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Neural Mechanisms underlying Iconic Memory Decay of Number and Color

숫자와 색깔에 대한

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Abstract

The decay of sensory representations stored in the primary visual cortex is known to be the neural mechanism underlying the decay rate of the iconic memory. However, the partial report task demands attention and working memory, which could be potential factors determining the decay rate of iconic memory as well. Moreover, the faster decay rate of iconic memory about number compared to color also suggests that attention and working memory may be factors that determine iconic memory' s decay rate. Three experiments were conducted to investigate the involvement of attention and working memory in determining iconic memory decay by assessing the role of the following two factors; attentional orienting efficiency and the central executive part of working memory.

In the first experiment, confirmatory factor analysis was performed with neuropsychological indices measuring potential factors that may cause iconic memory decay and the behavioral index of iconic memory to compare the models explaining the decay rate. In the second experiment, transcranial magnetic stimulation was used to investigate the influence of attentional orienting efficiency on the decay rate of iconic memory about number and color by modulating the neural activity of the primary visual cortex and frontal eye field. The third experiment was conducted using transcranial direct current stimulation and an eye tracker to investigate whether the activity of the primary visual cortex and attentional orienting efficiency could explain the different decay rates of iconic memory about number and color.

The converging evidence lowered the possibility that attentional orienting efficiency and the central executive part of working memory were neural mechanisms determining the decay rate of iconic memory in both number and color. Instead, the results of transcranial magnetic stimulation suggested that the additional process of visual feature grouping during number shape perception could be a significant factor that induced different iconic memory decay rates between colors and numbers. In addition, different visual working memory capacities with respect to color and numbers appear to be another possible factor. The results indicate that stimuli with multiple visual features should consider the grouping process of visual features and the capacity of visual working memory as potential neural mechanisms underlying the decay rate of iconic memory.

Keywords : Iconic memory, Iconic memory decay, Attentional orienting efficiency, Central executive, feature grouping, working memory

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1. Introduction

1.1. Concept of Iconic Memory

Visual stimuli do not wither away immediately after the physical disappearance. The stimuli stay visible after their offset and the trace is called, "visible persistence" (Coltheart, 1980). If the visual stimulus has a strong enough luminance for rod saturation, it induces a visual afterimage. However, the persistence of visual stimulus is not only limited to visible persistence but also the information about visual attributes of the stimulus last for a brief amount of time. The phenomenon is called, "informational persistence" (Coltheart, 1980; Turvey, 1978). Another term for visual sensory memory, namely iconic memory (IM), refers to the informational persistence of visual stimuli.

The concept of IM started to develop through the series of experiments conducted by Sperling in the 1960s (Sperling, 1960). In the experiments, participants saw a flash of an alphanumeric array and were instructed to report specific rows cued by sound pitch. The memory span increased when participants reported part of the array rather than the whole array. Sperling introduced the concept of high-capacity visual memory lasting for a very short amount of time to explain the superiority of memory span in partial report conditions. This high-capacity visual memory, later named IM, briefly stores sensory information as a base material of subsequent visual memory with limited capacities, such as visual short-term memory (Luck & Vogel, 1997; Pashler, 1988).

More complicated arguments were developed with the neural mechanisms of the IM after Sperling's experiment. Some studies tried to explain the increased memory span in terms of visible persistence which refers to visual afterimage. According to a study, information stored at the photoreceptor level appeared to be sufficient to reproduce the change in memory span resembling partial report superiority (Sakitt, 1976). Consistent observation of the inverse relationship between the intensity of visual stimulus and duration of visible persistence also contributed to the claim (Bowling & Lovegrove, 1982).

Visual afterimage can indeed contribute to the partial report superiority since weak afterimage lasts from 250ms to several seconds depending upon light intensity. However, many experiments observed partial report superiority under the condition that the luminance of visual stimulus was too weak to induce visual afterimage (Adelson, 1978; Eriksen & Rohrbaugh, 1970). In addition, the degree of partial report superiority appeared not to be inversely related to stimulus duration or stimulus intensity which is an important property of visible persistence without visual afterimages (Dick, 1974; Efron, 1970(a); Efron, 1970(b)). Lastly, the exposure field which saturated all rods and eliminated the possibility of additional rod saturation did not wipe out IM (Averbach & Coriell, 1961). As a result, it has become apparent that visible persistence and IM reflect different perspectives of the visual information process.

