Studies on contextual modulation of quantity perception in vision

文脈情報による
視覚的数量知覚の変調に関する研究

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Waseda University
Graduate School of Fundamental Science and Engineering
Department of Intermedia Studies, Research on Cognitive Science

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CHAPTER I.

GENERAL INTRODUCTION

1.1 Quantity Perception in Vision

1.1.1 Number Sense and Others: Size, Space, Density, and Time

We can easily perceive numbers of objects and observe their sizes. We can also estimate the width of the space in front of us and sense the passage of time. These quantities are different in the physical and mathematical senses. However, they also seem to be related each other. Large numbers, large objects, and wide spaces are all related to the concept of “more” and small numbers, small objects, and narrow spaces are all related to the concept of “less.” This conjecture has been supported by several studies showing the shared processes for perceiving these quantities (e.g., Ono & Kawahara, 2007; Walsh, 2003; Zimmerman & Fink, 2016).

Perceptions of quantities appear to happen instantaneously. Consider, for example, approximate numerosity estimation. Our visual system has a special ability to promptly and accurately judge the number of objects up to four without serial counting. This is called the subitizing range. When the number of objects exceeds this range, number estimation becomes a slower serial process with more errors for larger numbers (Jevons, 1871; Kaufman, Lord, Reese, & Volkmann, 1949). Animals other than humans have been shown to possess this ability as well (Dehaene, 2011) even though they do not have verbal representations of numbers. The quick perception of numerosity has provided us clear benefits in the evolutional process, allowing us to make accurate decisions in important scenarios such as when hunting for food or escaping from enemies. While many studies in a wide range of research fields have investigated numerosity perception, the mechanisms of numerosity perception remain subjects of intensive debate.

The most important and unsolved issue in numerosity perception or number sense is whether numerosity perception is independent from perceptions of other visual features. Numerosity is complicatedly associated with other physical features. For instance, it changes not only with the numerosity of objects but also with the density of the objects in designated spaces; having more objects in a limited space decreases the space between objects.

1.1.2 Studies Supporting Independency: Numerosity Perception is Independent from Other Visual Processes

Dehaene proposed the concept of "Number Sense" to explain the innate ability to approximately judge numbers of objects. He claimed with evidence that it already inheres in children and is fundamental for mathematical understanding (Dehaene, 1997; 2001). Given the apparent importance of understanding and reacting to different numbers of visual objects (natural enemy, foods, etc.), being equipped with a numerical representation of events or things in our brain is evidently quite beneficial (Gallistel, 1990).

Psychophysical studies have also supported the notion that numerosity perception in vision involves independent processes by showing that it occurs at a relatively early level of visual processing. Numerosity perception or number sense is strongly susceptible to adaption. Observing a visual stimulus for a few seconds causes a bias in the numerosity perception of a subsequent stimulus (Clifford & Rhodes, 2005; Thompson & Burr, 2009). For instance, in an experiment that asked participants to adapt to dot clouds with more or fewer elements and then, after a certain temporal interval, view another set of the dots, Burr and Ross (2008) observed a strong negative aftereffect. That is, participants perceived fewer dots in dot clouds after adapting to dot clouds with more elements and, correspondingly, they perceived more dots after adapting to dot clouds with fewer elements. By examining the adaptation pattern effect, the researchers found that numerosity perception follows a pattern approximated by Weber's law (Anobile, Cicchini, & Burr, 2014), which predicts a linear relationship between the threshold and the number of objects and represents an early sensory process.

1.1.3 Studies Against Independency: Numerosity Perception Depends on Other Visual Processes

On the other hand, another group of studies has generated findings that contradict the independency of numerosity perception. Durgin and colleagues (2008; 2011) investigated the adaptation effects by manipulating the number of dots and the area size to control numerosity, density, and the area size of the dots. They found that, even when the numbers of dots were identical, perceived density and area size affected adaptation in numerosity perception. Based on these findings, they proposed that both area size and the density of dot clouds interact with numerosity perception.

In addition to psychophysical evidence, theoretical and empirical studies in cognitive psychology have also shown that numerosity perception interacts with other visual processes. Seeking to explain the associations among different quantity estimates, Walsh (2003) proposed a general theory stating that humans process time, space, numbers, and other quantities using a common metric (A Theory of Magnitude; AToM). Starting as early as 1890, studies have documented the relationships between time and numbers, time and space, and space and quantities (for a review see Walsh & Pasual-Leone, 2003). In a neural study, Critchley (1953) found overlap in the putative neural mechanisms in the parietal cortex for time, space, size and number. Furthermore, these associations have also been observed in non-human species (Brannon & Roitman, 2003).

Cognitive psychological studies have accumulated evidence for a linkage between perceptions of time and space. One example is the distance effect—that it is easier to compare two numbers when they are numerically different (Moyer & Landauer, 1967). Another example is related to the so-called "mental number line," where numbers are placed along the mental representation of a line, with smaller numbers on the left and larger numbers on the right. Behaviorally, this immanent association between space and number can be demonstrated as the spatial-numerical association of the response code (SNARC) effect. People are likely to respond faster when shown a larger number on the right side and a smaller number on the left side in odd-even judgment tasks. The putative associations between small numbers and leftward space and large numbers and rightward space in mental representations explains this effect (Dahaene, Bossini, & Giraux, 1993; Fias, 1996).

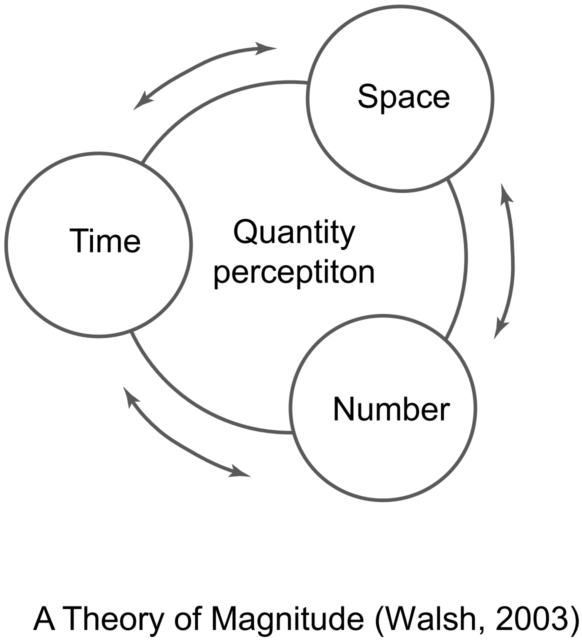

FIGURE 1.1 A THEORY OF MAGNITUDE

1.1.4 Eclectic Studies

Still, no consensus has been reached regarding whether numerosity perception is independent of or dependent on other visual processes. A series of recent studies have suggested that it may depend on the range of numbers of objects (e.g., Ross & Burr, 2010; Tokita & Ishiguchi, 2010). It has been suggested that there are three regimes for numerosity perception: subitizing (up to 4), numerosity estimation (between about 5 to 99), and texture-density perception (about over 100). For these regimes, the qualitative impressions of perception and the processes of determining thresholds differ. For instance, a discrimination threshold follows Weber's law in the regime of numerosity estimation but decreases with the square-root law in the regime of texture-density perception. In addition, the point of transition where numerosity estimation changes to texture-density perception depends on viewing eccentricity (i.e., whether a stimulus is presented in the fovea or the peripheral visual field; Anobile, Cicchini & Burr, 2016; Burr, Anobile & Arrighi, 2018).

1.1.5 Adaptation Paradigm and Methodological Issues

Some recent studies have adopted the adaptation paradigm, which is effective for examining processing levels and the dependence/independence of one process on/from others. One of these studies investigated the effect of size adaptation on number perception using the adaptation paradigm and generated results that affirmed the interdependency between size perception and numerosity perception (Zimmerman & Fink, 2016). In the context of the debate outlined above, this is a highly significant finding. Nevertheless, the adaptation paradigms do have methodological issues.

In a typical adaptation paradigm, a preceding (adapting) stimulus overlaps a test stimulus on the retinal coordinate. Therefore, the possibility of interference caused by residual signals on the peripheral sensory organs always remains. Moreover, while adaptation phenomena emphasize the dynamic and temporal aspects of vision, using adaptation to examine underlying mechanisms of perception always risks contamination with memory components, which are not favorable in examinations where processes for particular perceptions are based on independent processes.

1.2 Examining Quantity Perception with the Spatial Contextual Effect

1.2.1 Contextual Dependency in Vision: Temporal and Spatial

Vision is highly context dependent. Lights hitting the retina alone do not determine what we see. Our perceptions depend on what the brain has received so far and what the brain possesses. Adaptation is one example of temporal context dependency and can be considered a successive contrast effect.

Another type of context dependency in vision is spatial context dependency, where the perception of a certain feature is modulated by nearby or surrounding context. Many geometrical illusions, where conscious perceptions differ from physical realities, are based on context dependency in the spatial domain. Take size illusions as an example: visual objects look larger when placed in configurations that make them appear to be in distant locations than when placed to in configurations that make them appear to be in closer locations (Ponzo illusion; Ponzo, 1913: FIG 1.3). In the Delboeuf illusion, a circle closely surrounded by an annulus appears larger than a solitary circle even though the two circles are physically identical (Delboeuf, 1865; FIG 1.4). One of the most powerful and well-known geometrical illusions is the Ebbinghaus illusion, where a circle surrounded by smaller circles appears larger than the same circle surrounded by larger circles (Ebbinghaus, 1901; Titchener, 1902: FIG 1.5); the Ebbinghaus illusion can be considered a simultaneous contrast effect.

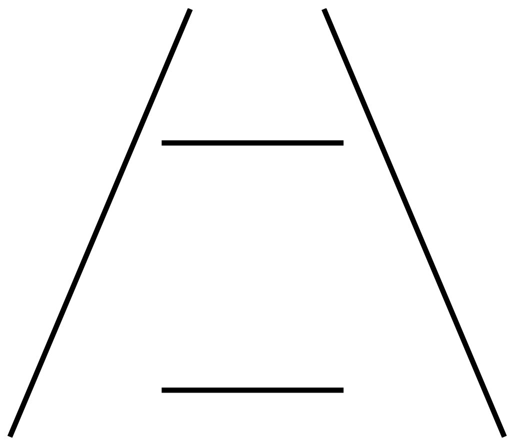

FIGURE 1.2   PONZO ILLUSION

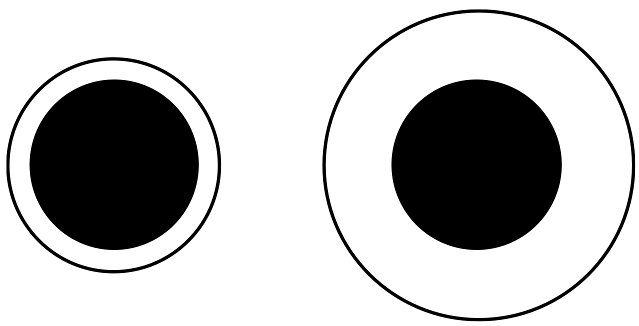

FIGURE 1.3   DELBOEUF ILLUSION

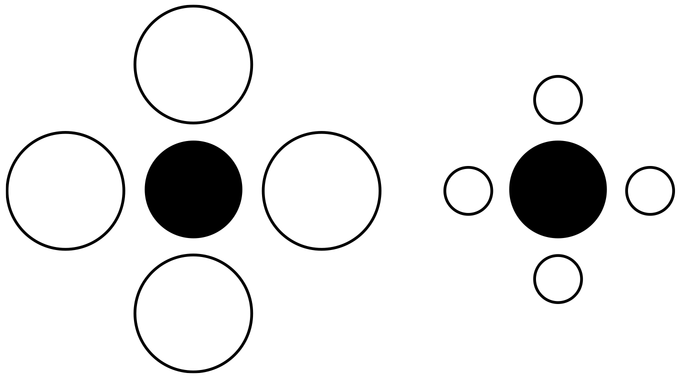

FIGURE 1.4 EBBINGHAUS ILLUSION

1.2.2 Using the Ebbinghaus Illusion to Examine Numerosity Perception

Simultaneous contrasts (or spatial context dependency) are much less susceptible to the memory components that exist for successive contrasts in large part because contextual stimuli do not overlap the tested stimulus. Inspired by this particular characteristic of simultaneous contrast effects, we examined numerosity perception using the Ebbinghaus illusion, which enabled us to avoid the methodological issues mentioned above.

