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Ebbinghaus illusion depends more on the retinal than perceived size of surrounding stimuli

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ABSTRACT

A stimulus surrounded by smaller/larger stimuli appears larger/smaller (Ebbinghaus illusion). We examined whether the Ebbinghaus illusion would depend on the retinal or perceived size of the surrounding stimuli. The flash-lag effect, where a flashed stimulus perceptually lags moving stimuli, was used to dissociate the retinal from perceived size of the surrounding stimuli. Two sets of four surrounding disks changed their size smoothly: one with larger disks shrinking, the other with smaller disks expanding. Two identical central disks were presented briefly at various timings relative to the moment when the surrounding disks were physically identical in their size (coincidence time). A significant flash-lag effect was observed for size change (Experiment 1). Participants reported the two central disks being in equal size when they appeared only slightly before the coincidence time. However, this asynchrony was not significantly different from zero and was significantly smaller than the perceptual delay expected from the flash-lag effect (Experiment 2). These results suggest that the Ebbinghaus illusion depends more on the retinal than perceived size of the surrounding stimuli.

1. Introduction

Since the extent on the retina of the visual projection of an object does not uniquely correspond to the actual size of the object, it is natural to think that size perception is context dependent and therefore involves deliberative processes with feedback from high-level processes. Many optical illusions of size perception have been explained by so-called unconscious inferences. For example, in the Ponzo illusion, a visual object looks larger when placed in a configuration that makes it appear at a far location than the same object appearing at a closer location. A popular explanation is that our visual system interprets the size of an object by considering visual perspective; a closer object should be smaller than a farther one when the two objects have the identical angular (i.e., retinal) size (Erkelens, 2015; Gilinsky, 1951; Hatfield, 2012).

The Ebbinghaus illusion is another optical illusion in size perception, where a stimulus surrounded by smaller/larger stimuli appears larger/smaller (Ebbinghaus, 1902; Titchener, 1901). Two major theories have been put forward to explain the Ebbinghaus illusion. The size contrast theory explains the Ebbinghaus illusion in that the visual system uses surrounding inducers as a referencing standard in order to estimate the size of a surrounded stimulus. Since the size of surrounding inducers needs to be registered and fed back to determine the size of a central stimulus, the size contrast theory implies the involvement of high-level inferential processes (Coren & Miller, 1974; De Fockert, Davidoff, Fagot, Parron, & Goldstein, 2007; Gold, 2014; Massaro & Anderson, 1971). The other account is the contour interaction theory (Jaeger, 1978), which explains the Ebbinghaus illusion without appealing to object size but to low-level interactions between visual contours. Contour edges of smaller surrounding inducers tend to be closer to the contour of a central stimulus. Contour interaction theory posits that contours closer to each other attract each other, leading to size overestimation of the central stimulus. On the other hand, contours of larger inducers tend to be further away from those of a central stimulus. Surrounding contours far from each other repel each other, hence size underestimation (Jaeger, 1978; Jaeger & Grasso, 1993; Jaeger & Klahs, 2015; Roberts, Harris, & Yates, 2005; Rose & Bressan, 2002; Sherman & Chouinard, 2016; Weintraub, 1979; Weintraub & Schneck, 1986). While both theories have received support and have limitations, recent theoretical and empirical investigations have accumulated evidence favoring the contour interaction theory (e.g., Chen, Qiao, Wang, & Jiang, 2018; Todorović & Jovanović, 2018). For example, Todorović and Jovanović (2018) pointed out that the size contrast theory is a mere description of the phenomenon and does not

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describe a mechanism and showed that size modulation can be observed when a stimulus was not surrounded by similar stimuli but confined with lines. Also, Chen et al. (2018) showed that even when surrounding stimuli were invisible, and therefore the size of inducers was not known to participants, size modulation of the central stimulus was observed.

