



Feature-based attentional selection affects the perceived duration of a stimulus having two superposed patterns



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ABSTRACT

The perceived duration of a visual event is highly related to stimulus attributes. It is well known that a moving stimulus appears to last longer than a static one does. Previous studies have demonstrated that the time dilation in a moving stimulus can be influenced by perceived motion, rather than by mere physical motion, and that a faster motion appears to last longer than a slower one does. However, whether a top-down attentional set for the feature value can modulate the time dilation in a moving stimulus when two different visual patterns coexist within the same region of the visual field is still unknown. To test this, in Experiment 1, we presented a moving and a static random-dot pattern simultaneously within the same region, and instructed the observer to attend to one of these two patterns. The results demonstrate that perceived duration was longer when attention was directed to the moving, rather than static pattern, although both patterns physically coexisted at the same time and place and for the same duration. In Experiment 2, slow and/or fast moving patterns were presented at the same time and place, and again, feature-based attentional selection affected the perceived duration of the identical physical display. These results suggest that attention to a moving stimulus is an essential factor that determines the time dilation in a moving stimulus. This study revealed that feature-based attention, as opposed to location-based attention, plays an important role in motion-induced time dilation.

1. Introduction

Perceived duration is easily distorted by various factors. For example, the duration may be perceived as longer when a threatening event is experienced (Stetson, Fiesta, & Eagleman, 2007); when a nontemporal task is required during a prospective time judgment task, the duration may be judged as shorter with increasing effort spent on the nontemporal task (Brown, 1985, 1997; Casini & Macar, 1997; Thomas & Weaver, 1975). Not only do these internal states of observers, but also various stimulus features affect duration judgment, such as stimulus size (Ono & Kawahara, 2007), magnitude (Xuan, Zhang, He, & Chen, 2007), visual flicker (Hashimoto & Yotsumoto, 2015; Herbst, Javadi, van der Meer, & Busch, 2013; Kanai, Paffen, Hogendoorn, & Verstraten, 2006; Okajima & Yotsumoto, 2016; Treisman & Brogan, 1992; Yuasa & Yotsumoto, 2015), stimulus presentation order (e.g., Kanai & Watanabe, 2006; Rose & Summers, 1995, first mentioned by Fechner, G. T., according to Hellstrom, 1985; Jamieson & Petrusic, 1975), expectancy (Matthews, 2011; Pariyadath & Eagleman, 2007, 2008; Schindel, Rowlands, & Arnold, 2011; Tse, Intriligator, Rivest, &

Cavanagh, 2004; Ulrich, Nitschke, & Rammsayer, 2006), and adaptation (Ayhan, Bruno, Nishida, & Johnston, 2009; Bruno, Ayhan, & Johnston, 2010; Heron et al., 2012; Johnston et al., 2008; Johnston, Arnold, & Nishida, 2006; Li, Yuan, & Huang, 2015; Li, Yuan, Chen, Liu, & Huang, 2015; Maarseveen, Hogendoorn, Verstraten & Paffen, 2017, 2018; Shima, Murai, Hashimoto, & Yotsumoto, 2016).

Another notable factor that affects the perceived duration of a visual stimulus is motion; it is well known that a moving stimulus appears to last longer than a static one does (e.g., Brown, 1995). This phenomenon, hereafter called motion-induced time dilation, is one of the best-studied distortions of perceived duration depending on stimulus features. Among previous studies investigating the possible determinant factors of this motion-induced time dilation, some suggest the relevance of temporal frequency (Kanai et al., 2006; Linares & Gorea, 2015), whereas others indicate the significance of motion speed (Gorea & Kim, 2015; Kaneko & Murakami, 2009; Yamamoto & Miura, 2012a). In both cases, it has been shown that the more rapidly changing stimulus appears to last longer. Recent studies suggest that perceived rather than physical speed is important for motion-induced time dilation (Gorea &

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Kim, 2015; Yamamoto & Miura, 2012a). Even in the absence of physical motion, time dilation can occur when the observer experiences some kind of motion impression, such as an illusory jittering motion within static random noise (Aoki, Kawano, Terao, & Murakami, 2016) and implied motion in static images (Yamamoto & Miura, 2012b).

One unaddressed question is whether motion-induced time dilation depends not only on stimulus factors, but also on attentional set. On the one hand, it is well established that perceived duration is longer for a static stimulus presented at a location to which attention is directed either exogenously (Osugi, Takeda, & Murakami, 2016; Seifried & Ulrich, 2011; Tse et al., 2004; Ulrich et al., 2006; Yeshurun & Marom, 2008) or endogenously (Enns, Brehaut, & Shore, 1999; Maarseveen, Hogendoorn, Verstraten, & Paffen, 2018; Mattes & Ulrich, 1998; Ono, Yamada, Chujo, & Kawahara, 2007). On the other hand, in previous studies on motion-induced time dilation, a moving stimulus and a static stimulus were typically presented in a temporally separated manner, with the latter serving as a comparison stimulus to identify the perceptual match to the former in terms of duration. In such conditions, the observer should naturally attend to the only stimulus that is present at any instant, meaning that the moving stimulus and comparison stimulus are always attended to whenever they are presented. Previous studies have also suggested that sufficient allocation of attentional resources to the temporal task in question is important for the estimation of duration (Brown, 1985, 1997; Casini & Macar, 1997; Thomas & Weaver, 1975). These lines of previous research suggest the hypothesis that attention is a required condition for motion-induced time dilation to occur, although not necessarily a sufficient condition; if the observer is instructed to refrain from paying attention to a moving stimulus, motion-induced time dilation may disappear even when the moving stimulus physically exists. This situation bears a resemblance to the selective looking paradigm, in which the visibility of task-irrelevant objects is reduced in a period during which the observer has to maintain endogenous attention to other task-relevant objects (e.g., Neisser & Becklen, 1975). This paradigm unequivocally demonstrated a striking phenomenon of inattention blindness to visual objects, to which endogenous attention is scarcely paid, illustrating the fact that our visual system has a limited capacity, and thus tends to filter unattended information. Similarly, it is possible that having an appropriate attentional set is critical in the extraction of temporal information of visual events that may in turn affect the processing of time.