In the first set of experiments, we examined whether the stimulus configuration that leads to the Ebbinghaus illusion would also change the perception of numerosity while carefully controlling the density and spatial extension of the test stimulus (Chapter II). As detailed in the next chapter, we found that the Ebbinghaus illusion changed numerosity perceptions as well as spatial extension perceptions, supporting the notion that numerosity perception and size perception are interdependent processes.

1.2.3 Dynamic Modulations of Size Perception and Numerosity Perception

After generating results that affirmed interdependency in the experiments described in Chapter II, we explored the dynamic aspects of the modulation of size and numerosity perceptions. That is, we sought to answer the following questions: how precisely should the modulating stimuli be synchronized with a test stimulus to elicit modulations? If this does not require precise synchronization, what would the temporal window for the modulations be? Would the sign of modulation (i.e., contrast versus assimilation) always be the same?

The above questions have rarely, if ever, been examined. The stimulus configuration of the Ebbinghaus illusion is ideal for this investigation. We used a series of experiments to examine the temporal aspects of the modulation of size and numerosity perceptions (Chapter III) and identified several important and novel characteristics of contextual modulations, including non-linear temporal dependency and the unexpected finding of predictive-contrast and a retrospective assimilation pattern.

After revealing the association between size and numerosity perceptions (Chapter II) and the temporal characteristics of contextual modulations (Chapter III), we examined the visual processing levels in the brain. Since we knew from the experiments described in Chapter III that there were temporal windows within which the contextual modulation was maximized, we were able to examine whether contextual modulation would depend on retinal or perceived timing (Chapter IV). To accomplish this, we utilized the flash-lag effect, where a suddenly appearing stimulus perceptually lags smoothly changing stimuli and dissociates the retinal versus perceived relative timings between the target stimulus and modulating stimuli. The results indicated that the contextual modulations depended more on the retinal timing than the perceived timing between a target stimulus and contextual stimuli, suggesting that contextual modulation may involve rather low-level visual processing.

1.3 Structure of the Thesis

This thesis consists of five chapters. Chapter I (this chapter) provides a general overview of the current state of investigations of quantity perception and points out that some methodological issues related to dependency/independency of numerosity perception would be avoided by using the stimulus configuration of the Ebbinghaus illusion. Chapter II reports the findings of experiments based on the above experimental design, highlighting the inherent relationship between quantity perceptions (in particular between size and numerosity) and thus supporting AToM. Chapters III and IV describe the experiments we used to explore the temporal characteristics of contextual modulations and report our novel findings. Finally, Chapter V summarizes the findings of our experiments, describes their theoretical implications, and discusses directions for future research.

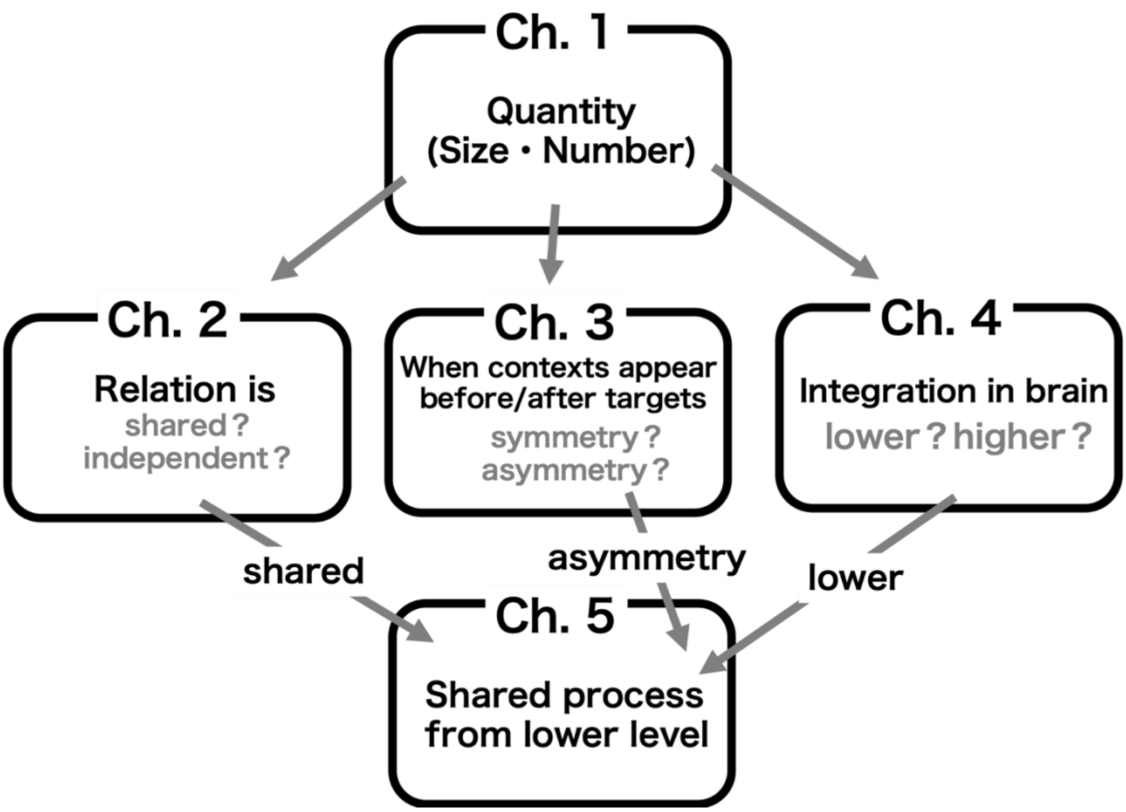

FIGURE 1.5　OVERVIEW OF THIS STUDY

CHAPTER II.

THE EBBINGHAUS ILLUSION CHANGES QUANTITY PERCEPTION

2.1 Introduction of Chapter II

Recently, Zimmerman and Fink (2016) investigated the effect of size adaptation on number perception using visual adaptation. Visual adaptation, where exposure to strong stimuli under normalization temporarily changes sensitivity or perception in the neural coding processing of the visual system, is often used in psychophysics research. It is novel way to examine the links between different quantities. In their experiment, participants reported their quantity perceptions (e.g., size, number, and density) regarding the displayed dots, which varied from 4 to 100 dots, after observing a circle-shaped patch for 5 seconds. For size judgment, the large patch decreased the perceived size but not differently between the number of dots. As with the size judgment, the large patch decreased the perceived number of dots and it was stronger as the number of dots increased for number judgment. However, the density judgments remained constant around zero for all numbers. These results indicate that number perception increased logarithmically with the presented number of dots in the patches. They also indicate that people make size and density judgments independently although size information influences number judgment. In other words, the link between size and number judgments exists independent of density judgment.

However, two potential methodological problems in the study's visual adaptation task may have led to this conclusion: (1) temporal delay between the observations of adaptors and the test stimulus; and (2) physical overlap between adaptors and the test stimulus in location. Given these potential problems, the results may have involved memory processing and image aftereffects.

2.2 Experiment 1: Control for Subjective Density

An examination of density still has been under argument as the previous studies suggested, although maintaining constant density in the experiments is crucial to investigating the relationship between size and number without texture-density processing. Therefore, we aimed to control subjective density by measuring subjective density along with the area size of the dots in Experiment 1.

2.2.1 Methods

Participants

Fourteen university students (nine men, aged between 18-25 years) with normal or corrected-to-normal visual acuity participated in Experiment 1. They were naive to the purpose of the experiment.

Stimuli

The stimuli included a black fixation cross (0 cd/m$_2$, 0.81°), a white background (120 cd/m$_2$), and black dots (63 cd/m$_2$, 0.53°).

Procedure

All stimuli were presented on an LCD monitor (23-inch, 60 Hz) with a viewing distance of 57.5 cm maintained by a chin rest. Participants initiated a trial by pressing the space key. At the beginning of each trial, a black fixation cross was presented at the center of the display on the white background for 500 ms. Then, two set of the dots with different area sizes were presented on the left and right sides of the fixation for 200 ms. One was always 10 dots with an area size of 2.16° as reference stimulus. The other one as between a 4.85° maximum or 0.59° to 1.57° minimum area size, depending on the number of dots from 4 to 16 in the test stimulus. After 500 ms, participants reported which area had a higher dot density by pressing appropriate keys.

Experimental Design

Seven number of dots in reference stimulus (4, 6, 8, 10, 12, 14 or 16), 2 starting stimulus strength of test stimulus (ascending series or descending series), repeated 4 times of 10 reverses in each starting stimulus strength of each number of dots, 480 sessions in total ($7 \times 2 \times 4 \times 10$). Participants were free to rest between the sessions. The ethics committee of Waseda University approved the experiment.

Adaptive Staircase Method

In this experiment, we used an adaptive staircase method where stimuli were modulated by participant responses. We arranged 1 step of stimulus strength to change 50% of the last step either up or down corresponding to the same response in the last response up to three times (i.e., the minimum step was 6.25 % of the standard stimulus). When participant responses reversed ten times, the point of subjective equality (PSE) to the reference stimulus was determined. For the sake of accuracy, we repeated each condition four times.

2.2.2 Results and Discussion

We obtained the mean PSEs of the four repetitions for each number of dots for each participant. The data for two participants did not converge and we therefore excluded them from the subsequent analysis. We then calculated the least square regression lines using the following formula.

$$y - \bar{y} = \frac{\sigma_{xy}}{\sigma_x^2}(x - \bar{x})$$

We also used the obtained formula (shown below) in the subsequent experiments to calculate the area size of the dots over the number of dots for constant subjective density.

$$y = 2.70x + 50.91$$

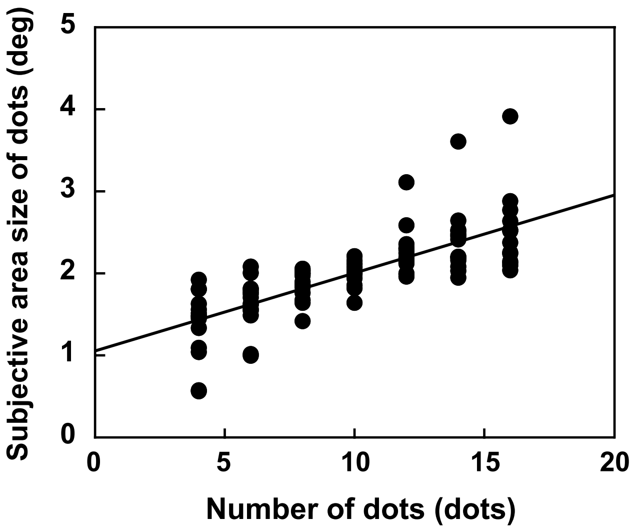

FIGURE 2.1 RESULTS OF EXPERIMENT 1

2.3 Experiment 2: The Ebbinghaus Illusion Changes Numerosity Perception

Using the obtained formula in Experiment 1 to dissociate numerosity perception from texture-density processing, we examined the relationship between size and number in Experiment 2. To avoid the effects of memory processing and aftereffects, we used a size perception visual illusion—the Ebbinghaus illusion in which a circle surrounded by smaller circles appears larger than a circle surrounded by larger circles (Ebbinghaus, 1901; Tichener, 1901). We replaced the central circle with dots for the numerosity judgment in Experiment 2.

