Perceived duration of plaid motion increases with pattern speed rather than component speed

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Several studies have shown that visual motion distorts perceived duration: The duration of fast-moving stimuli is judged to be longer than the same duration of stationary or slow-moving stimuli. However, it is still unclear which stages of motion processing are involved in this apparent dilation of the perceived duration. In this study, we systematically manipulated the speed of pattern and component motions of the plaid to examine which motion information influences the perceived duration of the plaid stimuli. Experiment 1 found that perceived duration increased with pattern speed, even though component speed was constant. Experiments 2 and 3 revealed that perceived duration was unchanged, even though component speed increased, as long as the pattern speed was identical. Experiment 4 used both static and moving plaids and confirmed that the results of Experiments 1–3 reflected duration dilation, not duration compression, induced by motion. These results suggest that higher order visual processing in the middle temporal area may play an important role in motion-induced duration dilation.

Keywords: time perception, plaid motion, speed, MT

Introduction

We naturally experience the passage of time. Although we can estimate the duration of events without mechanical clocks, our perceived duration sometimes differs from the physical duration. Previous studies have shown that eye movements (Morrone, Ross, & Burr, 2005; Schütz & Morrone, 2010), temporal frequency adaptation (Burr, Tozzi, & Morrone, 2007; Johnston, Arnold, & Nishida, 2006), emotion (Droit-Volet & Meck, 2007), attention (Tse, Intriligator, Rivest, & Cavanagh, 2004), predictability (Pariyadath & Eagleman, 2007, 2008), and various visual features (Eagleman & Pariyadath, 2009) can dilate or compress perceived duration. However, how and where these duration distortions occur in the brain is still under debate.

Motion is one of the visual features that influence perceived duration. Several studies have shown that visual motion causes duration dilation: The duration of moving stimuli is judged to be longer than the same duration of stationary stimuli (Brown, 1995; Mitrani & Stoyanova, 1982), and the duration of fast-moving stimuli is judged to be longer than the same duration of slow-moving stimuli (Kanai, Paffen, Hogendoorn, & Verstraten, 2006; Kaneko & Murakami, 2009; Tayama, Nakamura, & Aiba, 1987). Some researchers have suggested that this temporal illusion is caused by spatial or luminance changes accompanying visual motion. This idea is related to a change-based model of time perception (Poynter, 1989), in which the number of events determines perceived duration. To test the involvement of the change-based model in motion-induced duration dilation, Kanai et al. (2006) manipulated the spatial and temporal frequencies of an expanding concentric grating and examined which frequency is fundamental for duration dilation. They found that the perceived duration of the stimulus increased with temporal frequency irrespective of spatial frequency, and a similar duration dilation was found when using a simply flickering Gaussian luminance blob. These results are consistent with the change-based model because temporal frequency is a useful indicator of the speed of scene change. Kanai et al. argued that lower stages of motion processing (primary visual cortex, V1), in which neurons are separately tuned for spatial and temporal frequencies (Foster, Gaska, Nagler, & Pollen, 1985), might be involved in duration dilation.

In contrast to the results of Kanai et al. (2006), Kaneko and Murakami (2009) found that stimulus speed, rather than temporal frequency or spatial frequency per se, is critical for duration dilation induced by visual motion. They systematically manipulated the temporal frequency, spatial frequency, and speed of a moving Gabor patch, which is composed of a drifting grating with a stationary Gaussian envelope, and found that there was no significant difference between the partial regression coefficients for spatial frequency and temporal frequency. Their results indicate that (a) stimulus speed best explains perceived duration and (b) neither spatial nor luminance changes are

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sufficient to account for duration distortion induced by motion. Kaneko and Murakami explained that the expanding concentric grating used in Kanai et al. would be brighter or darker than that in a certain phase; thus, temporal frequency could become dominant. Because neurons in the middle temporal area (MT, also known as V5) are tuned for stimulus speed (Perrone & Thiele, 2001; Priebe, Lisberger, & Movshon, 2006), Kaneko and Murakami argued that higher order motion processing in MT is responsible for duration dilation.