To assess this possibility, we incorporated time perception in the framework of selective attention, in which appropriate stimulus selection, one of the most important functions of visual attention, is considered essential for efficient coding in the face of limited cognitive resources for visual processing (Desimone & Duncan, 1995). Selective attention can be endogenously paid to a subset of stimuli on the basis of stimulus features, such as color and motion direction. This feature-based attention has been shown to affect various behavioral tasks (Moore & Egeth, 1998) and cortical processing (for review, see Maunsell & Treue, 2006; Reynolds & Chelazzi, 2004). Importantly, feature-based attention can select one of the spatially superposed patterns to enhance the processing of the attended pattern exclusively. For instance, when a pattern of upward moving dots and another pattern of downward moving dots are presented simultaneously within the same region of the visual field, observers can attend to either one of these motion-transparent dot patterns moving in directions opposite to each other, and the motion aftereffect that occurs after prolonged observation is stronger in the direction predicted from the motion direction of the pattern to which the observer is attending during adaptation (Lankheet & Verstraten, 1995). This kind of superposed presentation enables us to focus on feature-based attention and distinguish it from location-based attention.

In this study, we presented two different random-dot patterns simultaneously within the same region of the visual field, and instructed observers to attend to one of these patterns. This manipulation enabled us to test whether feature-based attention, as opposed to location-based

attention, to a particular component of the stimulus affects time dilation. In Experiment 1, we simultaneously presented moving and static patterns, and investigated whether feature-based attention to the moving pattern is necessary for time dilation to occur in a visual stimulus composed of static and moving components. There was always a conscious experience of two motion-transparent surfaces, one moving and the other static, within the same region, but whether endogenous attention was directed to, or away from, the moving pattern was manipulated between the conditions. If time dilation occurs only when the moving pattern is attended to, the perceived duration should be longer when attention is paid to the moving pattern than the static pattern, even though the static and moving patterns physically coexist at the same time and place, and for the same duration, with the same onset and offset times. In Experiment 2, we simultaneously presented two fast and/or slow patterns moving in opposite directions within the same region of the visual field, and tested whether the perceived duration depended on the speed of the pattern to which attention was endogenously paid. In both experiments, we found that the perceived duration differed depending on which pattern the observer was attending to, even though the physical display was the same between conditions. This implies that attention to motion is a critical determining factor of the generation of motion-induced time dilation, and that selective processing with feature-based attention can affect duration perception.

2. Experiment 1: Superposition of static and moving patterns

2.1. Methods

2.1.1. Participants

Sixteen adults, including two of the authors, all of whom had normal or corrected-to-normal vision participated. The observers were naïve to the purpose of the experiment, except for the authors, and another observer who also served as a research assistant. We used the Ishihara test to screen for red-green color deficiency, and confirmed that all the observers had a trichromatic ability to discriminate red and green stimuli. Each observer gave written informed consent prior to the experimental sessions. The experiment was approved by the institutional ethics committee in the Graduate School of Humanities and Sociology at the University of Tokyo, and was conducted in accordance with the guidelines of the Declaration of Helsinki in using experimental participants. The experiment was conducted in a dark room. Observers viewed visual stimuli with both eyes open from a viewing distance of 57.3 cm constrained by a chin rest.

2.1.2. Apparatus

We used a computer (Apple Mac Pro) to generate the stimuli and a CRT monitor (Mitsubishi RDF223H Diamondtron M2) to display them. Luminance for each phosphor of the monitor was gamma-corrected with a 10-bit-depth color lookup table on a video card. The spatial resolution of the monitor was 1280×1024 pixels, and the refresh rate was 100 Hz. The size of the monitor was 40×30 cm, and the relationships between the visual angle and pixel were 1.88 min/pixel horizontally and 1.76 min/pixel vertically. The MATLAB R2012b (Mathworks) programming environment and the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) were used to generate the visual stimuli.

2.1.3. Stimuli

The visual stimuli consisted of small dots colored red or green (Fig. 1). Each dot was a square made of 2×2 pixels. Luminance of both red and green dots was 16.9 cd/m^2 . Dots were presented within an imaginary circle with a diameter of 200 pixels. Dots of the same color were either all static or all moving coherently at 400 pixels/s (11.73 deg/s) in a vertical direction. The background was uniform black ($< 0.1 \text{ cd/m}^2$). A white (82.4 cd/m^2) fixation cross subtending 32×32

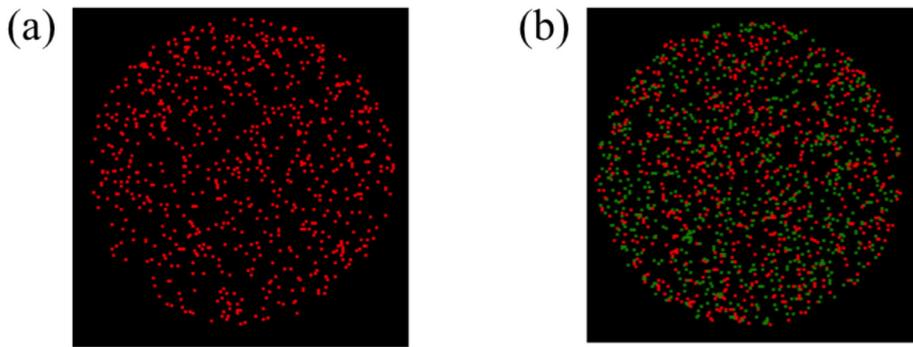


Fig. 1. Stimulus configurations. (a) The “single” configuration. Only dots of one color, red in this case, were presented within an imaginary circle. The number of dots was 300. (b) The “double” configuration. Both red and green dots (300 each) were presented simultaneously. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pixels was provided.

There were two types of stimulus configurations. In the “single” configuration, dots of only one color, red or green, were presented (Fig. 1a); there were 300 dots. In the “double” configuration, both red and green dots were presented simultaneously, and there were 300 dots each (Fig. 1b).

2.1.4. Conditions

Throughout the experiment, half of the observers were instructed to attend to the red dots and the others were instructed to attend to the green dots. For the sake of simplicity, we will only describe the conditions from the viewpoint of those observers who were instructed to attend to the red dots. For those observers who were instructed to attend to the green dots, all descriptions on colors were flipped so that “red” could be read as “green” and “green” could be read as “red.”

There were four conditions represented as 2 × 2 factors (Fig. 2). One factor was the stimulus configuration that was either “single” or “double.” The other factor was attention destination that was either the static dots (“attended-static”) or the moving dots (“attended-moving”).

- In the “single & attended-static” condition, only static red dots were presented.
- In the “single & attended-moving” condition, only moving red dots were presented.