1.2. The Decay Rate of Iconic Memory about Number and Color

According to the early experiments about the IM, participants reported an average of 9.1 out of 12 characters (Sperling, 1960), or an average of 10.4 out of 16 characters (Averbach&Coriell, 1961) when the location cue appeared simultaneously with the visual stimulus. Considering the various factors negatively affecting the report accuracy like individual differences in visual acuity and processing time, the high rate of correct answers in partial report tasks confirms that IM has a high capacity.

The report accuracy changed when the stimulus onset asynchrony (SOA) was introduced between the visual stimulus and the location cue. If the location cue appeared before the onset of the visual stimulus (pre-cue condition), the report accuracy increased to an average of 9.8 out of 12 characters (Sperling, 1960). If the location cue appeared after the onset of the visual stimulus (post-cue condition), the report accuracy decreased exponentially (Lu et al., 2015). The rate of decrease in the report accuracy depending upon SOA is called the decay rate and is regarded as the characteristic of IM.

The decay rate of IM can be calculated in two ways. First, it can be calculated by fitting exponential functions and measuring exponential half-life (Lu et al., 2015; Yi, Kang & Lee, 2018). The other way is to measure the maximum SOA between the cue and visual stimulus which can observe partial report superiority using backward masking (Coltheart, 1980). The latter method can eliminate the confounding effect of visual afterimages on the IM decay rate. Despite individual differences in the decay rate of IM, partial report superiority disappeared approximately after 500ms long SOA (Averbach & Sperling, 1961). The report accuracy maintained above the change level after an SOA longer than 500ms was interpreted to be the result of the transfer of visual information from the IM to a more durable form in visual memory, such as visual short-term memory.

Apart from the clear manifestation of the IM decay rate in a behavioral index, the neural mechanisms underlying IM decay rate are not yet clear. Although the possibility that IM is a type of visual afterimage has been disputed, there are still many factors that need to be explored regarding their effect on the decay rate of IM. In particular, one study that observed differences in the decay rate of IM according to the type of visual stimulus drew attention.

In the aforementioned study (Yi, Kang & Lee, 2018), participants were instructed to report two different types of visual attributes from the same visual stimulus: the kind of number (2,4,7,8) or the color of the number (blue, red, yellow, green) designated by the location cue.

When participants were asked to report the color of the number (color reporting condition), the IM tended to decay slower than when reporting the number itself (number reporting condition). The different decay rates between the color and number reporting conditions imply that the visual complexity of the attributes of an image could influence the decay rate of the IM.

Visual complexity refers to the amount of detail or intricacy in the visual stimulus (Forsythe, 2009). For example, a number is more complex than a color because multiple features constitute the shape of a number whereas color is a single feature. It requires more cognitive resources related to attention (Da Silva, Courboulay, & Estraillier, 2011; Donderi, 2006) and working memory to handle more complex visual attributes (Alvarez & Cavanagh, 2004; Brady, Konkle, & Alvarez, 2011; Luck & Vogel, 1997; Yi, Kang & Lee 2018). This indicates that individual differences in attentional and working memory could potentially be factors that influence the decay rate of IM. Particularly for a relatively complex visual stimulus such as a number, the involvement of the attentional and working memory factor may be likely causes of IM decay.

When it comes to seniors with cognitive aging, the involvement of attention and working memory is more likely. In their case, the results of the partial report task can be significantly affected by a decline in attention. In addition, limited accessibility caused by the aging of working memory can also influence performance levels.

According to a previous study, a group of patients with mild cognitive impairment and faster decay speed showed a higher correlation with the development of dementia (Lu et al., 2015). However, this study did not investigate the participation of attention and working memory in the mild cognitive impairment group. It would be of great importance to know whether the predictive value of IM performance demonstrated in the study indeed depended on the decay of sensory representation in primary visual cortex (V1) uniquely or whether it could be explained by the decline in attention and/or working memory factors associated with cognitive aging of the subjects studied therein.

The next section would specify the candidates of factors related to attention and working memory which require exploration.

1.3. Potential Factors Involved in the Decay Rate of Iconic Memory

Although IM can store a large amount of visual information for a brief moment, only a portion of its content can be accessed consciously through a more durable form of the visual memory system. The efficiency of information access from fragile, large-capacity IM is determined by the interplay of various cognitive factors, other than the sensory representation decay (SRD) of the IM stored in the V1 Gegenfurtner & Sperling, 1993). However, the effects of entangled cognitive factors have not yet been properly investigated.