Although the study of Kaneko and Murakami (2009) is important in that it focused on higher order motion-processing stages as critical areas of duration dilation, it has two limitations. The first is the possibility that spatial and temporal frequencies could influence perceived duration independently because Kaneko and Murakami simultaneously manipulated spatial and temporal frequencies to examine the speed dependence of duration dilation. Previous studies have shown that spatial frequency influences perceived duration of a stimulus directly (Aaen-Stockdale, Hotchkiss, Heron, & Whitaker, 2011; Long & Beaton, 1980). If spatial frequency has much the same effect as temporal frequency, stimulus speed that is determined by spatial and temporal frequencies might mistakenly be believed to influence perceived duration. Therefore, it is still possible that temporal frequency per se (i.e., lower motion-processing stages) is critical for motion-induced duration dilation. The second limitation is that speed dependence does not necessarily mean that motion-induced duration dilation depends on higher order motion processing. A recent study showed that, while V1 simple cells are tuned for spatial and temporal frequencies separately, one-quarter of V1 complex cells are tuned for speed as well as MT (Priebe et al., 2006). This suggests that, even though stimulus speed is dominant in duration dilation, lower order motion processing might play a role in duration dilation to some extent. These two limitations are inevitable when a one-dimensional motion stimulus, which is processed at both lower and higher stages of motion processing, is used.

To overcome these limitations, in the present study, we used a two-dimensional pattern motion of a plaid as a stimulus and examined the effect of higher and lower order motion processing on perceived duration. Each plaid stimulus was composed of two superimposed drifting sine-wave gratings with different orientations. Although the drifting directions of the component gratings were different from each other, the plaid stimulus appeared to move coherently in a single direction consistent with the pattern motion (Figure 1a). Adelson and Movshon (1982) have suggested that plaid motion is processed at two stages: the stage that processes one-dimensional motion and the stage that combines them to generate a perceived pattern motion. Previous neuroimaging and electrophysiological studies support this two-stage model by showing that neurons not in V1, but in extrastriate visual areas including MT, are related to the perception of coherent pattern motion, while neurons in V1 are related to the process of component motion (Huk & Heeger, 2002;
Movshon, Adelson, Gizzi, & Newsome, 1985; Thompson, Aaen-Stockdale, Koski, & Hess, 2009). On the basis of these studies, we used plaid stimuli and examined which motion information is critical for duration dilation, pattern motion, or component motion. If an increase of pattern speed dilates perceived duration regardless of component speed, higher order motion processing in MT is supposed to play an important role in duration dilation. By contrast, if an increase of component speed dilates perceived duration regardless of pattern speed, lower order motion processing in V1 is supposed to play an important role in duration dilation.

In Experiments 1–4, we manipulated the pattern speed of plaids in two ways: (a) manipulating component speed and (b) manipulating component orientations across trials (Figures 1b and 1c). Pattern speed of plaids increases with component speed (Adelson & Movshon, 1982; Welch, 1989). In this case, component and pattern speeds vary concurrently. By contrast, pattern speed of plaids also increases when the difference in component orientation becomes larger (Adelson & Movshon, 1982; Welch, 1989). In this case, pattern speed varies, even if the component speed of each plaid is stable. The combination of these manipulations made it possible to manipulate the plaids’ component and pattern speeds independently. Using these manipulations, we examined which stages of motion processing are critical for duration dilation.

**Experiment 1**

In Experiment 1, we manipulated the pattern speed of plaid stimuli by varying the component orientations of them and examined whether pattern speed dilates perceived duration. In this manipulation, component speed is unchanged even though pattern speed increases with component orientations. Hence, if perceived duration of the plaid stimuli increases with component orientations, it can be supposed that pattern speed dilates perceived duration. However, because both pattern speed and component orientations vary in this manipulation, it may be possible that it is not the pattern speed but the component orientations per se that influences perceived duration of the plaid stimuli. To exclude this possibility, we also used plaid stimuli composed of sine-wave gratings whose spatial frequencies differed from each other by three octaves. This spatial frequency difference negates the motion coherency of plaid stimuli, and two gratings appear to move transparently (Smith, 1992). If perceived duration increases only when the plaid appears to move coherently, it can be supposed that not component orientations per se but pattern speed that varies with component orientations dilates perceived duration.

In the experiment, a target and a test plaid appeared sequentially on the CRT monitor. The target plaid was composed of moving gratings, and the test plaid was composed of static gratings. The component gratings of the target plaid appeared to move coherently in one condition (pattern motion condition), and the gratings appeared to move transparently in another (component motion condition). Observers were asked to reproduce the perceived duration of the target plaid by pressing the space bar after a corresponding duration had elapsed from the onset of the test plaid.

