Pupillary dilation elicited by attending to two disks with different luminance

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Pupils become smaller when people attend to a bright disk as compared to a dark disk. However, people can divide their attention into several distinct positions, which is referred to as divided attention, and pupillary responses under such conditions have not been investigated. In this study, we examined how pupils would respond when people attended to two disks presented at two distinct positions by conducting three experiments. We found that the pupillary response when attending to two disks with different luminance was larger than when attending to a single brighter disk and was comparable to that when attending to a single darker disk, whereas the pupillary response when attending to two disks with identical luminance was not larger than when attending to a single disk (irrespective of the disk luminance). Furthermore, we found that the magnitude of pupillary dilation was determined by the magnitude of the luminance difference between two disks. These results make a useful contribution to the literature on human pupillary responses.

Introduction

It has long been known that pupils regulate the amount of light that enters the eye (Loewenfeld, 1993). Pupillary light response (PLR) is a phenomenon whereby pupils become smaller in response to the high intensity of light and larger in response to the low intensity of light (Ellis, 1981; Reeves, 1920; Robbins, Djamgoz, & Taylor, 1995). However, the intensity of light is not the only factor that affects PLR. Recently, several studies have shown that cognitive factors such as attention affect PLR as well (Binda, Pereverzeva, &

Murray, 2013; Binda, Pereverzeva, & Murray, 2014). For example, pupils become smaller when people covertly attend to a bright disk as compared to a dark disk. An important difference between the effects of light intensity and cognitive factors on PLR is the magnitude of modulation (Sperandio, Bond, & Binda, 2018; Mathôt, 2018). Usually, the magnitude of pupil change as a result of cognitive factors is approximately three to 10 times weaker than that caused by variations in physical light intensity (Sperandio et al., 2018; Mathôt, 2018).

Besides the effect of spatial attention on PLR, there are other types of attentional modulation on the pupillary response (Binda et al., 2014; Hu, Hisakata, & Kaneko, 2019; Whyte, 1992; Alnæs, Sneve, Espeseth, Endestad, van de Pavert, & Laeng et al., 2014; Wahn, Ferris, Hairston, & König, 2016; Daniels, Nichols, Seifert, & Hock, 2012). Binda et al. (2014) found that feature-based attention could affect PLR by using a stimulus with overlapped bright random dots and dark random dots. Hu et al. (2019) found that both spatial attention and object-based attention could affect pupillary response to spatial frequency. Furthermore, the strategic control of attention could also affect the pupillary response. Daniels et al. (2012) reported that the switching between global and local attention could elicit different pupillary responses, even when the property of attended stimulus remained unchanged. However, the previous studies have only investigated the effects of selective attention to a single position, object, or property on pupillary response. It has been reported that there can be more than one attentional position simultaneously (four to six positions at most), which is referred to as divided attention (Awh & Pashler, 2000; Müller, Malinowski, Gruber, & Hillyard, 2003;

McMains & Somers, 2004; Fisher, 1984; Kawahara & Yamada, 2006; Bettencourt & Somers, 2009; Cavanagh & Alvarez, 2005). Studies using the multiple object tracking (MOT) task showed that pupil size scaled with the number of tracking objects because of the mental effort elicited during MOT (Alnæs et al., 2014; Wahn et al., 2016). However, the properties of tracked objects were identical. To our knowledge, no studies have investigated the pupillary response when participants attend to stimuli with different properties simultaneously.

In this study, we aimed to examine how pupils would respond when attending to two disks with different luminance presented at two distinct positions. We designed the experiments while considering several characteristics of divided attention and pupillary response. We first instructed participants to divide their attention before each experiment because the deployment of attention, whether it is unitary or divided, depends on participants' expectations (Jefferies, Enns, & Di Lollo, 2014). Second, we presented two disks bilaterally across a central fixation dot because it is easier to divide attention when two disks are presented in the bilateral hemifield as compared to the unilateral hemifield (Kraft, Kehrer, Hagendorf, & Brandt, 2011; Alvarez, Gill, & Cavanagh, 2012; Ibos, Duhamel, & Hamed, 2009). Third, we used an easy and simple task in the experiments because some researchers reported that efficiency was not impaired for divided attention when an easy and simple task was used (McMains & Somers, 2005; White, Runeson, Palmer, Ernst, & Boynton, 2017; Bay & Wyble, 2014; Kraft et al., 2005). If the task is difficult or complicated, the cost of divided attention, which depicts impairments in behavioral accuracy and response time when divided attention is deployed, may contaminate the results of pupillary response because this is affected by mental effort, with pupils enlarging in response to a task with high mental effort (Bichot, Cave, & Pashler, 1999; Grubb, White, Heeger, & Carrasco, 2015; Scharff, Palmer, & Moore, 2011; Klingner, Tversky, & Hanrahan, 2011).

Three experiments were conducted. In Experiment 1, we examined the pupillary response when attending to two disks with different luminance, bright and dark, on a gray background. In Experiment 2, we examined the possible contamination of pupillary response caused by divided attention per se by presenting two disks with identical luminance (bright, gray, or dark) on a gray background. In Experiment 3, we examined what factor would affect the pupillary response when divided attention was deployed by manipulating the luminance of the disks and background. Note that, strictly speaking, the word "bright" refers to a perceptual attribute, but we used it to refer both perceptual and physical attributes to comply with the descriptions in previous studies (Binda et al., 2013; Binda et al., 2014).
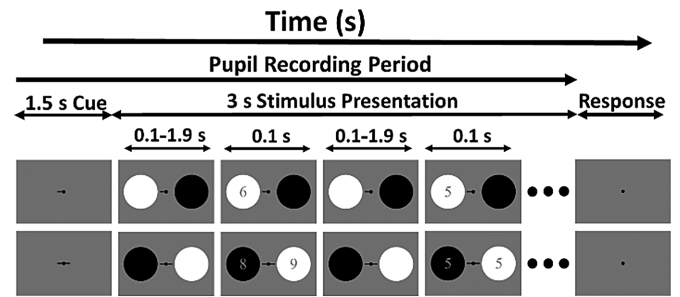

Figure 1. The time course of each trial. The top panels show an example of when participants were instructed to attend to the left disk, at the center of which, the digit stream was displayed. The bottom panels show an example of when participants were instructed to attend to two disks, at the centers of which, the digit streams were displayed. Each trial began with a presentation of a fixation dot and cue, and 1.5 seconds later, the two disks were presented for 3 seconds, during which participants counted the number of digit appearances or the times two digits matched. After the stimulus presentation, participants were asked to press a key to respond to the task. Note that the size of the cue, digit, and disk were rescaled for clarity in this figure.

