize the durations as ‘‘long’’ or ‘‘short’’ by pressing the ‘‘d’’ or ‘‘k’’ key. The response keys were counterbalanced across participants. After their response, visual feedback (‘‘correct’’ or ‘‘miss’’) was presented for 1 s and the trial was complete. Each participant was given successive blocks of 10 trials, consisting of five short standard duration trials and five long standard duration trials. The trial order was randomized across participants and across blocks. The training phase was terminated after the participants learned to correctly categorize standard durations by providing 10 consecutive correct responses.

In the test phase, the coherent and incoherent stimuli were presented in the center of the display individually with seven probe durations (0.4, 0.5, 0.6, 0.7, 0.8, 0.9, or 1.0 s) after a 1-s central fixation. The fixation was continuously present during stimulus presentation. The participants were asked to judge whether the probe duration was more similar to the long or short standard duration by pressing the corresponding key used in the training phase. No feedback was presented in this phase. Each participant completed 280 trials, including 20 repetitions. The trial order was randomized across participants and across blocks.

2.2. **Results and discussion**

We calculated the bisection point (the stimulus duration giving rise to 50 % long responses) to compare the mean perceived duration of the coherent and incoherent stimuli. Cumulative Gaussian psychometric functions were fitted separately to the proportion of long responses for each stimulus using the psignifit toolbox for Matlab, which implements the maximum-likelihood method (Wichmann & Hill, 2001a; 2001b). Figure 2A shows samples of psychometric functions from one participant. The mean and individual bisection points for each stimulus are shown in Figure 2B. Although there were individual differences in the bisection point, the direction of difference between the coherent and incoherent stimuli was almost consistent. A paired *t* test and effect size calculation (Cohen, 1992) revealed that the bisection point of the coherent stimulus (M = 718 ms) was significantly lower than that of the incoherent stimulus (M = 736 ms) ($t(11) = 2.38$, $p = 0.04$, Cohen's $d = 0.52$).

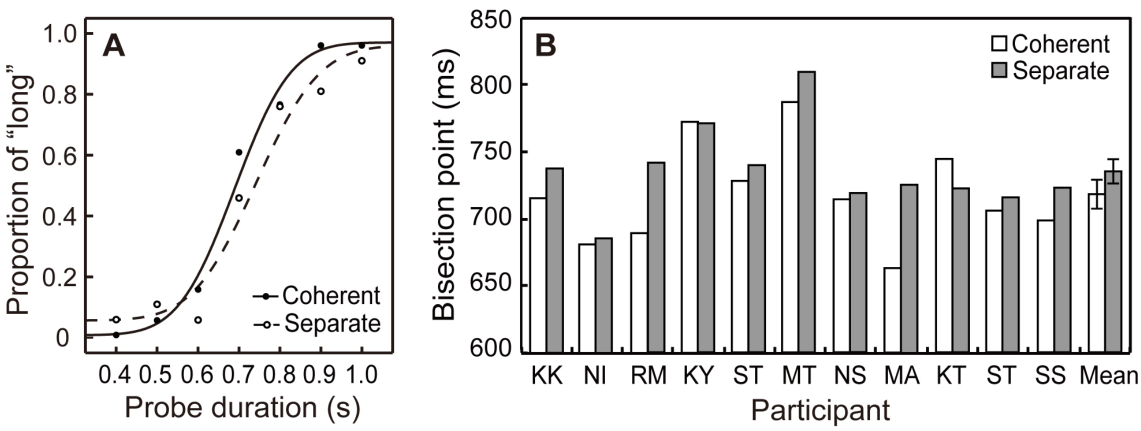

Figure 2. Results of Experiment 1. (A) Psychometric functions obtained from a typical participant. The dashed and solid curves show data from the incoherent and coherent stimuli, respectively. (B) The individual and mean bisection points for the incoherent and coherent stimulus. Error bars denote ±1 standard error.