**Methods**

**Observers**

Nine observers including the first author (KY) participated in the experiment. All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment except for KY and one observer. In this and in all the following experiments, observers gave written informed consent, and the experiments were conducted in accordance with the Declaration of Helsinki.

**Apparatus**

Stimuli were presented on a 17-inch gamma-corrected CRT monitor with a 1,024 × 768 resolution at a refresh rate of 100 Hz. The presentation of stimuli and collection of data were computer controlled (Mac Pro; Apple). A chin rest restrained the observer’s head movements at a viewing distance of 57 cm. Stimuli were generated by Matlab (The MathWorks, Natick, MA, USA) with the Psychtoolbox extension (Brainard, 1997; Pelli, 1997).

**Stimuli**

Stimuli were displayed on a gray background (43.5 cd/m²). The target stimulus was a plaid composed of two superimposed circular patches (10 deg in diameter) of drifting sine-wave gratings. The plaid had a Michelson contrast of 99% and a mean luminance of 48.5 cd/m². In half of the trials, each of two component gratings had a 1 c/deg spatial frequency (pattern motion condition), and in the other trials, one had a 0.25 c/deg and the other had a 2 c/deg spatial frequency (component motion condition). The drifting directions of the two component gratings were upper and lower right or left for each trial, and thus plaid pattern moved rightward or leftward when the component gratings appeared to move coherently.

The drifting speed of the component gratings was 1 deg/s in all the trials. Orientations of the component gratings were varied between ±60°, ±75.5°, ±82.8°, and ±86.4°. The speed of pattern motion calculated from the intersection of constraints (see Figure 1a) of the component gratings was approximately 2, 4, 8, and 16 deg/s, respectively, corresponding to the component orientations of ±60°, ±75.5°, ±82.8°, and ±86.4°.

The test stimulus was a static plaid whose size and luminance were the same as the target one. While spatial
frequencies of target gratings were identical in each orientation condition, apparent spatial frequency of plaid pattern changed in accordance with component orientations. Therefore, although it is unknown whether apparent spatial frequency of plaid pattern influences perceived duration, we varied the spatial frequencies and orientations of the test gratings in accordance with the target gratings in each trial to cancel out the possible effect. This is also the reason why we used a static plaid as the test stimulus instead of a common simple stimulus.

In addition, the test plaid was rotated 90° in a clockwise direction compared with the target one to prevent the effect of illusory motion of the test plaid, which can be caused by the motion aftereffect of the moving target plaid, on perceived duration (see Figure 2). Although it has been suggested that motion aftereffects are induced not only by a directional mechanism but also by a non-directional mechanism that transfers across different orientations (Stocker & Simoncelli, 2009), our static test plaid should not show any of these transferred effects because the non-directional aftereffect is zero at zero test speed.

Procedure

The experiment was conducted in a darkened room. Observers pressed the space bar to initiate each trial, and immediately after the key press, a fixation point appeared 5.5 deg above the center of the display. After a 500-ms fixation display, a target stimulus appeared at the center of the display for 500, 750, or 1,000 ms, and with a temporal interval of 750 ms, a test stimulus appeared at the same position. The task of observers was to press the space bar when the test stimulus was presented for a duration equally as long as the duration of the target stimulus presented before. The test stimulus disappeared after the observers’ response, and then the trial was finished. The fixation point was continuously presented during each trial.

Each observer performed 192 trials, consisting of two drifting directions of pattern motion (rightward and leftward) × three durations of the target stimulus (500, 750, and 1,000 ms) × two kinds of motion coherency (pattern and component) × four pairs of component orientations (±60°, ±75.5°, ±82.8°, and ±86.4°) × four repetitions. The trial order was randomized across observers and across blocks.

Analysis

Reproduced durations for the test stimuli that exceeded a range of mean ± 3 SD in each duration condition were excluded as outliers. We then calculated a T-corrected score ($T_{\text{corrected}} = (T_{\text{estimated}} - T_{\text{target}})/T_{\text{target}}$; Angrilli, Cherubini, Pavese, & Manfredini, 1997; Noulhiane, Mella, Samson, Ragot, & Pouthas, 2007; Yamada & Kawabe, 2011), where $T_{\text{estimated}}$ is the reproduced duration in each trial, and $T_{\text{target}}$ is the duration of the target stimulus of the trial. This transformation is necessary to analyze the reproduced durations of all duration conditions in the same parametric test because it is known that the intertrial variance of the reproduced duration is proportional to the presentation duration (Buhusi & Meck, 2005; Gibbon, 1977). The score represents the extent of error of temporal reproduction with direction information. Negative values indicate that reproduced durations were shorter than the target durations, whereas positive values indicate that reproduced durations were longer than the target durations.
The statistical analysis consisted of analysis of variance (ANOVA) followed by post-hoc analysis using Ryan’s (1960) method. A paired t test was also conducted to compare the perceived duration between two drifting directions of the component gratings.