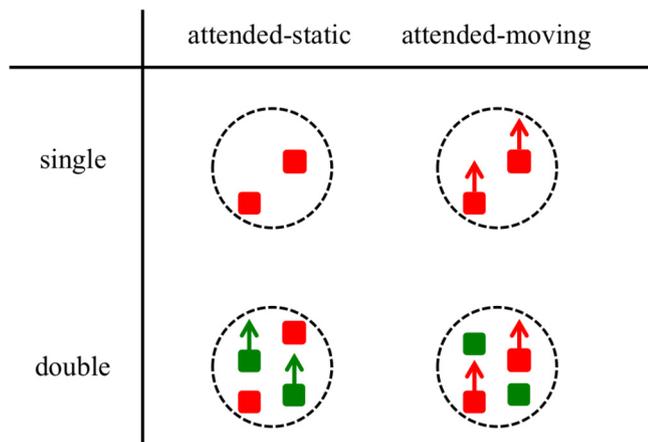


Fig. 2. Schematic description of stimulus conditions in Experiment 1. Black dotted circles are drawn only for illustrative purposes. Only two dots for each color are illustrated although actually there were 300 dots for each color. The dots with and without arrows denote moving and static dots, respectively. Note that the above descriptions of the conditions are valid for half of the observers who were instructed to attend to the red dots throughout the experiment; actually, the other half of the observers were instructed to attend to the green dots throughout the experiment, and for them, all descriptions on colors were flipped so that “red” read as “green” and “green” read as “red.” (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- In the “double & attended-static” condition, static red dots and moving green dots were presented simultaneously within the same region of the visual field, and participants were instructed to attend to the static, rather than moving dots.
- In the “double & attended-moving” condition, moving red dots and static green dots were presented simultaneously within the same region of the visual field, and participants were instructed to attend to the moving, rather than static dots.

2.1.5. Procedure

We used the two-interval forced-choice (2AFC) paradigm to determine the point of subjective equality (PSE) for duration with the method of constant stimuli (Fig. 3). At the beginning of each trial, the screen was left blank. When the observer pressed a button, the fixation cross was presented at the center of the screen for an interval randomly chosen within the range of 500–1000 ms, followed by the offset of the fixation cross together with the onset of the first stimulus, i.e., the “standard” stimulus, which lasted for 600 ms excluding the times required for the onset/offset temporal windows explained below. During an inter-stimulus interval randomly chosen within 500–1000 ms, the fixation cross was displayed again. After this interval, the fixation cross disappeared and the second stimulus, i.e., the “comparison” stimulus, was presented. The duration of the comparison stimulus was randomly chosen from seven predetermined durations, namely, 150, 300, 450, 600, 750, 900, and 1050 ms, with the times required for the temporal windows, which are explained below, being exclusive. Subsequently, the fixation cross was presented again until the observer’s response. The observer was requested to report whether the standard or the comparison stimulus appeared to last longer by pressing one of two buttons. The action of pressing the button triggered the offset of the fixation cross and the initiation of the next trial.

The standard and comparison stimuli were temporally blurred by gradually increasing and decreasing the luminance of the overall stimulus at its onset and offset with luminance windows defined using the following equation:

$$w(t) = 0.5 \left(1 - \cos \left(2\pi \frac{t}{60} \right) \right), \quad 0 \leq t \leq 60 \tag{1}$$

where parameter $t = \{0, 1, \dots, 29\}$ (frames) for the onset window, with frame 30 being identical to the first frame of the nominal stimulus duration, and $t = \{31, 32, \dots, 60\}$ (frames) for the offset window, with frame 30 being identical to the last frame of the nominal stimulus duration. Thus, the total actual duration of the standard stimulus with these temporal windows was equal to 1200 ms (300 ms for the onset window, 600 ms for the nominal duration at the maximum luminance, and 300 ms for the offset window). The same calculation also applied to the comparison stimulus.

The standard stimulus had the four conditions described above (i.e., “single & attended-static,” “single & attended-moving,” “double & attended-static,” and “double & attended-moving”), whereas the comparison stimulus was always comprised of static red dots only, as in the

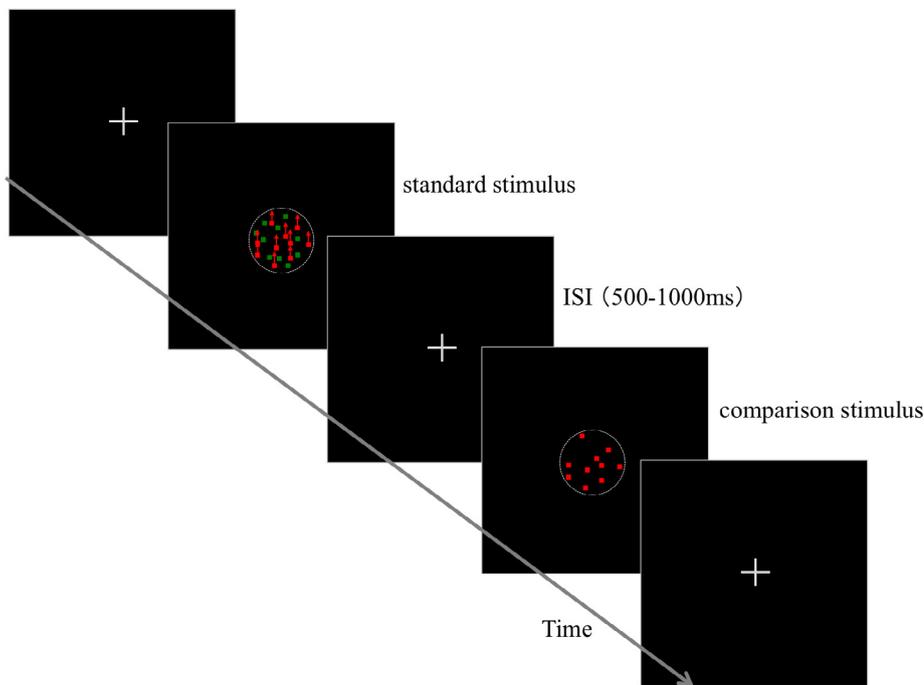


Fig. 3. Schematic description of a single trial in Experiment 1. The standard stimulus was presented first, and after an inter-stimulus interval (ISI) of variable lengths with a fixation cross, the comparison stimulus was presented. The observer was requested to report which stimulus appeared to last longer. White dotted circles are drawn only for illustrative purposes.

“single & attended-static” condition.

At the beginning of each block, the observer was verbally instructed to pay attention to the red dots whenever they appeared. When moving dots were presented, the direction of motion was reversed between consecutive trials to avoid the buildup of motion adaptation. The four conditions listed above were tested in separate blocks, and there were four such blocks for each condition. All four conditions were tested in a round of four blocks in a random order before they were repeated in each subsequent round of blocks. The first block for each condition was used as a practice block and was excluded from the data analysis. Each block consisted of 70 trials. The first seven trials were used for further practices for the seven duration levels of the comparison stimulus in a random order, and were excluded from the data analysis. In the other 63 trials, each duration level of the comparison stimulus appeared nine times in a random order. Thus, each duration level of the comparison stimulus was tested 27 times (9 trials per block \times 3 blocks) for each condition. A sufficient period of break was given between blocks.

