심리학석사학위논문

The effect of the numerical value in the physical size comparison task

Does the automatic activation of magnitude enhance the size contrast between Arabic numerals?

물리적 크기 판단 과제에서 숫자의 값이 미치는 영향: 수 개념의 자동적 처리가 아라비아 숫자 간 크기 대조 효과에 영향을 미치는가?

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이 논문을 심리학석사 학위논문으로 제출함

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Abstract

In the fields of the numerical Stroop-like tasks, it has been known that the conceptual magnitude of numbers influences the size comparison process (Henik & Tzelgov, 1982; Tzelgov, Meyer, & Henik, 1992). When the physical size of a larger number is bigger than that of a smaller number, it is a congruent condition. In contrast, the physical size of a larger number is smaller than that of a smaller number, it is an incongruent condition. Two distinguished information of numbers, the numerical value and the physical size, interact during the number comparison task, which triggers the different performance of reaction time and accuracy between the congruent and the incongruent conditions. Researchers have been mainly focused on response time and accuracy to verify the size coincidence effect. Accordingly, it is still unidentified whether the effect reflects the perceptual results during the comparison process, or simply the cognitive bias in the response stage. The purpose of this paper is to identify the effect of numerical value when people compare the physical size of numbers. The main hypothesis was that a number with a bigger value looks physically larger than a number with a smaller value. We measured the perceived size of Arabic numbers depending on the conceptual magnitude by applying the Ebbinghaus paradigm which is known to enhance the size contrast induced by the conceptual meaning of the displayed stimuli. Each stimulus consisted of a central number and six surrounding numbers. Participants were asked to respond to whether or not the target number looked smaller or larger than the inducers. As Dixon (2008) suggested the Generalized Linear Mixed Model to the repeated measures design with binary responses, we test the results with the GLMM model putting a random effect on each subject' variation. Furthermore, the points of subjective equality (PSE) were calculated from binary responses on the perceptual decision as being smaller or larger. The analysis showed that participants were more likely to perceive the physical size of the target number as being smaller when surrounded by numerically larger inducers, vice versa. In study 1, we tested this perceptual effect by the influence of magnitude with two sets of font size conditions. Furthermore, we found the similar pattern on both the upright and inverted number conditions by rotating the number stimuli in study 2. In study 3, the expected result was partially observed in the range of 3 to 7 of the inducers. These results indicate that the conceptual magnitude of numbers influences the perceived size of numbers during the number comparison process.

Keywords: number comparison; the size congruity effect; symbolic numbers; GLMM; Ebbinghaus illusion

Student Number: 2015-20225

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Introduction

1. The size congruity effect

How do you react to the object when the visual properties of it differ from what you previous remembered? Size congruity effect is a phenomenon that attests the relation of the physical size and conceptual magnitude embedded in the object during the comparison processing. The two different dimensional information of the stimuli interact when people compare the objects based on their physical size or conceptual size. The underlying mechanisms behind this interesting phenomenon are one of the controversial and favorite topics that surround the size congruity effect until now. Before dealing with the developed question on the mechanisms of the size congruity effect, we review the theoretical backgrounds on the size congruity effect.

The larger the difference between the actual sizes of the animals, the faster the response of participants on the written animal name when they were required to select the larger animal (Moyer, 1973). On the basis of this study, Paivio raised a question about the independently processed but connected systems containing verbal and nonverbal information in his memory size comparison task (Paivio, 1975). In his experiment 2, people responded the answer more rapidly and accurately when the monitor presented the physically bigger zebra than a lamp to a question, ‘Which one is actually a bigger object in the real life?’

The theoretical framework on the size congruity effect was drawn upon to understand the faster reaction time in the congruent condition and the slower reaction time in the incongruent condition. Besner and Coltheart (1979) devised this framework on the number and numerical information, which is called as to the numerical Stroop task. They asked participants to choose the numerically larger number of two Arabic numerals. The numerical information and the physical size were coherent in the congruent condition and two independent information was not coherent in the incongruent condition. Like the previous results with pairs of words and visual images, the congruent condition facilitated response and the incongruent condition impaired response.

Henik and Tzelgov (1982) extended this model by adding a physical size comparison task in addition to the numerical size comparison task. With the combinations of the physical size (small vs. large) and the numerical size (small vs. large), they found the aligned results of the congruency effect. When the numerical magnitude and the physical size are congruent (3 5) rather than incongruent (3 5), it prompts more rapid response and a lower error rate. For instance, when the numerical value of the physically larger number is smaller than the physically smaller number, people show slower reaction time despite that the value of numbers was an irrelevant dimension in the physical size comparison task. In contrast, the numerical size was the relevant information and the numerical size was the irrelevant information in the numerical size comparison task. They also concluded that the physical size congruity effect interacted with the numerical distance. Only in incongruent condition, the reaction time in the larger numerical distance was slower than that in the shorter numerical distance. Clearly, the result indicated that the numerical information activated even when the task was irrelevant to the information. The numerical size of numbers influences the perception of their physical size.

2. The automatic processing of numbers

For examining the mechanism resulting in the size congruity effect, the researchers took the numerical representation in various dimensions apart from the process during the perception and cognition. Numerical cognition process can be defined as the superordinate level encompassing three layers such as the pre-representation (i.e. recognizing the numerical stimuli), the numerical representation conveyed in number(i.e. the physical size and the numerical value), and the post-representation (i.e. working memory, judgment, and response) (Kadosh & Walsh, 2009).

Extending Paivio's dual coding theory (Paivio, 1975, 1991; Paivio & Csapo, 1973), the questions on theses encoding systems shed light on the direct and automatic process on the number. The results with Arabic numbers showed the facilitation and interference effect aligned with Paivio's previous study, which formed the consensus to the separate encoding process of pictures and words (Banks, 1977; Banks & Flora, 1977) and Arabic digits and number words (Besner & Coltheart, 1979). Besner and Coltheart (1979) found that the digits rather than words evoked the meaning directly like the pictorial stimuli evoked instant inner representation.

Within these flows to support the automatic encoding of meaning, the automatic processing of numerical magnitude has received much attention, which offers the plausible explanation on how magnitude information are processed and intervenes the task. Researchers have found various examples such as the interference effect by numerical magnitude in the physical size comparison (Henik & Tzelgov, 1982; Tzelgov, Meyer, & Henik, 1992) and the parity judgment task (Dehaene, Bossini, & Giraux, 1993; Sudevan & Taylor, 1987).

There are two types of automatic processing: 1) the intentional automatic processing refers to the process where the meaning embedded in the stimulus is processed with intentional monitoring and effort and 2) the autonomous automatic processing refers to the process where the meaning of stimulus is processed without intentional monitoring because it is irrelevant with the task requirement (Tzelgov & Ganor-Stern, 2005). The autonomous automatic processing is the marker that we consider as the underlying mechanism in the current study. Other examples of this autonomous processing on quantities are evident (Choplin & Logan, 2005; Ganor-Stern & Tzelgov, 2008; Henik & Tzelgov, 1982; Kadosh, Henik, & Rubinsten, 2008).

3. The shared representation account versus the shared decision account

On the other side, the endless arguments were formulated by the two distinguished approaches on how the numerical value and the physical size interact. Until now, there have been two theoretical models to account how the size congruity effect occurs in the underlying process. Since Moyer (1973) observed that animal words and stored information influenced the response time on the size comparison task using written animal words, researchers cast doubt on the dual coding theory and its possible response bias in the interconnected information process. The premise of a shared representation account is that the numerical and physical size information is mapped onto a single magnitude representation while being stored during the whole decision process (Henik & Tzelgov, 1982; Kadosh et al., 2007; Schwarz & Heinze, 1998; Walsh, 2003). Especially, the automatic processing of magnitude happens even in two numerical notations such as Arabic and Indian numbers (Ganor-Stern & Tzelgov, 2008).

In contrast to this, the shared decision account claims the separate parallel process of numerical and physical size information, which remain distinctive until the response stage (Faulkenberry, Cruise, Lavro, & Shaki, 2016; Santens & Verguts, 2011). Our study was hypothesized based on a shared representation model because the researchers have proven the associations between different magnitude domains such as luminance (Cohen Kadosh & Henik, 2006; Kadosh, Kadosh, & Henik, 2008), duration of time (Crollen, Grade, Pesenti, & Dormal, 2013; Dormal, Andres, & Pesenti, 2008), and nonsymbolic magnitude (Gebuis, Kadosh, de Haan, & Henik, 2009) as one of the major topics on the size congruity effect.

According to several ERP studies, physical attributes and numerical magnitude interacted before participants executed the response. Schwarz and Heinze (1998) assumed that two hypothesized models accounting at which level the numerical value and the physical size would undergo a merger and combine into an analogical representation: 1) an early interaction model, which supports an analogue integration between the numerical value and the physical size before the response process, and 2) a late interaction model, which supposes each information stored separately until the response process. They proposed the early interaction model strongly to support the facilitated and interfered responses stemming from automatic processing of numerical value. In their study, the ERP component such as P300 (stimulus discriminability) and LRP (lateralized readiness potential; preparation and execution of a motor movement) were compared during the numerical comparison and the size comparison tasks. The activated P300 for a cognitive load at around 300ms processed earlier than LRP. This onset latency patterns showed that there was no detectable sense of competition between two dimensions in the response stage. Thus, it is thought to reflect that the size congruity effect preceded the competition at the response.

Furthermore, the early interaction timing irrespective of notation has also been found in the study using both stimulus-locked and response-locked LRP and P3 (Gebuis, Kenemans, de Haan, & van der Smagt, 2010). Stimulus-locked LRP is thought to reflect neural activity related to response to the stimulus presentation, whereas response-locked LRP is related to the actual movement. The peak of P3 latency referring to cognitive conflicting was associated with the size congruity effect. And delayed sLRP in the incongruent than congruent condition stimulus-LRP with the absence of response-locked LRP in relation to the actual movement showed that two information occurred before motor activation.

4. The Ebbinghaus illusion effect

The contrast in optical illusion is automatically predominant over our intention to watch an object in real properties, whereas we can intentionally control our optical system and focus on the targeted object in a general scene. The basic logic of the illusion is that automatic translation towards the stimulus in a given context affects our perception (Snowden et al., 2012). For instance, the Ponzo illusion and the Müller-Lyer illusion are basically based on the geometric optical illusion and also the depth perception and linear perspective, judging the size of the object varying upon the background. In fact, Ebbinghaus illusion has a dissimilar aspect with those in that its contrast effect is modulated by stimuli modality and context. A circle surrounded by larger circles seems smaller than an opposite circle surrounded by smaller circles without any intention, although the central circle and the counterpart are geometrically and physically equal objects (Fig. 1). The inducers extended a reciprocal relationship with a test item.

There was the prior study to explore the reciprocal interaction between the cognitive and semantic category of object and perceived object and response behavior. Coren and Miller (1974) found a circle with circles in a same geometric modality appeared more contrast than a circle with triangles or irregular shape in a different modality condition. Coren and Enns (1993) linked the conceptual relatedness between geometric figures to the size contrast effect, which determined by perceptual properties of visual stimuli in low-level perception as well as the conceptual categorization in the higher cognitive process. Coren and Enns (1993) already associated the categorization effect on the illusion with a Stroop-like paradigm to argue that the conceptual similarity can bridge illusion effect and abstract concept. The Ebbinghaus illusion has been constantly utilized for understanding context-sensitivity from low to high level. Choplin and Medin (1999) were against the results of illusion effect identified by Coren and Enns (1993). However, by the fact that their newly devised symbols did not possess the generally established concept in it, Choplin and Medin's study was not able to entirely verify that only the perimeter was necessary for the size comparison task. So, their result was not directly compared with the Ebbinghaus illusion effect of geometric figures such as triangle, square, and circle (Coren & Miller, 1974).

This illusion effect showed the correlated effect with the strong symbolized objects.