We also calculated the Weber ratio to analyze the temporal sensitivity to the stimuli. This ratio is obtained by dividing the difference limen (half of the difference between the durations giving rise to 75 % and 25 % long responses) by the bisection point. The mean Weber ratios were 0.11 for both the coherent and incoherent stimuli. A paired *t* test showed no significant difference between the coherent and incoherent stimuli ($t(11) = 0.07$, $p = 0.95$, Cohen's $d = 0.02$).

The results of Experiment 1 show that the presentation duration of the coherent stimulus was judged to be longer than that of the incoherent stimulus. The Weber ratio was not different between the coherent and incoherent stimuli, indicating that the observed effect is not caused by differences in temporal sensitivity. These findings suggest that motion coherence increases perceived duration. However, perceived motion trajectory and speed profile are different between the coherent and incoherent stimuli (Table 1), and this difference may contribute to the duration distortion. To address this possibility, we performed a second experiment (Experiment 2) with a different stimulus configuration, in which both coherent and incoherent stimuli moved along a linear trajectory (Murray et al., 2002). Figure 3 shows examples of the stimulus displays used in Experiment 2. If the effect of motion coherence results from the difference in perceived motion trajectory, the perceived duration difference would disappear in this stimulus configuration.

Table 1. The mean and maximum speeds of stimulus motion calculated for each stimulus, and mean bisection points (BP) and weber ratios (WR) obtained from Experiments 1 and 2.

	Circular condition (Exp. 1)		Linear condition (Exp. 2)	
	Coherent	Incoherent	Coherent	Incoherent
Stimulus speed				
Mean	4.8	3.1	3.8	3.8
Max	4.8	4.8	6.0	6.0
Temporal performance				
BP	718	736	726	704
WR	0.11	0.11	0.12	0.12

3. Experiment 2

3.1. Methods

3.1.1. Participants

Eighteen paid volunteers (10 men and 8 women, age: 22.4 ± 1.3 years) were newly recruited and participated in the experiment. Three of them were excluded from the data because of poor performance (i.e., Weber ratio of above 0.2). All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. All provided written informed consent.

3.1.2. Apparatus, stimuli, and procedures

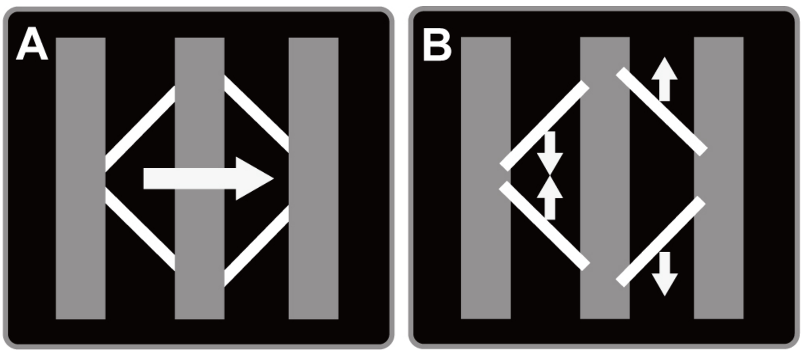

Figure 3. Schematic illustration of the (A) coherent and (B) incoherent stimuli used in Experiment 2. Each arrow represents the perceived motion direction of the stimuli.

The apparatus, stimuli, and procedure were similar to those of Experiment 1, except for the following: the occluders were replaced by three gray bars. The bars subtended 1.8 deg × 10.3 deg and were spaced at regular intervals of 2.4 deg. Both the line segments and the virtual diamond moved sinusoidally back and forth within a spatial interval of 1.3 deg at a mean speed of 3.8 deg/s. Whereas each line segment moved in a direction parallel to the bar length (Figure 3B), the virtual diamond moved in a direction orthogonal to the bar length (Figure 3A). To control the possible influence of the motion direction, the bars were placed vertically in one condition (vertical condition) and horizontally in the other condition (horizontal condition). Thus, the line segments moved in vertical and horizontal directions in the vertical and horizontal conditions, respectively. Meanwhile, the virtual diamond appeared to move in horizontal and vertical directions in the vertical and horizontal conditions, respectively. Participants were randomly assigned to either the vertical or horizontal condition. We confirmed that all participants correctly judged the motion direction of each stimulus (vertical or horizontal) before launching the main experiment.