2.3.1 Methods

Participants

Sixteen university students (six men, aged between 18 and 27 years) with normal or corrected-to-normal visual acuity participated in Experiment 2. They were naive to the purpose of the experiment.

Stimuli

The stimuli included a black fixation cross (0 cd/m$_2$, 0.81°), a white background (120 cd/m$_2$), two sets of four grey surrounding circles (inducers; 46 cd/m$_2$; 1.48° for small, 3.17° for middle, and 4.86° for large), and orange dots (63 cd/m$_2$, 0.53°).

Procedure

All stimuli were presented on an LCD monitor (23-inch, 60 Hz) with a viewing distance of 57.5 cm maintained by a chin rest. Participants initiated a trial by pressing the space key. At the beginning of each trial, a black fixation cross was presented at the center of the display on a white background for 500 ms. Subsequently, the two sets of inducers were presented on the left and right sides of the fixation for 600 ms with a distance of 0.1° from the edge of the inducers to the edge of the targets. Each set consisted of four identical grey disks. In the experimental condition, one small inducer and one large inducer were presented. In the control condition, two middle inducers were presented. Orange dots appeared in the areas inside the inducers 200 ms after the onset of the inducers and remained for 200 ms. The number of dots (6, 8, 10, 12, or 14) was selected independently for each side. The size of the dot areas was manipulated between 1.81-2.39° in diameter, depending on the preliminary experiment (Experiment 1). Participants reported which area contained the larger number of dots by pressing the appropriate keys. Based on calculations using the formula obtained in Experiment 1, we ensured that the subjective density was identical for all dot condition numbers. We conducted the stimulus presentation and data analysis using MATLAB (MathWorks, Inc.) with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Participants were free to rest after every 10 trials. The ethics committee of Waseda University approved the experiment.

Experiment Design

Each combination of the numbers of dots in the left (5) and the right (5) areas as well as the two inducer conditions (left large, right large) was repeated for 10 trials as the experimental condition. In addition, the condition without combinations where the numbers of dots on the left and the right were identical was repeated for 4 trials as the control condition, resulting in a total of 660 trials ($5 \times 5 \times 2 \times 10 + 4 \times 5 \times 2 \times 4$). We randomized all the trials.

Data Analysis

We calculated the correct rate of the trials for each participant in the control condition where the two identically sized inducers appeared with different numbers of dots. We used a logistic function to fit the proportion of reporting that the area surrounded by the smaller inducers contained a larger number of dots compared to the area surrounded by the large inducers. We calculated the PSE for each number of dots reported by each participant and subtracted it from the base number to compute the PSE shifts. A PSE shift indicates how many dots need to be subtracted in the area surrounded by the smaller inducer given the dot number in the area surrounded by the larger inducer. A positive value indicates that the number of dots in the area surrounded by the smaller (larger) inducers appeared larger (smaller) than the area surrounded by the larger (smaller) inducers. We also converted the PSE shifts into PSE shift ratios by dividing the PSE shifts by the base number.

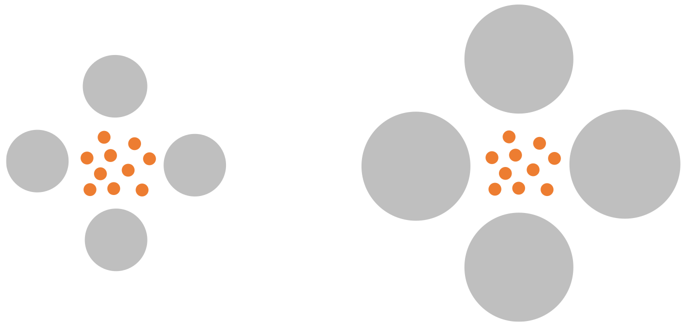

FIGURE 2.2 STIMULI CONFIGURATION OF EXPERIMENT 2

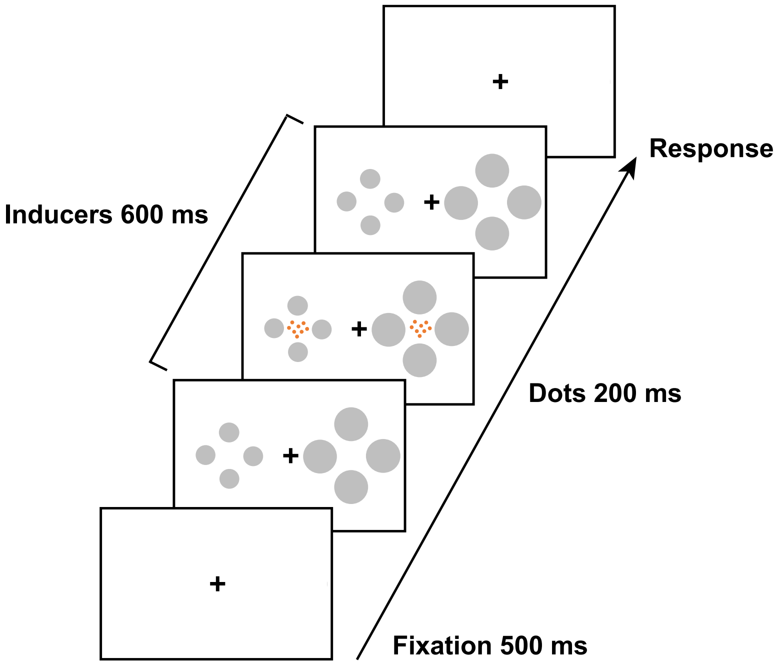

FIGURE 2.3 SCHEMATIC EVENT FLOW OF EXPERIMENT 2

2.3.2 Results and Discussion

On average in the control condition, participants were correct in 77.73 $\pm$ 8.19 % of the trials. We did not exclude any participants based on accuracy.

The PSE shift ratios were all positive; namely, participants perceived the numerosity of dots surrounded by the smaller (larger) inducers as larger (smaller). To confirm the effect statistically, we compared the PSE shift ratios against zero and they were all significantly different [base area size = 4 dots: $t(15) = 2.74$, $p = .015$, $r = .58$; 6 dots: $t(15) = 3.72$, $p = .002$, $r = .69$; 8 dots: $t(15) = 4.20$, $p < .001$, $r = .74$; 10 dots: $t(15) = 3.79$, $p = .002$, $r = .70$; 12 dots: $t(15) = 2.41$, $p = .029$, $r = .53$]. We conducted a one-way analysis of variance (ANOVA) within-participant factor and found no significant difference [$F(4, 60) = 0.48$, $p = .753$, $\eta_{p2} = .03$].

The results of Experiment 2 showed that the spatial configuration that would produce the Ebbinghaus illusion also affected numerosity perception. Together with the previous findings of a successive contrast effect (Zimmermann & Fink, 2016), the present results further confirm that size and numerosity perception might interact significantly and may be processed via shared mechanisms.

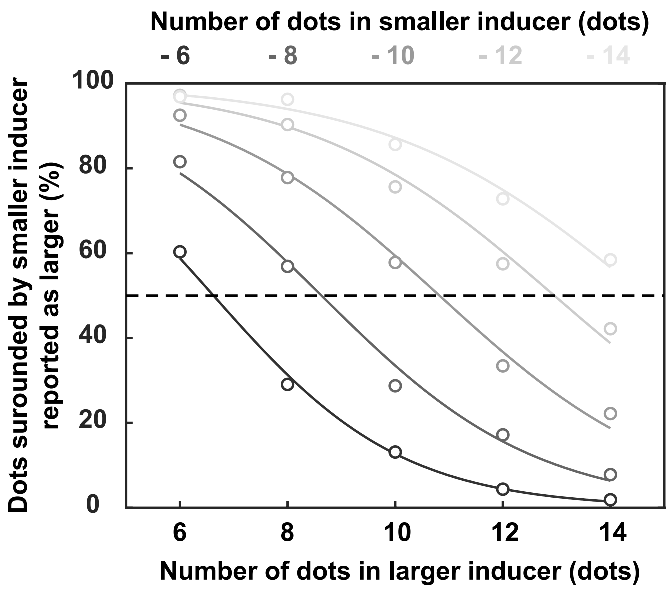

FIGURE 2.4 RESULTS OF EXPERIMENT 2

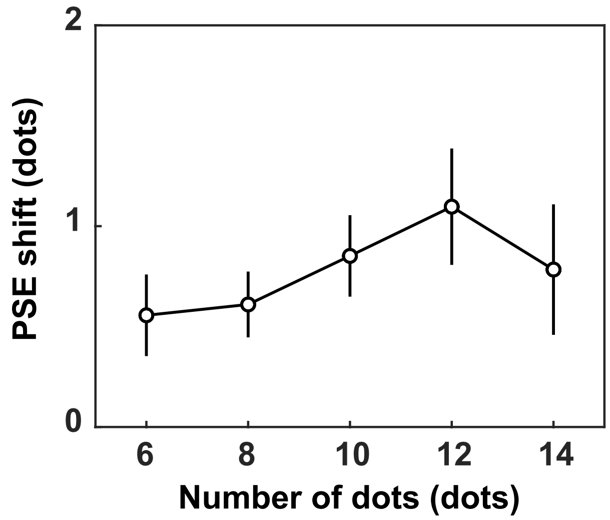

FIGURE 2.5 RESULTS OF EXPERIMENT 2

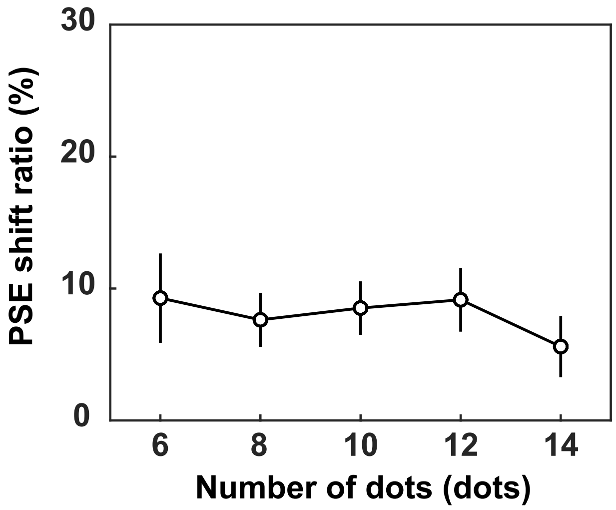

FIGURE 2.6 RESULTS OF EXPERIMENT 2

2.4 Experiment 3: Ebbinghaus Illusion Changes Spatial Extent of Area

In Experiment 2, we found a significant correlation between size and number using the Ebbinghaus illusion to avoid texture-density processing. If the subjective density in Experiment 2 was definitely constant, the area size of the dots should have increased along with the perceptual shifts in numerosity judgment. We also examined whether or not the area size of the central dots increased in Experiment 3.