2.1.6. Data analysis

For each condition and each observer, the proportion of trials in which the comparison stimulus appeared to last longer was plotted against comparison stimulus duration, and the cumulative normal distribution function was fit by the maximum likelihood method with the Palamedes Toolbox extensions for MATLAB (Prins & Kingdom, 2009). The μ and σ of the cumulative normal curve were free, with the floor and ceiling rates fixed at 1/54 and 1-1/54, respectively (Prins, 2012). The μ of the best-fit function was considered as the PSE for each condition for each observer. This PSE was used as the index of the perceived duration of the standard stimulus; a larger PSE indicated longer perceived duration.

2.2. Results and discussion

The PSE averaged across observers is plotted for each condition in Fig. 4 (PSEs for individual participants with bootstrapped error bars are shown in Supplementary Fig. 1). In a 2×2 repeated-measures analysis of variance (ANOVA) for the PSE with attention destination and stimulus configuration as factors, the main effect of attention destination was significant ($F(1,15) = 9.95$, $p = .0065$, $\eta_p^2 = 0.40$), whereas the

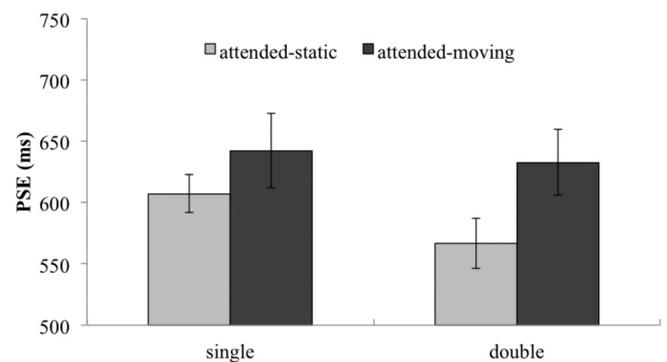


Fig. 4. Results of Experiment 1. The point of subjective equality (PSE) averaged across observers for each condition is plotted. Error bars indicate the standard error.

main effect of stimulus configuration was not ($F(1,15) = 2.10$, $p = .17$, $\eta_p^2 = 0.12$). The interaction was also not significant ($F(1,15) = 1.98$, $p = .18$, $\eta_p^2 = 0.12$), meaning that the standard stimulus appeared to last longer when the observers attended to the moving pattern than the static pattern regardless of stimulus configuration.

The main purpose of Experiment 1 was to examine whether perceived duration depends on the pattern to which endogenous attention is directed when both moving and static patterns are simultaneously present within the same region of the visual field, i.e., the “double” configuration. Not only the main effect of ANOVA but also paired t -test showed that the PSE in the “double & attended-moving” condition was significantly larger than that in the “double & attended-static” condition ($t(15) = 4.11$, $p = .00093$, $r = 0.73$). Indeed, in this configuration, the stimulus appeared to last longer when the observers attended to the moving pattern than the static pattern, even though the static and moving patterns physically coexisted at the same time and place. This indicates the importance of attention to moving stimuli for motion-induced time dilation to occur. This finding is not consistent with the view in which perceived duration is merely determined by physical information because the stimulus was physically identical between the “double & attended-static” and “double & attended-moving” conditions, but perceptually different in duration.

Although the interaction in ANOVA was not significant, we further conducted paired comparison in the “single” configuration alone to see whether the effect of attention destination really survived when analyzed separately. Paired *t*-test showed that the difference between the “single & attended-moving” and “single & attended-static” conditions did not reach significance ($t(15) = 1.64$, $p = .12$, $r = 0.39$), although the PSE under the former condition tended to be longer than that under the latter. This failure to replicate time dilation in the conventional “single” display is inconsistent with the findings of a previous study (Kanai et al., 2006), which demonstrated that time dilation occurs in a moving dot pattern. One possible reason for the discrepancy would be seen in the differences in stimulus configuration between the present experiment and Kanai et al. (2006) study. In Experiment 1, the dot pattern was presented at the center of the screen, whereas the dot pattern used in Kanai et al. (2006) study was presented below a fixation cross. Such a difference may have affected the magnitude or robustness of motion-induced time dilation if the reliability of visual cues to time has some eccentricity dependency; for example, central rather than peripheral vision may rely more heavily on information regarding timing of stimulus onset and offset, which may counteract the dilation effect induced by motion. Another reason to be considered for the discrepancy would be that motion speed was variable from trial to trial within each block in Kanai et al. (2006) study, but fixed in ours. Such variabilities in motion properties across trials may encourage observers to pay the maximal attention to the motion itself, rather than to the onset and offset times, possibly leading to an enhancement of motion-induced time dilation. These possibilities were explored in Experiment 2.

Experiment 1 demonstrated that attention to motion is necessary for motion-induced time dilation to occur in a visual stimulus composed of static and moving components. However, there were some points that need qualification in the results of Experiment 1. First, we did not present the fixation cross during the presentation of the dot pattern, raising the possibility of insufficient maintenance of fixation. When instructed to attend to the moving pattern, the observer’s eyes might have smoothly tracked the moving pattern, and saccadic eye movements during the stimulus presentation might also have occurred more often when the observer attended to the moving rather than static pattern. These potential differences in eye-movement patterns could have caused the difference in perceived duration (e.g., Karsilar & Balci, 2016). Second, there might have been asymmetry of attentional capture by the moving and static patterns in the “double” configuration, due to which the observer had to engage in multiple demanding tasks; the observer was asked to maintain feature-based attention to either the moving or static pattern upon the experimenter’s instruction and also to indicate the duration of the attended pattern while eliminating potential interference from the other pattern to be ignored. Given that a moving stimulus drew more exogenous attention than a static one did (Abrams & Christ, 2003; Kawahara, Yanase, & Kitazaki, 2012; Osugi & Murakami, 2015), endogenous attention to the static pattern might have been somewhat diluted when the observer needed to ignore the moving one, but failed to do so in the presence of vigorous attentional capture of it, thus shortening the perceived duration (Brown, 1985, 1997; Casini & Macar, 1997; Macar, Grondin, & Casini, 1994); but not vice versa when endogenous attention was paid to the moving pattern given that attentional capture by motion also promoted the same attentional engagement with motion. Such asymmetry of attentional capture could have resulted in the difference in perceived duration between the “double & attended-static” and “double & attended-moving” conditions. These issues were also addressed in Experiment 2.