General methods

Participants and apparatus

Six graduate students (24 to 26 years, one female) with normal or corrected-to-normal visual acuity participated in this study. Written consent was obtained from each participant. The protocol was approved by the Ethics Committee of the Tokyo Institute of Technology.

Participants' eye movements and pupil diameters were recorded using an infrared video-based eye tracker with a spatial resolution of 0.1% diameter (EyeLink 2000, 500 Hz sampling rate; SR Research, Kanata, Ontario, Canada). The spatial resolution was tested with a 5 mm artificial pupil. Visual stimuli were displayed on a cathode-ray tube monitor (Sony GDM-F500R, 1280 × 1024 pixels, 60 Hz refresh rate; Sony, New York, NY, USA). The monitor was placed 57 cm in front of the participants, and a chin rest was used to prevent participants' head movements. Participants had a numeric keypad at hand and were asked to press a key to respond to the task. The experiments were conducted in a completely dark room.

Stimulus and procedure

The stimulus was composed of horizontal lines for the attentional cue, a fixation dot, and two disks (see examples shown in Figure 1). There were three types

	1	2-1	2-2	2-3	3a-1	3a-2	3b-1	3b-2
Disk1	0.0	73.8	36.9	0.0	0.0	0.0	44.3	0.0
Disk2	73.8	73.8	36.9	0.0	73.8	73.8	73.8	29.5
Background	36.9	36.9	36.9	36.9	59.1	14.8	36.9	36.9

Table 1. The luminance of two disks and background. *Notes:* The row names represent the components of the stimulus, and the column names represent the experiment number. The unit of luminance is cd/m^2.

of cues (a left line, a right line, and both left and right lines), which instructed participants to attend to the left disk, the right disk, or both disks, respectively. The length of the line and radius of the fixation dot were 0.15° and 0.02°, respectively. The fixation dot was presented at the center of the monitor. The two disks were presented in the left and right visual hemifields with an eccentricity of 4°. The eccentricity was defined as the visual angle subtended by the center of the disk and fixation dot. The radius of each disk was 2°. A single-digit stream or dual-digit stream was displayed at the center of one disk or two disks based on the attentional cue. Each digit was displayed in an area of 0.5° × 0.8°. Note that a single-digit stream was displayed when participants were instructed to attend to one disk. If a dual-digit stream was displayed when participants were instructed to attend to one disk, it would be hard for them to attend to the cued disk because the other disk attracted their attention easily.

The luminance of the stimuli used in the three experiments is summarized in Table 1. The columns represent experimental blocks, and the three rows represent the components of the stimuli. The luminance of the cue and fixation dot was 0.0 cd/m^2. The luminance of digits in the digit stream was the same as that of the background, except in Experiment 2-2. In Experiment 2-2, two black circles, with a width of one pixel and a luminance of 0.0 cd/m^2, were presented at the rim of the disks to help participants locate the stimulus because the two disks were invisible when the luminance of the disks and background was identical. The luminance of digits was 0.0 cd/m^2 to make it visible.

The time course of each trial is depicted in Figure 1. During each trial, the fixation dot and cue were presented for 1.5 seconds to instruct participants where to direct their attention. Subsequently, the two disks, along with the fixation dot and cue, were presented for 3 seconds, during which the participants had to maintain the attentional states. When they were instructed to attend to the left or right disk, a single-digit stream was displayed at the center of the attended disk. The stream was made up of digits randomly chosen from one to nine. The number of digit appearances varied randomly from two to six times. Participants were asked to count the number of digit appearances (that is, two, three,

four, five, or six) irrespective of what the digit was. At least two digits were presented in the single-digit stream, and the interval between two digits varied from 0.1 to 1.9 seconds. When they were instructed to attend to two disks, a dual-digit stream was displayed at the center of two disks. Each stream was made up of digits randomly chosen from one to nine. The number of digit appearances was fixed at six times. Participants were asked to count how many times two digits matched (that is, one, two, or three) irrespective of what the two digits were. The duration of each digit was 0.1 second. A short duration was used to avoid shifting attention between two distinct positions rather than dividing their attention when participants were instructed to attend to two disks (Müller et al., 2003; McMains & Somers, 2004; McMains & Somers, 2005). After the presentation of the stimulus, only the fixation dot was left, and participants indicated the number of digit appearances or the times the digits matched. Participants could rest and blink during the responding period. Once they pressed a button, the next trial began.

During each block of Experiments 1 and 3, two disks with different luminance were presented randomly in the left and right visual hemifields with equal possibility, leading to two disk configurations. Each participant gazed at the fixation dot and attended to the left disk, right disk, or both disks based on the attentional cue. For each disk configuration and attentional state, 12 trials were repeated, leading to a total of 72 trials (12 repetitions × 2 disk configurations × 3 attentional states) in one block. During each block of Experiment 2, there was one disk configuration because the two disks were identical. For each attentional state, 24 trials were repeated, leading to a total of 72 trials (24 repetitions × 1 disk configuration × 3 attentional states) in one block.

To refrain from participants getting fatigued, three blocks at most were conducted in one day with a long interval. As a result, Experiment 1, Experiment 2, Experiment 3a, and Experiment 3b were conducted on separate days. Each block lasted approximately eight minutes. To ensure that all participants understood the procedure, practicing blocks were conducted until their correct answer rates of the task exceeded 90%.