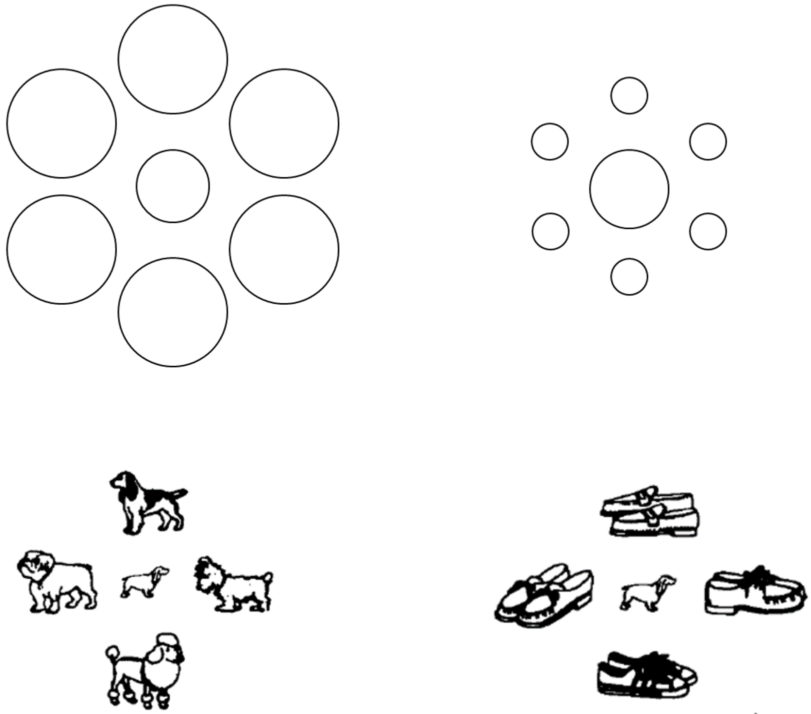

Figure 1. (top) A typical exemplar of Ebbinghaus illusion. (bottom) Stimuli sets of the prototype (dog-dog) and the different category (dog-shoes). Test item and inducer were paired from either the prototype, same, near, or different categories (from Coren and Enns, 1993).

5. The present study

Although considerable research has been devoted to reveal the process that the conceptual meaning of numbers are instantly and automatically processed with analysing the reaction time (Arend & Henik, 2015; Goldfarb, Henik, Rubinsten, Bloch-David, & Gertner, 2011; Tzelgov et al., 1992), rather less attention has been paid to more precise analysis with the psychometric function. Certainly, the time-series data of ERP for the timing where the confliction occurs and the relative ratio of deoxygenated to oxygenated haemoglobin of fMRI for the activated brain area on presented numbers were meaningful. Because it is possible to measure the neurological change that occurs during the overall size judgment process of the target to be larger or smaller than the other. However, unfortunately, the contributor on the size congruity effect cannot be fully identified by the previous attempts of the neurological data to record the activation in the brain and the traditional measurements like reaction time or error rates on the standard physical comparison task.

There was an attempt to resolve the trade-off problem between reaction time and accuracy with the aspect of drift rates, the rate of accumulated information until response, from the diffusion model (Ratcliff, Thompson, & McKoon, 2015). Nonetheless, they recognized the limitation that the simulated result was not able to reveal how the numerical information interacts with each other under beneath the process. Rather, the model was able to decompose the measurements such as reaction time and accuracy into the drift rate and the initial boundary setting, which was able to interpret the previous literature in an integrative perspective.

Recently, an alternative way handled whether the numerical meaning affected the size congruity effect in a visual search paradigm (Sobel, Puri, & Faulkenberry, 2016) and the signal detection theory (Reike & Schwarz, 2017). On a typical visual search array with number stimuli as fixed condition, they suggested the richer data of slopes depending on the number of display items as well as reaction time (Sobel et al., 2016). Sobel and colleagues concluded the influence on the top-down attention to extract the physical size from numbers by manipulating task requirement either of the numerical or the physical size. They asserted the shared decision accounts which were supported by the result that the physical size of numbers processed faster than the numerical size of them. This result was not aligned with our expectation, but, still, it is reasonable to introduce another method to see the mechanism of the size congruity effect and the representation model. In contrast to this, the signal detection theory made another practical option to prove the analog representation of magnitude and the automaticity of numerical information (Reike & Schwarz, 2017). The fundamental conclusion confirmed both the mere cognitive bias depending on the stimulus size set (small or large) and the sensitivity depending on the magnitude information. Indeed, the sensitivity was higher when the numbers were numerically smaller in the small physical size sets and the numbers were numerically bigger in the big physical size sets, which also suggested that the difference between the congruent and incongruent conditions. For example, participants chose the physically bigger target with greater value more readily in the physically big size condition rather than the physically small size condition. It was actually an important attempt to distinguish the cognitive bias and the influence of the numerical value, due to the nature of the size comparison task. Nevertheless, the question remains whether the value of number automatically and directly affects the perceptual process during the physical comparison process on Arabic numerals.

To fill this gap, we adopted another paradigm to assess the automatic influence of magnitude with the physical size comparison task, the Ebbinghaus illusion. The aim of this study was to investigate the effect that the value of numbers actually triggers the perceptual result of the enhanced size contrast effect. In particular, we emphasized the genuine perceptual influence of numerical value, when people compare the numbers perceptually, rather not the instant bias at the response stage. The process for this has not yet been determined. Furthermore, the claim that the conceptual value might influence the cognitive process has been strongly supported by several literatures studying the size congruity effect of numbers (Arend & Henik, 2015; Henik & Tzelgov, 1982; Reber, Wurtz, Knapstad, & Lervik, 2010; Tzelgov et al., 1992) and the relationship between the quantity representation and the numerical distance (Dehaene, 1989; Dehaene, Dupoux, & Mehler, 1990; Duncan & McFarland, 1980; Schwarz & Stein, 1998; Shepard, Kilpatric, & Cunningham, 1975; Sternberg, 1998). The semantic value of numbers delayed the response when participants were asked to choose a numerically large number in an incongruent condition, in which the physical size of numbers did not correspond to its numerical values. The semantic value of numbers might intervene between the perception and the response, which can also accompany the optical illusion as well like the case of Coren and Enn' study (1993) in which conceptual meaning of the objects at the cognitive level affected the size contrast effect at the perceptual level. As they connected the conceptual similarity and the geometric figures to a Stroop-like paradigm to see the enhanced illusion effect, this study incorporated the size comparison in the numerical Stroop paradigm to the Ebbinghaus illusion paradigm. In this light, our study developed an illusion typed number stimuli to interpret the physical comparison process within the illusion framework.

The perceived size of the target compared with the inducers will be estimated by measuring points of subjective equality (PSE) with continuous stimuli methods in varied target size conditions; physically smaller, equal, or bigger when it compared with the inducers. In calculating PSE on each condition, the PSE is given in which the perceived target size on each condition corresponded to the reported probability of 50% of the bigger responses. When we constructed the number pairs, the relationship between the target and inducers was composed of three semantic domains: 1) a larger target condition: the target was numerically larger than inducers, 2) an equal target condition: the target and inducers were same numbers, and 3) a smaller target condition: the target was numerically smaller than inducers. The analysis would present the pattern that participants are more likely to see the target number smaller when the larger inducers surrounded the target, *vice versa*. More importantly, the numerical distance effect should occur in Experiment 3. As the numerical difference between the target and the inducers increases, the PSE would be greater. lt would support the reason of the previous results in that the magnitude of numerals will show the forceful effect on the size comparison decision even without intentional processing.

We hypothesized that the numerical value both of the central number and surrounding numbers should elicit the processing of numerical information regardless of the task requirement, as the previous study has found the automatic processing of numbers in the physical size comparison task. Accordingly, the perceived size of the target number should vary depending on the numerical value of surrounding inducers in Experiment 1, 2, and 3. The pattern would be coherent in both font size conditions, small or big in Experiment 1, which will not constrain the effect of the numerical information to any particular font size to perceive the numbers. In addition to this, further support for the effect of magnitude will come from the design to manipulate the orientation of presented numerical stimuli. In experiment 2, we rotated the numbers inversely without manipulating its shape or visual elements. We expected that the inverted number condition would entail the weaker association between the physical size and numerical value of numbers. By testing the bigger responses pattern over the orientation difference between the upright number and the inverted number, the perceived illusion effect by the degrees of processed numerical information should differ in Experiment 2. The flat or irregular pattern of the perceived size, regardless of the numerical value, on the inverted number should be observed in contrast to the linear trends of the perceived size on the upright number stimuli as we hypothesized the numerical magnitude less engaged in when the number stimuli are inverted than upright. The expected results in Experiment 1 and 2 might be extended to the numerical distance effect in Experiment 3. If the influence of the numerical value is coherent across all design, those result would provide strong evidence that the autonomous processing of magnitude actually intervenes while perceiving and comparing physical size of numbers, even though the numerical information is irrelevant to the task. And we predicted that the numerical distance effect should appear in Experiment 3, which supports that the associated numerical value are instantly mapped onto the internal number line by recognizing and processing the number stimuli.

Experiment 1

The goal of Experiment 1 was to examine the influence of magnitude on the estimated perceived size of Arabic digit with illusion evoked stimuli sets. First, we arranged the target stimuli sets of the physical size into two global levels. The interest of this study is not about the illusion effect when viewing the number stimuli at the particular physical size, but about the general influence of numerical magnitude when viewing numbers of various sizes like in real life. Given the varied physical size of the target, if the value actually intervene between the participants' perception and decision in the physical size comparison, the font size rather than the value of numbers will not affect the perceived size of them. Experiment 1 aimed to single out the possibility of the specified effect within certain font size in order to approve a robust pattern of the affected illusion.

We organized the semantic relations between the target and inducers in the context that the semantic value of numbers will influence on the optical illusion of physical size. When judging the perceived physical size, whether the center target is larger or smaller than the surrounding inducer, a disparity of conceptual values would intervene in the perceptual decision. While number 5 kept as a central target, the physical size of the target varied within each range of the font size sets. In contrast to this, the inducers was constant as 22mm (a small font set) or 40mm (a big font set). Inducers, 3, 5, and 7, were paired with the target, number 5. To elaborate a relationship between each pair, it was distinguished to a domain of categorical comparison between the target and inducers. For instance, a pair of 5 and 3 represents a ‘bigger’ target condition in which the target 5 is semantically larger than an inducer 3. Another pair of 5 and 7 is a ‘smaller’ target condition because, apparently, a semantic value of the target is smaller than inducers, 7. The other pair of 5 and 5 is a ‘equal’ target condition in which the target and inducers were equal numbers as a condition of neutral relation. In sum, there were three conditions to define the semantic relationship of the target and inducers through all experiment. Apart from this, participants were unaware of these semantic domains and instructed exclusively to concentrate on the physical sizes.

Method

Participants

19 undergraduate students with normal or corrected to normal vision (10 females, mean age = 20.06 yrs, SD = 1.7) were recruited through the SONA R-Point system. All participants were students who volunteered. They gained course credit of the psychology class at the Seoul National University. This study was approved by the Institutional Review Board at the Seoul

National University. All participants gave consent to the written ethics and right on participation.

Stimuli

Number stimuli generated on Adobe Illustrator CC program were displayed using the E-prime 2.0 professional software on a 1920 × 1080 pixels 24-in. LCD monitor with 144 Hz (scanning rate). On one trial, each display contained one array consisting of the target number and six number inducers. The Ebbinghaus-typed number stimuli were presented on a screen for 3000ms (Fig. 1).

We chose the number '5' as the target number because it is the median of the single digits from 1 to 9. In addition, Oliveri and colleagues (2008) also took 5 as the target for their study about the relationship between number size and time perception. Three sets of stimuli were composed of a combination of Arabic numbers 3, 5, and 7, so the sets were 5-3, 5-5, and 5-7. The numerical value of a central target was constantly fixed as 5. The global size of the stimulus was divided into two sets, the small range and the big range according to the pilot study in order to find the optimized stimulus size based on Coren and Enns (1993). A pilot test of 10 subjects determined the central stimulus size by answering the ambiguous range to determine whether the central stimulus was larger or smaller than the peripheral stimulus.