3. Experiment 2: Superposition of slow and fast moving patterns

In Experiment 2, we took advantage of a notable characteristic of motion-induced time dilation: its dependency on motion speed (e.g., Kanai et al., 2006; Kaneko & Murakami, 2009). We simultaneously

presented dots in one color coherently moving rightward and dots in the other color coherently moving leftward, and instructed the observer to attend to one of these moving patterns; across conditions, we systematically varied the speeds of these two dot patterns. This manipulation enabled us to eliminate the above-mentioned potential asymmetry in attention between static and moving patterns because both patterns were now moving. Additionally, we presented the standard and comparison stimuli at the lower half of the visual field while presenting the fixation cross at the center of the screen throughout the stimulus presentation. This procedure encouraged the observer to maintain stable fixation during the stimulus presentation. These experimental setups were introduced to control the above-mentioned confounds and better focus on the relationship between attentional selection and motion-induced time dilation.

3.1. Methods

Methods were the same as those of Experiment 1 except for the following.

3.1.1. Participants

Participants were twelve adults, three of whom (including the first author) had also participated in Experiment 1.

3.1.2. Apparatus

We used a computer (Apple Mac Pro) to generate the stimuli and a CRT monitor (iiyama HM204DA/DTA) to display them. The spatial resolution of the monitor was 1280×960 pixels, and the refresh rate was 100 Hz. Each pixel was a square of 1.88 min.

3.1.3. Stimuli

The luminance of both red and green dots was 17.8 cd/m^2 . Dots of the same color were either all static or all moving coherently in a horizontal direction (see Conditions). The speed of motion was either slow (3.13 deg/s) or fast (9.38 deg/s). The background was uniformly black ($< 0.2 \text{ cd/m}^2$). A white (92 cd/m^2) fixation cross subtending 1×1 deg was provided. The standard and comparison stimuli were presented below the fixation cross at 5 deg eccentricity.

3.1.4. Conditions

Experiment 2 consisted of two sub-experiments, namely the “single” and “double” experiments.

In the “single” experiment, only red dots were presented. This experiment contained three conditions (Fig. 5a). In the “static” condition, all dots were static; in the “slow moving” condition, all dots were moving at a slower speed (3.13 deg/s); in the “fast moving” condition, all dots were moving at a faster speed (9.38 deg/s).

In the “double” experiment, red dots (to be attended to) and green dots (to be ignored) were presented simultaneously. There were five conditions (Fig. 5b). In the first condition, named the “attended-static & ignored-static” condition, both the red and green dot patterns were static. In the remaining four conditions, the red and green dot patterns were always moving in opposite directions. These four conditions were tabulated with 2×2 factors. One factor was the speed of the red (attended to) dot pattern, which could be at the slower or faster speed, the conditions of which are hereafter nicknamed “attended-slow” and “attended-fast,” respectively. The other factor was the speed of the green (ignored) dot pattern, which could be at the slower or faster speed, the conditions of which are hereafter nicknamed “ignored-slow” and “ignored-fast,” respectively. Combinations of these two factors, such as “attended-fast & ignored-slow,” comprised the four different conditions.

3.1.5. Procedure

At the beginning of each trial, the screen was left blank. When the observer pressed a button, the fixation cross appeared at the center of the screen and remained throughout the trial (Fig. 6). After an interval

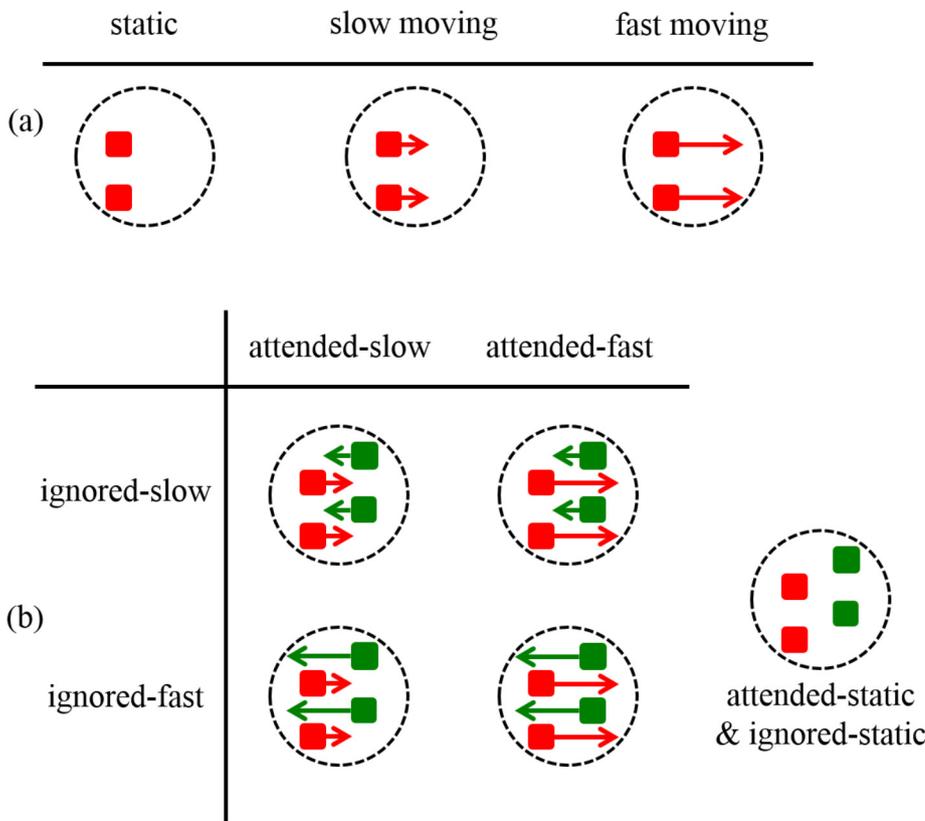


Fig. 5. Schematic description of the stimulus conditions in Experiment 2. Black dotted circles are drawn only for illustrative purposes. (a) “Single” experiment. Only red dots were presented. The speed of dots in the “slow moving” condition was 3.13 deg/s, while that in the “fast moving” condition was 9.38 deg/s. (b) “Double” experiment. In the “attended-slow & ignored-slow” condition, red dots slowly moving rightward and green dots slowly moving leftward were presented. In the “attended-slow & ignored-fast” condition, the red dots were moving slowly, whereas the green dots were moving fast. In the “attended-fast & ignored-slow” condition, the red dots were moving fast, whereas the green dots were moving slowly. In the “attended-fast & ignored-fast” condition, both the red dots and green dots were moving fast. In the “attended-static & ignored-static” condition, both the red dots and green dots were static. Note that the above descriptions are valid for half of the observers who were instructed to attend to the red dots throughout the experiment; actually, the other half of the observers were instructed to attend to the green dots throughout the experiment, and for them, all descriptions on colors were flipped so that “red” read as “green” and “green” read as “red.” (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

within 500–1000 ms, the first “standard” stimulus was presented for 600 ms, with the onset/offset temporal windows, as described in Experiment 1, being exclusive. With an inter-stimulus interval within the range of 500–1000 ms, the second “comparison” stimulus was presented. As in Experiment 1, it was always comprised of static red dots only. The duration of the comparison stimulus was randomly chosen from seven predetermined durations, namely, 300, 400, 500, 600, 700, 800, and 900 ms, with the onset/offset temporal window being

exclusive. Subsequently, the fixation cross disappeared after an interval within the range of 250–750 ms, and then the observer was requested to report which stimulus appeared to last longer by pressing one of two buttons. The act of pressing the button triggered the beep sound and the initiation of the next trial.