3.2. Results and discussion

As in Experiment 1, the responses of each participant were fitted with psychometric functions (Figure 4A). The mean and individual bisection points for each stimulus for the vertical and horizontal conditions are shown in Figure 4B and 4C. A two-way mixed analysis of variance (ANOVA) revealed a significant main effect of coherence ($F(1,13) = 5.90$, $p = 0.03$, $\eta_p^2 = 0.31$), indicating that the bisection point of the coherent stimulus ($M = 726$ ms) was higher than that of the incoherent stimulus ($M = 704$ ms). There was neither a significant main effect of orientation ($F(1,13) = 0.19$, p

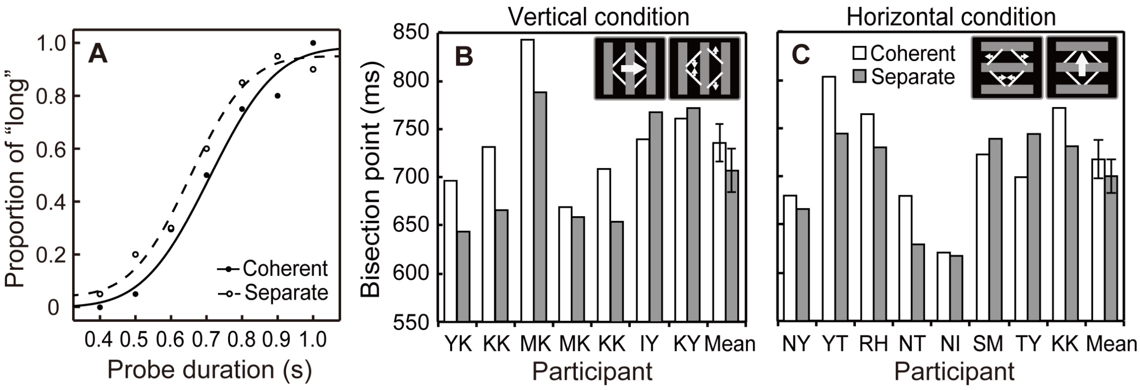

Figure 4. Results of Experiment 2. (A) Psychometric functions obtained from a typical participant. The dashed and solid curves show data from the incoherent and coherent stimuli, respectively. The individual and mean bisection points for the incoherent and coherent stimulus in the (B) vertical and (C) horizontal conditions. Error bars denote ±1 standard errors.

= 0.67, $\eta_p^2 = 0.01$) nor interaction between coherence and orientation ($F(1,13) = 0.33$, $p = 0.57$, $\eta_p^2 = 0.03$) signifying that the direction of motion is irrelevant to the effect of coherency. Moreover, a two-way mixed ANOVA for the Weber ratios showed no significant main effects or interaction (coherence: $F(1,13) = 0.002$, $p = 0.97$, $\eta_p^2 < 0.01$; orientation: $F(1,13) = 2.97$, $p = 0.11$, $\eta_p^2 = 0.19$; interaction: $F(1,13) = 0.85$, $p = 0.37$, $\eta_p^2 = 0.06$), indicating that the Weber ratio was not different between the coherent ($M = 0.12$) and incoherent ($M = 0.12$) stimuli.