Processing of pupil data

First, for missing samples due to blinking or tracking errors, a cubic Hermite spline interpolation was used to ensure monotonicity during the missing period (Dougherty, Edelman, & Hyman, 1989). Second, to reduce the higher frequency components of the recorded data, a Savitzky–Golay filter (order 2, window length 0.1 second) was used to smooth the pupillary responses (Bergamin & Kardon, 2003). Third, the baseline of each trial was calculated by averaging the

samples during 0.1 second preceding the stimulus onset. Subsequently, the pupil data were normalized by subtracting the baseline, leading to a negative or positive value that represented the constriction or dilation concerning the baseline (Mathôt, Fabius, Van Heusden, & Stigchel, 2018). Finally, the pupil data were averaged for each 0.25 s time bin, leading to 12 discrete values to be individually analyzed in statistics (Sabatino DiCriscio, Hu, & Troiani, 2018).

Excluding criteria for later analyses

Some of the obtained data were excluded from the analyses due to the following criteria. First, to ensure that participants fixed on the fixation dot, deviation in the horizontal eye position during the presentation of the two disks was calculated for each trial; if more than 5% of the samples were located over 1° from the fixation position, which was the average position value during 0.1 second preceding the onset of the two disks, the data of the trial were excluded. Second, to maintain participants' arousal states, the trials where the baseline size deviated more than 2.5 *SD* from the average baseline of each block were excluded (de Gee, Knapen, & Donner, 2014; Murphy, Vandekerckhove, & Nieuwenhuis, 2014; Urai, Braun, & Donner, 2017). Finally, trials with incorrect responses to the task were excluded.

Experiment 1

Objective

In this experiment, we aimed to examine the pupillary response when attending to two disks with different luminance. We presented both bright and dark disks on a gray background (See Table 1 for the luminance values). We manipulated participants' attentional states using three types of attentional cues.

Results

The average correct rates for the counting task when attending to the bright disk and dark disk were 97.2% (standard deviation was 3.9%, the lowest correct rate was 91.7%) and 100.0%, respectively. The average correct rate for the matching task when attending to two disks was 97.2% (standard deviation was 3.1%, the lowest correct rate was 91.7%). The excluding rate of data was 3.9% (standard deviation was 2.0%, the highest excluding rate was 5.6%).

The results of pupillary responses for three attentional states are depicted in Figure 2, wherein the

	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3
Both-Bright			*	*	**	**	**	**	**	**	**	**
Both-Dark												
Dark-Bright			**	**	**	**	**	**	**	**	**	**

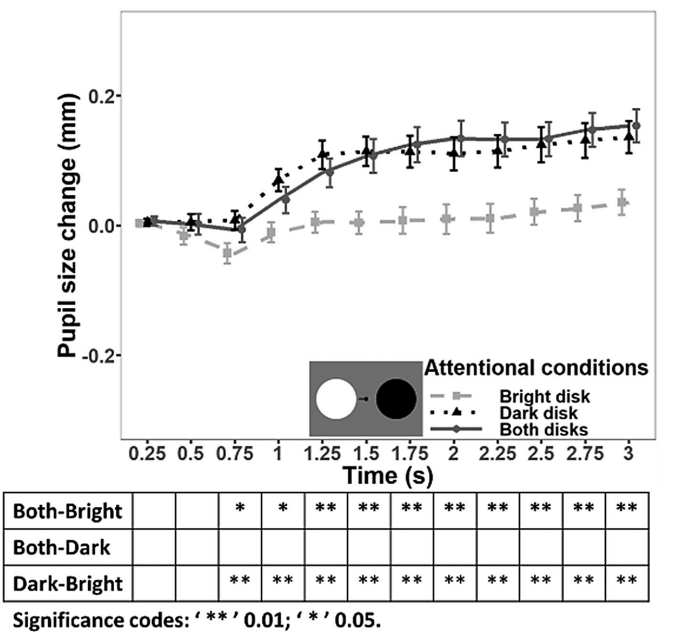Significance codes: ' ** ' 0.01; ' * ' 0.05.

Figure 2. Results of Experiment 1. The pupil size change (in mm) is plotted as a function of time (in seconds). The stimulus used is shown next to the legend. The black dotted line and the triangle represent the pupillary response when attending to the dark disk; the light gray dashed line and the square represent the pupillary response when attending to the bright disk; the dark gray solid line and the circle represent the pupillary response when attending to both disks. The results of multiple comparisons for every two attentional states are plotted below. The three rows from top to bottom represent the comparison between attending to both disks and the bright disk, attending to both disks and the dark disk, and attending to the dark disk and the bright disk, respectively. The symbols of one asterisk and two asterisks indicate that the difference in results reached a significance level of 5% and 1%, respectively. The error bars represent standard error of the means across six participants.

abscissa represents the time, and the ordinate represents the pupil size change averaged across six participants. The pupillary responses for three attentional states are plotted in different colors and types of symbols and lines. We first conducted a one-way repeated analysis of variance (ANOVA) with attentional states regarded as the within-subject factor for each time bin separately. Then, post hoc multiple comparisons (Tukey's test) were conducted for each time bin separately. Below the results of the pupillary response in the figure, the statistical results for the data of the corresponding time on the abscissa are tabulated. The three rows from top to bottom represent the comparison between two of the three attentional states. The symbols of one asterisk and two asterisks indicate that the difference in results reached a significance level of 5% and 1%, respectively.

As shown in Figure 2, we found that the pupillary response when attending to the dark disk was

significantly larger than when attending to the bright disk, which was consistent with previous studies (Binda et al., 2013; Binda et al., 2014). We also found that the pupillary response when attending to two disks with different luminance was comparable to that when attending to the dark disk and was significantly larger than when attending to the bright disk. Although luminance determined the pupillary response when attending to a single disk, it could not determine the pupillary response when attending to two disks because the mean luminance of the two disks was between the luminance of the bright and dark disks, whereas the pupillary response when attending to two disks was not in the middle of responses when attending to each disk.

We examined the pupillary response when attending to two disks with different luminance and found that pupils dilated with divided attention deployed, but the reason for this was unclear. In the following experiments, we aimed to examine what factor would affect the pupillary response when attending to two disks.