**Results and discussion**

Data from one observer were excluded from further analysis because she reported that the test stimulus appeared to move due to a motion aftereffect. There was no significant difference between two drifting directions of the component gratings, t(7) = 0.63, p = 0.54. Thus, the subsequent analysis was conducted using the data averaged across the drifting directions (Figure 3). A three-way within-subject ANOVA showed significant interactions between target duration and component orientation (F(6, 42) = 2.51, p < 0.05) and between motion coherency and component orientation (F(3, 21) = 3.72, p < 0.05). There were also significant main effects of target duration (F(2, 14) = 35.71, p < 0.001), motion coherency (F(1, 7) = 7.17, p < 0.05), and component orientations (F(3, 21) = 6.58, p < 0.01).

Analysis of simple main effects based on the interaction between motion coherency and component orientation revealed a significant main effect of component orientation in the pattern motion condition (F(3, 42) = 10.07, p < 0.001). Multiple comparisons revealed that the T-corrected score was larger in the ±75.5°, ±82.8°, and ±86.4° conditions than in the ±60° condition (ps < 0.05). By contrast, there was no significant main effect of component orientation in the component motion condition (F(3, 42) = 0.48, p = 0.70).

Multiple comparisons based on the main effect of target duration revealed that the T-corrected score was higher in the 500- and 750-ms conditions than in the 1,000-ms condition and was larger in the 500-ms condition than in the 750-ms condition (ps < 0.05). Moreover, simple main effects based on the interaction between target duration and component orientation revealed that these differences were significant in all orientation conditions (ps < 0.01).

This experiment was conducted to examine whether pattern speed dilates perceived duration by manipulating component orientations. The results showed that perceived duration increased with the difference of component orientations only when the coherent pattern motion could be observed. This indicates that, not component orientations per se, but pattern speed that varies with component orientations dilates perceived duration. Given that the pattern motion of the plaid is processed after V1 (Huk & Heeger, 2002; Movshon et al., 1985; Thompson et al., 2009), our results further suggest that higher order motion processing may play an important role in duration dilation.

The results also showed that the magnitude of the overestimation of the target duration became smaller as the target duration increased. Kanai et al. (2006) have reported a similar pattern of duration distortion: The duration of the brief interval stimuli was overestimated, whereas the duration of the longer interval stimuli was underestimated. This phenomenon, which is known as Vierordt’s law, has been reported by a number of studies (e.g., Fortin & Rousseau, 1998; Yarmey, 2000). Despite the presence of the Vierordt bias in the present experiment, our data clearly showed that perceived duration

![Figure 3](https://jov.arvojournals.org/pdfsaccess.ashx?url=/data/journals/jov/932804/)
increased with the component orientations in the pattern motion condition, suggesting that the Vierordt bias does not counteract motion-induced duration dilation.

**Experiment 2**

The results of Experiment 1 showed that pattern speed dilates perceived duration. This supports the idea that higher order motion processing plays an important role in motion-induced duration dilation (Kaneko & Murakami, 2009). However, another possibility is that both lower and higher order motion processing are involved in duration dilation. Eagleman and Pariyadath (2009) proposed that the amount of neural energy required to represent a stimulus influences perceived duration of that stimulus. From their point of view, it is expected that increases of neural processing in lower and higher order processing areas independently dilate perceived duration. To address this possibility, in Experiment 2, we compared the magnitude of duration dilation between the condition in which only pattern speed varied and the condition in which both pattern and component speeds varied. If lower order motion processing is also important for duration dilation, it is predicted that the magnitude of duration dilation would be higher when both pattern and component speeds increase than when only pattern speed increases.