Partly inspired by the fact that the contour interaction theory does not require high-level inferential process, two recent studies have examined whether conscious perception of surrounding inducers is necessary for modulation of perceived size by the Ebbinghaus illusion (Chen et al., 2018; Nakashima & Sugita, 2018). Nakashima and Sugita (2018) showed that the illusion occurs even when the surrounding inducers are made invisible by using the continuous flash suppression method, where a visual target is rendered invisible for a long time by presenting it in one eye while high contrast dynamic patterns are presented in the other eye (Tsuchiya & Koch, 2005). By using continuous flash suppression, Chen et al. (2018) also provided evidence for the modulation of size processing by invisible surrounding inducers. In addition, they demonstrated that the Ponzo illusion cannot be observed with the context rendered invisible. These studies point to the idea that the modulation of size processing by the Ebbinghaus configuration does not require conscious perception of the surrounding inducers.

While previous studies have shown that conscious perception of size differences in surrounding inducers is *not necessary* for the Ebbinghaus illusion to occur, it still remains to be tested whether the perception of size differences in surrounding inducers is *sufficient* to produce the Ebbinghaus illusion. In other words, a condition where the Ebbinghaus illusion does not occur even when a size difference in the surrounding inducers is perceived has yet to be demonstrated. This prompted us to ask whether the Ebbinghaus illusion depends more on the retinal or perceived size of the surrounding stimuli.

To investigate this, we needed to dissociate the retinal size of the surrounding inducers from their perceived size. For this, we used the flash-lag effect. The flash-lag effect (FLE) is the phenomenon where a flashed stimulus perceptually lags moving stimuli (Eagleman, 2000; MacKay, 1958; Mateeff & Hohnsbein, 1988; Nijhawan, 1994; Nijhawan, 1997; Watanabe & Yokoi, 2006; Whitney & Murakami, 1998). For example, when a moving and a flashed stimulus are presented in spatial alignment, a compelling spatial dissociation between the physically given stimulus and the perceived stimulus occurs; namely the flashed stimulus is seen to spatially lag the moving stimulus. While the FLE is most commonly examined with motion, studies have shown the FLE with various dynamic features other than visual motion, including color, luminance, spatial frequency, etc. (e.g., Sheth, Nijhawan, & Shimojo, 2000). Although the mechanism of the FLE and its processing stage(s) in the visual system are still not completely known, it serves as a method to dissociate a stimulus projecting on the retina from its perception. For example, Khurana, Carter, Watanabe, and Nijhawan (2006) examined whether the impairment of face recognition when the upper and lower halves of different faces are aligned (Chimeric face effect; Young, Hellawell & Hay, 1987) depends on retinal alignment or perceived alignment. By using the FLE, they produced a condition where two face halves were physically aligned but perceived to be misaligned and another condition where face halves were physically misaligned but perceived to be aligned. The results showed that the impairment occurred when the two halves were perceptually aligned but not physically aligned, suggesting that the chimeric face effect depends on perceived rather than retinal alignment (and also that the processing for face recognition occurs after that for the FLE). By contrast, Arnold, Durant, and Johnston (2003) showed that, in the tilt illusion, where the perceived orientation of a line or grating is affected by the orientation of the surrounding stimuli (e.g., Clifford, 2014; Gibson, 1937), there was only a negligible influence of the perceived orientation of the surrounding stimulus from the FLE. This suggests that the tilt illusion depends more on the retinal rather than perceived orientation of the surrounding stimulus (and also that the processing for the tilt illusion occurs before that for the FLE). Qualitatively similar results were also observed in the tilt aftereffect, that is, the tilt aftereffect depends more on the retinal rather than perceived orientation of the adapting stimulus (Fukiage & Murakami, 2010).

In the present study, we first established that the FLE was observed with continuous size changes of surrounding stimuli. This was because no study has shown that the FLE occurs with size change (Experiment 1). Obtaining affirmative results (i.e., significant FLE with size change), we then proceeded to examine whether the Ebbinghaus illusion would depend more on the retinal or perceived size of the surrounding stimuli (Experiment 2).