Experiment 2

Objective

All participants achieved the correct answer rate of more than 90% in our tasks of Experiment 1. This fact may imply that the difficulties were not actually the same for different attentional tasks because of ceiling effect. As a result, pupils dilated when attending to two disks because of task difficulty. Furthermore, divided attention per se might elicit a larger pupillary response. In this experiment, we aimed to examine such possibility that the task or divided attention per se would elicit a larger pupillary response when attending to two disks. We presented two disks with identical luminance on a gray background. We carried out three conditions of disk luminance (bright, gray, and dark in Experiments 2-1, 2-2, and 2-3, respectively). See Table 1 for the luminance values. The participants' attentional states were manipulated as was done in Experiment 1.

Results

The average correct rates for the counting task when attending to the single disk were 99.0% (standard deviation was 2.5%, the lowest correct rate was 91.7%), 99.3% (standard deviation was 1.6%, the lowest correct rate was 95.8%), and 98.6% (standard deviation was 2.0%, the lowest correct rate was 95.8%) for Experiments 2-1, 2-2, and 2-3, respectively. The average correct rates for the matching task when attending to two disks were 98.6% (standard deviation

was 2.0%, the lowest correct rate was 95.8%), 100.0%, and 96.5% (standard deviation was 2.9%, the lowest correct rate was 91.7%) for Experiments 2-1, 2-2, and 2-3, respectively. The excluding rates of data were 2.3% (standard deviation was 2.4%, the highest excluding rate was 5.6%), 1.6% (standard deviation was 1.5%, the highest excluding rate was 4.2%), and 3.0% (standard deviation was 2.0%, the highest excluding rate was 5.6%) for Experiments 2-1, 2-2, and 2-3, respectively.

The results of pupillary responses for two attentional states are depicted separately in Figure 3, wherein the abscissa represents the time, and the ordinate represents the pupil size change averaged across six participants. The pupillary responses for the two attentional states are plotted in different colors and types of symbols and lines. Since there were only two attentional states, we conducted a paired two-tailed *t*-test for each time bin separately. Below the results of the pupillary response in the figure, the statistical results for the data of the corresponding time on the abscissa are tabulated. The symbols of one asterisk and two asterisks indicate that the difference in results reached a significance level of 5% and 1%, respectively.

As shown in Figure 3, we found that the pupillary response when attending to two disks with identical luminance was not larger than when attending to the single disk (irrespective of the disk luminance). These results indicated that the difference in tasks or attentional states per se could not explain the pupillary dilation with divided attention deployed that was found in Experiment 1. Surprisingly, the pupillary response during the early period when attending to the single dark disk was larger than when attending to two dark disks in Experiment 2-3. We have no ideas to explain this difference and must verify this finding in the future. Nevertheless, the task or attentional state per se could not be the reason the pupillary response was larger when attending to two disks with different luminance.

Experiment 3

Objective

In this experiment, we aimed to examine what factor would affect the pupillary response when attending to two disks. Based on the results of Experiments 1 and 2, wherein pupils dilated when attending to two disks with different luminance but did not dilate when attending to two disks with identical luminance, we speculated that the luminance difference between the two disks would affect the pupillary response with divided attention deployed. If this speculation were correct, other factors, such as the luminance of the background, which could change the optical properties of pupils, would not affect the results of Experiment 1 (Loewenfeld, 1993;
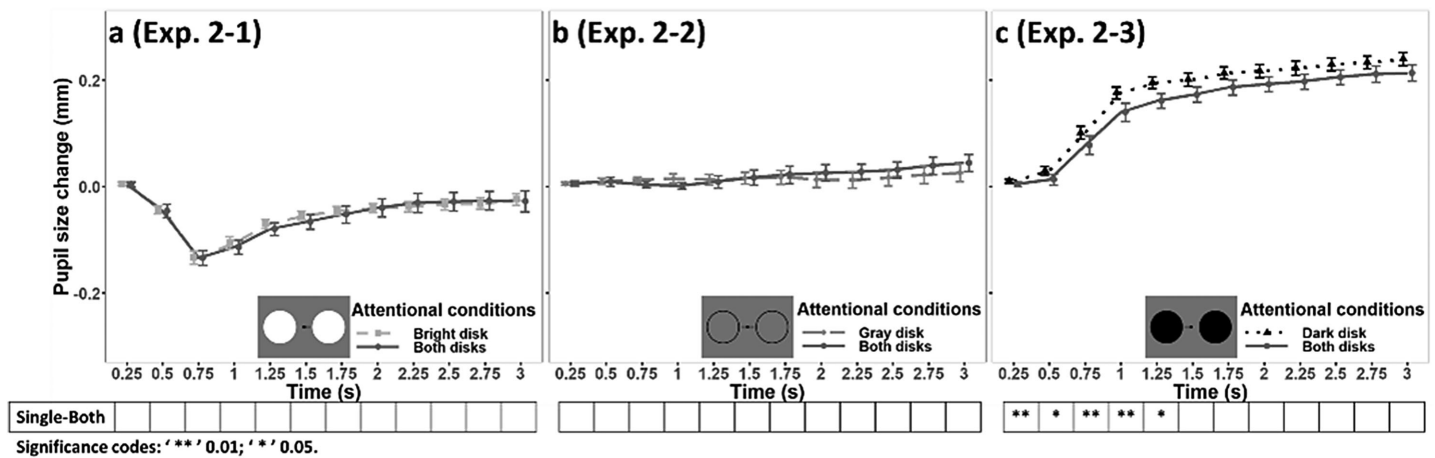
Figure 3. Results of Experiment 2. The results in three blocks are plotted separately. The pupil size change (in mm) is plotted as a function of time (in sec). The stimulus used is shown next to the legend. The light gray dashed line and the square represent the pupillary response when attending the single bright disk for Experiment 2-1; the middle gray long dashed line and the diamond represent the pupillary response when attending the single gray disk for Experiment 2-2; and the black dotted line and the triangle represent the pupillary response when attending the single dark disk for Experiment 2-3. The dark gray solid line and the circle represent the pupillary response when attending both disks in three blocks. The results of a paired two-tailed *t*-test between attending to the single disk and attending to both disks are plotted below. The symbols of one asterisk and two asterisks indicate that the difference in results reached a significance level of 5% and 1%, respectively. The error bars represent standard error of the means across six participants.