In the experiment, we manipulated the component orientations or the component speed of the plaid stimulus across trials. In one condition, the component speed was held constant while the component orientations varied as in Experiment 1 (orientation change condition). In another condition, the component orientations of the plaid were held constant while the component speed varied (speed change condition). As we mentioned earlier, the pattern speed would vary in both the orientation change and the speed change conditions, and the component speed would vary only in the speed change condition. By comparing the magnitude of duration dilation between these conditions, we examined whether component speed also dilates perceived duration.

**Methods**

**Observers**

Nine observers including an author (KY) participated in the experiment. Five of them had also participated in Experiment 1. All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment except for KY.

**Apparatus, stimuli, procedure, and analysis**

The apparatus, stimuli, procedure, and analysis used in Experiment 2 were identical to Experiment 1 except for the following: Each of the two component gratings had spatial frequencies of 1 c/deg in both the orientation change and the speed change conditions. In the orientation change condition, the drifting speed of the component gratings was always 1 deg/s, whereas orientations of the component gratings varied between ±60°, ±75.5°, ±82.8°, and ±86.4°. In the speed change condition, orientations of the component gratings were always ±60°, whereas the drifting speed of the component gratings varied between 1, 2, 4, and 8 deg/s. The speed of pattern motion computed from the intersection of constraints of the component gratings was approximately 2, 4, 8, and 16 deg/s, respectively, corresponding to the component orientations of ±60°, ±75.5°, ±82.8°, and ±86.4° in the orientation change condition and to the component speeds of 1, 2, 4, and 8 deg/s in the speed change condition. Although both conditions contained common trials of ±60° in orientations and 1 deg/s in speed, observers performed these trials once in each repetition.

Observers performed 168 trials in total, consisting of two drifting directions of the component gratings (rightward and leftward) × three durations of the target stimulus (500, 750, and 1,000 ms) × two change attributions (orientation change and speed change) × four kinds of pattern speed (2, 4, 8, and 16 deg/s) × four repetitions. The trial order was randomized across observers and across blocks.

**Results and discussion**

There was no significant difference between two drifting directions of the component gratings, F(8) = 0.66, p = 0.53. Thus, the subsequent analysis was conducted using the data averaged across the drifting directions (Figure 4). We performed a three-way within-subject ANOVA to see the effect of pattern speed in each duration and change attribution. As in Experiment 1, there was a significant main effect of target duration (F(2, 16) = 40.195, p < 0.05), and the T-corrected score was larger in the 500- and 750-ms conditions than in the 1,000-ms condition and larger in the 500-ms condition than in the 750-ms condition (p < 0.05).

The speed of pattern motion also influenced perceived duration (F(3, 24) = 5.81, p < 0.01). Multiple comparisons revealed that the T-corrected score was larger in the 16 deg/s and 8 deg/s conditions than in the 2 deg/s condition (p < 0.05), suggesting duration dilation. However, there was neither a main effect of change attribution (F(1, 8) = 0.24, p = 0.64) nor any interactions (F < 1.21, p > 0.32).

In this experiment, we examined whether component speed dilates perceived duration by manipulating the pattern speed in two ways: by varying the component orientations or by varying the component speed. However, the magnitude of duration dilation was not different between these change attributions. The results showed
only duration dilation induced by pattern speed as observed in Experiment 1. This indicates that perceived duration increases with pattern speed regardless of component speed, further suggesting that lower order motion processing is less important for duration dilation than higher order motion processing.

**Experiment 3**

The results of Experiment 2 suggest that lower order motion processing is less important for duration dilation than higher order motion processing. Because pattern and component speeds of plaids co-varied in Experiment 2, however, the effect of component speed might have been obscured by the effect of pattern speed. To address this possibility, we manipulated both the component speed and orientations simultaneously in the same experiment and examined the effect of component speed on perceived duration again. Pattern speed increases with either component speed or a difference between the component orientations. Therefore, if the difference between component orientations reduces at an appropriate rate concurrently with their increasing speed, the change of pattern speed would be counteracted; thus, pattern speed would be unchanged even though component speed increases.

In the experiment, we used two types of plaid stimuli as in Experiment 1. In one condition, the spatial frequencies of the component gratings were identical to each other, and the plaid appeared to move coherently (pattern motion condition). In another, the spatial frequencies of the component gratings differed from each other by three octaves (component motion condition). In the latter case, coherent pattern motion was not observed, and two component gratings appeared to move transparently. Hence, in the component motion condition, the component motion is supposed to be processed by both lower and higher motion-processing areas regardless of component orientations. If lower order motion processing is less important for duration dilation, perceived duration would be unchanged regardless of the component speed in the pattern motion condition, while perceived duration would increase with the component speed in the component motion condition.