2. Experiment 1: Does the Flash-lag effect occur in size perception?

2.1. Method

2.1.1. Participants

Twelve students at the University of New South Wales participated for course credit in Experiment 1 (4 males, age range between 18 and 25 years old). They were not informed of the purpose of the study and had normal or corrected-to-normal vision.

2.1.2. Stimuli

The stimuli were composed of a black fixation cross (0 cd/m^2, 0.33°), two sets of four grey surrounding disks (inducers; 60 cd/m^2, minimum 0.66° and maximum 7.37° in diameter), and two black central disks (targets; 0 cd/m^2, 4.01° in diameter). The distance from the edge of the central disks to the inner edge of each inducer was 0.64°.

2.1.3. Procedure

The stimuli were presented on a 32-inch Display++ LCD monitor (Cambridge Research Systems, Rochester, UK) with a frame rate of 120 Hz and the observation distance was kept at 57 cm by using a chinrest in the dark room. The experiment was done in an otherwise totally dark room where the sole light source was the computer display. On each trial, after the participant pressed the space key, the black fixation cross was presented at the center of the monitor for 500 ms on a white background (120 cd/m^2). Then, the two sets of the four inducers, one with small disks (0.66°) and the other with large disks (7.37°), appeared at the left and right side of the fixation. The large inducers shrunk, and the small inducers expanded by 0.37° every 50 ms for a duration of 950 ms, and then disappeared. The two identical central disks were presented simultaneously for 50 ms at the centers of the imaginary circles on which the inducers were positioned. These target disks appeared with temporal offsets of −250, −100, −50, 0, 50, 100, or 250 ms relative to the moment when the inducer disks were physically identical in size (coincidence time). 500 ms after the stimulus presentation, participants reported which of the two sets of inducers appeared larger at the moment when the central disks were presented by pressing the appropriate keys (Fig. 1). The next trial started immediately upon response. Before starting the experiment, participants practiced some trials until they became familiar with the task. For each combination of 2 inducer configurations (larger inducer on the left or right) and 7 target timings, 10 trials were repeated in a randomized order, resulting in 140 trials in total. A rest was taken in every 10 trials. The Human Research Ethics Committee (Panel C) of UNSW Sydney approved the procedure. We obtained written and informed consent before the experiment. The stimulus presentation and data analysis were done by using MATLAB (MathWorks, Inc.) with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997).

2.2. Results and discussion

For each participant, the proportion of trials on which the surrounding inducer disks changing from smaller to larger were reported

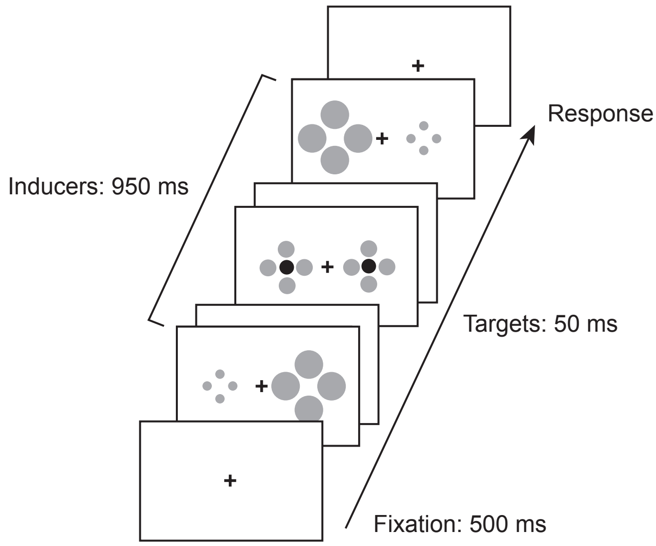

Fig. 1. Schematic example of event flow in one trial. The presentation of the fixation cross was followed by the small-to-large and large-to-small smooth changes of the surrounding disks. The two central disks were flashed simultaneously at a variable time. This figure represents a temporal offset of 0 ms. In Experiment 1, participants reported which of the two sets of the surrounding disks appeared larger at the moment when the central disks were presented (measuring the FLE for size change). In Experiment 2, participants reported which of the two central disks appeared larger (measuring the Ebbinghaus illusion) [see also Supplementary video 1].