Campbell & Woodhouse, 1975; Campbell & Gregory, 1960). Therefore in Experiment 3a we maintained the luminance difference of the two disks but varied the luminance of the background as compared to that in Experiment 1 (see Table 1 for the luminance values). Furthermore, it was reasonable to speculate that the magnitude of the luminance difference between the two disks could affect pupillary dilation when attending to two disks. Therefore in Experiment 3b we reduced the luminance difference between the two disks as compared to that in Experiment 1 but maintained the luminance of the background (see Table 1 for the luminance values). The participants' attentional states were manipulated as was done in the previous experiments.

Results

The average correct rates for the counting task when attending to the brighter disk and the darker disk were 97.9% (standard deviation was 3.2%, the lowest correct rate was 91.7%) and 97.2% (standard deviation was 3.1%, the lowest correct rate was 91.7%), 99.3% (standard deviation was 1.6%, the lowest correct rate was 95.8%) and 96.5% (standard deviation was 3.7%, the lowest correct rate was 91.7%), 97.2% (standard deviation was 3.1%, the lowest correct rate was 91.7%) and 97.9% (standard deviation was 3.2%, the lowest correct rate was 91.7%), and 98.6% (standard deviation

was 3.1%, the lowest correct rate was 91.7%) and 95.8% (standard deviation was 3.4%, the lowest correct rate was 91.7%) for Experiments 3a-1, 3a-2, 3b-1, and 3b-2, respectively. The average correct rates for the matching task when attending to two disks was 93.8% (standard deviation was 6.7%, the lowest correct rate was 83.3%), 99.3% (standard deviation was 1.6%, the lowest correct rate was 95.8%), 97.9% (standard deviation was 3.2%, the lowest correct rate was 91.7%), and 96.5% (standard deviation was 2.9%, the lowest correct rate was 91.7%) for Experiments 3a-1, 3a-2, 3b-1, and 3b-2, respectively. The excluding rates of data were 4.4% (standard deviation was 1.7%, the highest excluding rate was 6.9%), 3.2% (standard deviation was 1.7%, the highest excluding rate was 6.9%), 3.2% (standard deviation was 1.3%, the highest excluding rate was 5.6%), and 4.4% (standard deviation was 2.9%, the highest excluding rate was 8.3%) for Experiments 3a-1, 3a-2, 3b-1, and 3b-2, respectively.

The results of pupillary responses for three attentional states are depicted separately in Figure 4, wherein the abscissa represents the time, and the ordinate represents the pupil size change averaged across six participants. The pupillary responses for three attentional states are plotted in different colors and types of symbols and lines. We first conducted a one-way repeated ANOVA with attentional states regarded as the within-subject factor for each time bin separately. Then, post hoc multiple comparisons (Tukey's test) were conducted for each time bin
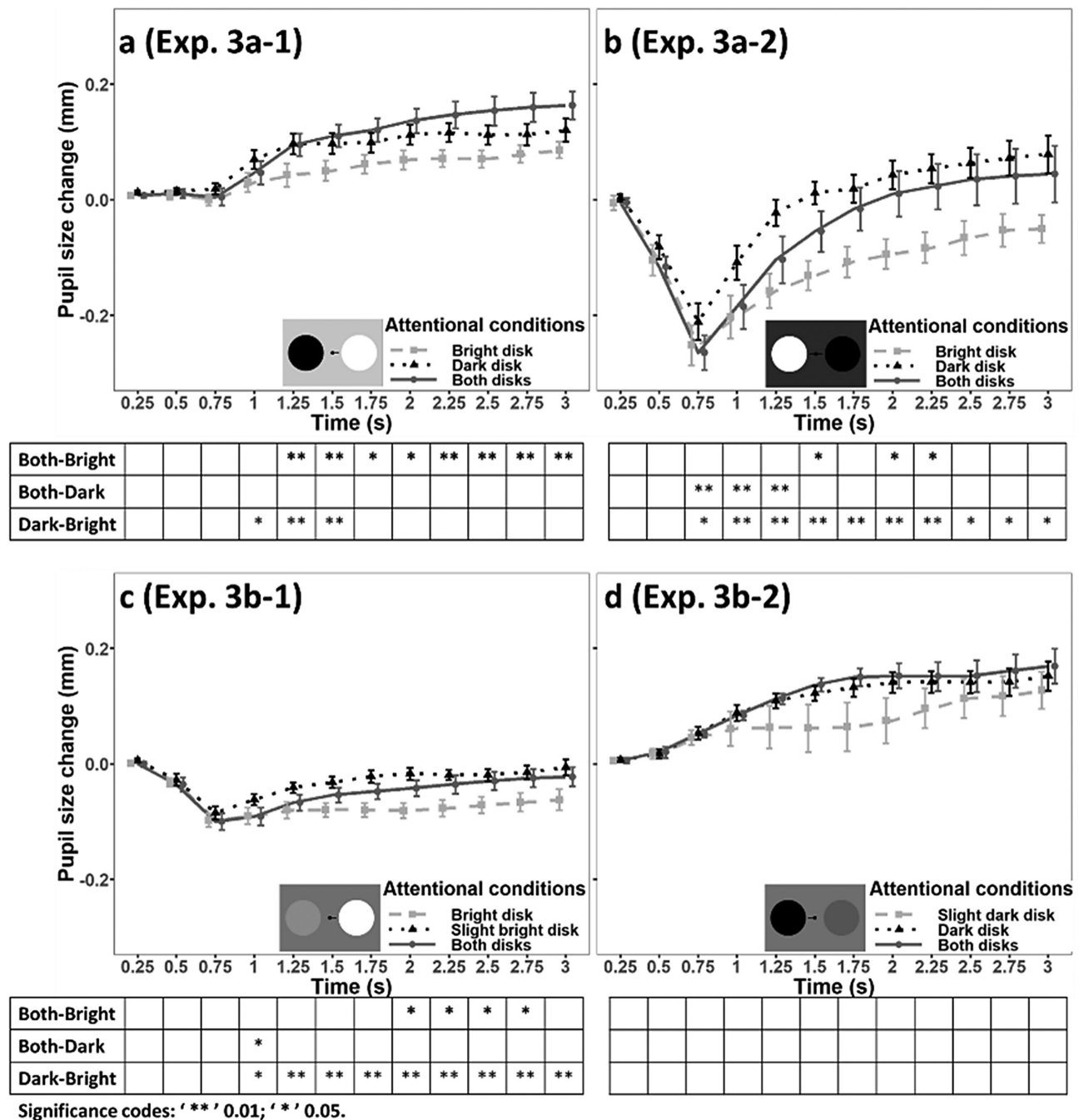
Figure 4. Results of Experiment 3. The results in four blocks are plotted separately. The pupil size change (in mm) is plotted as a function of time (in seconds). The stimulus used is shown next to the legend. The black dotted line and the triangle represent the pupillary response when attending to the darker disk; the light gray dashed line and the square represent the pupillary response when attending to the brighter disk; and the dark gray solid line and the circle represent the pupillary response when attending to both disks. The results of multiple comparisons for every two attentional states are plotted below. The three rows from top to bottom represent the comparison between attending to the brighter disk and both disks, attending to the darker disk and both disks, and attending to the darker disk and the brighter disk, respectively. The symbols of one asterisk and two asterisks indicate that the difference in results reached a significance level of 5% and 1%, respectively. The error bars represent standard error of the means across six participants.