**Methods**

**Observers**

Nine observers including an author (KY) participated in Experiment 3. Four of them had also participated in both Experiments 1 and 2, and one of them had also participated only in Experiment 2. All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment except for KY.

**Apparatus, stimuli, procedure, and analysis**

The apparatus, stimuli, procedure, and analysis used in Experiment 3 were identical to Experiment 1 except for the following: In both the pattern motion and the component motion conditions, the drifting speed of the component gratings varied between 1, 2, 4, and 8 deg/s, and orientations of the component gratings co-varied with speed between ±86.4°, ±82.8°, ±75.5°, and ±60°, respectively. The speed of pattern motion computed from the
intersection of constraints of the component gratings was approximately 16 deg/s.

Observers performed 192 trials in total, consisting of two drifting directions of the component gratings (rightward and leftward) × three durations of the target stimulus (500, 750, and 1,000 ms) × two kinds of motion coherency (pattern and component) × four kinds of component speed (1, 2, 4, and 8 deg/s) × four repetitions. The trial order was randomized across observers and across blocks.

Results and discussion

There was no significant difference between two drifting directions of the component gratings, \( t(8) = 0.41, p = 0.69 \). Thus, the subsequent analysis was conducted using the data averaged across the drifting directions (Figure 5). A three-way within-subject ANOVA showed a significant interaction between motion coherency and component speed and significant main effects of target duration, motion coherency, and component speed (\( F(3, 24) = 3.44, p < 0.05; F(2, 16) = 59.03, p < 0.001; F(1, 8) = 9.81, p = 0.014; \) and \( F(3, 24) = 4.08, p < 0.05 \), respectively). Analysis of the main effect of target duration revealed that the \( T \)-corrected score was larger in the 500- and 750-ms conditions than in the 1,000-ms condition (\( ps < 0.05 \)) as in Experiments 1 and 2.

Analysis of simple main effects based on the interaction between motion coherency and component speed revealed a significant main effect of component speed in the component motion condition (\( F(3, 48) = 6.82, p < 0.001 \)). Multiple comparisons revealed that the \( T \)-corrected score was larger in the 8 deg/s and 4 deg/s conditions than in the 1 deg/s condition (\( ps < 0.05 \)). However, there was no significant main effect of component speed in the pattern motion condition (\( F(3, 48) = 0.13, p = 0.75 \)).

We examined the effect of component speed on perceived duration by manipulating both pattern and component speeds simultaneously. Results showed that perceived duration increased with the component speed only when the coherent pattern motion could not be observed. The pattern speed was constant in the pattern motion condition, indicating that pattern speed plays a more important role for duration dilation than component speed. These findings support the results of Experiment 2 that lower order motion processing is less important for duration dilation.

Experiment 4

The results of our three experiments clearly demonstrated that stimulus speed computed in higher processing areas influences perceived duration. However, because we did not use any stationary objects as target stimuli in these experiments, it was ambiguous whether the effect reflected duration dilation or duration compression induced by motion. To confirm the absolute effect of the duration distortion, in this experiment, we used static plaids as target stimuli in addition to moving plaids selected from previous experiments. If the previous results indeed

Figure 5. Mean \( T \)-corrected scores for the pattern motion and component motion conditions in Experiment 3. Data are plotted as a function of component speed. The square, diamond, and circle symbols denote the target durations of 500, 750, and 1,000 ms, respectively. Red arrows represent perceived direction of target plaid motions. Length of each arrow is approximately proportional to speed of perceived motion in each condition. Error bars indicate within-subject standard errors of the mean.
reflected duration dilation, perceived duration of the moving plaids should be longer than that of the static plaids.

**Methods**

**Observers**

Eight observers including an author (KY) participated in Experiment 4. All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment except for KY.

**Apparatus**

Stimuli were presented on a 22-inch gamma-corrected CRT monitor with a 1,024 × 768 resolution at a refresh rate of 100 Hz. All other features of the apparatus were the same as in Experiments 1–3.