2.4.1 Methods

Participants

Sixteen new paid volunteers (9 men, aged between 18 and 27 years) with normal or corrected-to-normal visual acuity participated in Experiment 3. They were naive to the purpose of the experiment.

Stimuli, Procedure, and Data Analysis

The stimuli, procedure, and data analysis were identical to those in Experiment 2. However, the task for participants was to judge which area of dots appeared larger.

2.4.2 Results and Discussion

On average, participants were correct in 83.67 ± 4.99 % of the trials. We did not exclude any participants based on accuracy.

Positive PSE shift ratio values showed that participants perceived the area size of the dots surrounded by the smaller (larger) inducers as larger (smaller). We performed one sample *t*-test for the PSE shift ratios against zero, which showed a significant difference from the physical number of the dots [base area size = 1.81°: $t(15) = 4.91$, $p < .001$, $r = .79$; 1.96°: $t(15) = 5.35$, $p < .001$, $r = .81$; 2.25°: $t(15) = 4.42$, $p < .001$, $r = .75$; 2.39°: $t(15) = 2.22$, $p = .042$, $r = .50$] but marginally for 2.10° [$t(15) = 2.13$, $p = .051$, $r = .48$]. We also performed a one-way ANOVA for the PSE shift ratios with the base number as a within-participant factor and found no significant difference [$F(4, 60) = 0.48$, $p = .747$, $\eta_{p2} = .03$].

The simple geometric prediction based on the numerosity perception results from Experiment 2 was that the size of the area would become larger with the smaller inducers because participants would perceive the density as constant. Consistent with the geometrical prediction, the perceived area size of the dots surrounded by smaller inducers increased in concert with the increase in numerical judgment. Therefore, the increase in perceptual numerosity in Experiment 2 was not due to density.

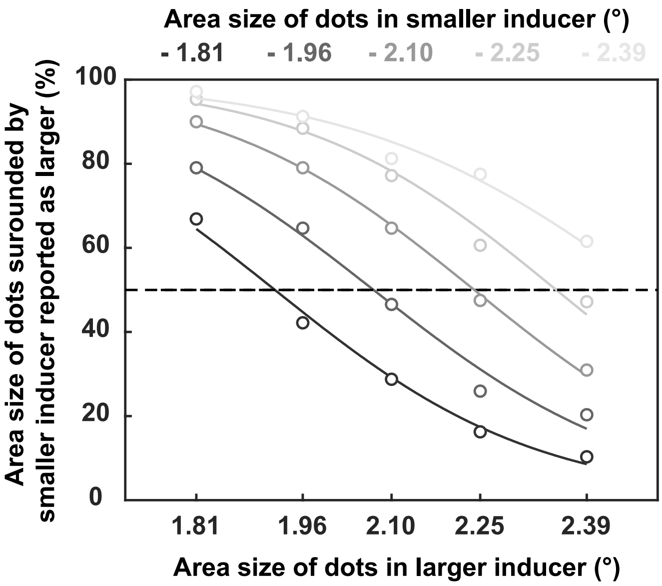

FIGURE 2.7 RESULTS OF EXPERIMENT 2

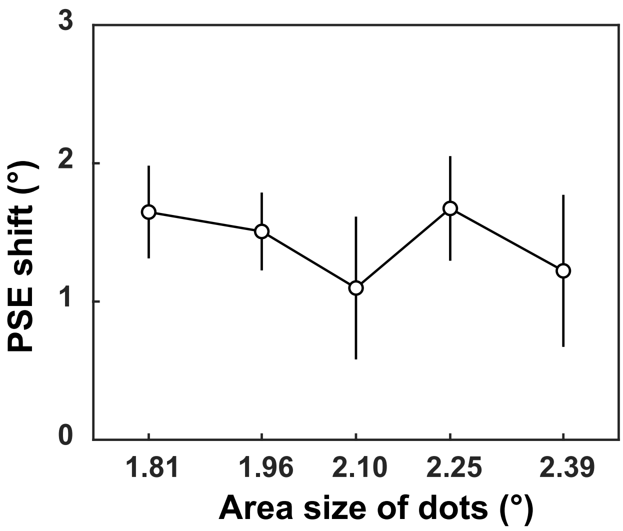

FIGURE 2.8 RESULTS OF EXPERIMENT 2

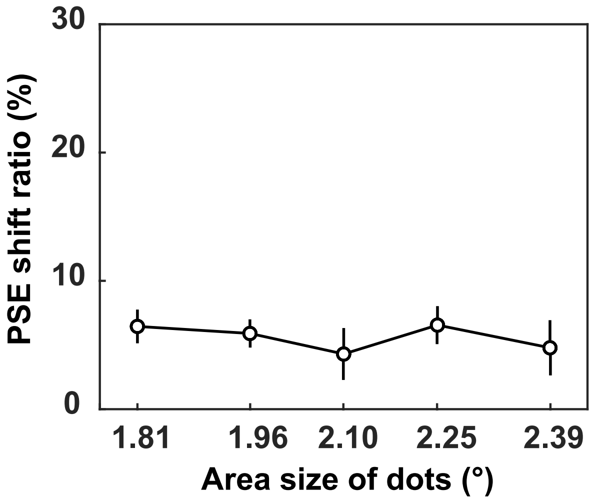

FIGURE 2.9 RESULTS OF EXPERIMENT 2

2.5 Summary of Chapter II

In Chapter II, we examined that the relationships between size and number/space using the Ebbinghaus illusion under constant subjective density. First, we measured the subjective density by manipulating the area size of the dots for each number of dots in Experiment 1. The numerosity judgment results using the obtained formula showed that participants perceived the dots surrounded by smaller inducers as more numerous than the dots surrounded by larger inducers. We asked the participants to judge the area size of the dots in Experiment 3 to confirm the results in Experiment 2 and found that the perceived area size of the dots also increased as the number of the dots increased.

These findings suggest that the processes for number, density, and spatial extension might overlap at least partially in the range tested in the present study and support the notion that the visual processes for quantities such as size, time, and space have shared mechanisms (Walsh, 2003).

CHAPTER III.

TEMPORAL CHARACTERISTIC OF

MODULATON OF QUANTITY PERCEPTION

3.1 Introduction of Chapter III

Jaeger and Pollack (1977) used cards to manipulate brightness and the presentation of stimuli in the Ebbinghaus illusion. In manipulating the brightness of the stimuli, they separately colored the surrounding circles and the central circles black or grey. For the overestimated illusion, where smaller circles surround a circle, they used eight circles as the surrounding stimuli. They presented four circles as surrounding stimuli in the underestimated illusion using a three-channel tachistoscope (Scientific Prototype, Model GB), where larger circles surrounded a circle. They successively presented the surrounding circles and then the central circle. While the successive presentation decreased overestimation of the illusion, it significantly increased the underestimation of the illusion. The effect of brightness on the Ebbinghaus illusion was confirmed only in the simultaneous presentation. In short, the magnitude of the Ebbinghaus illusion tended to be smaller in the successive presentation. However, duration or presentation timing of the stimuli has not been clear as it was difficult to control them with technical problem at their age.

Kreutzer, Weidner and Fink (2015) further compared adaptation effects between the physical and perceived size of the adaptor on behavioral and neural measurement. In the experiment, the small or large adaptor circle was presented for 5 seconds. For manipulation of perceived size of the adaptor, they used the surrounding circles of the Ebbinghaus illusion. After a variable interstimulus interval (ISI), test circles appeared in peripheral vision for 200 ms. Compared with the no adaptor condition for the physical or perceived size of the adaptor, participants perceived the test circle as larger with the small adaptor but smaller with the large adaptor for both physical and perceived adaptor size.

Recently, Nakashima and Sugita (2018) also examined the magnitude of the Ebbinghaus illusion in a successive presentation-based preliminary experiment. To confirm whether continuous flash suppression (CFS)—a psychophysical method—is suitable for the Ebbinghaus illusion, they presented the surrounding circle of the Ebbinghaus illusion before the central circle for 100, 300, or 500-ms. The PSE seemed to decrease as the ISI increased although the study did not statistically confirm this because doing so was beyond the study's purpose.

Together, the above studies suggest that the magnitude of the Ebbinghaus illusion may vary based on the presentation duration of the surrounding circles and the central circles. That is, our visual system may change as time passes, as we predicted. Therefore, we examined the impact of temporal characteristics (e.g., varying the timing between inducers and targets, and the case of subsequent inducers) on visual perception in detail in Chapter III.

3.2 Experiment 1: Temporal Tuning of Contextual Modulation of the Size-Size Interaction

We set out to determine the temporal tuning of the Ebbinghaus illusion in the size-size interaction using the successive presentation of inducers and the target in Experiment 1.

3.2.1 Methods

Participants

Twenty-eight paid volunteers (15 males, aged between 18 and 31 years) participated in Experiment 1. The participants were naïve to the purpose of the study.

Stimuli

The visual stimuli consisted of a black fixation cross (0.81°; 2 cd/m2), two types of grey inducer circles (60 cd/m2), and two orange target circles (130 cd/m2). Stimuli were presented on a white background (260 cd/m2). The target's color was set as orange to ensure that it was distinct from the inducers. The distance between the fixation cross and the center of target circles was 8.12° to provide enough space for the inducers to appear without overlapping (e.g., Saneyoshi, 2018). One inducer was composed of 8 circles (small inducers; 1.48° each) on the concyclic points with equidistance. The other was composed of 4 circles (large inducers; 4.86° each). The size of the central circle was identical in most trials (3.17°); however, in the catch trials, one was 2.97° and the other was 3.37°. The space between the central circles and each inducer circle was 0.36°.

Procedure

Participants observed the visual stimuli on a 23-inch LCD monitor (60 Hz). The observation distance was 57.5 cm. The fixation cross appeared and remained throughout the experiment. After a 1000 ms fixation period, either the two target circles or the two sets of inducers (one small and the other large) were presented on the left and right sides of the fixation cross for 50 ms, depending on the positive-negative of SOA. We randomized the sides of the inducers. For each trial, an SOA from target onset to inducer onset was selected pseudo-randomly from the following values: -3200, -1600, -800, -400, -200, -100, -50, 0, 50, 100, 200, 400, 800, or 1600 ms. After 500-ms, the last stimuli disappeared. The participants then reported which of the two target circles they perceived as larger by pressing the pre-assigned keys. For each combination of two inducer configurations (large inducer at left or right) and 14 SOAs, 10 trials were repeated as experimental trials ($2 \times 14 \times 10 = 280$ trials) and 2 trials as catch trials ($2 \times 14 \times 2 = 56$ trials), resulting in 336 trials in total. The trials were all counterbalanced. Subsequent trials started when participants responded. Participants were free to take breaks at any point during the experiment by withholding their responses and they were forced to rest every 36 trials. The internal review board of Waseda University approved the procedure. All participants provided written and informed consent before the experiment.

Data Analysis

For the catch trials, we calculated the percentage correct for each participant. If a participant's overall percentage correct in the catch trials was less than 60%, we excluded the participant from the analysis. For the experimental trials, we calculated the illusion effect as the rate at which the target with the small inducers was reported as appearing larger; that is, an effect of more than 50% indicated a size contrast effect and an effect of less than 50% indicated a size assimilation effect.