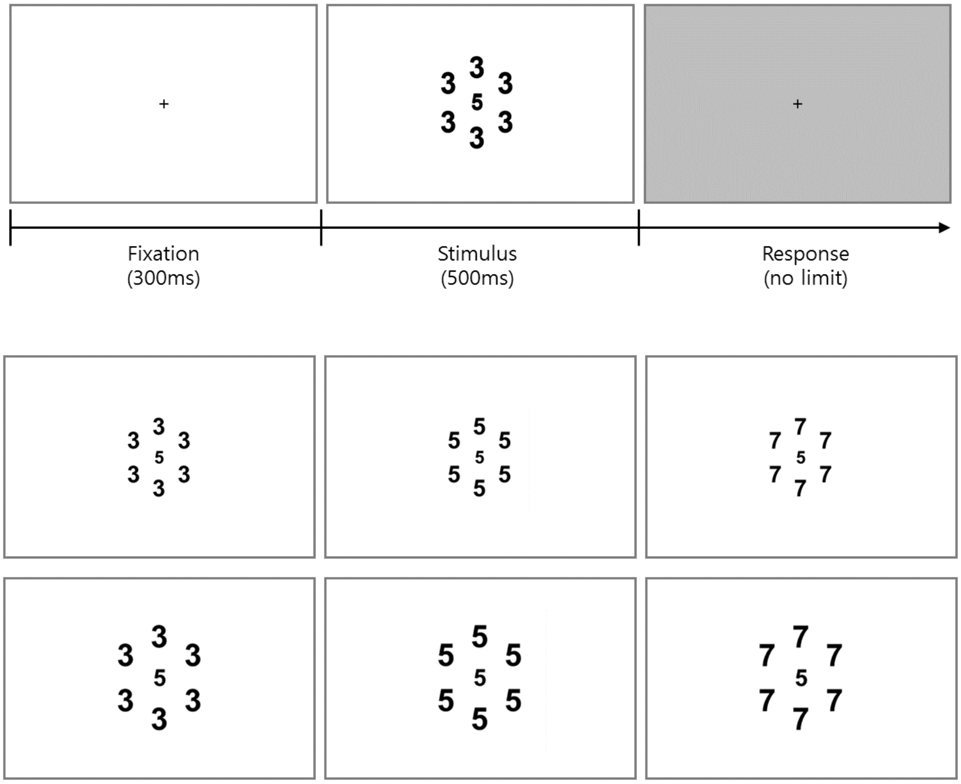

Figure 2. (Top) Procedure (bottom) Stimuli in Experiment 1. Top rows are for the small font size condition and bottom rows are for the big font size condition. The columns are distinguished by the semantic relationship between the target and inducers. (Left) A smaller domain: inducers are conceptually smaller than the target. (Middle) The same domain: the target and encompassing inducers are equal units. (Right) A bigger domain: The semantic size of inducers are bigger than the target. The physical size of inducers was identical with each other within a single trial.

The font size of target figures varied randomly among thirteen levels of each font size condition, small or big, while the physical size of inducers was constant as either 28mm (small) or 51mm (big) depending on the font size condition: 1) In a small font size condition, the target ranged from 45mm to 57mm, which was surrounded by the small peripheral stimulus (28mm) and 2) in a big font size condition, the target ranged from 25mm to 31mm, which was surrounded by the large peripheral stimulus (51mm). Inducers in each condition were adjusted to subtend 2.08° (small) or 3.8° (big) of the visual angle vertically. The font size of numbers randomly decreased or increased during the presentation. In one array of a trial, the six inducers were equal in both the physical size and the numerical value.

Procedure

According to Im & Chong(2009), the procedure with the Ebbinghaus typed number stimuli was organized. After the fixation presentation for 200 msec, Arabic numerals were presented for 500 msec. In the next display with gray background, participants performed to report whether a central target seems perceptually bigger or smaller than surrounding numbers. The response page remained until they pressed the button without no time limitation. This is a part of main instructions. “During the experiment procedure, please hold the position upright. If a central stimulus seems bigger comparing with the surrounding stimuli, press the ‘Bigger’ (p) button on the right of the keyboard. Or if the center number seems smaller than surrounding inducers, press the

‘Smaller’ (q) button on the left. Rapid and correct responses are required in 3 seconds of duration.” An experimenter underscored the sentence to compare a perceived size only, even though the target and an inducer seemed to appear almost equal. Likewise, participants refrained from any speculation or supposition. The practice session was preceded by the main session for participants to understand the procedure unquestionably. In the practice session of 18 trials, participants were required to compare the physical size among the pairs of same one-digits (1-1, 2-2, 3-3, 4-4, 5-5, 6-6, 7-7, 8-8, 9-9) were presented randomly to accustom participants to the task before starting the main section. In this practice sets, a pair of number 5 was presented physically equal, and the rest of the pairs were composed of a digit physically bigger and another digit physically smaller, which rotated the physical size sets. While executing the task, participants leaned on their face to a chin rest with a fixed distance of 31.5 inches (80cm) from their binocular vision to the monitor. For parallel viewing, a height of the chin rest was adjusted personally. During the de-briefing, we checked that there was no misunderstanding on the procedure. Some participants made a faint expectation of the effect of numerical value when we asked the purpose of the experiment after the experiment ended. But no one guessed the hypothesis of our study perfectly.

Design

In a repeated measures design, two within-subject factors were the numerical value of inducers (3 vs. 5 vs. 7) and the font size (small vs. big). The numerical value of inducers indicates the semantic relationships between the target and inducers: 1) The larger target condition of the target 5 and numerically smaller inducers, 3, 2) the equal target condition in which inducers and the target are equal numbers, and 3) the small value condition of the target 5 and numerically larger inducers, 7. The design was 3 (Numerical value) × 2 (Font size) × 13 (Physical size variation of the target) on 78 trials in each block. Each blocks consisting of 78 trials were repeated 10 total 780 trials

Results

Among 19 participants, all data sets were analyzed. We analyzed our data by fitting the binary responses on the size judgment using a Generalized Linear Mixed-effects Models (GLMM). The model specified the fixed effects and random effect with Glmer in the lme4 package in R (Version 3. 3. 0.). We also presented our code scripted in R (see Appendix B). There were a few papers which accommodated the results with generalized linear mixed models especially on the binary responses in the psychology fields (Dixon, 2008). The major way to adopt this mixed effect model is in the sense that we can correct the value of subject variation by setting the random component for the subject variable that varied from participant to participant. Therefore, by adopting this GLMM with the binary responses, we corrected the variation such as the participants' overall tendency of choosing the bigger responses on the target during the whole experiment. Subjective differences between participants can be due to inner standard on numbers, contextual cue in the paradigm, personal tendencies and so on. Consider a case that participant A tends to see the target figure to be bigger than inducers and participant B tends to see the target figure to be smaller than inducers, whether the physical size of the target is small or large. When our modeling contains a term of each participant in its random part, on neither of the stimuli condition nor the residual, individual tendencies on the responses can be corrected regardless of these overall tendencies on the responses. We were not interested in the individual variability as much as we are interested in assessing the influence of numerical value on the physical size judgment, which is set to be the fixed effect across the trials. Therefore, we described the influence of numerical value condition accurately while eliminating that of individual's response tendency on the stimuli by applying the random effect for the participant factor.

We presented the formula of (1) Linear Model, (2) Generalized Linear Model, and (3) Generalized Linear Mixed Model. A linear model is a statistical model suitable for cases where the dependent variable is continuous and follows a normal distribution. The Generalized Linear Model (GLM) is an extension of the linear model that includes cases where the dependent variable is not normally distributed like in this study with binary responses. When a dependent variable is a binomial variable (0: smaller or 1: bigger) frequently used in perception psychology research, performing logistic regression analysis adds binomial as family to transform the dependent variable in the binomial distribution, which uses the 'GLM' function in R. The GLM formula shows the main effect of independent variables X and W and the interaction effect of those with logit link function transforming probability of the bigger responses (2). We transformed Y into logit of the probability of the binary response with the mixed term in this experimental design. The Generalized Linear Mixed Model (GLMM) is a re-expanded version of a general linear model in which the linear predictor was applied so that fixed effect and random effect (random effect) are included (3).

$$\mathrm{Y} = \beta_0 + \beta_1 X_{1,i} + \beta_2 W_{1,i} + \beta_3 X_{1,i} W_{1,i} + \epsilon_i \ (1)$$

$$\mathrm{logit}(p_i) = \beta_0 + \beta_1 X_{1,i} + \beta_2 W_{1,i} + \beta_3 X_{1,i} W_{1,i} \ (2)$$

$$\text{logit}(p_{i,j}) = \beta_0 + \beta_1 X_{1,i,j} + \beta_2 X_{2,i,j} + \beta_3 W_{1,i,j} + \beta_4 X_{1,i,j} W_{1,i,j} + \beta_5 X_{2,i,j} W_{1,i,j} + \gamma_i$$

(3)

i represents the participant's id.

j represents j_{th} experiment trial on the total experiment

X_1 = 1 (if inducer = 3)

X_2 = 1 (if inducer =7)

W = 1 (if font size = big)

γ_i represents the mixed effect term, which represents each subject's variability

$\gamma_i \sim N(0, \sigma^2)$

Our data was analyzed by adding this random effects for a subject variable with GLMM. We selected the best model that contains the main effect terms of each factor and the interaction term between the numerical value factor and the font size factor. The model has the least AIC values compared with other models by comparing AIC scores of each model. The estimated variance of the random effect was 0.13 both for the model 1 and 2, which means participants' variability about the response intercept.

In this physical size comparison task, a generalized linear mixed model with binary responses revealed the significant main effect of numerical value ($\beta = 0.7$, $SE = 0.04$, $z = 16.66$, $p < .001$ for a numerically larger condition and $\beta = -0.3$, $SE = 0.04$, $z = -7.29$, $p < .001$ for a numerically smaller condition). The numerical value of inducers affected the perceived size of the target number. The main effect of font size was not significantly found ($\beta = 0.03$, $SE = 0.03$, $z = 0.97$, $p = 0.33$). It indicates that the effect of numerical value did not depend on the font size of the presented number stimuli.

In Table 1, Model 2 showed the more detailed analysis to compare the small and the big conditions and each level in a small font size condition. As we found in the model 1, the tendencies influenced by the numerical value in a small font size condition were similar to the Model 2. The difference between a semantically bigger condition of the target number 5 with inducer 3 ($\beta = -0.61$, $SE = 0.05$, $z = -10.29$, $p < .001$) and a semantically smaller condition of inducers 7 ($\beta = 0.32$, $SE = 0.05$, $z = 5.61$, $p < .001$) were significant, compared with the semantically equal condition of the target 5 with inducers 5 as a reference.

Table 1.

The independent variables were the numerical value of the inducers (3 vs. 5 vs. 7) and the font size (small vs. big) of numbers and the dependent variable was the percent of the bigger responses on the perceived target compared with the inducers in Experiment 1. Model 1 was for the main effect of the numerical value and the font size conditions. The difference between the numerical value of the font size small condition was analyzed in Model 2.

Model	Variable	β	SE	*z*	*p-value*
1	Intercept	-.00	.09	-.1	.92
	Numerical value				
	3 versus 5	.7	.04	16.7	.00*
	7 versus 5	-.3	.04	-7.3	.00*
	Font size				
	Small versus Big	.03	.03	.97	.33
2	Intercept	-.02	.09	.31	.75
	Numerical value				
	3 versus 5	.61	.06	10.29	.00*
	7 versus 5	-.33	.06	-5.61	.00*
	Font size	-.04	.06	-.75	.45
	3 versus 5 × Font size Big	.18	.08	2.23	.03*

7 versus 5 × Font size Big	.05	.08	.65	.51

*$p \leq .001$

In the font size big condition, there was a significant difference between a condition with inducers 3 (β = -0.40, SE = 0.06, z = -6.98, p < .001) and a condition with inducers 7 (β = 0.40, SE = 0.06, z = 5.91, p < .001) compared respectably with a condition with inducers 5. To be specific, the effect of numerical value was slightly larger in the larger target condition than in the smaller target condition. On the equal target condition, the font size does not show the significant effect. The value of the coefficient, 0.18, in the 3 versus 5 conditions of the big font size means that the probability of the bigger responses was larger in the big font size set than in the small font size set. Therefore, even though there was no overall effect of the font size, the percent of the bigger responses on the perceived target size were significantly different between the small and the big font size conditions when participants compared the target 5 versus inducers 3. However, it does not mean that the effect of numerical value on the bigger responses varied depending on the font size condition. In the 7 versus 5 conditions, there were no significant differences depending on the font size.

When participants compared the physical size of the target 5 with inducers 7 than with inducers 3, they were less likely to press the bigger responses based on a perceived target size (See Fig. 3). As the numerical value of surrounding inducer was bigger, it decreased the probability that participants perceived the target number of being bigger. This descending trend of the perceived size of the target based on PSE was aligned with the results of the bigger responses proportion. To summarize the result of the main effect and the interaction effect, the range of the font size had no effect on the perceived size of the target number. However, the font size effect of inducers did not significantly predict the probability that the numerical value affected the decision on perceived size of target numbers.

And the coefficient score in the condition comparing a number 5 with inducers 5 corresponded to the point of 50 percent chance level of the bigger responses ($\beta = 0.00$, $SE = 0.05$, $z = 0.08$, $p < .01$). From the difference between the value of the coefficient of 5 versus 5 from 5 versus 3, we calculated that the increased rate of the bigger responses was about 17%. And for the interaction effect between the numerical value and the orientation of numbers, the physical size of numbers. The overall tendency showed that the numerical value of inducers influenced the perceived size of the target number, even though the numerical value was task-irrelevant information.