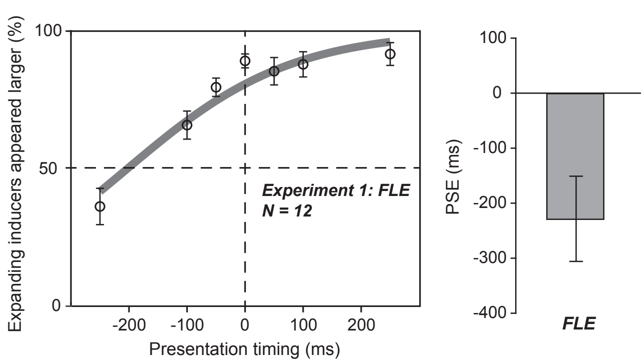

Fig. 2. Experiment 1 – The mean proportions of trials where the expanding surrounding disks changing from smaller to larger were judged as larger at the moment when the central target disks appeared, as a function of presentation time of the central target disks (left panel). The estimated PSE, corresponding to the FLE for size change (right panel). Error bars indicate standard errors of means (SE).

as larger was calculated for each presentation timing. We fitted a sigmoid function to the calculated proportions to estimate the point of subjective equality (PSE) where the surrounding inducers appeared equal in size by using custom software written in MATLAB (corresponding to the FLE for size change: Fig. 2 left panel). The averaged PSE was -228.40 ms (Fig. 2 right panel). This meant that, in order for the surrounding disks to be perceived as equal in size, the central disks must be presented almost 230 ms before the coincidence time. A one sample *t*-test revealed that the mean PSE was significantly smaller than zero [$t(11) = -2.95$, $p = .013$, $r = 0.66$]. Thus, the results of Experiment 1 clearly showed the FLE for size change. The magnitude of FLE has been known to depend on the stimulus feature changing. For the traditional FLE between flash and moving objects, it has been reported to be about 80–100 ms (e.g., Nijhawan, 1994). The magnitude of FLE observed in the present experiment was about 230 ms, which was closer to the magnitude found in FLE with color change (Sheth et al., 2000).

The results of Experiment 1 confirmed that for the smoothly changing surrounding disks to appear the same size, the central disks must be flashed almost 230 ms before the moment when the surrounding disks were physically equal in size (coincidence time). In other words, if the central disks are presented 230 ms before the coincidence time, the central disks should be perceived with surrounding disks of equal size, although the retinal sizes are different. On the other hand, if the central disks are presented at the coincidence time, they should be perceived as surrounded by inducer disks with different sizes, although the retinal sizes are the same. In the following experiment, by asking participants to judge the relative sizes of the two central disks with the stimuli identical to those in Experiment 1, we sought to examine whether the Ebbinghaus illusion would depend more on the retinal or perceived size of the surrounding inducers.

3. Experiment 2: Does the Ebbinghaus illusion depend more on the retinal or perceived size of the surrounding stimuli?

3.1. Method

3.1.1. Participants

Nineteen students at the University of New South Wales were newly recruited and participated for course credit in Experiment 2 (4 males, age range between 17 and 23 years old). They were not informed of the purpose of the study and had a normal or corrected-to-normal vision. None of the participants overlapped with those in Experiment 1.

3.1.2. Stimuli and procedure

The visual stimuli and stimulus sequence were identical to those of Experiment 1. However, in Experiment 2, participants reported which of the two central disks appeared larger by pressing the appropriate keys.