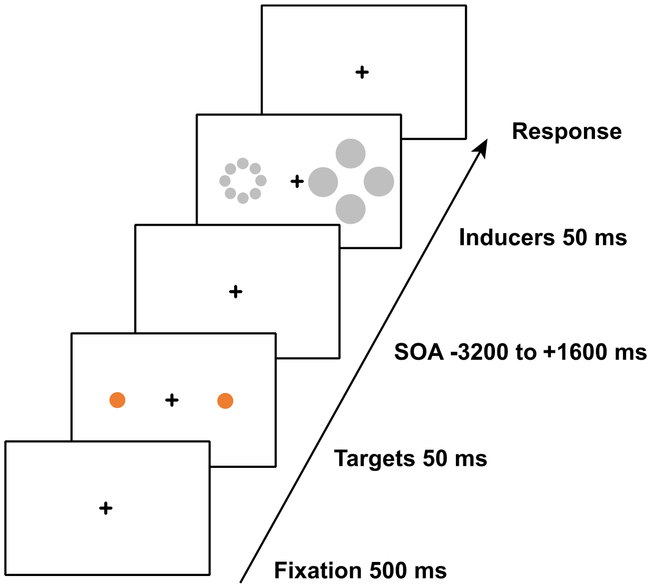

FIGURE 3.1 SCHEMATIC EVENT FLOW OF EXPERIMENT 1

3.2.2 Results and Discussion

One participant had a correct response accuracy rate of less than 70% in the catch trials and was therefore excluded from analysis. We observed the size contrast effect, where the central circles appeared larger (smaller) with smaller (larger) inducers, when the inducers preceded the target (negative SOAs); however, with the small positive SOAs where the inducers followed the target, we observed the size assimilation effect (i.e., the central circles appearing larger (smaller) with larger (smaller) inducers).

A one-way repeated measures ANOVA indicated that SOA had a statistically significant main effect [$F(13, 338) = 54.96$, $p < .001$, $\eta_{p2} = 0.68$]. At each SOA, we conducted a one-sample *t*-test against the chance level (50%) with Bonferroni correction for multiple comparisons (α = 0.05). We observed a significant size contrast effect for SOAs -1600 to 0 ms. The size assimilation effect was statistically significant for the SOAs +50 to +400 ms. The effect did not reach statistical significance with the SOAs -3200, +800 to +1600 ms.

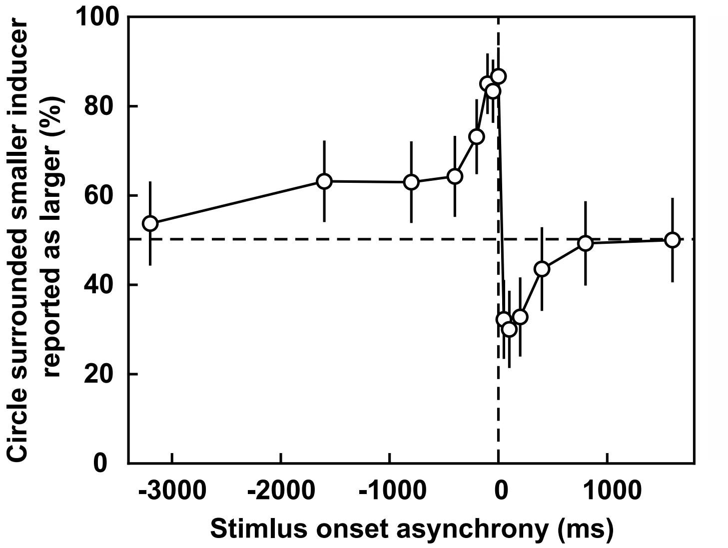

FIGURE 3.2   RESULTS OF EXPERIMENT 1

TABLE 3.1

SOA (ms)	*t*	*p*	*r*
-3200	1.247	> 0.999	0.238
-1600	4.208	0.008	0.637
-800	3.905	0.002	0.608
-400	4.334	< 0.001	0.648
-200	7.750	< 0.001	0.835
-100	13.014	< 0.001	0.931
-50	11.729	< 0.001	0.917
0	9.794	< 0.001	0.887
+50	-3.951	0.007	0.613
+100	-5.152	0.003	0.711
+200	-6.324	< 0.001	0.779
+400	-3.809	0.011	0.599
+800	-0.395	> 0.999	0.077
+1600	-0.066	> 0.999	0.013

By using a wider range of SOAs between inducers and targets than in previous studies, we obtained a more refined view of the temporal dependency of the Ebbinghaus illusion when the targets and inducers were presented briefly with temporal intervals. The inducers preceded the targets in negative SOAs, but the inducers followed the targets in positive SOAs. Our findings are partially consistent with the findings of previous studies, indicating that the Ebbinghaus illusion occurs with a brief presentation, even when the surrounding context and the target are not presented simultaneously (Jaeger & Pollack, 1977; Kreuzer et al., 2015; Nakashima & Sugita, 2018). We further found that the classic Ebbinghaus illusion (i.e., size contrast effect) manifested when the inducers preceded the target, but that the size assimilation effect occurred when the targets preceded the inducers.

In this study, we aimed to highlight the dynamic and multiple processes involved in the Ebbinghaus illusion. Some studies have suggested that neither the contour integration theory nor the size constant theory alone could explain the Ebbinghaus illusion (e.g., Rose & Bressan, 2002; Sherman & Chouinard, 2016). Given the present results, we have reservations concerning the general applicability of major theories regarding the Ebbinghaus illusion since none predict and/or explain the size *assimilation* effect.

3.3 Experiment 2: Temporal Order Judgment

Before addressing the issues mentioned above, we sought to exclude the possibility that the results observed in Experiment 1 were due to perceived simultaneity—that is, the possibility that the participants might have perceived the inducers and the target simultaneously and the degree of such perceived simultaneity generated the size contrast (and assimilation) effect.

3.3.1 Methods

Participants

The same 28 paid volunteers who participated in Experiment 1 also participated in Experiment 2.

Stimuli, Procedure, and Experimental Design

The stimuli and procedure were identical to those used Experiment 1. However, the participants reported whether the targets appeared earlier than the inducers by key pressing.

Data Analysis

For the experimental trials, we calculated the correct rate as the rate at which participants reported the temporal order between the inducer and the target correctly.

3.3.2 Results and Discussion

The data from the five participants who were excluded from Experiment 1 were also excluded from the analysis in Experiment 2. The mean of correct rates for all SOA conditions except the SOA 0-ms condition was higher than 90%.

Thus, participants perceived the temporal order of the surrounding stimuli and surrounded stimuli correctly, and the results in Experiment 1 were not due to perceived simultaneity of the surrounding stimuli and surrounded stimuli. These results indicate that neither physical nor perceived simultaneity are prerequisite for the Ebbinghaus illusion.

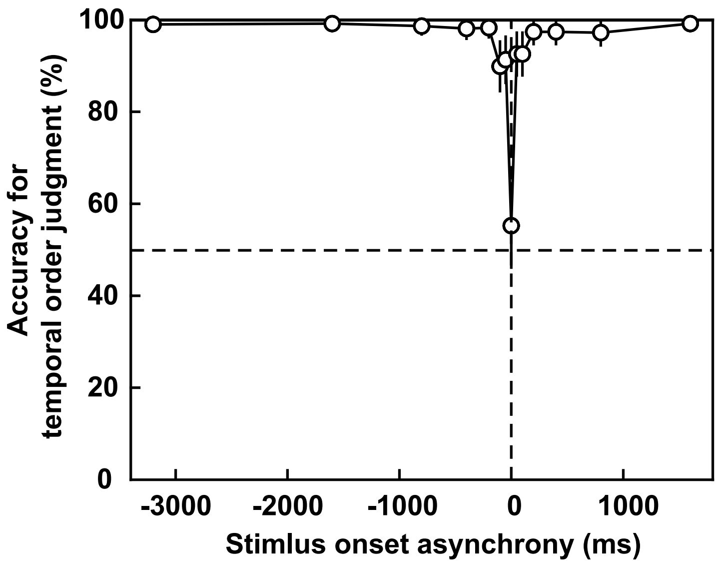

FIGURE 3.3 RESULTS OF EXPERIMENT 2

3.4 Experiment 3: Temporal Tuning of Contextual Modulation of the Size-Numerosity Interaction

In Experiments 1 and 2, the contrast effect occurred when the inducer preceded the target, but the assimilation effect occurred when the inducer followed the target in the size-size interaction. To compare the temporal tuning in the size-numerosity interaction, we used the same stimuli as in Experiments 1 and 2 in Chapter III except that the central circle replaced the dots as in Experiments 2, 3, and 4 in Chapter II.

3.4.1 Methods

Participants

Sixteen paid volunteers participated in Experiment 3 (4 males, aged between 18 and 25 years).

Stimuli, Procedure, Experimental Design, and Data Analysis

The stimuli, procedures, experimental design, and data analysis were identical to those used in Experiments 1 and 2; however, we asked participants to judge the numerosity of the dots surrounded by the circles with different sizes.

3.4.2 Results and Discussion

None of the participants was excluded from analysis because none of them had correct response rates under 60% in the catch trials for Experiment 3. We observed the number contrast effect, where the central dots surrounded by smaller inducers are perceived as larger, when the inducers preceded the targets (negative SOAs). However, we observed the number assimilation effect, where the central dots surrounded by smaller (larger) inducers are perceived as smaller (larger), when the inducers slightly followed the target (positive SOAs).

Using a one-way repeated measures ANOVA, we found the effect of the SOA to be significant [$F(13, 143) = 12.10$, $p < .001$, $\eta_{p2} = 0.52$]. We then performed a one-sample *t*-test against the chance level (50%) with Bonferroni correction for multiple comparisons ($\alpha = 0.05$). We found a significant size contrast effect for SOAs -1600 to 0 ms. We also found a significant number assimilation effect for SOAs +50 to +400 ms, but the effect did not reach statistical significance for SOAs -3200, +800 to +1600 ms.

We examined the temporal characteristics of the size-numerosity interaction in Experiment 3. As with the size-size interaction (i.e., the standard Ebbinghaus illusion) results in Experiment 1, our analysis revealed the number contrast effect when the inducers preceded the target but the number assimilation effect when the inducers followed the target. This suggests that common visual processing may exist in quantity perception.

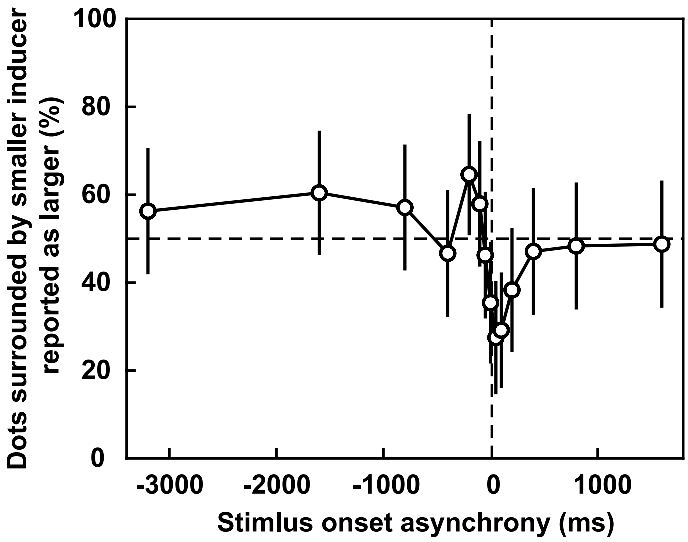

FIGURE 3.4 RESULTS OF EXPERIMENT 3

TABLE 3.2

SOA (ms)	*t*	*p*	*r*
-3200	1.529	> 0.999	0.419
-1600	4.172	0.022	0.783
-800	2.429	> 0.999	0.591
-400	-1.146	> 0.999	0.327
-200	4.037	0.027	0.773
-100	1.867	> 0.999	0.491
-50	-1.216	> 0.999	0.344
0	-5.115	0.005	0.839
+50	-4.952	0.006	0.831
+100	-6.096	0.001	0.878
+200	-3.843	0.038	0.757
+400	-0.774	> 0.999	0.227
+800	-0.449	> 0.999	0.134
+1600	-0.522	> 0.999	0.156

3.5 Summary of Chapter III

Recognizing that visual environments change continuously, in Chapter III, we examined the temporal characteristics of visual perception using the Ebbinghaus illusion. Most studies that have investigated visual perception have not taken such an approach. To clarify the temporal characteristics of visual processing, we first examined the temporal tuning of the Ebbinghaus illusion (i.e., size-size interaction) in Experiment 1. Subsequently, in Experiment 2, we confirmed that the results in Experiment 1 were not due to perceived simultaneity. Replacing the central dots of the Ebbinghaus illusion with the dots for numerical judgment, we observed a similar functional tuning in the size-numerosity interaction in Experiment 3.