Table 2.

The mean PSEs on each condition in Experiment 1.

Value	Font size			
	Small		Big	
	mean	SD	Mean	SD
3	27.00	0.54	48.48	1.53
5	27.97	0.52	51.02	1.42
7	28.50	0.66	51.93	1.75

Depending on the purpose of our study, we calculated the point of subjective equality (PSE) from the probability of bigger responses and the perceived target size of Arabic numbers. PSE means a specific point among stimulus dimensions at which is considered to be equal to a compared target by an observer. It corresponds to x value in a sigmoid graph, which results in 50% of frequency (y) when participants choose the bigger response with half of certainty. The PSE is given by the point at which the perceived size is considered to be same with inducers (Oh, 2015). In this study, when participants were uncertain whether the target is perceptually bigger than inducers, the estimated 50% probability (y) corresponding to the target size (x) indicates the point that participants perceive the target to be perceptually equal with inducers in each condition. For example, participants selected 'smaller' or 'bigger' responses equally towards 47mm of the target 5 with inducers 3 of 51mm, participants perceived them to be equal though the difference between them.

From every participant, we used 'GLM' package in 'R' software to calculate PSE with maximum likelihood as an estimation method as well. With the range of thirteen levels in target font sizes, the small font size condition was from 25mm to 31mm and the large font size condition was from 45 to 57. The percentage was calculated in $p = k / n$ (k: reported number of choosing the target bigger than inducers, n: 10 trials). To determine a PSE (Point of Subjective Estimation) on the target size, the percentages along a stimulus size were inputted into a logistic function formula with maximum likelihood as an estimation method (for more details, see Oh, 2015). The calculated methods used in GLM package was similar to the methods in Oh's study. The mean PSEs on 6 conditions resulted from 2 (font size) × 3 (value of inducers) were presented in table 2. The subjective point on the sigmoid function is indicative of the influence of surrounding inducers among the continuous target size on each condition.

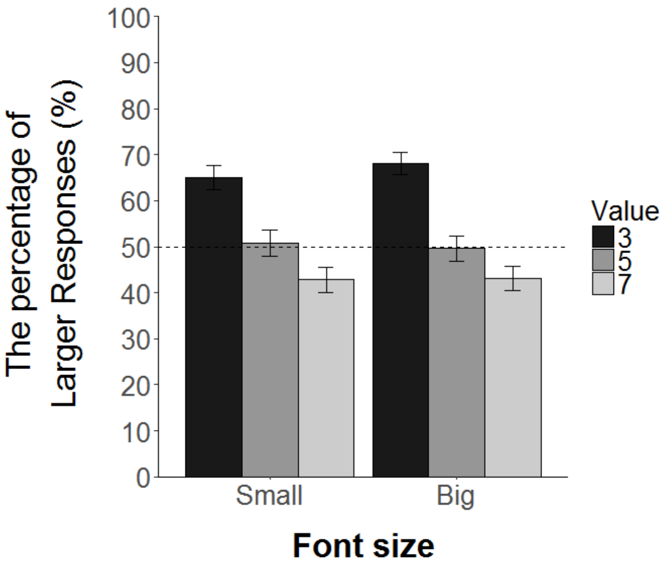

Figure 3. A bar graph split by each inducer number in Experiment 1.(Black bars for the bigger target condition with inducers 3, middle gray bars for the equal target condition with inducers 5, and light gray bars for the smaller target condition with inducers 7.

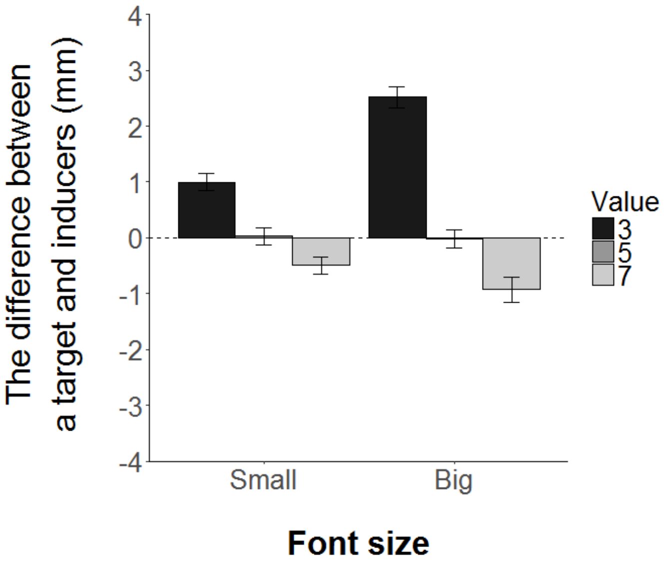

Figure 4. The differences between the perceived size of the target and inducers were driven based on PSEs on each condition in Experiment 1. The

horizontal x-axis represented the font size condition respectably divided by the inducers, 3, 5, and 7 and the vertical y-axis marked the PSEs.

According to the formula of GLM, when log odds equals zero, we can calculate the PSE on the x values which represented the target size. The coefficients for intercept and the target size were driven by the GLM formula (4) here. Per participants, as the value of x target size changes, logit transformed Y value represented the percentage of the bigger responses on each condition. PSEs were calculated based on the 6 conditions formulated by 3 (numerical value) and 2 (font size) respectably.

$$\log\left(\frac{p}{1-p}\right) = \alpha + \beta x \ (4)$$

$$0 = \alpha + \beta x$$

$$x = -\frac{\alpha}{\beta}$$

Another main interest was to estimate whether the perceived size of the central figure is smaller or larger than the surrounding numbers depending on the numerical value of inducers. The response probability graph for target size on x-axis was fitted with the GLM with logit link function. In Figure 4, the point of subjective equality (PSE) let us know at which point the perceived disparity between the central number and surrounding numbers were vague to compare their physical size. Total 114 PSE values (19 participants × 6 conditions) were analyzed (see Appendix 2). The mean PSE on each condition gradually increased depending on the numerical value of inducers. As the value of inducers increased, the perceived size of the target perceived to be equal increased (see Fig. 4 and Table 2). Figure 4 illustrated at which point the 50 percent of the bigger responses occurred while inducers numerically varied. The point that the target and inducers were perceived to be physically equal was 27mm with inducers 3, 27.97mm with inducers 5, and 28.50 with inducers 7 in a small font size condition and 48.48mm with inducers 3, 51.02mm with inducers 4, and 51.93mm with inducers 7 in a big font size condition. Indeed, the target size corresponding to the midpoint of the responses rather than the slope of the graph varied. Findings of this study showed that the perceived size of the target decreased as the inducer number increased. The result that participants were influenced by the irrelevant information on the physical size comparison tasks is aligned with the previous studies that numerical value of numbers processed automatically (Arend & Henik, 2015; Henik & Tzelgov, 1982; Reber, Wurtz, Knapstad, & Lervik, 2010; Tzelgov et al., 1992).

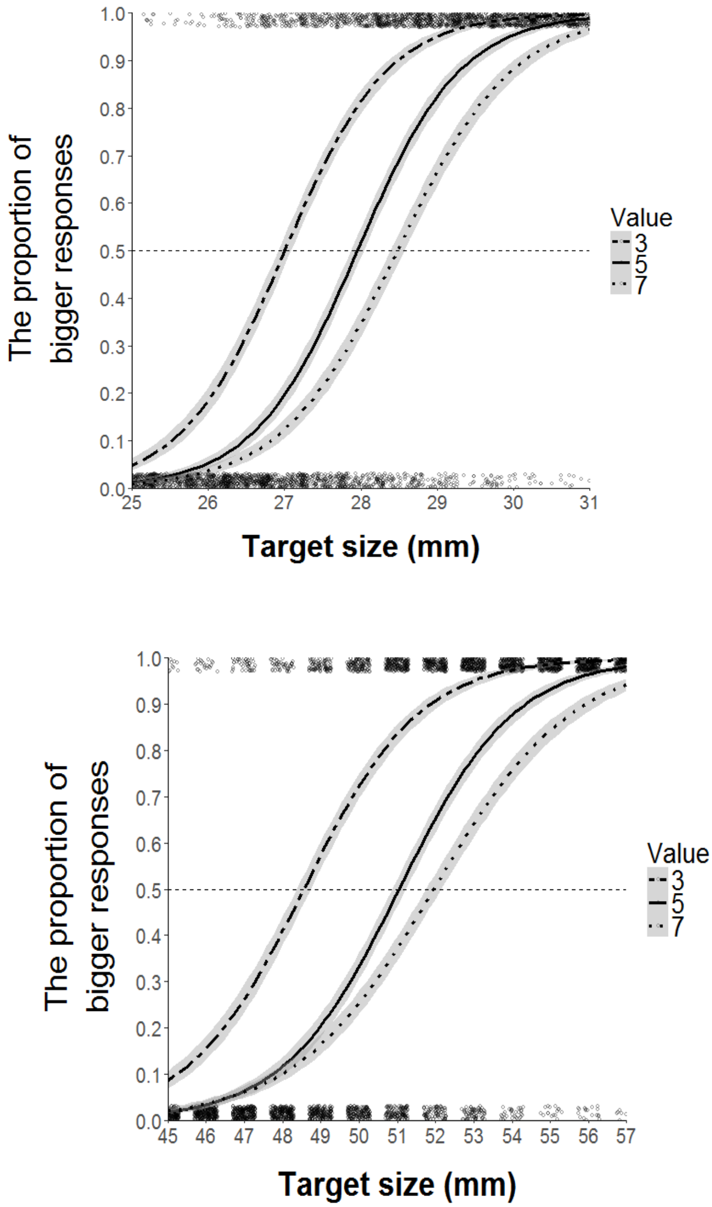

Figure 5. The estimated PSE graph in Experiment 1. (Top) A small font size condition. (Bottom) A big font size condition.

Experiment 2

We predicted that the orientation of number stimuli would affect the perceived size of numbers. Related to the results of Experiment 1, the size congruity effect allowed participants to perceive the physical size of the target larger than inducers with smaller value. In the smaller target condition, in which the numerical value of the target is smaller than that of inducers, participants perceive the target to be physically smaller than inducers. On top of this result, we were interested in the effects of automatic processing of magnitude in Arabic numbers. We expected to observe the inverse effect of numbers like the case, when the geometric figures or faces were presented inversely, the processing for the whole scene was hindered. We assumed that the participants will be less influenced by the numerical value of the inverted number stimuli rather than the upright number stimuli. Therefore, the perceived size of the targets should be approximately same or randomly different. In order to validate this assumption, we ran the second study of the same procedure with Experiment 1 while presenting two different oriented stimuli sets. The exactly same number stimuli used in Experiment 1 was the upright version and the other one was the inverted version.

Method

Participants

As part of their course requirements, 22 undergraduate students (10 female) took part in Experiment 2. Their age ranged from 18 - 29 (M = 20.09, SD = 2,33). One of the participants was excluded from the data analysis later due to the incomplete answers. None of them participated in the previous experiment, and all of them reported the normal or corrected to normal vision.

Stimuli

The Arabic stimuli used in Experiment 2 were the same as that of the large font size condition in Experiment 1. There were two stimulus types used in this study: 1) the upright number condition and 2) the inverted number condition. The Arabic stimuli sets for the upright version was identical to that of Experiment 1 and other stimuli sets for the inverted version was also basically same except that the target and inducers were rotated 180 degrees.

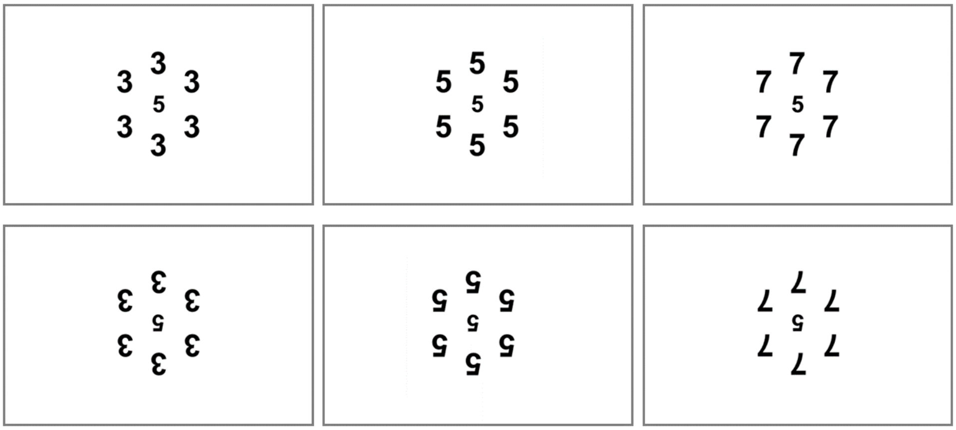

Figure 6. The stimuli of Experiment 2. (Top) A upright number version. (Below) The inverted number version.