3.2. Results and discussion

For each participant, the proportion of trials on which the central disks surrounded by the shrinking inducers were reported as larger was calculated for each presentation timing. The calculated proportions were fitted with a sigmoid function to estimate the PSE where the central disks appeared equal in size (Fig. 3, left panel). The averaged PSE was -21.64 ms (Fig. 3, right panel) but this small effect did not reach significance [$t(18) = -0.99$, $p = .334$, $r = 0.23$]. Additionally, we performed a two sample *t*-test on the obtained PSEs between Experiment 1 and Experiment 2 and observed a significant difference between them [$t(29) = -3.09$, $p = .004$, $r = 0.50$].

If the modulation of the perceived size of the central disks depends on the perceived size of the surrounding inducers, the fitted function and estimated PSE should be similar to those obtained in Experiment 1.

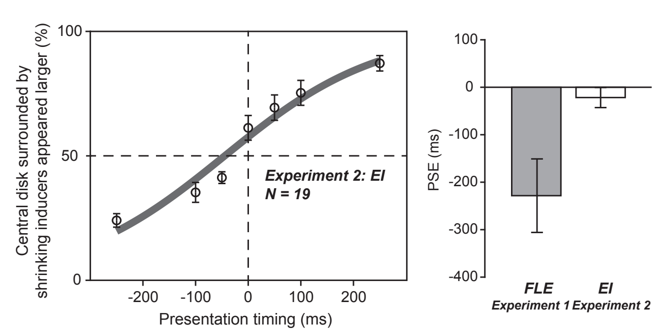

Fig. 3. Experiment 2 – Mean proportion of trials where the central target disk surrounded by the shrinking inducers appeared larger as a function of presentation time (left panel). The estimated PSE, corresponding to the Ebbinghaus illusion (EI) driven by the physical size of the surrounding stimuli (right panel). Error bars indicate standard errors of means (SE).

The results of Experiment 2 clearly showed otherwise and suggested that the modulation of the perceived size of the central disks depends more on the retinal size of the surrounding inducers.

4. General discussion

By using the flash-lag effect (FLE) to dissociate physical from perceived size, this study examined whether the Ebbinghaus illusion would depend on the retinal or perceived size of the surrounding inducers. We firstly confirmed the existence of a significant FLE for size perception (Experiment 1). In this experiment, the two sets of the surrounding disks changed their sizes in opposite ways and became identical at the coincidence time. When the central target disks were flashed almost 230 ms before the coincidence time, the central disks appeared to be surrounded by inducer disks of equal size despite the fact that the inducer disks were physically different. If the Ebbinghaus illusion depended more on the perceived size than the retinal size of the inducers, the illusion should disappear with this 230-ms timing difference but should still be observed at the physical coincidence time. However, the results of Experiment 2 clearly showed that the Ebbinghaus illusion followed the retinal size rather than the perceived size of the surrounding inducers (Fig. 3).

Recent studies have found that conscious perception of the surrounding stimuli is *not necessary* for the Ebbinghaus illusion to occur (Chen et al., 2018; Nakashima & Sugita, 2018). However, it has not been empirically demonstrated whether perception of a size difference between the surrounding inducers is *sufficient* to produce the Ebbinghaus illusion. The present study provided a condition where the Ebbinghaus illusion does not occur even when a size difference between the surrounding inducers is perceived. Thus, taken together with the findings from the previous studies, the present findings point to the possibility that conscious perception of a size difference between the surrounding stimuli is *neither necessary nor sufficient* for the Ebbinghaus illusion.

As mentioned in the introduction, the absence of a contribution from the conscious perception of the surrounding stimuli partially supports the contour interaction theory, one of the two major theories of the Ebbinghaus illusion (Chen et al., 2018; Jaeger, 1978; Jaeger & Grasso, 1993; Jaeger & Klahs, 2015; Roberts et al., 2005; Rose & Bressan, 2002; Sherman & Chouinard, 2016; Todorović & Jovanović, 2018; Weintraub, 1979; Weintraub & Schneck, 1986). This is because the contour interaction theory does not require computation and registration of the size of the surrounding stimuli. The classical size contrast theory, on the other hand, implicitly assumes the involvement of high-level inferential processes (Massaro & Anderson, 1971). At the least, the size contrast theory needs to be revised such that the size of surrounding stimuli is processed without reaching conscious awareness.