separately. Below the results of the pupillary response in the figure, the statistical results for the data of the corresponding time on the abscissa are tabulated. The three rows from top to bottom represent the comparison between two of the three attentional states. The symbols of one asterisk and two asterisks indicate that the difference in results reached a significance level of 5% and 1%, respectively.

Figure 4a (Experiment 3a-1) shows the pupillary response to the same disks used in Experiment 1 with a brighter background. We found that the pupillary response when attending to two disks was significantly larger than when attending to the brighter disk. However, the pupillary response from 1.75 seconds when attending to the darker disk was not significantly larger than when attending to the brighter disk. We speculated that the small pupillary baseline caused by the high luminance of the background made the pupillary constriction less obvious, leading to a nonsignificant difference between pupillary responses when attending to the brighter and darker disks. The pupillary response when attending to two disks was not affected by the small pupillary baseline, suggesting that it was a pupillary response based on a mechanism different from the pupillary response when attending to the darker disk. In other words, this response would not be the attentional modulation in PLR.

Figure 4b (Experiment 3a-2) shows the pupillary response to the same disks used in Experiment 1 with a darker background. We found that the pupillary response from 0.75 to 1.25 seconds when attending to two disks was significantly smaller than when attending to the darker disk, and the pupillary response from 1.5 to 2.25 seconds when attending to two disks was significantly larger than when attending to the brighter disk. We speculated that the high contrast of the brighter disk (the Weber contrast of 4) as compared to the low contrast of the darker disk (the Weber contrast of −1) attracted participants' attention more right after stimulus onset, even if they were instructed to attend to two disks. As a result, the transient period of pupillary response when attending to two disks could be comparable to that when attending to the brighter disk. Thereafter, participants divided their attention endogenously and had a larger pupillary response, as in the cases of Experiments 1 and 3a-1.

Figure 4c (Experiment 3b-1) shows the pupillary response to the stimulus with reduced luminance difference between the two disks relative to those of Experiment 1. Also, the luminance of the two disks was brighter than that of the background. We found that the pupillary response from 2 to 2.75 seconds when attending to two disks was significantly larger than when attending to the brighter disk. Additionally, the pupillary response when attending to the darker disk was significantly larger than when attending to the brighter disk. Figure 4d (Experiment 3b-2) shows

the pupillary response to the stimulus with reduced luminance difference between the two disks relative to those of Experiment 1. Also, the luminance of the two disks was darker than that of the background. We found that there was no significant difference among the three pupillary responses. We speculated that the results were caused by the asymmetry of the attentional modulation in luminance reported by Binda et al. (2013, 2014). They reported that the pupillary response when attending to a bright disk was smaller than when attending to a slight bright disk, whereas the pupillary response when attending to a dark disk was comparable to that when attending to a slight dark disk. This asymmetry is similar to the results in Experiment 3b.

General results

So far, the results were analyzed for each block. Next, we conducted an additional analysis by collapsing all the experiments. The mean pupil change (MPC), which reflected the sustained component of pupillary response and was defined as the average value of the last six time bins (that is, the values 1.5 seconds before the stimulus offset), was calculated. Considering that the luminance of two disks and background in each experiment was different, we analyzed relative, not absolute, MPC value, which was defined as the difference between MPC of every two attentional states. As a result, there were three conditions of relative pupillary difference: the MPC difference between when attending to both disks and when attending to the dark disk ("Both-Dark"), that between when attending to the dark disk and when attending to the bright disk ("Dark-Bright"), and that between when attending to both disks and when attending to the bright disk ("Both-Bright"). Note that, when there was no luminance difference between disks (Experiment 2), the disk could be treated as either "Dark" or "Bright". In other words, we used either "Bright" or "Dark" to refer to the bright disk in Experiment 2-1, gray disk in Experiment 2-2, or dark disk in Experiment 2-3.