Procedure

Each participant performed the physical size comparison task which is identical to that in experiment 1. The order of the upright and inverted version stimuli session was counterbalanced across the two groups. Half of the participants were randomly assigned to a session starting with the upright condition and then with the inverted condition. The order of the session was reversed for the remaining participants. Each trial consisted of the presentation of a fixation, one array of number stimuli, the gray screen receiving the response, and the mask screen. After the stimulus presentation lasted 500ms, the response screen remained until the participants chose the bigger or the smaller button on the keyboard. All the stimuli were randomly presented within each block. The whole session lasted approximately 40 minutes.

Design

The variable that we were particularly interested in was the orientation (upright vs. inverted) of numbers. The semantic relationship between the target number 5 and inducers were same with the experiment 1. Thus, the design was 3 (numerical value) × 2 (orientation) × 13 (physical size variation of the target) with all variables within the subject. Every block had 78 trials (3 numerical value × 13 levels of physical size × 2 orientations), thus 10 cycles of each block created total 780 trials in the whole experiment.

Results

In Model 1, the significant main effect of the numerical value indicates that the reason why the perceived size of the target decreased resulted from the different magnitude of inducers. It showed how much participants were affected by the numerical value in the target smaller or bigger condition compared with the equal target condition as a standard. The perceived size of the target 5 with inducers 3 ($\beta = 0.59$, $SE = 0.04$, $z = 15.5$, $p < .001$) and that with inducers 7 ($\beta = -0.31$, $SE = 0.04$, $z = -8.5$, $p < .001$) were significantly different. The value of the coefficient, 0.77 in the target larger condition (5 vs. 3) means that participants perceived the target physically bigger when the target was larger than the surrounding numbers, compared to when the target was equal to or smaller than the inducers. There was no statistically significant orientation effect. The perceived size of the target did not depend on the orientation of the number stimuli.

For Model 2 to elaborate the effects depending on each condition, the intercept indicated the condition comparing a number 5 with inducers 5 (β = 0.00, SE = 0.05, z = 0.08, $p < .01$). From the difference between the value of the coefficient of 5 versus 3 and 5 versus 5, we can calculate that the rate of the bigger responses was increased by about 17%. The Model 2 presented that each condition of 5 versus 3 and 5 versus 7 was significantly different in an upright number condition.

Table 3

The independent variable was the orientation of numbers (Upright vs. Inverted) and the numerical value of the inducers (3 vs. 5 vs. 7) and the dependent variable was the percent of the bigger responses on the perceived target compared with the inducers in Experiment 2.

Model	Variable	β	SE	*z*	*p-value*
1	Intercept	.08	.05	1.77	.07
	Numerical value				
	5 versus 3	.59	.04	15.5	.00*
	5 versus 7	.31	.04	-8.5	.00*
	Orientation	.03	.03	.97	.33
2	Intercept	.00	.05	.08	.93
	Numerical value				
	5 versus 3	.77	.05	14.46	.00*
	5 versus 7	-.23	.05	-4.56	.00*
	Orientation	.20	.05	3.86	.00*
	5 versus 3 × Orientation I	-.38	.08	-5.86	.00*
	5 versus 7 × Orientation I	-.15	.07	-2.06	.00*

*$p \leq .001$

For examining the further analysis, the equation (2) needs to be factorized with X_1 and X_2. Each factor represents the condition according to the numerical value: X_1 is for a condition of the target 5 versus inducers 3 and X_2 is for a condition of the target 5 versus inducers 7, and W is for a condition of the orientation. The coefficients in the parenthesis with the factor X_1.

$$\text{logit}\left(\frac{p}{1-p}\right) = \beta_0 + (\beta_1 + \beta_4 W_{1,i})X_{1,i} + (\beta_2 + \beta_5 W_{1,i})\, X_{2,i} + \beta_3 W_{1,i} \quad (3)$$

i represents the participant's id.

$X_1 = 1$ (if inducer = 3)

$X_2 = 1$ (if inducer =7)

W = 1 (if the orientation = inverted)

When W = 1,

$$\text{logit}\left(\frac{p}{1-p}\right) = \beta_0 + (\beta_1 + \beta_4)X_{1,i} + (\beta_2 + \beta_5)\, X_{2,i} + \beta_3 \quad (3)$$

And if Y equals 1, which represents the inverted version, we can test the difference according to the numerical value condition whether the combined coefficients of each X, numerical value, is zero or not. For the condition of 3 versus 5 with the inverted number stimuli, the coefficient of X_1 can be tested: β_1 is the coefficient comparing a 5 versus 3 condition in the upright number condition and β_4 is the coefficient comparing the increased difference of a 5 versus 3 condition between the upright number and the inverted number. The coefficient of X_2 was tested along this line for each β: β_2 is when comparing 5 versus 7 in a upright number condition, β_5 is when comparing the increased difference of a condition of 5 versus 7 in an inverted number and a upright number condition. So, when testing the hypothesis that the summed coefficients of each X_1 and X_2, there were significant difference in both conditions (β=-0.40, SE = 0.06, z = -6.99, $p < 0.001$ for 5 versus 3 and β=0.40, SE = 0.06, z = 5.91, $p < 0.001$ for 5 versus 7).

The proportion of the bigger responses and the difference between the perceived size of the target and inducers showed the consistent pattern that, when participants compared the physical size of the target 5 with inducers 7 rather than with inducers 3, they were less likely to press the bigger responses (Fig. 7 Top). As the numerical value of inducers increase, the percentage of the bigger responses decreased, which seems that participants perceived the target number to be smaller. This descending trend of the PSEs was aligned with the results of the bigger responses proportion. It was noticeable that we could not observe the orientation-driven effect because it was assumed that the orientation was closely tied to the processing of the numerical representation. The orientation of numbers did not significantly predict the probability that the numerical value affected the decision on the perceived size of target numbers.

As in experiment 1, PSEs per each condition were calculated in the same way. In Fig. 8 of the upright version condition, the perceived target size, when the target and inducers were perceived to be physically equal, was 48.49mm with inducers 3, 50.99mm with inducers 5, and 51.80 with inducers 7. And, in the inverted version condition, the perceived target size was 49.03mm with inducers 3, 50.32mm with inducers 5, and 51.64mm with inducers 7 in a big font size condition. The Ebbinghaus illusion effect emerged with inducers 3 in both the versions. Participants perceived the target with inducers 3 to be perceptually smaller than its actual size of 51mm, whereas there was no illusion effect to perceive the target to be smaller than surrounding numbers 7. The differences between PSEs on each condition show slightly different patterns, yet. Participants responded coherently whether the numbers were presented upright or inverted.

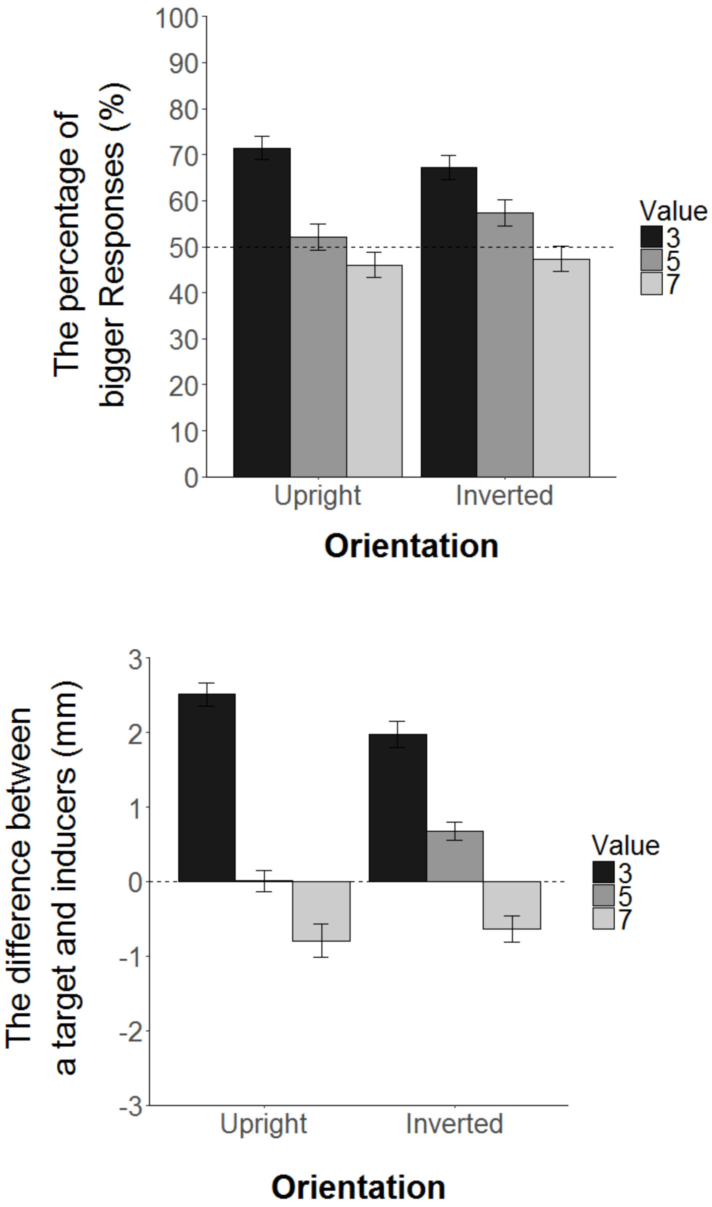

Figure 7. Experiment 2. (Top) The bigger response rate. The dotted line indicates the chance level where participants perceived the target figure to be equal with the inducers. The error bars indicate standard errors. (Bottom) The difference between the target and inducers calculated based on the PSE points.

The dotted line from the y-axis corresponding to 0 indicates the physical size of inducers fixed as a reference point. The error bars indicate standard errors.

Table 4. The mean PSEs on each condition in Experiment 2.

Value	Orientation			
	Upright		Inverted	
	mean	SD	mean	SD
3	48.49	1.00	49.03	0.91
5	50.99	0.90	50.32	0.84
7	51.80	1.20	51.64	0.97

The major manipulation in which Experiment 2 differed from Experiment 1 is that we rotated the orientation of Arabic numerals. Unlike our assumption, the inverse effect generally found with the complex configurations was not observed in the inverted number condition. The face turned upside down has been widely identified to impair the recognition performance (Goldstein, 1965; Hochberg & Galper, 1967; Yin, 1969), whereas the inverted numbers in this experiment and the inverted geometric figuration in Coren and Enns' study (1993) did not change the illusion effect with the prototype stimuli. However, it has been suggested that the effect can be specifically confined to the face compared to other types of materials such as canine and building (Scapinello & Yarmey, 1970) and the expert domain of dogs (Robbins & McKone, 2007). Also, high familiarity with one digits can delete the inversion effect. The difficulty to recognize the rotated stimuli can vary depending on how we encounter the objects frequently. Another aim of Experiment 2 was to rule out the influence by the different visual perimeters of numbers on the perceived size. This result robustly stands for the idea that automatically processed magnitude of numbers has a predominant influence than perimeter of numbers even when the participants gave an attention to their physical appearance.

Furthermore, we suspected that the consistent pattern with inducers 3, 5, and 7 in both conditions can be the subsets triggered by the numerical distance between the target and inducers, not only by the simple inner encoding to classify the target based on a binary criterion, smaller or greater than inducers by their magnitude. If the percent of the bigger responses gradually decrease as the value of surrounding numbers increases by testing this effect within more wide range, this result implies that the exquisite mapping between the target and inducers as in the mental number line.