Unexpectedly and interestingly, by letting the surrounding circles occur later than the central circle, we found the size assimilation effect instead of the classical size contrast effect (i.e., the Ebbinghaus illusion). Similar temporal dependency in successive presentation—namely, contrast with preceding inducers and assimilation with following inducers—has been reported in other phenomena (e.g., Au, Ono, & Watanabe, 2013; Ono & Watanabe, 2011, 2014; Suzuki & Cavanagh, 1998). For example, a brief visual stimulus distorts the perceived shape of a subsequent visual stimulus as being dissimilar from the shape of the preceding stimulus. This is termed the shape-contrast effect (Suzuki & Cavanagh, 1998). By contrast, the shape-assimilation effect occurs when the perceived shape of the target stimulus appears to resemble the shape of the successive stimulus (Ono & Watanabe, 2011, 2014).

Together with the results of the other experiments in Chapter III, the finding of similar temporal tunings in different properties indicates that common visual processing may exist in quantity perceptions such as size and number.

CHAPTER IV.

PROCESSING LEVEL FOR VISUAL CONTEXTUAL MODULATION

4.1 Introduction of Chapter IV

As the mentioned in Chapter Ⅳ, the temporal tuning of the Ebbinghaus illusion was asymmetric with the presentation timing of the inducers to the targets such that the size contrast effect appeared when the inducers preceded the target, but the size assimilation effect appeared when the inducers followed the target. Furthermore, the magnitude and direction of the illusion effect depended—at a scale of just a few milliseconds—on the stimuli presentation timing. Then, it still has been not clear whether the timing of integration of the inducers and the targets was perceptually or physically.

To aim this, the next experiment examined whether the size modulation in the Ebbinghaus illusion occurred perceptual or physical size of the surrounding information using flash-lag effect.

4.2 Experiment 1: Confirming the Flash-Lag Effect in Size Change for the Size Judgment Experiment

4.2.1 Methods

Participants

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

Stimuli

The stimuli included a black fixation cross (0 cd/m2, 0.33°), two sets of four grey surrounding disks (inducers; 60 cd/m2, minimum 0.66° and maximum 7.37° in diameter), and two black central disks (targets; 0 cd/m2, 4.01° in diameter). The distance from the edge of the central disks to the inner edge of each inducer was 0.64°.

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 chin-rest. The experiment was done in a totally dark room where the sole light source was the computer display. In each trial, after the participant pressed the space key, the black fixation cross appeared at the center of the monitor for 500 ms on a white background (120 cd/m^2). Then, the two sets of 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. 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 total trials. Participants rested after every 10 trials. The Human Research Ethics Committee (Panel C) of UNSW Sydney approved the procedure. We obtained written and informed consent from the participants before the experiment. We presented the stimulus and analyzed the data using MATLAB (MathWorks, Inc.) with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997).

Data Analysis

We calculated the proportion of trials in which each participant reported the surrounding inducer disks changing from smaller to larger as larger for each presentation timing. We fitted a sigmoid function to the calculated proportions to estimate the PSE where the surrounding inducers appeared equal in size by using custom software written in MATLAB.

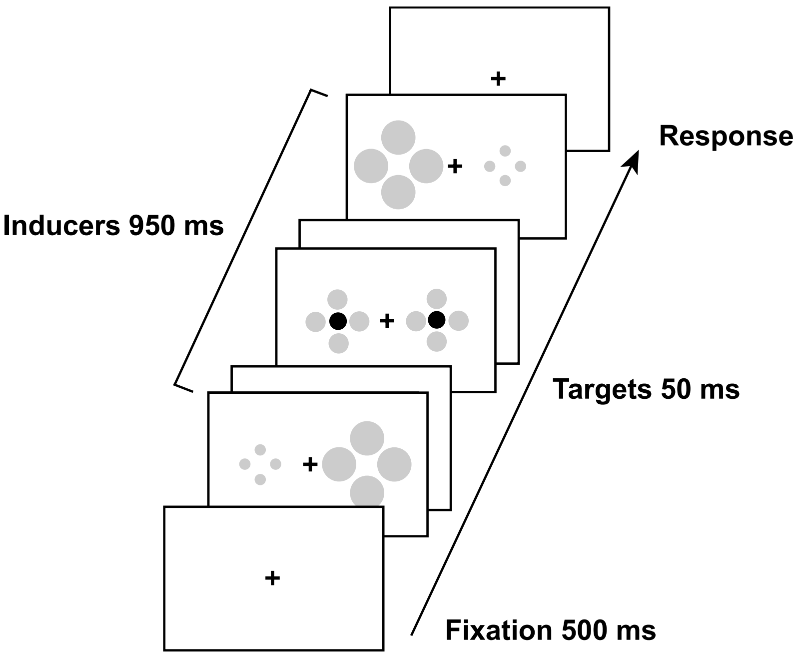

FIGURE 4.1 SCHEMATIC EVENT FLOW OF EXPERIMENT 1

4.2.3 Results and Discussion

The averaged PSE was -228.40 ms. This meant that, for the surrounding disks to be perceived as equal in size, the central disks needed to be presented almost 230 ms before the coincidence time. A one sample *t*-test revealed that the mean PSE was significantly smaller than zero [$t(11) = -2.95$, $p = .013$, $r = .66$]. Thus, the results of Experiment 1 clearly showed the FLE for size change. The magnitude of FLE has been known to depend on changes in stimulus features. Research has shown the traditional FLE between a flash and moving object 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, Nijhawan & Shimojo, 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 as the same size as the surrounding disks, 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 of different sizes, although the retinal sizes are the same. In the next experiment, we asked participants to judge the relative sizes of the two central disks using the same stimuli as in Experiment 1 with the aim of examining whether the Ebbinghaus illusion would depend more on the retinal size or the perceived size of the surrounding inducers.

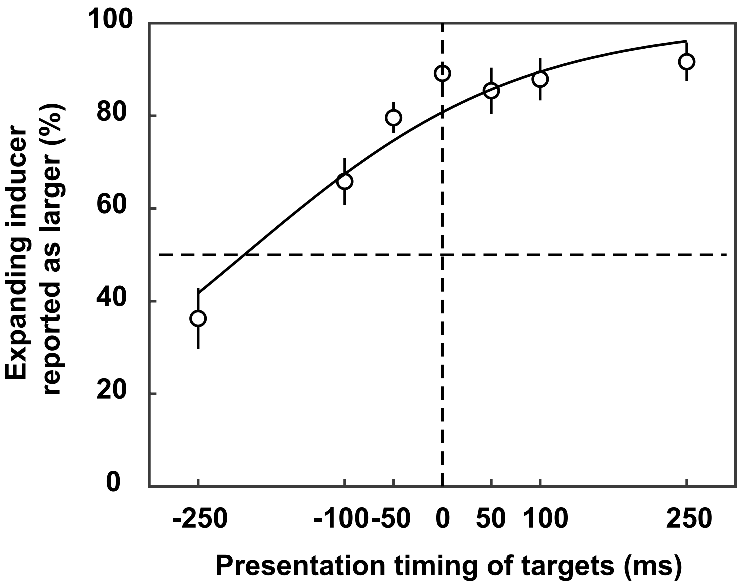

FIGURE 4.2 RESULTS OF EXPERIMENT 1

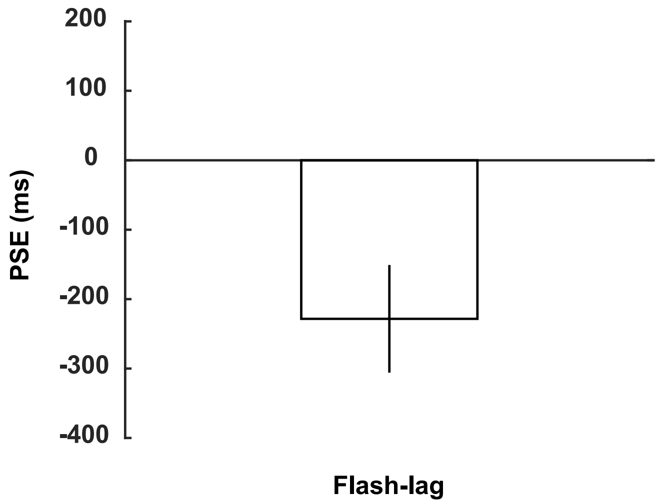

FIGURE 4.3 RESULTS OF EXPERIMENT 1

4.3 Experiment 2: Size-Size Interaction Depends more on Retinal Timing

After obtaining affirmative results (i.e., significant FLE with size change), we proceeded to examine whether the Ebbinghaus illusion would depend more on the retinal size or the perceived size of the surrounding stimuli in Experiment 2.

4.3.1 Methods

Participants

We recruited nineteen new students at the University of New South Wales to participate for course credit in Experiment 2 (4 males, aged between 17 and 23 years). They were not informed of the purpose of the study and had normal or corrected-to-normal vision. None of the participants overlapped with those in Experiment 1.

Stimuli, Procedure, and Data Analysis

The visual stimuli and stimulus sequence were identical to those of Experiment 1. However, participants reported which of the two central disks appeared larger in Experiment 2. We calculated the proportion of trials in which the central disks were surrounded by the shrinking inducers.

4.3.2 Results and Discussion

We fitted the calculated proportions with a sigmoid function to estimate the PSE where the central disks appeared equal in size. The averaged PSE was -21.64 ms but this small effect did not reach significance [$t(18) = -0.99$, $p = .334$, $r = .23$]. Additionally, we performed a two-sample *t*-test on the obtained PSEs between Experiments 1 and 2 and observed a significant difference between them [$t(29) = -3.09$, $p = .004$, $r = .50$].