The results of the analysis are depicted in Figure 5. The abscissas in panels a, b, and c represent the luminance of each component of stimulus, bright disk, dark disk, and background. Regarding panel d, we chose the luminance difference between bright and dark disks as the abscissas since we found no difference in pupillary response when the luminance of two disks was identical, as shown in Experiment 2 (Figure 3). The ordinate represents the relative MPC difference. The three conditions of difference are plotted in different shapes and types of symbols and lines. We conducted a one-way repeated ANOVA for each difference condition separately for each panel. In Figure 5a, there were main effects of luminance of bright disk for "Dark-Bright"
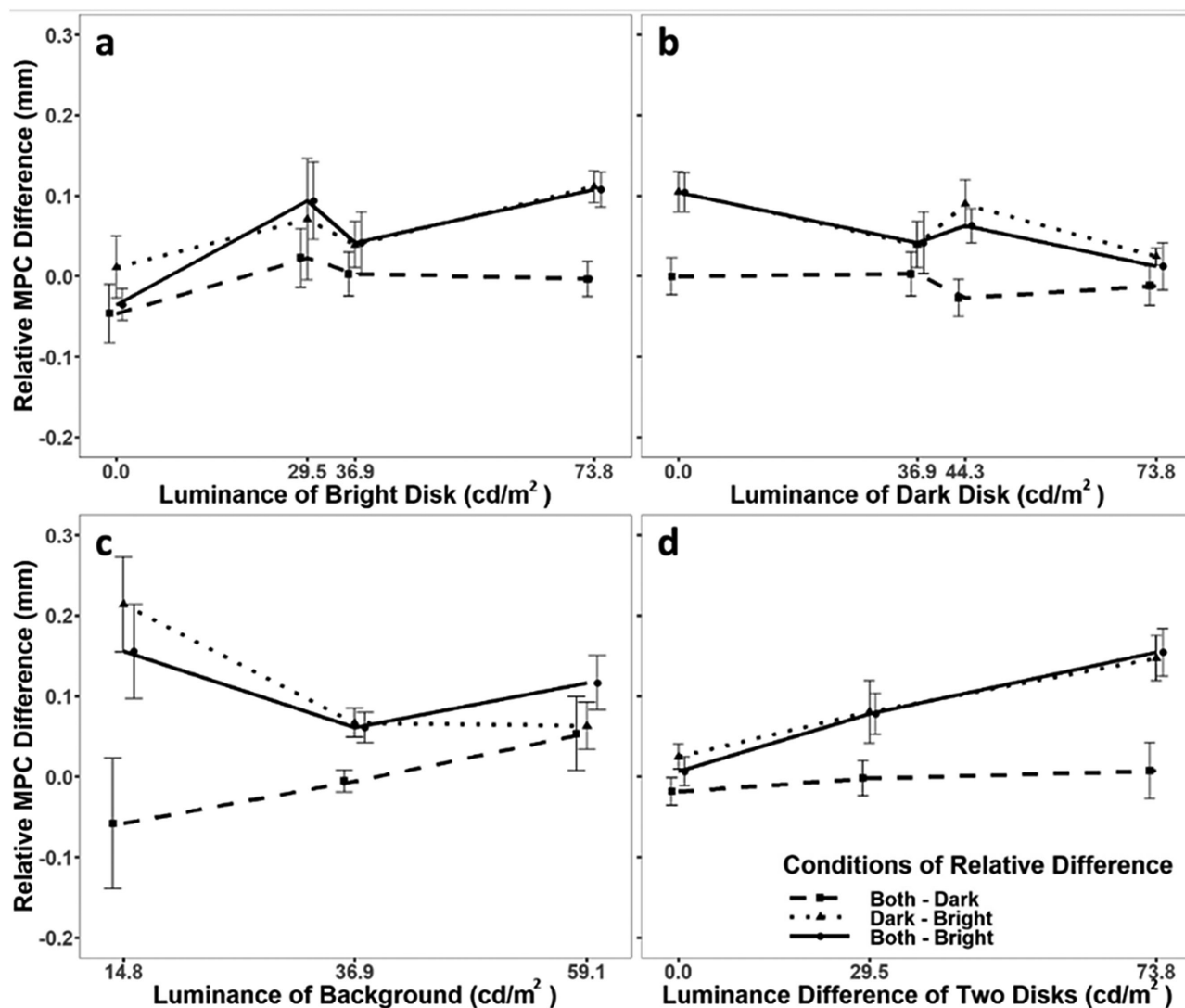
Figure 5. Results of relative MPC difference for different independent variables. The abscissas from panels a, b, c, and d represent the luminance of the bright disk (in cd/m^2), the luminance of the dark disk (in cd/m^2), the luminance of the background (in cd/m^2), and the luminance difference between the two disks (in cd/m^2). The ordinate represents the relative MPC difference (in mm). The dashed line and the square represent the MPC difference between when attending to both disks and when attending to the dark disk; the dotted line and the triangle represent the MPC difference between when attending to the dark disk and when attending to the bright disk; and the solid line and the circle represent the MPC difference between when attending to both disks and when attending to the bright disk. The error bars represent standard error of the means across six participants.

($F(1,5) = 6.93$, $p = 0.046$) and "Both-Bright" ($F(1,5) = 72.32$, $p < 0.001$), whereas there was no significant effect for "Both-Dark" ($p = 0.350$). In Figure 5b, there was a main effect of luminance of dark disk for "Dark-Bright" ($F(1,5) = 9.40$, $p = 0.028$), whereas there were no significant effects for "Both-Bright" ($p = 0.096$) and "Both-Dark" ($p = 0.743$). In Figure 5c, there were no significant effects of luminance of background for all three conditions of difference (all $p > 0.05$). In Figure 5d, there were main effects of luminance difference for "Dark-Bright" ($F(1,5) = 19.36$, $p = 0.007$) and "Both-Bright" ($F(1,5) = 21.68$, $p = 0.006$),

whereas there was no significant effect for "Both-Dark" ($p = 0.576$).

Interestingly, although the luminance difference of two disks determined both MPC differences of "Dark-Bright" and "Both-Bright", the underlying reason seemed to be different. We found that there was a main effect of luminance of dark disk for "Dark-Bright", whereas not for "Both-Bright." Specifically, the MPC difference of "Dark-Bright" varied significantly with both luminance of bright and dark luminance (see the dotted line in Figures 5a and 5b), whereas the MPC difference of "Both-Bright"

only varied significantly with the luminance of bright disk (see the solid line in Figure 5a). Therefore we presumed that the mechanism of pupillary response when attending to both disks was different from that when attending to the dark disk.

General discussion

We aimed to examine how pupils would respond when attending to two disks by conducting three experiments. We found that the pupillary response when attending to two disks with different luminance was larger than when attending to a single brighter disk and was comparable to that when attending to a single darker disk, whereas the pupillary response when attending to two disks with identical luminance was not larger than when attending to the single disk (irrespective of the disk luminance). Furthermore, we found that the magnitude of luminance difference between the two disks determined the dilation of the sustained component of the pupillary response, which was defined as the difference between the mean pupil changes when attending to two disks and when attending to a single brighter disk.