The difficulties in investigation mainly come from the lack of methodology, dissociating factors influencing the efficiency of information access, and the dependence of IM on attentional resources. The outcome of the partial report task, which was regarded as the main index to measure the decay rate and capacity of IM, could have been the result of the interplay among IM, attention, and working memory. To consciously report the visual inputs during the partial report task, participants should use working memory (De Brigard & Prinz 2010; Mack, Erol, Clarke & Bert, 2016). In the case of attention, IM appeared not to be the case of an attention-free process. According to previous studies, when participants were distracted during the process of IM storage, their performance level decreased accordingly (Mack, Erol, Clarke & Bert, 2016; Persuh, Genzer & Melara, 2012). The orienting of attention also affected the performance level of IM tasks (Gegenfurtner & Sperling, 1993). To elicit the confounding variables influencing the results of the partial report task, we specified the alternative hypothesis explaining the decay rate of IM in terms of attention and working memory accordingly.

The first alternative hypothesis in this study is that the decay rate of IM is determined by the attentional orienting efficiency (AOE) of an individual. Attentional orienting helps people pick up necessary information from sensory inputs (Miniussi, Wilding, Coull & Nobre, 1999). Especially in the case of numbers, the lack of attention due to inefficient AOE could cause illusory conjunction of multiple visual features necessary for shape perception (Treisman & Schmidt, 1982).

Two major methods of attentional orienting have been confirmed in previous studies. Attention can be voluntarily oriented to an object based on the current behavioral goal(endogenous orienting) or involuntarily by salient exogenous cues (exogenous orienting) (Posner, 1980; Posner, 2016). It takes more time to shift attention in the case of volitional orienting, than in exogenously cued orienting. The time required for the former is approximately 200–300 ms, whereas the latter takes approximately 75-175 ms (Carlson, Hogendoorn & Verstraten, 2006; Müller & Rabbitt, 1989). As reported in a study, the cueing effect reached a maximum at 300 ms of SOA when the attention shifted voluntarily (Fuentes & Campoy, 2008).

Since orienting one's attention frequently accompanies eye movement, the correlation between one's gaze and attentional orienting has been extensively studied. According to a previous study, a shift in spatial attention is voluntary when it is elicited by one's gaze direction (Yokoyama, Noguchi & Kita, 2012). Microsaccades have shown potential as an index to map covert attention orienting (Engbert & Kliegl, 2003). Regarding the neural substrate of AOE, previous neuroimaging studies have found distinct neural networks for two attention-orienting mechanisms. The right-lateralized ventral frontoparietal network and occipitotemporal regions are activated when participants shift attention involuntarily, while the bilateral dorsal frontoparietal network was activated in the case of voluntary attentional orienting (Kincade, Abrams, Astafiev, Shulman & Corbetta, 2005; Ptak, Schnider, & Fellrath, 2017).

In the partial report task, participants voluntarily orient their attention to the cued location to achieve an accurate report. The involvement of AOE is more likely as it occurs through a broader time window than mere detection of salient stimulus and increases the possibility of information decay. Namely, even if the decay rate of IM does not change and participants attend to the presented stimulus, they can still fail to report the correct answer when the process of orienting attention is not sufficiently efficient in reaching the store contents before the decay. In this perspective, AOE could be considered as one of the potential independent factors influencing the decay rate of IM.

The second alternative hypothesis in this study is that the decay rate of IM is determined by the central executive part (CEP) of working memory. As a modality-free controlling center, CEP plays various roles in attention control related to the update and maintenance of information at subsidiary slave systems in working memory, focusing on the role that was discussed in the study by Yi in 2018. In this study, the difference in the speed of information-transfer from IM to visual working memory by the degree of visual complexity (Kemps, 2001) was mentioned as a factor responsible for the different IM decay rates of numbers and color. This suggests that the main factor determining the decay rate of IM is the cognitive factor related to the information-transfer speed from IM to visual working memory, which is the role of CEP, since encoding efficiency influences the capacity of visual working memory (Eng, Chen & Jiang, 2005). It has been reported that CEP coordinates the process of transferring sensory information to a modality-specific working memory system (Imbo & Vandierendonck, 2007). In addition, the degree of visual complexity lowers encoding efficiency when the visual stimulus is briefly presented (Eng, Chen & Jiang, 2005). Therefore, it is plausible a number, which is more complex than color, was transferred slower to visual working memory and allowed more time for sensory representation decay stored in V1.