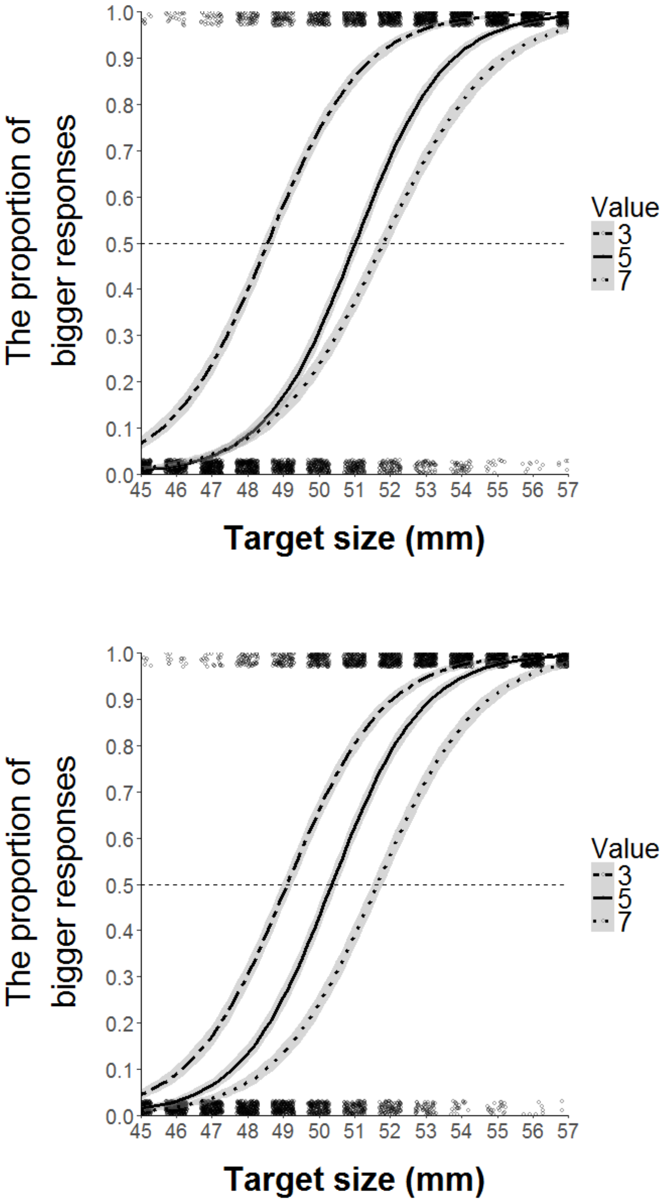

Figure 8. The fitted logistic graph of the bigger responses in Experiment 2. The dashed line in the y-axis represents the uncertainty when participants perceived the target to be physically equal with the inducers. (Top) A upright number condition. (Bottom) An inverted number condition.

Experiment 3

Experiment 3 was conducted to investigate the numerical distance effect in addition to supporting the results in Experiment 1 and 2. Our interpretation of the results in the previous experiment was based on the assumption that the numerical value generated the variation of the perceived size even while people compare the physical size of numbers. So far, we tested the size congruity effect with repetitive stimuli sets of 5-3, 5-5, and 5-7, which was organized by the three kinds of semantic relationship between the target and inducers (the numerically larger target, the equal target, and the numerically smaller target). If the illusion effect was caused primarily by the automatic processing of magnitude, and not by the visual properties of numbers or the response bias to follow just the relative difference between two numbers, it should reveal that the numerical distance effect occurs systematically based on a mental number line or memory-wise association of numerical value in this illusion paradigm. If the visual properties were not the main factor to cause the size congruity effect in experiment 1 and 2, the size contrast between the target and inducers would increase as the numerical distance increase between the target and inducers. Also, if the results were caused solely by the cognitive bias, even we ruled out the tentative possibility by manipulating the orientation of stimuli in experiment 2, there should be little difference in the perceived size of the target. Otherwise, there will be the symmetric pattern in the perceived differences regardless of the numerical distance between the target and inducers. The reason behind this assumption is that, if there is the numerical distance effect in this design, it should be constrained to one of the memory-based models: the laterality model, the graded associations model, and the retrieved instance model (Choplin & Logan, 2005). The laterality model assumes that laterality, where number 5 is the criterion to classify the smaller numbers from 1 to 4 as small and the greater numbers from 6 to 9 as large, functions as a dichotomous standard. The graded associations model posits the symmetric semantic association according to the distance between the number 5 and other one digits increases. For example, the most distant digit 1 is strongly associated as small compared with the middle digit 5, whereas, another most distant digit 9 is strongly associated as large compared with the digit 5. The retrieved instance model took the assumptions of the frequency of occurrence, where the digit has already had the attribute "small" or "large", and the link between the digit and the retrieved "small" or "large" attribute is related to how we are familiar with the digits in daily lives. For example, we accustomed to digits from 1 to 4 frequently than greater digits, and number 1 is strongly associated with "small" than when number 9 is less associated with "large". We regard the graded associations model as our function to predict the numerical distance effect here. The broad range of inducers from 2 to 9 was only adopted in the repeated design for this experiment without any additional factors in order to verify the numerical distance effect. Number 1 was short in the width, so it initially excluded from the stimuli set when compared with other numbers. Also, the size congruity effect of incongruent condition in the physical size task was strong when the numerical distance is far rather than close (Henik & Tzelgov, 1982). For instance, in our design, with the target 5 which serves as a standard, the variation of the distance 1 compared with 4 or 6 and distance 2 compared with 3 and 7 can modulate the physical comparison process and the greater numerical distance may enhance the semantic influence of numbers on illusion. Therefore, the effect by pairs of the distance 1 (4-5, 6-5), distance 2 (3-5, 7-5), distance 3 (2-5, 8-5), and distance 4 (5-9) can be examined. We expected that the illusion effect of the pairs of the distance 3 is larger than that of the distance 1 or 2.

Method

Participants

22 students (female = 11, mean age = 20.23 years, SD = 1.76) participated in the experiment. None of them participated in the any of previous experiments.

Stimuli

The properties of stimulation were the same as those in experiment 2, except for the ranges of numerical value. We used inducers from 2 to 9 with the target 5 that created three numerical distance pairs except for number 9: Unit 1 of numerical distance (4-5, 6-5), unit 2 of numerical distance (3-5, 7-5), and unit 3 of numerical distance (2-5, 8-5). The number 1 was initially excluded for the relative lack of the width compared with the rest of the numbers. But number 9 was included as a number with unit 4 of numerical distance. The central stimulus was the number '5' and the peripheral stimuli varied among the numbers from 2 to 9.

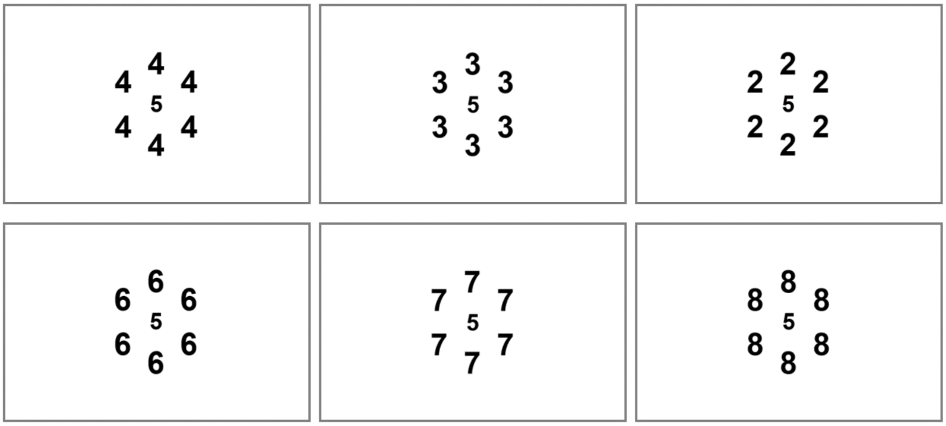

Figure 9. The stimuli in Experiment 3. The sample of 5 versus 9 was not presented. The first column is for numerical distance 1, the second column is for numerical distance 2, and the third column is for numerical distance 3.

Procedure

The procedure was identical to the previous experiment in all aspect without the range of stimuli. Each numerical stimuli were randomly presented as an array once in each block. Participants performed three sessions of trials and there were 5 minutes breaks between the sessions. All the stimuli were randomly presented within each block. The whole session lasted approximately 50 minutes.

Design

The variables that we are particularly interested in were the numerical value of inducers (2, 3, 4, 5, 6, 7, 8, or 9). The semantic relationship between the target number 5 and inducers was same with the experiment 1. Thus, the design was 8 (numerical value) × 13 (physical size variation of the target) with all variables within the subject. Every block had 108 trials, thus 10 cycles of each block created total 1080 trials in the whole experiment.

Results

The each condition of numerical value were all significantly different compared to the condition of the target 5 versus inducers 5 as a reference (Table 5). However, the expected influence of numerical value was only confirmed in the conditions of inducers 3 ($\beta = 0.92$, $SE = 0.06$, $z = 16.48$, $p < .01$), 4 ($\beta = 0.2$, $SE = 0.05$, $z = 3.78$, $p < .01$), 5 ($\beta = -0.06$, $SE = 0.08$, $z = -0.79$, $p < .01$), 6 ($\beta = -0.19$, $SE = 0.05$, $z = -3.52$, $p < .01$), and 7 ($\beta = -0.51$, $SE = 0.05$, $z = -9.3$, $p < .01$). In this range of inducers from 3 to 7, as the numerical value is getting larger, the bigger responses rate was smaller. In the conditions with inducers 2, 8, and 9, the perceived size of numbers appeared to return to the point of the equal target condition.

Table 5

The independent variable was the numerical value of the inducers (2-9) and the dependent variable was the percentage of the bigger responses on the perceived target compared with the inducers in Experiment 3.

Variable	β	*SE*	*z*	*p-value*
Intercept	-.06	.08	-.79	.43
Numerical value				
2 versus 5	-.13	.05	-2.47	.01*
3 versus 5	.92	.05	16.48	.00***
4 versus 5	.20	.05	3.78	.00***
6 versus 5	-.18	.05	-3.52	.00***
7 versus 5	-.50	.05	-9.30	.00***
8 versus 5	.22	.05	4.16	.00***
9 versus 5	-.13	.05	-2.52	.01*

Note: *p<.01; ** $p \leq .001$; ***p ≤ 0

As in Experiment 1 and 2, PSEs per each condition were calculated. In Table 6, clearly, the perceived target size varied depending on the numerical value of inducers. Indeed, the perceived size of the target increased, as the numerical magnitude of inducers increased in the ranges from 3 to 7. Yet, the results of Experiment 1 and 2 were partially replicated in Experiment, nor is it coherent with the idea of the distance effect that the reaction time increased linearly as the units were getting distant between two numbers during the physical comparison task. That is, though the unexpected downturn appeared with inducers 2, 8, and 9, it is likely that the illusion effect emerged with inducers from 3 to 7. Therefore, we assumed that, unlike the previous results, the edge digits such as 2, 8, and 9 have some particular reason to overwhelm the influence of magnitude, which we will discuss later in the discussion section. This suggests that the visual properties and the semantic magnitude of numbers compete with each other interchangeably rather than constantly, which implies the possibility to support the shared representation account.

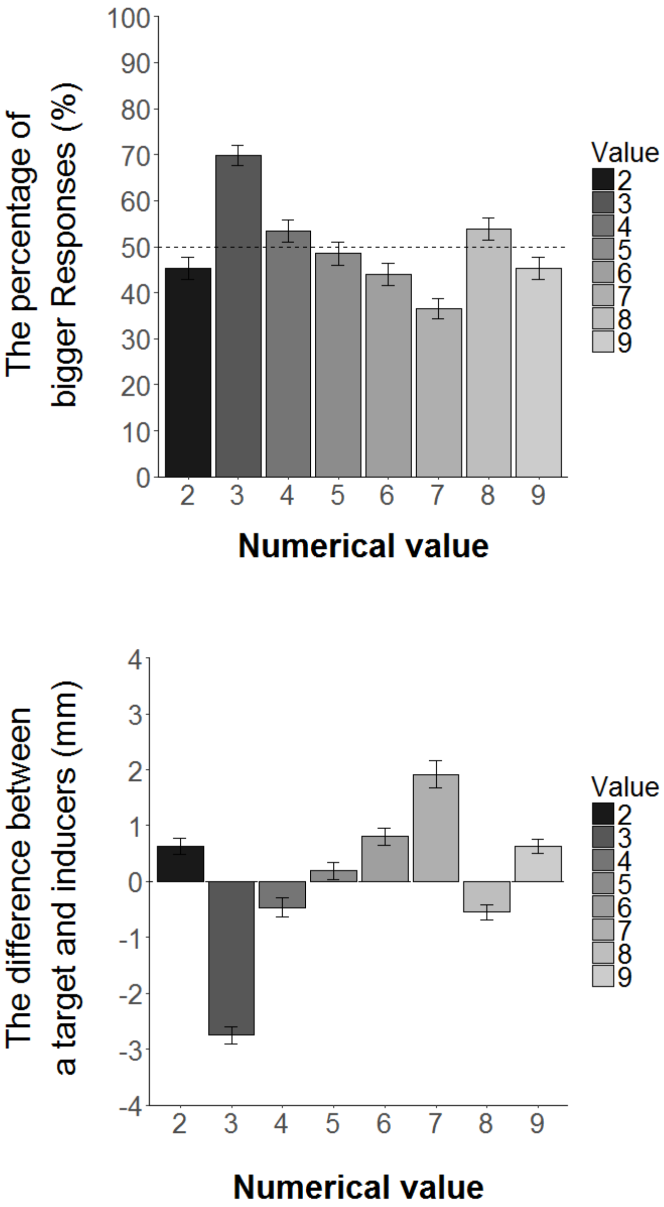

Figure 10. Results of Experiment 3. (Top) The percentage of the bigger responses. The dotted line indicates the chance level where participants perceived the target figure to be equal with the inducers. The error bars indicate standard errors. (Bottom) The differences between the target and

inducers calculated by PSEs (mm). The dotted line indicates the physical size of inducers as a reference point. The error bars indicate standard errors.