In the “single” experiment, the three conditions (i.e., “static,” “slow moving,” and “fast moving”) were mixed within the block and presented in a random order. In each block, each of the seven duration

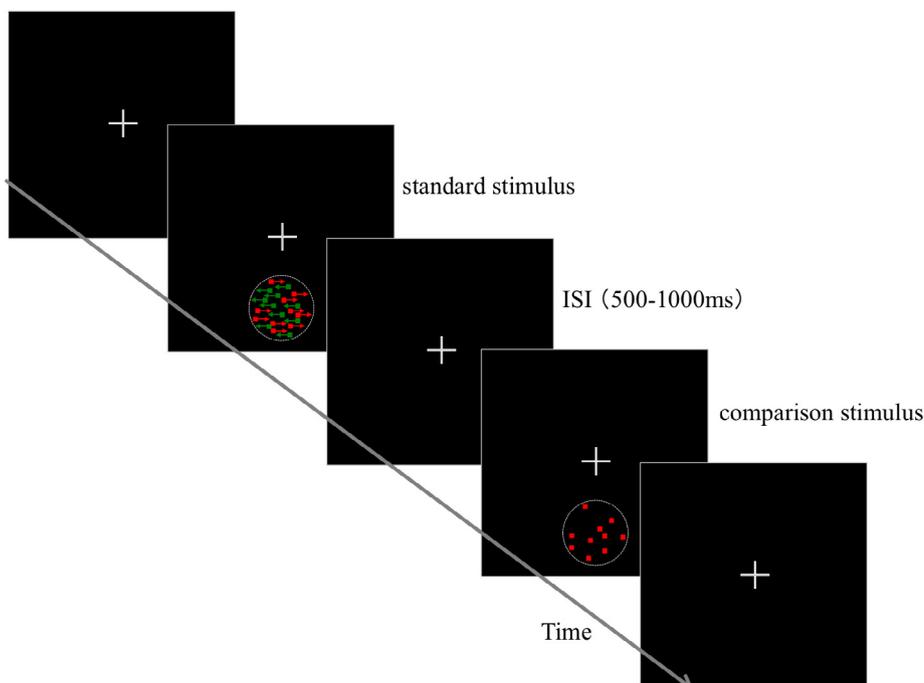


Fig. 6. Schematic description of a trial in Experiment 2. In each trial, the standard stimulus was presented first, and after an inter-stimulus interval (ISI) of variable lengths, the comparison stimulus was presented. The fixation cross was presented at the center of the screen throughout the stimulus presentation, and the experimental stimuli were presented below it. The observer was requested to report which stimulus appeared to last longer. White dotted circles are drawn only for illustrative purposes.

levels of the comparison stimulus was tested four times for each condition, and six blocks were conducted for each observer. Thus, each level was tested 24 times for each condition for each observer.

In the “double” experiment, each block began with a verbal instruction to pay attention to the red dots whenever they appeared. The control condition, namely the “attended-static & ignored-static” condition, was tested in separate control blocks. The other four conditions, i.e., “attended-slow & ignored-slow,” “attended-slow & ignored-fast,” “attended-fast & ignored-slow,” and “attended-fast & ignored-fast” were mixed within a block and presented in a random order. Each level was tested 24 times for each condition for each observer.

3.1.6. Data analysis

The cumulative normal distribution function was fit to the proportion of trials in which the comparison stimulus appeared to last longer, with the μ and σ being free and with the floor and ceiling rates fixed at 1/48 and 1–1/48, respectively (Prins, 2012).

3.2. Results

3.2.1. “Single” experiment

The PSE averaged across observers is plotted for each condition in Fig. 7a (PSEs for individual participants with bootstrapped error bars are shown in Supplementary Fig. 2). In a repeated-measures ANOVA, the main effect was significant ($F(2, 22) = 5.68, p = .010, \eta_p^2 = 0.34$), and multiple comparisons with step-down procedure using Ryan’s method (Ryan, 1960) revealed that the PSE was larger in the “fast moving” than “static” condition ($t(22) = 3.18, p = .0043, r = 0.56$), indicating the occurrence of motion-induced time dilation; in contrast, the PSE did not significantly differ between the “slow moving” and “static” conditions ($t(22) = 0.63, p = .54, r = 0.13$). Importantly, the PSE was significantly larger in the “fast moving” than “slow moving” condition ($t(22) = 2.55, p = .018, r = 0.48$). This longer perceived duration in the faster pattern is consistent with previous observations (e.g., Kanai et al., 2006; Kaneko & Murakami, 2009).

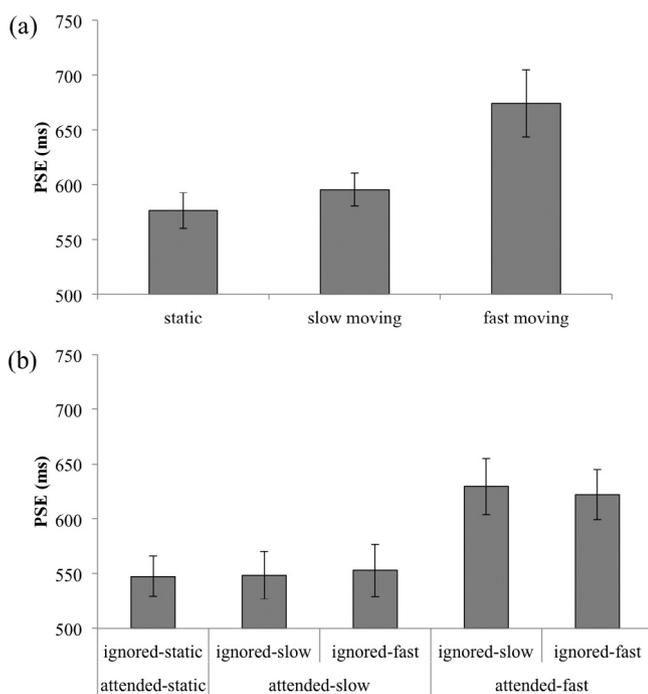


Fig. 7. The results of Experiment 2. The PSE averaged across observers for each condition is plotted. Error bars indicate the standard error. (a) The result of the “single” experiment. (b) The result of the “double” experiment.