Although CEP's role is concerned with broader attention control mechanisms, the second hypothesis is distinguished from the first hypothesis in that the transfer speed to working memory has been regarded as influenced by one's attentional blink (Todd, Han, Harrison & Marois, 2011) rather than AOE.

To summarize, there are two alternative hypotheses to explain the main factor determining the decay rate of IM. Also, these two factors (AOE and CEP) could be responsible for the decay rate of IM for number and color and/or explain the difference in decay rate.

1.4. The aim of the Study

The present study aims to investigate 1) the two alternative hypotheses concerning whether one’ s AOE and CEP are factors involved in influencing the decay rate of IM and 2) whether those factors can explain the different decay rates of IM between color and numbers or vice versa. These two aims may be distinguished by noting that the factor of interest could influence the decay rate of IM in both color and numbers, but could not explain the difference in the IM decay rate between the two. Color and numbers were selected as visual attributes to maintain consistency with previous studies that used color, numbers, and letters (Sperling, 1960; Yi, Kang & Lee, 2018)

The existing hypothesis was that the IM decay rate is mainly determined by the SRD in V1. After reaching the consensus that visual afterimage is not a significant confounding factor determining the IM decay rate, V1 became a potent candidate for neural correlates with respect to IM. Many studies have observed neural activity in V1 and higher visual cortical areas outlasting the duration of visual stimuli (Duysens, Orban, Cremieux & Maes 1985; Keysers*, Xiao, Földiák & Perrett, 2005; Super, Super, Spekreijse & Lamme, 2001; Teeuwen, Wacongne, Schnabel, Self & Roelfsema, 2021) and the activity of V1 as being related to IM. Voluntary blinking, which reduces V1 activity disrupts IM (Thomas & Irwin, 2006). Furthermore, it has also been found that the activity of V1 after the disappearance of visual stimulus could predict the performance of partial report tasks in macaque monkeys (Teeuwen, Wacongne, Schnabel, Self & Roelfsema, 2021).

However, a previous study consistently observed a difference in the decay rate of IM with respect to two visual attributes: color and numbers. Specifically, the memory of a number decayed faster than the one of color. The difference in the IM decay rate between color and numbers suggests the necessity of discriminating the neural mechanisms according to the stimulus type to insist on the existing hypothesis. It is possible that different neural mechanisms are involved, depending on the stimulus type. In particular, the involvement of factors related to attention and working memory, which influence information processing with different visual complexities, cannot be overlooked.

Three experiments were performed to investigate the neural mechanisms underlying the IM decay rate. In the first experiment, confirmatory factor analysis was performed with neuropsychological indices measuring potential factors and the behavioral index of IM to compare the models explaining the decay rate. The aim was to determine whether the model showed better fit indices when the decay rate of IM for the two visual attributes (color and number) and the difference in IM decay rate between color and numbers were explained in terms of AOE and CEP. The difference in reporting accuracy between −100ms SOA and 100ms SOA was used as the index to analyze the changes in the decay rate of IM.

Conventional neuropsychological tests, such as the Trail Making Test (TMT) and the Digit Span Test (DST), were used as indicators of the two potential factors. The TMT was used as a measure of AOE, which is related to the visual search ability required during the task (Grubert & Eimer, 2015). A visual search task is one way of measuring the orienting speed of visuospatial attention (Carlson, Hogendoorn & Verstraten, 2006). The function of CEP was measured using the DST, which was composed of forward and backward readings of numbers. DST measures the working memory span of numbers, which reflects the executive aspects of working memory and the capacity of verbal short-term memory (Davis, Marra, Najafzadeh & Liu-Ambrose, 2010; Tamez et al., 2011). The results of the first experiment showed the best-fit indices to the model which supported the existing hypothesis.

However, the first experiment was an observational retrospective experiment and the IM index with a limited number of SOA data points could have been insufficient to indicate the decay rate of IM. The following experiments were conducted to observe the causal relationship between potential factors and the decay rate of IM with respect to numbers and color by modulating relevant factors. Subsequent experiments compared the IM decay rate using the report accuracy of the IM task with different SOAs. The significant differences in reporting accuracy with different SOAs between groups or conditions suggested that the contents of IM decayed at a significantly different rate since the SOA between the groups and conditions remained the same.