To compare the results between the experiments, we also conducted a two-way mixed ANOVA for the bisection points with experiment (Experiment 1 vs. Experiment 2) and motion coherence (coherent vs. incoherent) as factors. While there were no significant main effects of experiment and coherence (experiment: $F(1,24) = 0.44$, $p = 0.51$, $\eta_p^2 = 0.02$; coherence: $F(1,24) = 0.18$, $p = 0.67$, $\eta_p^2 = 0.01$), a significant interaction was found between them ($F(1,24) = 10.33$, $p = 0.004$, $\eta_p^2 = 0.30$). Further analysis showed that the bisection point was significantly lower for the coherent stimulus than for the incoherent stimulus in Experiment 1 ($F(1,10) = 5.81$, $p = 0.04$, $\eta_p^2 = 0.37$), but an opposite effect was observed in Experiment 2 ($F(1,14) = 6.03$,

$p = 0.03$, $\eta_p^2 = 0.28$). No simple main effect of experiment was significant in each stimulus (coherent: $F(1,24) = 0.14$, $p = 0.70$, $\eta_p^2 = 0.06$; incoherent: $F(1,24) = 2.80$, $p = 0.11$, $\eta_p^2 = 0.11$).

In Experiment 2, we compared the perceived duration of the coherent and incoherent stimuli while controlling the perceived motion trajectory. The results again revealed the influence of motion coherence on perceived duration. However, in contrast to Experiment 1, the presentation duration of the coherent stimulus was judged to be shorter than that of the incoherent stimulus. This opposite effect was observed irrespective of the motion direction, and temporal sensitivity was not different between the conditions. These results suggest that motion coherence can reduce as well as increase perceived duration, depending on the stimulus configuration.

Recent studies have shown that the moving speed of a global object is perceived as slower than that of local components (Kohler, Caplovitz, & Tse, 2014). Apparent speed can influence time perception, similar to the effect of physical speed (Gorea & Kim, 2015). Thus, the time distortion resulting from the perceived motion coherence observed in each experiment may be attributed to the difference in perceived speed between the coherent and incoherent stimuli. To address this possibility, in Experiment 3, we measured the perceived speed difference between the coherent and incoherent stimuli used in Experiment 1 (circular condition) and Experiment 2 (linear condition). Each participant performed a speed comparison task in which the coherent and incoherent stimuli were presented sequentially, and participants were asked judge which of the two stimuli seemed to move faster.

4. Experiment 3

4.1. Methods

4.1.1. Participants

Twenty-two paid volunteers (12 men and 10 women) were newly recruited and participated in the experiment. Participants were randomly assigned to either the circular condition (12 participants) or the linear condition (10 participants). All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. All provided written informed consent.

4.1.2. Apparatus, stimuli, and procedures

The apparatus and stimuli were identical to those of Experiment 1 for the circular condition and were identical to those of Experiment 2 for the linear condition. In each trial, the coherent and incoherent stimuli were presented sequentially. One of them was presented as a standard and the other was presented as a test. The moving speeds of the line segments of the standard were fixed at 3.1 deg/s for the circular condition and 3.8 deg/s for the linear condition. The moving speeds of the test varied among 1.24, 1.86, 2.48, 3.10, 3.72, 4.34, and 4.96 deg/s for the circular condition and among 1,52, 2.28, 3.04, 3.80, 4.56, 5.32, and 6.08 deg/s for the linear condition. The proportions of the difference between the standard and test speeds were -0.6, -0.4, -0.2, 0, 0.2, 0.4, and 0.6, respectively, for both of the conditions.

The standard and test stimuli were presented in the center of the display after a 1-s central fixation. Each stimulus was presented for 700 ms and a 500-ms interval was inserted between them. The presentation order of the two stimuli was randomized across trials. The participants were asked to judge whether the first or the second stimulus was faster by pressing one of two response keys. The fixation was continuously presented during each trial. Each participant completed 140 trials, consisting of two types of stimulus combinations (coherent standard / incoherent test and incoherent standard / coherent test) × 7 test speeds × 10 repetitions. The trial order was randomized across participants and across blocks. Half of the participants in the linear condition observed the stimuli presented in a vertical orientation, and the other half of the participants observed them presented in a horizontal orientation.