3.2.2. “Double” experiment

The PSE averaged across observers is plotted for each condition in Fig. 7b (PSEs for individual participants with bootstrapped error bars are shown in Supplementary Fig. 3). Paired t-tests revealed that, compared with that in the “attended-static & ignored-static” condition, the PSE was significantly larger when the faster pattern was attended to, regardless of the speed of the ignored pattern ($t(11) = 2.59, p = .025, r = 0.62$ for the “attended-fast & ignored-slow” condition; $t(11) = 2.65, p = .023, r = 0.62$ for the “attended-fast & ignored-fast” condition). In contrast, the PSE did not differ from that in the “attended-static & ignored-static” condition when the slower pattern was attended to, regardless of the speed of the ignored pattern ($t(11) = 0.035, p = .97, r = 0.01$ for the “attended-slow & ignored-slow” condition; $t(11) = 0.26, p = .80, r = 0.08$ for the “attended-slow & ignored-fast” condition).

Next, we focused on the conditions that were tabulated with the 2×2 factors (Fig. 5). In a 2×2 repeated-measures ANOVA with the speeds of the attended and ignored patterns as factors, the main effect of the speed of the attended pattern was significant ($F(1, 11) = 7.47, p = .020, \eta_p^2 = 0.40$), whereas neither the main effect of the speed of the ignored pattern ($F(1, 11) = 0.031, p = .86, \eta_p^2 = 0.0028$) nor the interaction ($F(1, 11) = 1.06, p = .33, \eta_p^2 = 0.088$) was significant. These results clearly demonstrate that regardless of whether the ignored pattern was in slow or fast motion, the perceived duration depended on the speed of the attended pattern; the perceived duration was longer when the observers attended to the faster pattern than the slower one.

3.3. Discussion

The main finding that the perceived duration was longer when the faster rather than slower dot pattern was attended to, is consistent with that of previous studies demonstrating that the faster motion exhibited greater time dilation (e.g., Kanai et al., 2006; Kaneko & Murakami, 2009). Importantly, such a relationship was found to persist even when the slower and faster patterns were superposed. These results support the view that the visual system is capable of selecting one of the superposed patterns on the basis of information of motion direction (e.g., Lankheet & Verstraten, 1995) and color (e.g., Saenz, Buracas, & Boynton, 2003), and unequivocally demonstrate that such feature-based attentional selection affects perceived duration depending on the speed of the attended pattern as if the ignored pattern were absent from the screen. Therefore, attention to motion is a critical requisite for motion-induced time dilation, and feature-based attentional selection governs the occurrence of dilation.

The present findings refute the concern of eye movements that was raised in the discussion of Experiment 1 because we presented the fixation cross throughout each trial and instructed the observers to maintain fixation until the fixation cross disappeared at the end of each trial. Furthermore, the present results cannot be accounted for by the idea that moving stimuli will draw more exogenous attention than static ones will (Abrams & Christ, 2003; Kawahara et al., 2012; Osugi & Murakami, 2015). If such asymmetry of attentional capture were generalizable to the competition between the faster and slower motion stimuli such that the faster one captures attention more strongly than the slower one does, perceived duration should have been shorter when the ignored pattern was moving at the faster than slower speed. However, no such difference was observed.

The present results also confirmed that motion-induced time dilation occurred in a more conventional motion stimulus configuration, namely, the “fast” condition in the “single” experiment. Thus, it is likely that the absence of time dilation in a comparable stimulus configuration in Experiment 1, referred to as the “single & attended-moving” condition, was due to either the chosen eccentricity or the statistics of motion speeds. In Experiment 1, the stimulus was viewed foveally, and the

same motion stimulus was presented repeatedly within each single block. In Experiment 2, the stimulus was presented at 5 deg eccentricity, with three varieties of speeds (“static,” “slow,” and “fast”) being intermingled within the session, and a reliable time dilation was observed in a moving dot pattern at the faster speed.

There appeared to be a general tendency for the standard stimulus in the “double” experiment to be judged as having a shorter duration than the standard stimulus in the “single” experiment (Fig. 7). This tendency was unexpected, as perceived duration has been shown to increase with dot density (Long & Beaton, 1981), but this may be explained in terms of the difference in task requirements. In the “double” experiment, the observers were instructed to ignore half of the presented dots, and this top-down effort may have consumed a considerable portion of attentional resources. In contrast, there was no such task requirement in the “single” experiment. Given that the reduction in attentional resources can cause the shortening of perceived duration (Brown, 1985, 1997; Casini & Macar, 1997; Macar et al., 1994), this difference in task requirements may have caused the general tendency for the standard stimulus in the “double” experiment to be judged as shorter in time.

4. General discussion

In the present study, we examined whether the perceived duration of a superposed stimulus depends on feature-based attentional set. In Experiment 1, we presented static and moving patterns within the same region of the visual field, and found that the perceived duration was longer when the observers attended to the moving than the static pattern, even though the physical display was the same between the conditions. Moreover, in Experiment 2, we simultaneously presented slower and faster patterns moving in opposite directions, and found that the stimulus appeared to last longer when the observers attended to the faster than the slower pattern. These results clearly showed that feature-based attentional selection affects the perceived duration of a superposed stimulus.

Therefore, motion-induced time dilation depends not only on bottom-up stimulus factors, but also on top-down attentional set. Beyond the basic psychophysical notion that a moving stimulus appears to last longer than a static one does (Brown, 1995; Kanai et al., 2006; Kaneko & Murakami, 2009), recent studies have suggested that the perceived, rather than physical speed, is important for motion-induced time dilation to occur (Gorea & Kim, 2015; Yamamoto & Miura, 2012a). Studies have further shown that even if there is no physical motion, time dilation can occur when the observer experiences some kind of motion impression, such as a jittering illusory motion (Aoki et al., 2016) and implied motion in static images (Yamamoto & Miura, 2012b), suggesting that the perceived motion is critical. However, because a static stimulus and a moving stimulus have always been presented in a temporally separated manner in previous studies, it has been unclear whether attention to a moving stimulus plays a role for the occurrence of motion-induced time dilation. In the present study, we used the same display in the “double” configuration, in which a vigorously moving stimulus and a static (or slowly moving) stimulus co-existed, and manipulated whether attention was directed to or away from the vigorous motion. Our results robustly showed the dependency of duration perception on this attentional manipulation, indicating that the physical existence of vigorous motion is not sufficient by itself, but that an individual’s endogenous attention directed to the vigorous motion is a crucial requisite for the occurrence of motion-induced time dilation.