Although we postulated that divided attention was deployed when participants were instructed to attend to two disks, the debate still exists. Jans, Peters, and De Weerd (2010) indicated that divided attention was difficult to achieve and could only be deployed by well-trained participants. Apart from the divided attention model, other prevalent explanations of attending to multiple objects include the model of the moving spotlight (that is, the sequential attentional shift among different positions) and the zoom-lens model (that is, expansion of the attentional area to include multiple positions) (Posner, Snyder, & Davidson, 1980; Eriksen & St. James, 1986; Barriopedro & Botella, 1998). The model of the moving spotlight is not appropriate for the present experiments because the duration of digits (0.1 second) used to control participants' attentional states in this study was much shorter than the necessary time needed to accomplish the attentional shift, which was reported to be around 0.15 second (Müller et al., 2003; McMains & Somers, 2004; McMains & Somers, 2005). However, we cannot exclude the explanation by the zoom-lens model. Although we made specific instructions to the participants before experiments and deployed two disks bilaterally during experiments to make them easily divide their attention, it was possible for participants to expand their attention to include both the two disks and background (Jefferies et al., 2014; Kraft et al., 2011; Alvarez et al., 2012; Ibos et al., 2009). Based on the zoom-lens model, however, the pupillary response when attending to two disks should be smaller compared to that when attending to

the dark disk because the attentional areas included the background between the disks and the luminance of background was higher than that of the dark disk, which was not the case of Experiment 1 (Figure 2). Hence, we supposed that divided attention would be deployed when participants were instructed to attend to two disks in the present study. Further studies are needed to examine the possibility of the zoom-lens model in pupillary light response.

Furthermore, although it is possible to assume that more attentional resources were allocated to the dark disk compared to the bright disk, leading to the pupillary dilation when attending to both disks, we suppose this possibility would not fit to our results. First, despite the reversed relationship of Weber contrast between bright and dark disks, the pupillary response when attending to both disks was always larger than that when attending to the bright disk. The Weber contrast of bright disk is higher than that of the dark disk in Experiments 3a-2 and 3b-1 (Figures 4b and 4c), whereas the Weber contrast of dark disk is higher than that of the bright disk in Experiments 3a-1 and 3b-2 (Figure 4a and 4d). Since it has been known that stimulus with high contrast attracts attention easily (Carrasco, 2011), the bright disk in Experiments 3a-2 and 3b-1 should get more attentional sources, leading to a smaller pupillary response when attending to both disks, which was inconsistent with our results. Second, despite the reversed relationship of digit visibility between bright and dark disks, the pupillary response when attending to both disks was always larger than that when attending to the bright disk. Because the luminance of the digit was the same as that of the background, the digit in the dark disk was harder to recognize than that in the bright disk in Experiments 3a-2 and 3b-1 because of the smaller Weber contrast for the digit (Figure 4), whereas the digit in the bright disk was harder to recognize than that in the darker disk in Experiments 3a-1 and 3b-2 because of the smaller Weber contrast for the digit (Figure 4). Since it has been shown that more attentional resources are needed for a difficult task, the digit in the bright disk in Experiments 3a-1 and 3b-2 should get more attentional sources, leading to a smaller pupillary response when attending to both disks, which was inconsistent with our results. To sum, we presumed that the pupillary dilation elicited when attending to two disks with different luminance was not caused simply by the more allocation of attentional sources to the darker disk. However, we need to consider some points related to the arguments above because we did not directly measure the distribution of attention. For example, the increase of salience for a high-contrast stimulus seems primarily to affect the transient attention, rather than the sustained attention with specific task goals. In addition, regarding the digit saliency and attention distribution, there might be other interpretations of the

relationship among the luminance distribution of the stimulus, task difficulty, and attention.

Besides the above hypotheses, there is another speculative hypothesis. Because we found that the luminance difference between the two disks determined the relative MPC difference (Figure 5d), we assume that the conflict in the information being processed elicited the larger pupillary response when attending to two disks with different luminance. Indeed, it has been well known that conflict paradigms, such as Stroop task, Flanker task, and Simon task, can elicit pupillary dilation when conflict information are presented (van der Wel & van Steenbergen, 2018; Eckstein, Guerra-Carrillo, Singley, & Bunge, 2017). Therefore the pupillary dilation when attending to two disks with different luminance might share the same mechanism with conflict paradigms. Although our results do not provide direct support for this hypothesis, the luminance difference of two disks must play a specific role in eliciting pupillary dilation. Further studies are needed to test this hypothesis by using methodologies of conflict paradigms.

Some researchers have used the properties of attentional modulation in PLR to develop a new system of human-computer interface (HCI) because it has advantages in that for patients who cannot move their eyes over ordinary systems using eye position signals or PLR (Naber, Alvarez, & Nakayama, 2013; Mathôt et al., 2013, 2016; Máté, 2017). In a system proposed by Mathôt et al. (2016), participants' attentional position could be identified solely by the pupil size. Under the condition when participants fixed their gaze position at the center of a monitor, they achieved an average of 87.6% accuracy of attentional position identification for a visual keyboard with eight inputs. They also reported an information-transfer rate of 4.86 bits/min, although it depended on both accuracy and speed. Their performance was comparable to that of the invasive brain-computer interface, suggesting the bright potential that lock-in patients could communicate with others through HCI using pupillary response (Treder, Schmidt, & Blankertz, 2011; Riccio, Mattia, Simione, Olivetti, & Cincotti, 2012). Our results provide new insights on HCI. When bright and dark objects are presented simultaneously, it is possible to consider that users are attending to both objects or attending only to the dark object when larger pupils are detected, rather than attending only to the bright object. However, it remains to be solved about differentiating attentional states between attending to both dark and bright objects and attending only to the dark object.

In conclusion, pupillary dilation was elicited when attending to two disks with different luminance. The limitation of the present study is that divided attention in only two positions was examined. Considering the capacity of divided attention (Kawahara & Yamada, 2006; Bettencourt & Somers, 2009; Cavanagh & Alvarez, 2005), further studies on more than two attentional positions should be conducted. Furthermore, studies that test the hypotheses of zoom-lens model or conflict paradigm are also needed.

Keywords: pupillary response, divided attention, luminance

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