4.2. Results and discussion

The proportion of the "faster" responses to the coherent stimulus was calculated as a function of the differences between the speeds of the coherent and incoherent stimuli. The data of each participant was fitted with psychometric functions to obtain the point of subjective equality (PSE). We then calculated the percentage of difference in perceived speed between the coherent and incoherent stimuli by using the PSE (Figure 5). Positive and negative values indicate that the coherent stimulus was

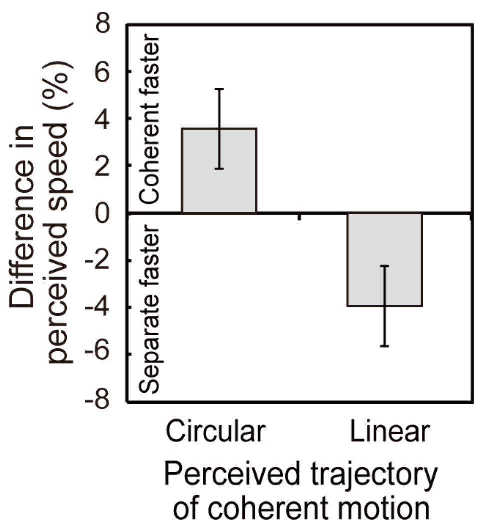

Figure 5. Mean percentage of difference in perceived speed between the coherent and incoherent stimuli in the circular and linear conditions. Error bars indicate ±1 standard error.

perceived to move faster and slower than the incoherent stimulus, respectively.

One-sample *t* tests revealed that the percentage of difference was significantly larger than zero for the circular condition (M = 3.6%; $t(11) = 2.21$, $p = 0.05$, Cohen's d = 0.90) and significantly smaller than zero for the linear condition (M = -3.9%; $t(9)$ = 2.32, $p = 0.04$, Cohen's $d = 1.04$). Moreover, there was a significant difference between the circular and linear conditions ($t(20) = 3.26$, $p = 0.004$, Cohen's $d = 1.37$).

The results of Experiment 3 showed that the effect of motion coherence on perceived speed differed depending on the stimulus configurations. In the circular condition, the coherent stimulus was perceived to move faster than the incoherent stimulus. As shown in Table 1, in this condition, maximum speed of each line segment was identical to that of the coherent diamond. This means that the participants might estimate the separate stimulus speed based not only on its maximum speed. It was possible that they might compare the averaged line speeds with the coherent diamond speed. However, the difference in mean speed between the stimuli was much larger than the difference in perceived speed. This suggests that speed estimation of the periodic sinusoidal motion is largely different from that of the constant motion, possibly being influenced by the acceleration and deceleration or the inversion of motion direction. In contrast, for the linear condition, the coherent stimulus was perceived to move slower than the incoherent stimulus, although both stimuli had the similar speed profile. This result is consistent with the previous study showing that global motion appears to move slower than local motion (Kohler et al., 2014), suggesting that motion coherence reduces perceived speed. Given that the difference in perceived speed correlates to the difference in perceived duration observed in the previous experiments, the effect of motion coherence on perceived duration might be mediated by the perceived speed difference between the stimuli.

5. General discussion

In the present study, we used a modified diamond display to determine that the duration of a coherently moving stimulus is perceived differently from that of a incoherently moving stimulus. Perceived duration was longer for the coherent circular motion than for the incoherent linear motion (Experiment 1). In contrast, perceived duration was shorter for the coherent than for the incoherent motion when each appeared to move linearly (Experiment 2). Experiment 3 revealed that perceived speed differences between the coherent and incoherent motions in each experiment were consistent with the differences in perceived duration. Indeed, the stimulus used in Experiment 1 was perceived as faster for the coherent than for the incoherent motion, while the stimulus used in Experiment 2 was perceived as slower for the coherent than for the incoherent motion. These results suggest that the coherence of local motion signals influences time perception, and this effect may reflect the changes in perceived speed rather than the motion coherence per se.