One might say that there may have been little or no motion experience when observers ignored the moving pattern. In other words, it could be the conscious awareness of motion, rather than feature-based selective attention, that directly determines the occurrence of time dilation. In the selective looking paradigm, ignored items sometimes go totally unnoticed (e.g., Simons & Chabris, 1999), so it is technically

possible that our observers did not see the moving pattern when they were instructed to ignore it. However, introspective reports from our observers confirmed that they could not help noticing the existence of the moving pattern however hard they might have attentively tried to ignore it. Indeed, it is extremely unlikely that motion impression vanished when the observers did not attend to the moving pattern.

Another type of dynamic stimulus, namely flicker, can also cause time dilation (Hashimoto & Yotsumoto, 2015; Herbst et al., 2013; Kanai et al., 2006; Treisman & Brogan, 1992; Yuasa & Yotsumoto, 2015). Okajima and Yotsumoto (2016) found that when both static and flickering stimuli in different colors were presented simultaneously at different locations, the perceived duration was longer when the observer was asked to time the flickering stimulus while ignoring the static one than in the opposite case. This is consistent with the present finding that the perceived duration was longer when attention was directed to the dynamic pattern. Whereas the observers in the previous study were able to use both location and feature (i.e., color) information to select the stimulus, those in our study were only able to use feature-based attention to one of the superposed patterns. This generality of the findings suggests that attention to dynamic events is important in inducing time dilation, although the underlying mechanism of the time dilation induced by flicker may differ from that of the time dilation induced by coherent motion examined in our study.

The present results also shed light on the relationship between attention and duration perception. The perceived duration of a visual stimulus has been shown to depend on how much attention is directed to the stimulus location by exogenous cues (Osugi et al., 2016; Seifried & Ulrich, 2011; Yeshurun & Marom, 2008), endogenous cues (Enns et al., 1999; Maarseveen et al., 2018; Mattes & Ulrich, 1998), task relevance (Ono et al., 2007), and unexpected presentation (Tse et al., 2004; Ulrich et al., 2006; see also Pariyadath & Eagleman, 2007; Schindel et al., 2011). These previous studies have used stimuli that should appear as neutral without the manipulation of attention for examining how perceived duration might be altered when attention is directed to or away from the stimulus. These studies have suggested that the individual’s attentional state *per se* can affect perceived duration. In contrast, the present study focused on the difference in feature values of attended and unattended patterns by using the selective looking paradigm (Neisser & Becklen, 1975) for examining how the perceived duration might change when observers attentively select one of two competing stimuli (static and moving stimuli in Experiment 1 and slower and faster stimuli in Experiment 2), each of which would appear to have a distinct duration if presented in isolation. The present results clearly demonstrate that the perceived duration of a physically identical stimulus depends on the feature value (either the static or moving one in Experiment 1 and either the slower or faster one in Experiment 2) that is endogenously attended to, even when the stimulus patterns having these values are presented simultaneously within the same region of the visual field. Therefore, unlike the previous studies focusing on the relationship between duration perception and the individual’s attentional state *per se*, the present study focused on the relationship between duration perception and selective processing by feature-based attention, and thus, our research outcomes provide a novel framework for studies on the relationship between attention and duration perception. In addition, it is worth mentioning that the present study used a spatially superposed stimulus, which enabled us to focus on feature-based rather than location-based attention. It has been indicated that feature-based attention and location-based attention have separate functions and mechanisms (e.g., Li & Saiki, 2015); thus, to reveal the relationship between selective attention and duration perception comprehensively, it is necessary to investigate both feature-based and location-based attention separately. Therefore, the present study, which focused on feature-based attentional selection and duration perception, gives a significant process to comprehend the linkage between selective processing of attention and duration perception.

Certain possible neural substrates that may be consistent with the

present results are worth mentioning. One candidate is seen in the cortical area MT, and other motion-related areas in the dorsal stream. The possible contribution of these areas to the phenomenon of motion-induced time dilation has been suggested (Aoki et al., 2016; Gorea & Kim, 2015; Kaneko & Murakami, 2009; Yamamoto & Miura, 2012a, b). Moreover, attentional modulation based on stimulus features has been observed in the activations in the MT of macaques (Treue & Martinez Trujillo, 1999) and humans (Saenz, Buracas, & Boynton, 2002). Taken together, these lines of physiological evidence indicate that when two different types of stimuli, such as slower and faster motions, are presented, the activation in MT may depend on which stimulus is being attended to and may produce some activity modulation that correlates with the difference we observed in perceived duration. Another possibility is the involvement of relatively higher stages of processing, such as the frontal-parietal network. It has been indicated that activations in the frontal-parietal network depend on the attentional state (Corbetta & Shulman, 2002; Corbetta, Patel, & Shulman, 2008). Moreover, neuropsychological studies have shown that lesions in the parietal lobe can cause deficits in not only spatial tasks, but also a nonspatial tasks that requires attention (Humphreys, Romani, Olson, Riddoch, & Duncan, 1994; Husain & Rorden, 2003; Husain, Shapiro, Martin, & Kennard, 1997), suggesting the possibility that the parietal lobe plays an important role in attentional selection for spatially overlapped visual stimuli. A recent study suggests that the inferior parietal lobule, which likely belongs to the frontal-parietal network, is involved in visual duration processing (Hayashi et al., 2015). Taken together, it is conceivable that the activations in the frontal-parietal network depend on the attentional state and play a role in duration perception in spatially superposed visual patterns.

We have to note that, with the 2AFC paradigm employed here, there remains a possibility that the shift in PSE is due to decision criterion change rather than a true change in perceived duration. In both Experiments 1 and 2, the PSEs obtained for the same physical display differed depending on the observers' attentional state, demonstrating that the feature-based attentional selection affected the PSE. Nevertheless, we cannot totally exclude the possibility that, when the observers had to guess which to choose, they are somehow biased toward choosing the standard stimulus only if the attended stimulus was a moving/faster one. In future studies, other psychophysical methods, such as a variant of the mAFC method (e.g. Morgan, Melmoth, & Solomon, 2013), may help us to discern which, perceived duration or decision criterion, is truly modulated.

5. Conclusions

To summarize, the present study demonstrated that perceived duration depends on which stimulus is currently focused upon by feature-based attention when two different types of visual patterns, such as moving and static patterns (Experiment 1), and slower and faster motion patterns (Experiment 2), exist simultaneously within the same region of the visual field. This implies that the selective processing with feature-based attention can affect duration perception.

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Appendix A. Supplementary data

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