In the second experiment, transcranial magnetic stimulation (TMS) was used to investigate the influence of AOE on the decay rate of IM in terms of number and color. The results of the partial report task were compared after the stimulation of V1, the left frontal eye field (FEF), and the vertex. The left FEF was selected as an area generating saccades and playing a central role in the allocation of spatial attention in humans (Kincade, Abrams, Astafiev, Shulman & Corbetta, 2005; Muggleton, Juan, Cowey & Walsh, 2003; Tehovnik, Sommer, Chou, Slocum & Schiller, 2000; Thompson, Biscoe & Sato, 2005).

The third experiment was conducted using tDCS and an eye tracker to investigate whether V1 activity and AOE could explain the decay rate of IM in terms of number and color. The use of tDCS allows the manipulation of the membrane potential of neurons beneath the stimulation site according to the type of electrode. When an anode is attached to the scalp over the target site, it causes depolarization of neurons and increases the probability of action potential occurrence. The use of a cathode causes an effect opposite to that of the anode, which hyperpolarizes the neurons and inhibits the occurrence of action potentials (Thair, Holloway, Newport & Smith, 2017).

The results of the following two experiments provided converging evidence that the factors related to AOE did not influence the decay rate of IM. However, the reporting accuracy in the partial report task appeared to increase regarding IM about color and decrease regarding IM about numbers when TMS was applied to the V1. The results suggested that in the case of number reporting condition, the decay rate of IM can be influenced by the grouping process at the higher visual area (Murray, Kersten, Olshausen, Schrater & Woods, 2002). If the grouping process significantly affected the IM decay rate of a number, this could be the reason for the different decay rates with respect to numbers and color.

2. Experiment 1

2.1. Participants

The neuropsychological records of 357 senile patients (mean age = 67.5 years; standard deviation = 8.9; 227 females, 130 males) who visited the Department of Neurology at Seoul National University Hospital were collected and analyzed retrospectively. The collection of neuropsychological data was approved by the Institutional Review Board of Seoul National University Hospital and conducted in accordance with the Declaration of Helsinki (Association, G. A. o. t. W. M., 2014).

Patients whose report accuracy was less than 25 in more than one condition were not included in the analysis to screen those who were unable to understand the instructions of the partial report task or those who had problems with the peripheral visual system. Accuracy under 25 percent was considered to be the result of a random response.

2.2. Methods

2.2.1. Trail Making Test

Seoul National University Hospital uses three types (A, B, and C) of the TMT. Among the three types, types A and B were used in the experiment. TMT type A is identical to the conventional type A TMT in which participants have to connect the numbers from 1 to 26 as fast and as accurately as they can (Bowie & Harvey, 2006). TMT type B requires participants to connect all triangles and squares in an alternate order starting from a designated point using the figure only once. The TMT type B used in the hospital was customized to eliminate the case that patients were illiterate and could not understand the rule. The finishing time and the number of errors were recorded for both the tasks accordingly.

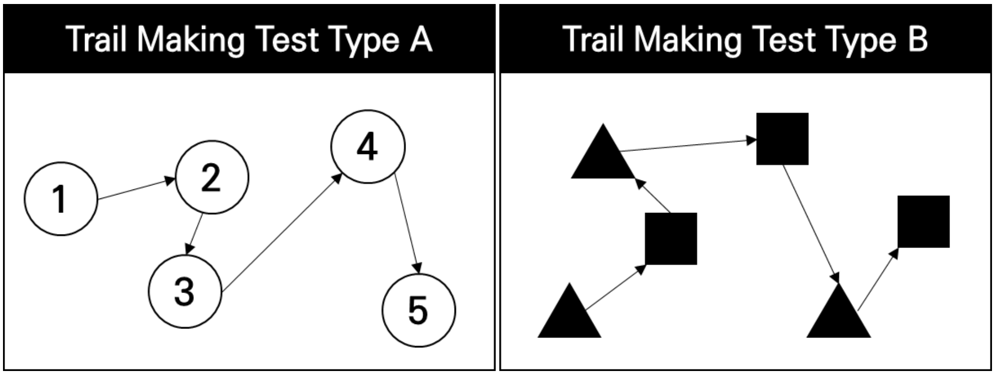

Figure 1. Diagram describing two types of TMT included in the neuropsychological test battery

2.2.2. Digit Span Test

The DST measures the length of the numbers that can be memorized at one time. In this test, there was a list of numbers with sequentially increasing lengths. An examiner read a line of numbers only once, and the participants repeated the numbers verbally. When repeating the numbers, the participants received instructions to report the numbers in the forward or backward order. The maximum length of the numbers was eight, and participants could retry once with a different set of numbers that had the same length.