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

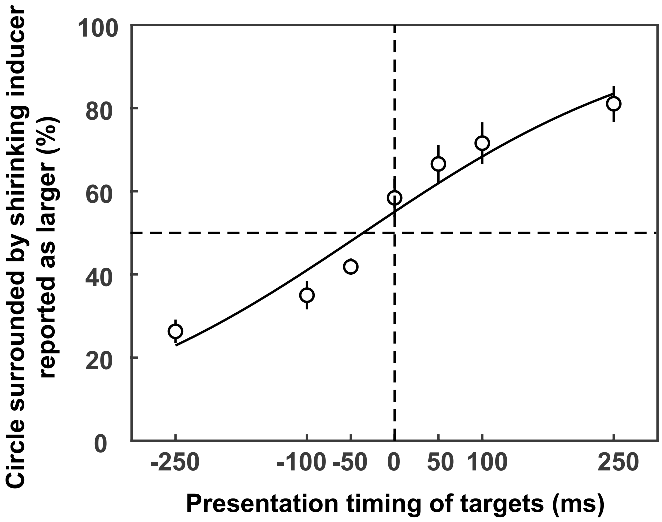

FIGURE 4.4 RESULTS OF EXPERIMENT 2

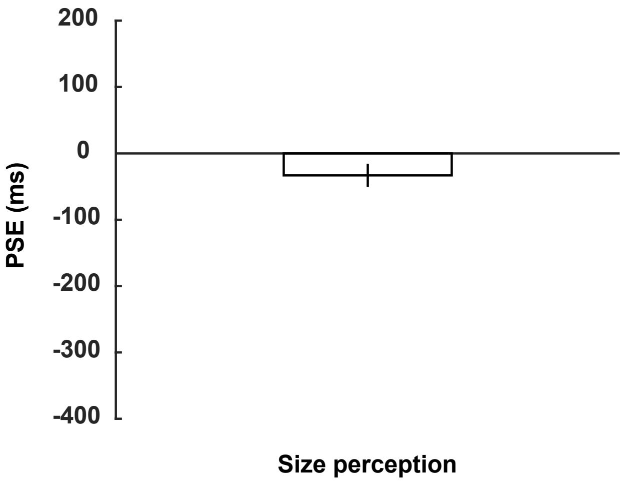

FIGURE 4.5 RESULTS OF EXPERIMENT 2

4.4 Experiment 3: Confirming the Flash-Lag Effect in Size Change for the Numerosity Judgment Experiment

In the size-size interaction using the Ebbinghaus illusion, size perception depends more on the retinal size than on the perceived size of the surrounding stimuli. To develop a clearer understanding of quantity perception-related visual processing, we further investigated the numerosity perception using the same stimuli as in Experiments 2, 3, and 4 in Chapter II.

4.4.1 Methods

Participants

We recruited fifteen university students (5 males, 19.93±5.00 years old) for Experiment 1. They reported normal or corrected-to-normal visual acuity. They were naïve to the purpose of this study.

Stimuli, Procedure, and Data analysis

The visual stimuli and procedure were identical to those of Experiment 1. However, the orange dots (63 cd/m2, 0.2°) appeared as the target. The task was to report which inducers appeared larger when the central dots appeared in Experiment 3.

4.4.2 Results and Discussion

We excluded one participant who was clearly 3SD beyond the mean PSE from the analysis. The mean PSE was -256.25 ms, indicating the perception of the dots lagged about 250 ms the timing of when the inducers were physically identical. The results of a one sample *t*-test showed that the mean PSE was significantly smaller than zero [$t(13) = -6.90$, $p < .001$, $r = .89$]. These results suggest that the flash-lag effect occurred even for size perception (Takao, Clifford & Watanabe, 2019).

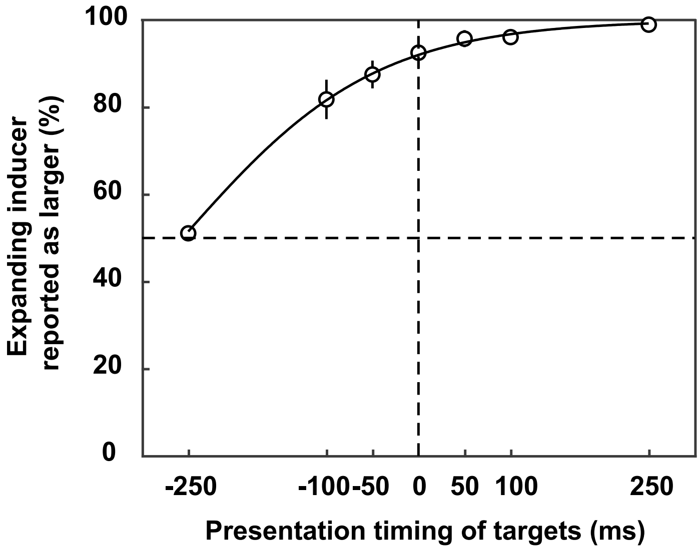

FIGURE 4.6   RESULTS OF EXPERIMENT 2

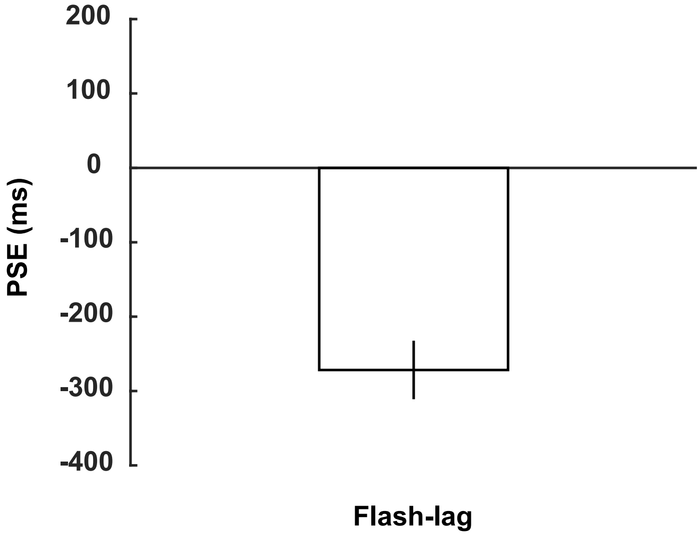

FIGURE 4.7   RESULTS OF EXPERIMENT 2

4.5 Experiment 4: Size-Numerosity Interaction Depends more on Retinal Timing

In Experiment 3, we confirmed the flash-lag effect with the present stimulus configuration on size perception. This enabled us to investigate whether the modulation of numerosity perception by the inducers would depend on the physical or perceived size of the surrounding stimuli. If it depended on the perceived size of the surrounding stimuli, the modulation of numerosity perception would reflect the pattern of the flash-lag effect in Experiment 3.

4.5.1 *Methods*

Participants

Fifteen university students (8 males, 20.73±1.95 years old) were newly recruited for Experiment 2. They reported normal or corrected-to-normal visual acuity. They were naïve to the purpose of this study.

Stimuli, Procedure, and Data Analysis

The stimuli and procedure were identical those used in Experiment 1 except that participants reported which side the number of dots appeared larger by pressing the appropriate keys. We calculated the proportion of trials where the dots were surrounded by the shrinking inducer.

4.5.2 *Results and Discussion*

The PSE, where participants perceived the dots on both sides as identical in numerosity, was 32.42 ms on average. The results suggested that the dots on both sides were perceived differently with the visual illusion when the sizes of the surrounding circles were physically different. A one sample *t*-test showed that the PSE was not significantly different from zero [$t(14) = 0.24$, $p = .816$, $r = .06$].

Furthermore, we conducted a two samples *t*-test for the PSEs between Experiments 1 and 2 and observed a significant difference [$t(27) = 2.07$, $p = .047$, $r = .37$]. These results indicate that numerosity modulated by size information depended more on the physical than perceived size of the surrounding stimuli.

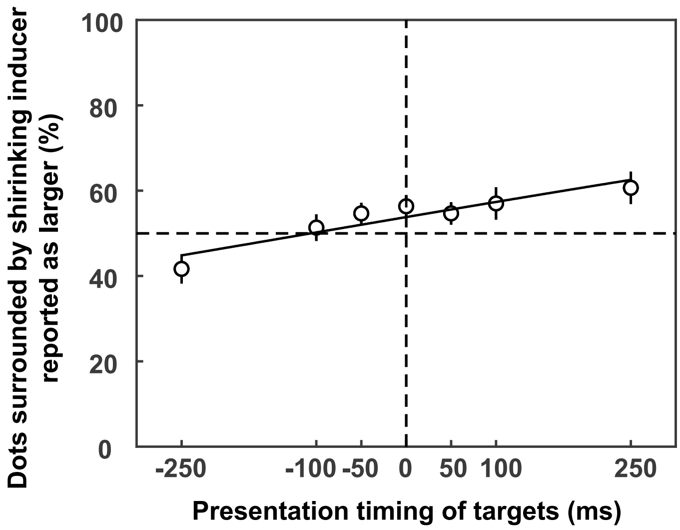

FIGURE 4.8   RESULTS OF EXPERIMENT 2

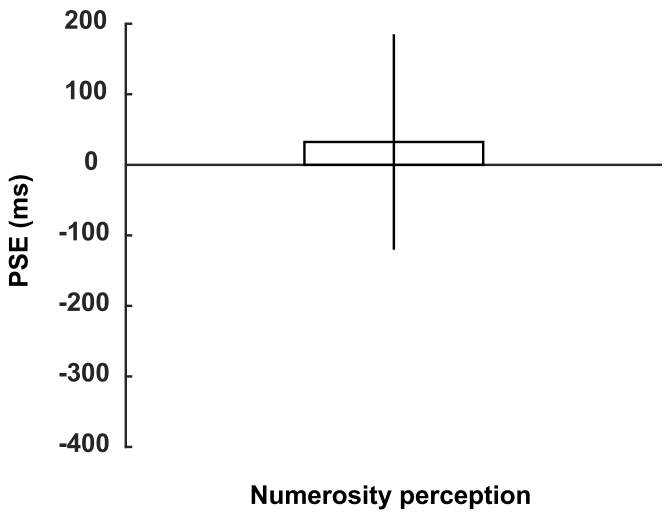

FIGURE 4.9   RESULTS OF EXPERIMENT

4.6 Summary of Chapter IV

In Chapter Ⅳ, we tested whether quantity perception would integrate with contextual information in the retinal size or the perceived size of the surrounding stimuli.

People perceive a circle surrounded by smaller circles as larger than the same circle surrounded by larger circles (Ebbinghaus illusion; Ebbinghaus, 1902; Tichener, 1901). In Experiments 1 and 2, participants perceived the dots surrounded by smaller circles as more numerous than the dots surrounded by larger circles. The Ebbinghaus illusion depended more on the retinal size than the perceived size of surrounding stimuli and we tested whether the modulation of numerosity perception based on the size of surrounding stimuli depended more on the retinal size or the perceived size of the surrounding stimuli in Experiments 3 and 4. In Experiment 3, we confirmed that the flash-lag effect occurred with the present stimulus configuration on size perception. After that, in Experiment 4, we measured the modulation of numerosity perception by changing the inducers. We found that the size-numerosity interaction did not follow a flash-lag effect pattern consistent with that of the size-size interaction.

The results of these experiments suggest that the modulation of numerosity perception by size information depends more on the retinal size than the perceived size of the surrounding stimuli in size-numerosity perception. Given that the Ebbinghaus size illusion depends more on the retinal size of surrounding stimuli (i.e., size-size interaction), the interaction between size and numerosity perception involves visual processes that precede the perceptual registration of the size of modulating stimuli, partially supporting the AToM.

CHAPTER V.

GENERAL DISCUSSION

5.1 Summary of the Findings

A Theory of Magnitude (AToM) proposed a common mechanism for different quantity perceptions (Walsh, 2003). Zimmerman and Fink (2016) found that perceived numerosity increased after adaptation to a smaller patch but decreased after adaptation to larger patch, supporting AToM. While their study convincingly showed a significant relationship between perceptions of size and numerosity, the adaptation paradigm has methodological limitations due to the spatial and temporal configurations of the visual stimuli, including potential contamination through memory and residual sensory signals on the retina.