**Stimuli and procedure**

Four moving plaid stimuli were selected from previous experiments and used in this experiment. Two of them were selected from the pattern motion condition in Experiment 1 (one at ±60°, 1 deg/s; the other at ±86.4°, 1 deg/s), and the other two were selected from the component motion condition in Experiment 3 (one at 1 deg/s, ±86.4°; the other at 8 deg/s, ±60°). Therefore, the former two plaids had component gratings of 1 c/deg spatial frequency and appeared to move coherently, whereas the latter two plaids had component gratings of 0.25 and 2 c/deg spatial frequencies and appeared to move transparently. The former coherent plaids had also been used in the orientation change condition of Experiment 2, and one of them (±86.4°, 1 deg/s) had also been used in the pattern motion condition of Experiment 3. Similarly, one of the latter transparent plaids (1 deg/s, ±86.4°) had also been used in the component motion condition in Experiment 1. We selected these plaids because they were typical stimuli in each experiment (i.e., the slowest and the fastest pattern/component speed conditions), and thus they were sufficient to judge the absolute effect of duration distortion.

We also used four static plaids in addition to the four moving plaids. The features of the static plaids were the same as the moving plaids except that they kept still. These eight plaids were presented in two separate sessions. The coherent moving plaids and the corresponding static plaids were presented in one session, and the transparent moving plaids and their static plaids were presented in the other session. Each plaid stimulus (31.4 cd/m² at mean luminance) was displayed on a gray background (31.0 cd/m²). The procedure of each trial was identical to those of previous experiments. Observers performed 96 trials in each session, including three duration conditions (500, 750, and 1,000 ms) and eight repetitions. The trial order was randomized across observers and across blocks, and drifting directions of the moving plaids were randomly determined in each trial.

**Results and discussion**

To assess the absolute effect of duration distortion, we calculated the effect size by subtracting the T-corrected score of the static plaid from that of the corresponding moving plaid. Figure 6 shows the mean effect size used in the orientation change condition of Experiment 2, and one of them (±86.4°, 1 deg/s) had also been used in the pattern motion condition of Experiment 3. Similarly, one of the latter transparent plaids (1 deg/s, ±86.4°) had also been used in the component motion condition in Experiment 1. We selected these plaids because they were typical stimuli in each experiment (i.e., the slowest and the fastest pattern/component speed conditions), and thus they were sufficient to judge the absolute effect of duration distortion.

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**Results and discussion**

To assess the absolute effect of duration distortion, we calculated the effect size by subtracting the T-corrected score of the static plaid from that of the corresponding moving plaid. Figure 6 shows the mean effect size

![Figure 6](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932804/)
averaged across three duration conditions for each plaid pattern. The 95% confidence intervals showed that the effect size was significantly higher than zero in each plaid pattern, indicating that perceived duration of moving plaids is longer than that of static plaids. Furthermore, there were significant differences in the effect size between the two plaids in each session (coherent, t(8) = 2.46, p < 0.05; transparent, t(8) = 5.10, p < 0.01). These differences were consistent with the results of the previous experiments, which showed that stimulus speed computed in higher processing areas increases perceived duration. The results of Experiment 4 suggest that the duration distortions observed in previous experiments indeed reflected duration dilation induced by motion.

### General discussion

In the present study, we used plaid stimuli and examined which stages of motion processing are critical for motion-induced duration dilation. We found that perceived duration of plaids increased with the difference of component orientations (Experiment 1). This effect was observed only when the plaid appeared to move coherently as pattern motion, suggesting that the pattern speed that varies with component orientations influences perceived duration. We also found that the magnitude of duration dilation was indistinguishable regardless of whether the pattern speed was manipulated by varying the component orientations or the component speed (Experiment 2). This suggests that component speed per se might be less important for duration dilation. The results of Experiment 3 confirmed this possibility by showing that perceived duration was unchanged, even though the component speed increased, when the pattern speed was fixed by varying the component orientations concurrently. Moreover, an additional experiment using static and moving plaids confirmed that these duration distortions indeed reflected duration dilation, not duration compression, induced by motion (Experiment 4). Taken together, our findings suggest that perceived duration of plaid motion increases with pattern speed rather than component speed. Because plaid’s coherent pattern motion is processed after the primary visual cortex (Huk & Heeger, 2002; Movshon et al., 1985; Thompson et al., 2009), we conclude that higher order visual processing from MT plays an important role in motion-induced duration dilation.