Despite their perceptual dissimilarities, the movements of visible elements were exactly the same between the coherent and incoherent stimuli, and both the stimuli were comprised almost the same local features. This suggests that the effect observed in the present study is caused by perceptual rather than physical differences. However, because we asked participants about the appearance of each stimulus only before the experiments, it was not clear whether the coherent and incoherent motions were observed in each probe duration. To address this, four additional participants were asked to report whether the stimulus used in each experiment appeared to move coherently or incoherently. Each participant performed 560 trials and showed a high proportion of correct responses (99% on average). Moreover, there was no significant effect of probe duration ($F(6,18) = 1.07$, $p = 0.41$). This result suggests that the coherent and incoherent motions can indeed be seen irrespective of the probe duration.

The results of the present study are consistent with Yamamoto and Miura (2012a), showing that speed of a coherently moving stimulus influences perceived duration. However, the present study did not directly manipulate the speed of the coherent motion, and the difference in perceived speed between the coherent and incoherent motions was small. This may be the reason that the magnitude of the duration distortion was smaller (about 3%) in this study, as compared to the previous study (about 10–20%). Unlike the plaid pattern used in Yamamoto and Miura (2012a), the moving components of the stimulus were spatially segregated and did not contain second-order motion components. Therefore, the present results provide stronger evidence for the involvement of global motion processing in time perception.

Our results show a difference in perceived duration between coherent and incoherent stimulus motion. This finding is inconsistent with Kanai et al. (2006), which suggests that motion coherence has no influence on time perception. However, the effect of motion coherence observed in this study was different depending on the stimulus configurations. This suggests that the effect of motion coherence was very weak and that other features such as speed largely influenced perceived duration. This may also explain why the effect of motion coherence was not present when using a random-dot pattern in Kanai et al. (2006) because perceived speed of that pattern has been shown to be unaffected by coherence level (Schuz, Braun, Movshon, & Gegenfurtner, 2010; Zanker & Braddick, 1999). Although Kanai et al. argued that temporal frequency is critical for the motion-induced duration distortion, Kanai and

Murakami (2009) found that perceived duration changes not only with temporal frequency but also with spatial frequency of a moving stimulus, suggesting that perceived duration may depend on speed rather than temporal frequency per se. The present results support the speed hypothesis and further suggest the importance of perceived speed on temporal processing.

Recently, it was hypothesized that perceived duration is related to the amount of neural activity in response to the stimulus (Eagleman & Pariyadath, 2009; Sadeghi, Pariyadath, Apte, Eagleman, & Cook, 2011). According to this hypothesis, the stimulus that leads to greater neural activities is perceived as longer in duration, and suppressed neural activity results in a reduction in perceived duration. This is a consistent explanation of the relationship between stimulus magnitude and perceived duration since higher magnitude stimuli generally lead to higher neuron firing rates (see Table 1 of Eagleman & Pariyadath, 2009). Previous neuroimaging studies have shown that neural activity in the middle temporal area (MT/V5) is modulated by motion coherence (Braddick et al., 2001; Caclin et al., 2012; Castelo-Branco et al., 2002). This suggests that the changes in neural activity in MT induced by motion coherence influenced perceived duration. However, Caclin et al. (2012) used the diamond stimulus and found that neural responses in MT decreased for a coherent circular motion compared to a incoherent linear motion. Our results, together with the findings of Caclin et al. (2012), are inconsistent with the neural activity account because the coherent circular motion was perceived to be longer in duration than the incoherent linear motion (Experiment 1). This suggests that the amount of neural activity is not the only substrate of time perception (Gorea & Kim, 2015). As suggested by Kaneko and Murakami (2009), it is possible that the tick rate of the internal clock increases for moving or faster objects than for stationary or slower objects because of an ecological advantage. The role of motion processing on time perception should be addressed in future studies.

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