Table 6.

The mean PSEs on each condition in Experiment 3.

Value	mean	SD
2	51.63	1.24
3	48.25	1.24
4	50.53	1.24
5	51.19	1.16
6	51.80	1.42
7	52.91	1.91
8	50.45	1.34
9	51.63	1.26

General discussion

The overarching question was whether the automatic processing of magnitude influences the perceived size of number while the size contrast between the target and inducers were enhanced in the Ebbinghaus typed arrangement. In this study, we have strongly argued that the numerical value with an autonomous processing affected the perceptual decision even when the physical size comparison task requires no numerical information, the irrelevant dimension of information. Participants were required to answer whether the central Arabic symbol is physically larger than other surrounding numbers. When the irrelevant attribute of numerical value was matched with the relevant attribute of the task, it was called a congruent condition. When a numerically bigger number 5 is perceptually bigger than 3, it is congruent in that the task-relevant attribute, the numerical value of 5, is associated with the physical size of 5. However, previous studies observed the pattern mostly in the reaction time paradigm. Accordingly, it was unclear whether the effect reflects a perceptual process, or simply a cognitive bias because analyzing the response duration data can be interpreted as both, a perceptual early process and a competition at the decision. In this study, we measured the perceived size of numbers across different semantic relation between numbers in the Ebbinghaus paradigm.

One of our key findings supported this argument in that the perceived size of the target figure can be affected by the value of the surrounding numbers regardless of font size (Experiment 1) and the orientation (Experiment 2) of number stimuli. Before discussing the unexpected results in Experiment 3, we summarized the main results of these experiments. The data from Experiment 1, where the digit 3, 5, and 7 in two font size conditions were displayed, results on small font size condition mirrored those for the big font size condition. The resembled pattern between two font sizes showed that the digits with bigger value were processed perceptually larger. This implies that the automatic processing of numbers generally occurred regardless of the global size of the number stimuli. In Experiment 2 where the orientation of the stimuli was manipulated, the influence of numerical value was consistent with both the upright number stimuli and the inverted number stimuli. The repeated finding of the size congruity effect on the perceived size was found in Experiment 2 as well.

We can get a hint on this result of the inverted number condition from the study on size perception in the relationship between meaning and symmetry using meaningful and meaningless stimuli (Reber, Christensen, & Meier, 2014). The authors do not only distinguish the effect on the judged font size between meaningful Arabic numbers and meaningless characters constructed of numbers, but also suggest that large numbers tend to be perceptually larger than smaller numbers. They let participants judge the font size after the stimuli were presented for 200 msec, which is a similar aspect of the procedure accepting the responses after 500 msec of the presentation in our study. It also appears plausible that the digits in the illusion arrangement were presented long enough to activate the automatic magnitude processing of both the upright condition and the inverted condition in our study. They observed the positive and significant correlation between the numerical value and the perceived font size only for numbers, not for meaningless words. Unlike the meaningless word, the inverted numbers seem to bear numerical meaning even though the numerical meaning may not be significantly harder to process than the upright condition. These results are an interesting demonstration that the automatic processing occurs even the task was irrelevant to the numerical value and the numbers were presented inversely. Coren and Enn's study also provides some experimental evidence to keep the magnitude information by presenting the prototype geometric figures and the inverted version of it (Coren & Enns, 1993). When the orientation of the stimulus changes in the state where the visual properties and the conceptual category were preserved, the illusion effect was the same in the Ebbinghaus paradigm (see Coren & Enns, 1993; Fig. 7 in Exp. 4).

Though this kind of inverse effect was commonly identified with the complex figurations, the physical elements of numbers in our Experiment 2 were kept in the inverted condition as well. Still, there was a strong and coherent result when participants judged the perceived size of the inverted numbers, which was aligned with the results of Experiment 1. Therefore, we suggest that this result appeared while the semantic meaning of the inverted number was stronger than the effect of visual properties such as different lines and perimeters.

To be specific, there would be two possibilities to explain the observed findings. The first possibility would be that the physical properties were dominant rather than the numerical value, which randomly yields the similar pattern for both the upright and the inverted stimuli. However, given that the differences between the coefficients of the condition with inducers 3 and 7 are respectably consistent in the inverted condition, it is unlikely that participants were affected only by the physical properties. The descending percent of the bigger responses in the inverted condition resembled with that in the upright condition. Second, another possibility would be that participants only relied on their retrieved numerical meaning from memory. Consider the case that participants roughly guessed the perceived size and biased by the numerical value of inducers. That is, if participants' performance reflected just the memory-based retrieval or the response bias to select the numerically greater number, the intervals between PSEs for each condition were much larger than the current result in Experiment 2. However, it says little as to the simple cognitive bias while ruling out the possibility based on the fact that the PSEs depended on the numerical value in both conditions.

With this line of interpretation, an alternative hypothesis would be strong that this occurred as a part of the mental number line. The result in the inverted number condition can substantiate the autonomous process of magnitude with Arabic numbers as another evidence to support in the situation when the semantic meaning of the symbols may be harder to process. On theoretical grounds, we believe that the automatic processing of numerical information relies on the stored numerical representation of single-digit integers, whereas we initially speculated that the inverted number may not activate the automatic processing. Numerical representation by automaticity was not dependent on the different orientation of numerical stimuli within the same format of Arabic numerals. The mental number line implemented by the single-digit numbers was in line with the previous researches on the automaticity based on the retrieved memory (Logan, 1988). The form of the one-digit numerals was exclusively necessary for the primitive characteristics of numerical representation, whereas other forms such as double-digits (Ganor-Stern, Tzelgov, & Ellenbogen, 2007), negative integers (Tzelgov, Ganor-Stern, & Maymon-Schreiber, 2009), and fractions (Kallai & Tzelgov, 2009), and decimals (Kallai & Tzelgov, 2014) were found to be processed intentionally but not automatically. As far as we know, there was no literature which tested the size congruity effect on the perceived size while presenting the inverted number stimuli. Thus, we found that the values are definitely perceived and affect our judgment process even when the numbers are rotated. In addition, this can be attributable to how numerals are stored and compared with each other as an analogue form in the several studies on the size congruity effect (Ganor-Stern & Goldman, 2015; Ganor-Stern & Tzelgov, 2008; Ganor-Stern et al., 2007; Gilmore, Attridge, & Inglis, 2011; Tzelgov & Ganor-Stern, 2005). Taken together, similar results even with rotation-related differences can explain that the size congruity effect influences the perceived size of numbers. These results were very probable that, when participants were asked to compare the physical size of numbers, they autonomously processed the physical size as well as the numerical value together. This was aligned with the time-series data of ERP methods showed that numerical value of numbers was processed faster than physical size of numbers (Gebuis et al., 2010)

One unexpected result from Experiment 3 was that the increased pattern from numbers 3 to 7 was not consistent with that with numbers 2, 8, and 9. If the numerical representation of numbers were considered simultaneously in this physical comparison task, this is attributable to the automatic process of magnitude which is irrelevant to the performance of the task. However, the incoherent findings suggest that the linearized pattern found in the small numerical distance with 3 to 7 is the main effect and no distance effect of the large numerical distance with 2, 8, and 9 stemmed from another reason such as visual saliency only with those numbers. Sobel and colleagues' study can be compatible to support this explanation. When the targeted singleton popped out among the visual array due to red color or the increased density, the target captured the participant's attention (Sobel et al., 2016). With the red singleton, this boosted saliency of the target yield flat function for reaction time and the size congruity effect disappeared in the incongruent condition (Sobel et al., 2016; see Experiment 2). As they also noticed the possibility that the shape rather than the numerical value of numbers were a guideline to search the target, there was an interaction between the numerical value and physical size in their Experiment 1. Indeed, in our Experiment 3, it is unlikely that the significant difference from 3 to 7 was not carved out from the influence of numerical value. It had been already showed that, irrespective of the visual properties of the rotated numbers, the existence of surrounding Arabic numbers coherently made a similar impact on the perceived size of the target in Experiment 2. In the view of this, the visual properties such as the line and the shape of numbers play little role in the appearance of the numerical distance effect from 3 to 7, whereas it is possible that the particular visual saliency of numbers 2, 8, and 9 outplayed the influence of numerical magnitude.

Extending the possibility of the saliency of the physical properties, one may argue that all the result of Experiment 3 were caused by the physical characteristics of Arabic numbers rather than the numerical value of those. Related to this question, recently, the physical similarity function was suggested by calculating the differences between 5 and other one-digits based on the number of strokes in the digital clock number format (Cohen, 2009). The physical similarity correlated with the numerical distance affected the reaction time even when using 70 random fonts (Cohen, 2009; Experiment 2). It was doubtful that the physical similarity as a fundamental theory revolving around the numerical distance effect in the standard physical comparison task because it was proven only in the same/different matching task between 5 and other one-digits, where the physical similarity and the numerical value was both the relevant information. As Goldfarb et al (2011) noted the task-dependent distance effect, the distance effect occurred in the numerical comparison task, which triggered the intentional processing of magnitude, but, did not occur in the matching task, which triggered the automatic processing of magnitude, not requiring the strong activation of the mental number line. Therefore, the distance effect found in the standard comparison task should be attributable to the magnitude representation of numbers, not to the physical similarity. Therefore, Cohen's result observed with the matching task was neither compatible with the physical comparison task in the current study nor the necessary reason on why the partial results were observed with edge digits, 2, 8, and 9. Still, though the height of numbers was constant based on the globlal font size (mm), the most lengths of width or height can generate uncontrolled perceptual properties (i.e. pixels, height or width). So, it is possible that the magnitude of illusion can be differed by the visual properties of each number. Thus, if we consider the further study, drawing circle lines around the number stimulus can control the influence of the inherent shape of numbers.

Numerical distance effect and the laterality

If the numerical magnitude influences the perceptual process, what are the properties of numbers that manipulate whether the distance effect disappears? The partial effect can be a product of other factors: consider the situation that the expected PSEs from 3 to 7 are due to the numerical value invading the perceptual decision process as an irrelevant information and other unexpected PSEs of 2, 8, and 9 are due to the changed criterion based on perimeter of the visual stimuli. Similarly, there was a case that the numerical distance effect did not appear in the physical size comparison task excluding 5 (Tzelgov et al., 1992). In their Experiment 1, to verify the numerical distance effect, a rectangle, which held the physical size information without the numerical information was presented as the standard stimulus. Although displaying the standard stimuli at the beginning of the session triggered "the interdimensional consistency" to classify the numbers as only smaller or bigger in the physical size and the size congruity effect with the automatic processing of magnitude in the parity task, the numerical differences between the number stimuli and the inner standard were not dominantly assessed. The distance effect requires the exquisite intentional processing to map the stimuli onto matched magnitude in the mental number line (Tzelgov et al., 1992). Therefore, lack of the elaborated automatic processing of magnitude between digits and the standard, even with the presentation of number 5, the numerical distance effect was absent in the physical size comparison task (Tzelgov et al., 1992, Experiment 3). Even though, previously, there was the fact that slower reaction time with unit distance 4 rather than 2 in the incongruent condition of the standard physical comparison task, the pairs of distance 4 were bilateral not including the number 5 (Henik & Tzelgov, 1982). In this discussed physical comparison task including 5, this can explain the result with the edge digits such as 2, 8, and 9 compared to the target 5 in our study because our number stimuli sets were bilateral including digit 5. We presented the number 5 explicitly as the target. If the crude automatic processing happens as in Tzelgov and colleagues' study (1992), it is possible that the weaker association between number 5 and other distant digits such as 2, 8, and 9 can diminish the numerical distance effect, while participants perceive the bilateral pairs including the digit 5. This finding with inducers the edge digits, 2, 8, and 9, is not completely in line with the graded association model as our first assumption, rather, is in line with the laterality model. Again, it is clear that the distance effect largely depends on the task requirement and the number pairs.