In each experiment, we manipulated pattern speed by manipulating plaids’ component orientations and component speed. Although we assumed that coherent motion could be seen in the pattern motion conditions, a recent study showed that a transparent percept can be induced by certain combinations of component orientations and component speed (Hedges, Stocker, & Simoncelli, 2011). Thus, it is important to assess whether coherent motion can, indeed, be seen for all applied orientations and speeds. Five additional observers performed a brief version of Experiments 1–3, in which only target plaids were presented and observers were asked to report whether each plaid appeared to move coherently or transparently. All observers reported that, in each duration condition, coherent motion was observed for all applied orientations and speeds. This result suggests that, at least in our experimental setup, the plaids’ component orientations and component speed were appropriate for observers to perceive coherent pattern motion.

Although the idea that higher stages of motion processing mediate duration dilation was also proposed by Kaneko and Murakami (2009), previous studies including Kaneko and Murakami used a one-dimensional motion stimulus. Therefore, it was difficult to separate the effect of higher order motion processing from that of lower order motion processing. This study affords more direct empirical evidence for the relationship between motion-induced duration dilation and higher order motion processing by using a two-dimensional motion of a plaid pattern. Moreover, we compared the effect of lower and higher order motion processing and showed that lower order motion processing has little influence on perceived duration when motion information is distinctly different between lower and higher order processing stages. This result further suggests that higher stages of motion processing are more critical than lower stages of motion processing for motion-induced duration dilation. However, because the information processed in MT would be processed in higher processing areas including the parietal cortex (Ungerleider & Desimone, 1986), our results do not allow us to determine whether motion area MT is solely responsible for duration dilation. A further study will be necessary to clarify this issue.

Our results are consistent with previous research suggesting the importance of higher stages of visual processing on duration distortion. For example, Burr et al. (2007) showed that time distortion induced by temporal frequency adaptation is spatially selective in spatiotopic coordinates (but see also Bruno, Ayhan, & Johnston, 2010, for a counterexample). It has been shown that the primary visual cortex is organized in retinotopic coordinates, whereas higher order areas such as the parietal cortex and MT are organized in spatiotopic coordinates (d’Avossa, Tosetti, Crespi, Biagi, Burr, & Morrone, 2007; Duhamel, Bremmer, BenHamed, & Graf, 1997). These results suggest that higher level neural mechanisms underlie temporal processing of the visual events. The present results provide further evidence that higher visual processing areas are also involved in motion-induced duration dilation.

How does motion processing in higher stages influence perceived duration? Given that visual area MT is tuned for speed rather than for spatial and temporal frequencies separately, a change-based model cannot fully explain motion-induced duration dilation. Therefore, we have to consider another mechanism to explain this illusion. A
traditional model of time perception is a centralized internal clock model, in which ticks (or pulses) are internally generated by an oscillator and detected by a counter (Creeelman, 1962; Treisman, 1963). In this model, duration is estimated based on the number of ticks counted, and a change of tick rate causes time distortion: When tick rate increases, more ticks are counted in a given period, and thus the duration is judged as longer. Several studies have revised and applied this model to explain duration distortion phenomena, the idea has not yet been supported by physiology (Eagleman & Pariyadath, 2009). Furthermore, recent studies revealed that there are modality-dependent and modality-independent clocks in duration estimation (Bueti et al., 2007; Kanai, Lloyd, Bueti, & Walsh, 2011), suggesting that the brain uses several circuits rather than a centralized clock to determine the duration.

A more plausible explanation is that the “when” visual pathway from V1 to the right parietal lobe is involved in motion-induced duration dilation. Battelli et al. proposed that the right parietal lobe has a dominant role in visual time processing of event order, and several cortical areas around the right parietal lobe including sensory area MT also contribute to computing when visual events occur (Battelli, Pascual-Leone, & Cavanagh, 2007; Battelli, Walsh, Pascual-Leone, & Cavanagh, 2008). This view is consistent with recent transcranial magnetic stimulation studies showing that disruption of the MT or right posterior parietal cortex causes disruptive effects on temporal duration estimation (Alexander, Cowey, & Walsh, 2005; Bueti et al., 2008). It might be possible that an increase of stimulus speed changes the activity patterns of neurons in MT, and perceived timing of the stimulus onset (or offset) shifts forward (or backward). This is an explanation of why higher order motion processing influenced perceived duration but lower order motion processing did not in the present study. We assume that motion-induced duration dilation is caused by the shift of visual timing associated with the change of activities in visual area MT or in higher areas such as right parietal lobe. Further explorations are warranted for this hypothesis.

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