Nevertheless, the contour interaction theory does have limitations, too (see Rose & Bressan, 2002). For example, the Ebbinghaus illusion is highly dependent on the similarity between the central and surrounding stimuli (Coren & Miller, 1974) and cannot be explained solely by the presence of contours and some additional interaction processes proposed in the past studies (e.g., biphasic interaction model; Jaeger, 1978). Rose and Bressan (2002) conducted an experiment to compare predictions based on the size contrast theory (also termed the cognitive similarity account) and the contour interaction theory (also termed the spatiotopic contour interaction theory) by manipulating the central and surrounding shapes and concluded that none of the previously proposed theories could explain the pattern of data observed in their experiment. They conjectured that the distinction between sensory (e.g. contour) and cognitive (size contrast) processes may not be adequate for explaining the Ebbinghaus illusion because top-down influences exist at all levels of visual processing (e.g., Ahissar & Hochstein, 2000; Deco & Schürmann, 2000; Rose & Pardhan, 2000; Suder & Wörgötter, 2000). Then, although not conclusive, the size and/or contours of the central and surrounding stimuli all have the potential to influence the final perception of size, irrespective of whether they are consciously perceived or not. However, the present findings demonstrate that, if such top-down influence exists, it does not necessarily have to be in the form of conscious inferences.

Partially consistent with the notion above, it has been shown that the area of an individual's primary visual cortex is inversely related to the magnitude of the Ebbinghaus illusion and the Ponzo illusion that they report (Schwarzkopf, Song, & Rees, 2011). Additionally, changes in the perceived size of a visual stimulus by depth cues (Fang, Boyaci, Kersten, & Murray, 2008; Murray, Boyaci, & Kersten, 2006; Sperandio, Chouinard, & Goodale, 2012) and by size adaptation (Pooresmaeili, Arrighi, Biagi, & Morrone, 2013) correlate with activation in the primary visual cortex. Therefore, it is still possible that visual size is represented at a level as low as the primary visual cortex, but that contextual modulation goes on unconsciously.

Obviously not all optical illusions and contextual modulations of visual size are equivalent. For example, Grzeczkowski, Clarke, Francis, Mast, and Herzog (2017) examined various optical illusions and estimated correlations in their magnitudes. They found correlations only between the Ebbinghaus illusion and the “hallway” Ponzo illusion, where disks were presented at different positions so that they were perceived at different distances due to perspective cues, but not with Ponzo illusions with simple lines. Furthermore, Chen et al. (2018) showed that, while the Ebbinghaus illusion can be modulated with invisible context, the Ponzo illusion cannot. This implies that the mechanisms for the Ebbinghaus illusion and those for the Ponzo illusion are largely different, particularly in terms of the involvement of feedback projections from higher visual processes (Fang et al., 2008; Schwarzkopf et al., 2011; Song, Schwarzkopf, & Rees, 2011). It would be an interesting avenue of future research to dissociate the retinal from the perceived angle made by the lines in the Ponzo illusion using the FLE and to compare the results with the present findings on the Ebbinghaus illusion. It would also be interesting examine what the causes and consequences of the size modulation would be. For example, asking participants to judge the space between the central disks and the surrounding disks would clarify the relation between the perceived size of the central stimulus and the perceived distance between the central and surrounding stimuli. Size and distance may correlate highly with each other; e.g., for the identical physical distance, a smaller size would lead to larger distance. Or, size and distance may be estimated independently, which would result in inconsistencies between size and distance.

5. Conclusion

In the present study, we examined whether the Ebbinghaus illusion would depend on the retinal or perceived size of the surrounding stimuli and obtained results favoring the involvement of the retinal size. In conjunction with previous findings, the present results suggest that conscious perception of size difference in the surrounding stimuli is *neither necessary nor sufficient* for the Ebbinghaus illusion.

6. Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2018.10.010.

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