Forward	Backward
Sequences	
5, 8, 2	7, 2, 4
6, 9, 3	4, 1, 5
6, 7, 2, 4	3, 5, 8, 6
8, 7, 1, 5	9, 2, 1, 6
⋮	⋮
5, 8, 2, 7, 1, 4, 6, 3	9, 4, 7, 3, 6, 2, 5, 1
3, 7, 4, 9, 5, 1, 8, 2	7, 2, 4, 8, 9, 6, 5, 3

Figure 2. Diagram of DST included in the neuropsychological test battery

2.2.3. Iconic Memory Task

The IM task used a partial report methodology. Participants watched a visual stimulus via a monitor and verbally reported the number or color of the number at the cued location. The visual stimulus consisted of eight colored numbers located at eight cardinal points with equal distances from the center of the monitor (radius = 3.34°). Four numbers (2, 4, 7, and 8) with four colors (red: RGB(1, 0, 0), blue: RGB(0, 0, 255), gray: RGB(0.7, 0.7, 0.7), and yellow: RGB(1, 1, 0)) were shown in a black background (0.5 cd/m2). The numbers were selected to avoid shape similarity. For each presentation of the visual stimulus, the number and color were randomly combined. Fig 3(a) shows a diagram of the IM task procedure.

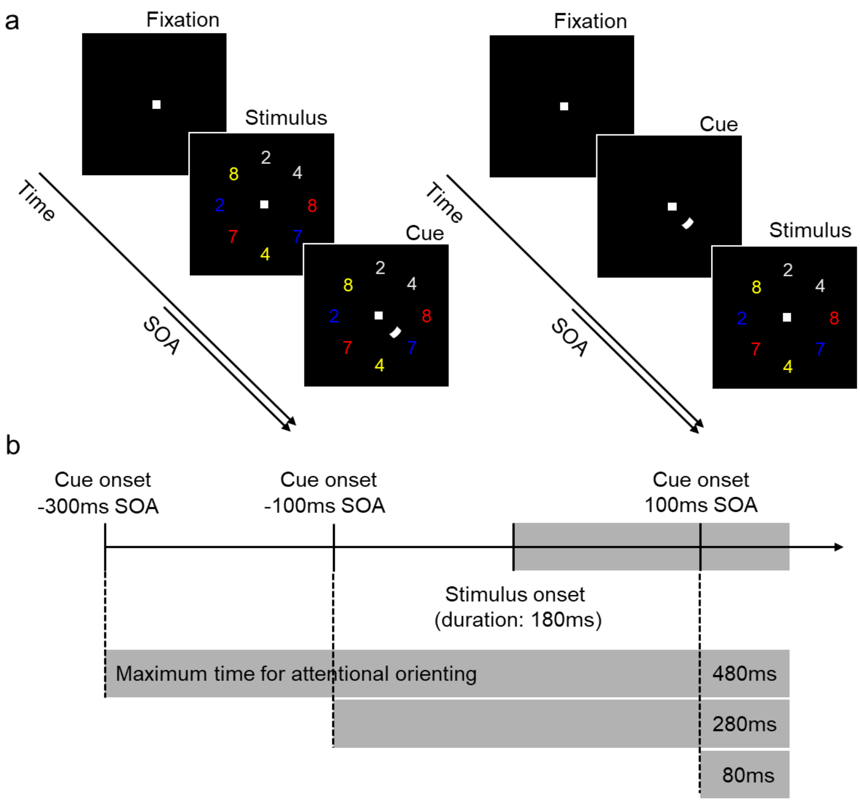

Figure 3. Procedural description of partial report task (a) Procedure of partial report task. The left shows the onset of visual stimulus precedes the onset of location cue(SOA 100ms). The right shows the onset of visual stimulus follows the onset of location cue(SOA −300ms, SOA −100ms) (b) The maximum time allowed for attentional orienting according to the time course of cue onset and visual stimulus onset

Before starting the experiment, participants were instructed to fix their gaze at the fixation point located at the center of the monitor. The fixation point was a small white box (0.40° × 0.40°). Three different SOAs were introduced between the appearance of the location cue and the visual stimulus (-300 ms, -100 ms, and 100 ms).