Conceptual categorization of numbers in size comparison

A robust finding cemented that conceptual categorization of numbers intervened on a judgment of perceived size in Ebbinghaus illusion paradigm.

If the semantic categorization of number doesn’t affect the illusion, the PSE would be equivalent across conditions and near at the actual size of inducers, 22mm or 51mm. Reversely, if the illusion is influenced by a semantic value, the perceived stimulus size will decrease or increase depending on the numerical value by its contextual relations. Certainly, PSEs with the target smaller domain was below the standard size of inducers, whereas PSEs with the target bigger domain was above the standard size of inducers in Experiment 1 and 2. For instance, when comparing the target 5 with surrounding numbers 7, 5 might look much smaller than 7 in that 5 is semantically smaller than 7. Therefore, a dimension of the target 5 had to be big enough to be perceived equal with the inducer 7. In other words, only when 5 reached about 52mm, which is physically larger than inducers, it was vague to judge whether 5 looks bigger or smaller than 7. In the same target domain, PSE reached below around 51mm, which the illusion effect occurred. Lastly, PSE in the smaller domain with the inducer 3 was slightly lower than a condition with the inducer 5. As 3 has less numeric value than 5, inducer 3 rather than 5 or 7 might enhance the apparent size of the target 5. Thus, participants clicked the ‘bigger’ button when they compared about 49mm of the target 5 and 51mm of inducer 3. Note that, until PSE on the perceived size, the target seemed to be smaller than surrounding inducers, even the physical size of the target was equal or larger than inducers. In sum, the level of PSEs increased because the target seemed to be the same as the inducers with bigger value until the physical size of the target became actually bigger than them. It may be ticklish concerning in that semantic difference among numbers may hinder when participants judge a perceived size of the center number relative to surrounding numbers, but still, it is clear that participants were affected by both the magnitude and visual properties of numbers. Beyond the optical illusion at the low level, we identified the dynamics of the perceptual and cognitive process with Arabic numbers, which was perfectly aligned with the previous literature that the conceptual meaning influences the illusion effect (Coren & Enns, 1993; Coren & Miller, 1974).

Three major issues related to the influence of numerical magnitude

We would like to wrap up the discussion by presenting how the largely ongoing three issues are in relation to this study as follows. Controversial debates brought the questions at which phase the two distinguished information of numbers are compared and combined. Existing response time and accuracy measurements did not reveal whether the two attributes would cause a collision from the moment we saw the numbers, or at the decision stage where we were worried about which number to choose. Response time includes all the steps of representing two attributes in our mind from the perception step to process the stimulus and determining the response to it and putting it into practice, but it is a measurement that includes the reaction at each step. However, it is essential to note which step affects the magnitude coincidence effect of the number. During the process from perceptual phase to the judgment phase, there are two kinds of the model to explain the processing of numbers and its relational mechanism of the size congruity effect. This triggered our main concern on the autonomous processing of magnitude in the physical comparison task.

The first issue is to clarify in this study whether the size coincidence effect is a phenomenon occurring at the stage of perception or cognitive decision. There has been a discussion that it is necessary to ascertain which layer of the competition is occurring when the size consistency effect occurs due to the competition between two numerical attributes, the semantic size and the physical size (Walsh, 2003; Keus and Schwarz, 2005; Gevers et al., 2006). Schwarz and Heinze (1998) assumed that an integrated representation occurred between two attributes of numbers supported before the response in the early stage model by testing the numerical size congruity effect with EEG. Based on this theory, the P300 component of EEG recorded more rapidly in the processing of the difference between the 'semantic size' and 'perceptual size' of the numbers than the LRP component that captures hand movements in the response phase (Gebuis et al., 2010). However, there is no attempt to measure directly the perceived size of numerals as we attempted with calculating PSEs. By applying the illusion paradigm in the experiment design, we found that the numerical value of numbers is a powerful property which affected on how numbers were actually perceived, even when the physical size of numbers is solely a dimension of a task related property.

In addition, the second issue is a subset under the theory of magnitude (ATOM), which outlined the shared magnitude dimensions among different scaled units such as space, time, and number (Walsh, 2003). Explorative studies to associate the possible combination generating the size congruity effect between magnitude and quantitative elements such as pitch, brightness, color, texture, and so on. The researchers have explored the various associations between numerical magnitude and quantitative dimensions. The observed results were as follows on luminance the priming effect on conceptual size of animals (Gabay, Leibovich, Henik, & Gronau, 2013), numerosity, length, and duration of time (Crollen et al., 2013), brightness (Kadosh, Kadosh, et al., 2008; Viarouge & de Hevia, 2013), cross-sensory congruity effect on brightness and edibility (Walker, Walker, & Francis, 2015), action and perception (Chiou, Chang, Tzeng, & Wu, 2009). Though the integrative effect covering the inputs from sensory organs associated with quantities were broadly identified, without accounting the interactive process between symbolic numbers and magnitude, these studies only find the possible associations among various dimensional information.

The similar implication of the current study holds in the third approach on what is the structural and functional basis of the brain on to be. The neuroscientific attempts toward numerical cognition have extensively proved the shared location managing numerical and physical size, and luminance (Pinel, Piazza, Le Bihan, & Dehaene, 2004) and the activated area during processing magnitude information (Dehaene et al., 1998; Kadosh et al., 2008). Hence, it is necessary to understand the perceptual research and the neuroscientific research in an integrated way, not just on finding the related activation in the brain, but also on how the automatic processing of the numbers affects them. Because, when we look at numbers, it is difficult to integrate the significance of the previous studies without a closer look on the mechanism where numerical and physical information of symbolic numbers are processed and connected.

Appendix A. Stimuli

Table 1. Descriptive statistics for stimuli (mm) in Experiment 1.

Font size condition	Big		Small	
	height	Width	height	width
Inducer size	57	38.21	31	20.78
	56	37.54	30.5	20.44
	55	36.87	30	20.11
	54	36.20	29.5	19.77
	53	35.52	29	19.44
	52	34.86	28.5	19.10
	51	34.19	28	18.77
	50	33.52	27.5	18.43
	49	32.84	27	18.10
	48	32.17	26.5	17.76
	47	31.50	26	17.43
	46	30.83	25.5	17.09
	45	30.16	25	16.76
Distance between the target and inducers	20		11	

Note: the stimuli unit is mm. A calibration of stimuli set. (Left) A small stimulus set in which inducer was fixed as 22mm. (Right) A big stimulus set in which inducer was fixed as 40mm. In both conditions, a size of center target varied in seven steps. The Stimulus size was labeled into a small set and a big set was to identify the universal effect of illusion in a pilot study. A big set was applied again in experiment 2 and 3.

Table 2. Descriptive statistics for stimuli in Experiment 2 and 3.

Condition	Experiment 2 Upright / Inverted	Experiment 3
	57	57
	56	56
	55	55
	54	54
	53	53
	52	52
Inducer size	51	51
	50	50
	49	49
	48	48
	47	47
	46	46
	45	45
Distance between the target and inducers	20	20

Appendix B. Modeling scripts in R code. The script was for testing the statistical differences on the results and calculating PSEs per participants in Experiment 2.

Model 1 for the main effect of the numerical value and the orientation. Response ~ inducer + proc with random effect for the subject variable

```
g09resp <- glmer(response ~ inducernum + proc +
(1|subject), data=d09r, family = binomial)
```

Model 2 for the effect of the numerical value in the upright condition. Response ~ inducer * proc with random effect for the subject variable

```
g09resp2 <- glmer(response ~ inducernum * proc +
(1|subject), data=d09r, family = binomial)
```

Further analysis the effect of the numerical value in the inverted condition

```
contrast=matrix(0,2,6)

contrast[1,c(2,5)]=1
contrast[2,c(3,6)]=1
rownames(contrast)=c("3 in orientationR","7 in
orientationR")
summary(glht(gdr,linfct=contrast))
```

Calculating the PSEs of each participant in all conditions.

```
result=matrix(0,length(unique(dr$subject)),6)
nm=names(table(dr$subject))

for(i in 1:length(nm)){
   sub=nm[i] #ith subject name
   count=1
   for(j in c("S","R")){
   for(k in c("3","5","7")){

dr1=dr[dr$inducern==k&dr$direction==j&dr$subject==
sub,]
```

```
        m1=glm(resp~targetsize,dr1,family = 
binomial(link = "logit"))
        result[i,count]=-
 summary(m1)$coefficients[1,1]/summary(m1)$coeffici
 ents[2,1]
        count=count+1
      }
    }
 }
```

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국문 초록

물리적 크기 판단 과제에서 숫자의 값이 미치는 영향: 수 개념의 자동적 처리가 아라비아 숫자 간 크기 대조 효과에 영향을 미치는가?

황지현

지각심리학 전공

서울대학교 대학원

숫자의 두 가지 고유 정보, 숫자 값과 물리적 크기는 수 비교 과제 중에 상호 작용하여 일치 조건과 부적절한 조건의 차이를 유발한다. 숫자 스투룹 과제 분야에서, 물리적 크기를 비교할 때 숫자의 개념적 크기는 지각되는 크기에 영향을 준다는 것이

알려져왔다 (Henik & Tzelgov, 1982; Tzelgov, Meyer, & Henik, 1992). 그러나 행동 수준에서의 크기 일치성 효과는 반응 시간이나 정확도를 위주로 연구되어 왔다. 따라서 크기 일치성 효과가 비교 과정에서의 지각적 반응을 반영하는지 아니면 단순히 반응 단계에서의 인지적 편향을 반영하는지는 아직 명확하게 밝혀지지 않았다. 이 논문의 목적은 사람들이 숫자의 물리적 크기를 비교할 때 숫자 값이 미치는 영향을 확인하는 것이다. 주된 가설은 더 큰 값을 지닌 숫자가 더 작은 값을 지닌 가진 숫자보다 물리적으로 더 크게 보인다는 것이다. 우리는 자극의 개념적 의미에 의해 유도된 크기 대비를 향상시키는 것으로 알려진 에빙하우스 착시 패러다임을 적용함으로써, 수의 의미적 크기에 따라 다르게 인식되는 아라비아 숫자의 지각적 크기를 측정했다. 각 자극은 중앙 숫자 하나와 그를 둘러싼 6 개의 주변 숫자로 구성되었다. 참여자는 표적 숫자가 주변 숫자보다 물리적으로 작거나 크게 보였는지 여부에 응답하도록 요청 받았다. Dixon (2008)이 이항 반응에 대한 반복 측정 설계를 분석하는 데에 특화된 일반화 선형 혼합 모델을 제안함에 따라, 이 GLMM 모델을 사용하여 결과를 통계적으로 검증하였다. 또한, 표적 숫자에 대한 주관적 평등점 (PSE)의 포인트는 작다, 크다의 이항

반응으로부터 계산되었다. 분석 결과, 참여자들은 더 높은 수치를 지닌 숫자들에 의해 표적 숫자가 둘러싸인 경우 대상 숫자의 물리적 크기가 더 작다고 인식하였으며, 반대의 경우도 마찬가지였다. 연구 1 에서, 우리는 두 가지의 글자 크기 조건 (작은 또는 큰)으로 숫자 값의 지각적 효과가 물리적 크기에 국한되지 않고 일반적임을 확인하였다. 또한, 또한, 연구 2 에서는 수 자극을 회전시킴으로써 똑바로 쓰여진 숫자 조건과 거꾸로 된 숫자 조건 모두에서 동일한 반응 패턴을 발견했다. 연구 3 에서는 제시된 주변 숫자 중 3 에서 7 까지의 범위에서 숫자 값의 영향이 관찰되었다. 이러한 결과들은 숫자의 개념적 크기가 숫자 비교 과정에서 지각되는 숫자의 물리적 크기에 직접적으로 영향을 미친다는 것을 나타낸다.

주요어: 숫자 비교, 크기 일치성 효과, 상징적 숫자, 일반 선형화 혼합 모형, 에빙하우스 착시

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