To overcome these limitations, we used the Ebbinghaus illusion as the contextual stimuli (Ebbinghaus, 1902; Titchener, 1901) because the surrounding stimuli would not overlap with the test stimulus. In Chapter II, we described the first set of experiments, which examined whether the stimulus configuration of the Ebbinghaus illusion would influence perceptions of numerosity and area size when we carefully controlled the density and spatial extension of the test stimulus (Experiment 1-1). The points of subjective equality (PSEs) for numerosity judgment shifted positively for all base-number conditions that we tested (Experiment 1-2) and participants perceived the number of dots surrounded by the smaller (larger) inducers as larger (smaller) for both the estimation and subitizing ranges. Similarly, there were the while carefully controlling density and spatial extension of the test stimulus PSEs shift for area size judgment except for the 2-dot condition (Experiment 1-3), confirming the Ebbinghaus size illusion for space; participants perceived the spatial extension of the space where the dots appeared as larger (smaller) when surrounded by the smaller (larger) inducers. Meanwhile, the experiments in Chapter II showed that the stimulus configuration of the Ebbinghaus illusion changes the perceptions of numerosity and the spatial extension of an area. Together with Zimmerman and Fink (2016), these findings provide convincing evidence for the use of common metrics for numerosity and size perceptions and support the AToM.

Our findings in Chapter II motivated us to explore the dynamic and temporal processing of contextual modulation in quantity perception by manipulating the presentation timing of the inducers and the targets. This area drew our attention because the temporal tuning of the Ebbinghaus illusion had seldom been examined and the dynamic aspect of modulation for numerosity perception had never been investigated. Our configuration with the Ebbinghaus illusion enabled us to examine these unexplored questions. Using a wide range of stimulus onset asynchrony, we identified the finer temporal tuning function of the Ebbinghaus illusion and compared the size-size interaction with the size-numerosity interaction. Chapter III described the experiment and the results. Experiment 2-1 showed that the Ebbinghaus illusion occurred with a brief presentation and even when the surrounding context and the target were not presented simultaneously (e.g., Jaeger & Pollack, 1977; Nakashima & Sugita, 2018; Takao et al, 2019). In addition, in Experiment 2-2, we tested whether temporal order perception could explain the results in Experiment 2-1 using a temporal order judgment task. We found: (1) the size contrast effect manifested when the inducers preceded the target, whereas the size assimilation effect manifested when the inducers followed the target; (2) the size contrast effect became more conspicuous when the inducers appeared less than 200 ms before the target; and (3) awareness of the temporal discrepancy between the target and surrounding stimuli did not appear to be related to the magnitude of the illusion. Additionally, in Experiment 2-3, we observed a similar temporal tuning even for the size-numerosity interaction, further bolstering the notion that size and numerosity perceptions partly share mechanisms and, again, supporting the AToM. The findings reported in Chapter III suggest that the contextual modulation of quantity perception changes depending on the timing of the modulating stimuli; the contrast effect occurred when the inducers preceded the targets, but the assimilation effect occurred when the inducers followed the targets. Previous studies have reported similar prospective contrast and prospective assimilation effects (Au, Ono, & Watanabe, 2013; Ono & Watanabe, 2011, 2014), but our findings are the first to show the non-linear dynamic characteristics (i.e., the shift from contrast to assimilation) of the contextual modulation of size and numerosity perceptions.

Having found that the contextual modulation of qualitative perception is most prominent when the test and surrounding stimuli appear simultaneously, we investigated the processing level of contextual modulation and reported and the results in Chapter IV. The question was whether the contextual modulation of qualitative perception depended on the physical (i.e., retinal) or perceived size of the surrounding stimuli. By using the flash-lag effect (FLE), we dissociated the retinal size and the perceived size of the surrounding circles. First, in Experiment 3-1, we confirmed that the FLE occurred for the gradual size change of the surrounding circles; participants perceived the flashed surrounded test stimuli as occurring about 200 ms later than the physically simultaneous time of the surrounding circles. In Experiment 3-2, we found that the modulation of size perception depended more on the retinal size than the perceived size of the surrounding circles. We used the same procedures to test the size-numerosity interaction in Experiments 3-3 and 3-4. We observed the FLE at a significant level even when the central circle was replaced with the dots. Again, the size-numerosity interaction depended more on the retinal size than the perceived size of the surrounding circles. Together, the results in Chapter IV indicate that both size perception and numerosity perception involve visual processes that precede the perceptual registration of the size of the modulating stimuli and share common mechanisms at relatively lower levels of visual processing.

5.2 Implications for the Dependency versus Independency Debate

In general, the findings of this thesis provide empirical evidence that favors the notion that perceptions of different quantities are interdependent, supporting the AToM's supposition that perceptions of various quantities such as time, size, and number are processed via shared mechanisms (Walsh, 2003). However, these findings do not completely contravene the relative independence of numerosity perception (e.g., Anobile, Cicchini, & Burr, 2015) or number sense (e.g., Dehaene, 2011).

Considering the hierarchical and parallel organization of the visual system (Felleman & Van Essen, 1991), it is highly likely that the dependency of numerosity perception on other processes differs at different levels of visual processes. Several studies have shown that the neural correlate of size perception is present in the primary visual cortex (Schwarzkopf & Rees, 2013), signaling that the process occurs at relatively early levels. This aligns with our findings that the modulation of size and numerosity perceptions by the size of surrounding stimuli is based on the retinal coordinate (Chapter IV). Such modulation in the retinal coordinate in the early visual cortices may feed up to the higher processing area (e.g., the parietal cortex for quantity perception including numerosity; e.g., Bueti & Walsh, 2009). Therefore, the possibility that number is a primary perceptual attribute at the early level of visual processing that is integrated into one of quantities at higher levels remains. That said, it is also possible that number and size are treated as a single "quantity" even at the early levels and differentiated as they proceed to higher levels. In any case, our findings and the findings of other studies make clear that size and number are processed with shared mechanisms somewhere in the brain.

5.3 Prospective Contrast and Retrospective Assimilation

The findings of the experiments reported in Chapter III highlight the dynamic and multiple processes involved in the Ebbinghaus illusion. Similar temporal dependency in successive presentation—namely, contrast with preceding inducers and assimilation with following inducers—has been reported in studies of other phenomena (e.g., Au, Ono, & Watanabe, 2013; Ono & Watanabe, 2011, 2014; Suzuki & Cavanagh, 1998). For example, research has shown that a brief visual stimulus distorts the perceived shape of a subsequent visual stimulus so that it appears dissimilar to the shape of the preceding stimulus. This is termed the shape-contrast effect (Suzuki & Cavanagh, 1998). Meanwhile, the shape-assimilation effect occurs when the perceived shape of the target stimulus appears similar to the shape of the successive stimulus (Ono & Watanabe, 2011, 2014).

Ono and Watanabe (2014) explained the prospective contrast and retrospective assimilation effects in terms of an immediate switch between the exclusion of a distractor signal and the inertial uptake and inclusion of a target signal. In dynamic visual environments, the exclusion of a signal from stimuli other than the target is vital (e.g., Prinz, 1979). We propose that the size contrast effect (the classical Ebbinghaus illusion) might be caused by the over-exclusion of signal input from distractors. For example, if the input signal from small surrounding circles were excluded from the signal of a middle-size target circle, the perceived size of the target circle would be larger. However, once the signal uptake process starts after the middle-size target circle appears, the visual system cannot immediately cease the uptake (e.g., Visser, Bischof, & Di Lollo, 1999). The size assimilation effect might result from the over-intake of input from the inducers. Specifically, if the input signal of the small surrounding circles were added while the signal of the middle-size target circle was still present, the perceived size of the target circle would be smaller.

It is important to note that even a slight temporal offset (as short as 50 ms) produced the opposite effects (consider the contrast with 0 ms versus the assimilation when the inducers followed a 50 ms delay). This may be because the visual system switches from over-exclusion (leading to contrast) to over-inclusion (leading to assimilation) immediately after the registration of the target (Visser et al., 1999). Assuming a fixed processing delay from stimulus onset to stimulus registration, the switch may appear immediately at the time of target onset. Thus, the processes underlying the prospective-contrast and retrospective-contrast may be highly sensitive to the order of stimulus registration.

5.4 Future Directions

5.4.1 Dynamic Modulation of Quantity Perception

The patterns of prospective contrast and retrospective assimilation are novel and therefore there are several avenues of future investigation. First, the patterns of prospective contrast and retrospective assimilation may not be limited to the Ebbinghaus illusion; they may be also found in other geometric illusions. For example, Schmidt and Haberkamp (2016) investigated the temporal characteristics of the Ponzo illusion with temporal offset and their findings suggested that two components that differ in time course might exist. Few studies have tested how inducers or contexts presented after a target influence a particular illusion. Moreover, the neural mechanisms or consequences of such modulation would be interesting to examine. An fMRI study demonstrated that the surface size and central cortical magnification of the human primary visual cortex (V1) could predict the magnitude of the Ebbinghaus illusion (Schwarzkopf & Rees, 2013; Schwarzkopf, Song & Rees, 2011). It would be interesting to examine how cortical structures and activities in V1 would be modulated by SOAs between inducers and targets; such an examination could provide insights into the underlying neural mechanisms of the prospective contrast and retrospective assimilation effects.

5.4.2 Individual Differences and Developmental Study

Using the Ebbinghaus illusion, Bremner, Montanaro & Shephered (2016) found a significant difference in the magnitude of the illusion between UK participants and the Himba of Namibia. They did not observe the classic Ebbinghaus illusion effect among Himba children up to 10 years old, whereas they found that it manifested robustly among UK children at 7 to 8 years of age. In contrast, they did observe the illusion effect among Namibian children growing up in urban areas and adults. They have suggested that the cross-cultural difference in perceptual shift due to urban environment to process the contextual information appears in children. Such influences of environment on the development of the illusion are of particular interest because they certainly influence and interact with the development of quantity perception. Our participants were university students. In future studies, we hope to extend the present experimental paradigms to investigate different populations.

5.5 Conclusions

The results of our cognitive psychological experiments suggest that size and number are processed by shared mechanisms (Chapter II). We also found that size and numerosity perceptions are dynamically modulated (Chapter III). The pattern of prospective-contrast and retrospective-assimilation revealed the surprising but robust non-linearity of contextual modulation for quantity perception. The last sets of the experiments demonstrated that contextual modulation by surrounding stimuli depends more on the retinal size than the perceived size of the surrounding stimuli (Chapter IV), implying that visual processes precede the perceptual registration of the size of modulating stimuli. In all the experiments described in this thesis, we found that size and number were similarly affected by the surrounding stimuli, which supports the AToM (Walsh, 2003). Also, the technique that focused on contextual dependency using visual illusion (e.g., the Ebbinghaus illusion in this study) would be better way to examine the relationships in different visual characteristics.

We can perceive the number and size of objects before us and although these quantities differ in the physical and mathematical senses, they also seem to be related to each other as "quantities." This thesis helps explain the reasons we feel that way.

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LIST OF FIGURES AND TABLES

ACHIVEMENTS

Journal Papers

- Takao, S., & Watanabe, K. (in press). Size-numerosity interaction depends retinal rather than perceived size. *Proceedings of 12th International Conference on Knowledge and Smart Technology*.
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International Conference

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