The negative sign indicated that the onset of the location cue occurred before the onset of the visual stimulus (pre−cue condition). The duration between fixation point onset and the location cue onset was 1500 ms. The inter−trial interval was randomized between 500 to 1000 ms. The stimulus duration was adjusted to 180 ms to ease the level of difficulty for the seniors who visited the hospital.

As a result, a brief overlap of visual stimulus and cue occurred for 80 ms in the 100 ms SOA condition. However, the overlap did not disturb the participation of IM because the time gap was too short for the volitional orienting of attention (Carlson, Hogendoorn & Verstraten, 2006; Fuentes & Campoy, 2008; Müller & Rabbitt, 1989). In addition, the overlap was not sufficient for conscious perception or perceptual judgment of visual information, which allowed participants to use the information from IM (Koivisto & Grassini, 2016; Parodi, Combe & Ducom, 1996).

In addition, there can be a concern about confounding of the attentional orienting factor in the −100 ms SOA condition when the duration of the visual stimulus was 180 ms, which led to a total time gap of 280 ms between the onset of the location cue and the end of the visual stimulus. Despite the possibility of confounding, −100 ms SOA was a more reasonable starting point to cover the performance variance maximally arising from the decay of IM than the 0ms SOA condition. The confounding effect of attentional orienting factor was relieved by considering the time course of volitional orienting of attention.

Participants went through 32 trials for each SOA condition, and 96 trials consisted of one block of the IM task. Three different SOA conditions were randomly distributed across each block. During the experiment, two blocks of IM tasks were performed accordingly. In the number block, participants reported the target number, whereas, in the color block, they reported the color of the target number. The order of the two blocks was randomized between the participants.

2.2.4. Procedure

Patients who were assigned to undergo a neuropsychological test visited the examination room at Seoul National University. It took approximately 40 minutes to complete the entire test battery. Before the start of the examination, patients received information about its purpose. Patients underwent DST, TMT, and IM tasks in a fixed order. A single-practice test was allowed before the main test. In the case of the IM task, the practice was permitted until the participants understood the procedure of the task completely.

2.2.5. Statistical Analysis

The difference of report accuracy at each SOA condition between color and number was analyzed using Wilcoxon signed-rank test to confirm that the color and number decay in different rate.

First CFA was conducted to analyze if SA, AOE, and CEP hypotheses could explain the results of IM decay indices better than SRD hypothesis regardless of reporting visual attributes(model A, B, C, D, I). Second CFA was conducted to compare the fit indices of alternative hypotheses to the SRD hypothesis in the case of number reporting condition (model E, F, G, H). Finally, CFA was conducted to analyze if the difference of decay rate in color and number could be explained by the SRD hypothesis (model J).

The first CFA compared the fit indices of the four theoretical models (model A, B, C, D). The second analysis was conducted by separating IM decay index about number and color to see if the number reporting condition alone could be better explained by potential factors (model I, E, F, G, H). Finally, one model assigning the difference of the decay rate of IM between number and color as the indicator of SRD was analyzed to see if the difference rate of decay could be explained by the decay of sensory representation (model J).

The analysis tool used was the R 4.2.0 and RStudio 1.0.136 with the lavaan 0.6-11 and semPlot 1.1.5 packages (Epskamp, 2015). Since the data did not satisfy the normality assumption, we used maximum likelihood estimation with robust standard error (MLM) implemented in the lavaan package (Rosseel, 2012). The estimator MLM uses classic robust standard errors and computes a Satorra-Bentler scaled (mean adjusted) test statistics. Lastly, the finishing time of the TMT was inverted and multiplied by 100 to eliminate negative correlations. Variances of latent variables were constrained to 1.

The four theoretical models (model A, B, C, D) allocated the accuracy difference between −100 ms and 100 ms SOA conditions as indicators of latent variables, such as sustained attention (SA), SRD, AOE, and CEP respectively. SA model (model B) was added as a control analysis to confirm the fact that attention level did not influence the IM decay rate among participants. Additional CFA was performed on the models of the alternative hypotheses (model B, C, D) to investigate the improvement of fit indices when only Ndecay was used as an indicator of IM decay (model E, F, G, H). The analysis was performed to confirm if the number reporting condition, which is a more complex stimulus, was more appropriate to be assigned as the indicator of SA, AOE, or CEP. Lastly, the model assigned Ndecay and Cdecay as indicators of the different latent variables of IM (model I). The variance of Ndecay and Cdecay were set to zero to make latent variables account for all of the variances of the Ndecay and Cdecay since those two indicators were the only indicator assigned to the latent variables. Finally, the difference between Ndecay and Cdecay was extracted by regression as a residual and assigned to model J. All models assumed a correlation between latent variables to reflect the interaction between each cognitive function.

Goodness−of−fit was evaluated by chi−square (χ^2) test. However, the test shows a tendency to yield significant results with large sample size. To mitigate the dependency on sample size, comparative fit index (CFI), robust comparative fit index (robust CFI), Tucker-Lewis index (TLI), robust Tucker-Lewis index (robust TLI), Akaike information criterion (AIC), Bayes information criterion (BIC), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR) tests were used. CFI is an index which is less dependent on sample size. TLI reflects the parsimony of the model and favors more simple model. AIC and BIC was additionally used to see the parsimony of the models. RMSEA and SRMR are useful measures since each is sensitive to the misspecification of factor loadings and factor covariances respectively.

2.3. Results

The model that allocated the accuracy difference of −100 ms and 100 ms SOA conditions (Cdecay, Ndecay) as the indicator of SRD (model A) was found to be the most adequate among the five theoretical models. Model A also recorded a p−value > 0.05, ($p = 0.340$) after testing the hypothesis that RMSEA ≤ 0.05, which means that the model has a close fit. A p−value under 0.05, which means that the model has RMSEA over 0.05, cannot satisfy the criteria of close fit. Since model A did not record a p−value under 0.05, it passed the test of close fit accordingly.

Table 1 shows the results of Wilcoxon signed−rank test about report accuracy between color and number. Table 2 describes the nonparametric descriptive statistics for each observed variable. Table 3 lists the fit indices of the five models. The results of the chi-square tests are all significant owing to the large sample size. All models, except for model A and model I, did not pass the close fit test. Between model A and model I, model A had lower RMSEA, AIC, and BIC values while model I showed lower SRMS value and higher CFI value. The simpler model which did not assume different neural processes between number and color was selected as the best-fitted model. Figure 4 and figure 5 show the diagram of model A and model I.

Table 1. The results of Wilcoxon signed-rank test between report accuracy of color and number.

SOA	Wilcox V	P-value
-300ms	9.225*	<0.001
-100ms	-2.958*	0.003
100ms	-13.198*	<0.001

* p-value<0.05

Table 2. Descriptive Statistics of observed variables

Observed variable	Minimum	1st Qu.	Median	3rd Qu.	Maximum
Cpre300	0.3750	0.8438	0.9375	0.9688	1.0000
Npre300	0.4375	0.9375	0.9688	1.0000	1.0000
Cdecay	–0.1250	0.0938	0.1875	0.2813	0.6250
Ndecay	–0.1875	0.2187	0.3437	0.4375	0.6875
Forw	4.000	6.000	7.000	8.000	8.000
Back	0.000	3.000	4.000	5.000	8.000
Tmta	0.5263	1.6129	2.1739	2.8571	7.6923
tmtb	0.4386	1.7544	2.5000	3.3333	10.0000

Note. Cpre300 and Npre300 refer to the pre-cue condition, reporting color, and number, respectively. Cdecay and Ndecay refer to the difference between the– 100 ms and 100 ms SOA conditions reporting colors and numbers, respectively. tmta and tmtb refer to the type A and type B trail making tests, respectively. Back and forw refer to the results of the backward and forward digit span tests, respectively. 1^{st} Qu. And 3^{rd} Qu. refer to the values of 25 percentile and 75 percentiles, respectively.

Table 3. Fit indices of the five models allocating Cdecay and Ndecay as an indicator of SRD and other potential factors.

Model	A(SRD)	B(SA)	C(AOE)	D(CEP)	I
Chi (df)	29.258 (14)	79.872 (17)	81.955 (17)	77.659 (17)	26.112 (12)
CFI	0.968	0.866	0.862	0.871	0.970
TLI	0.935	0.780	0.772	0.787	0.930
Robust CFI	0.974	0.894	0.885	0.892	0.977
Robust TLI	0.948	0.825	0.811	0.822	0.945
AIC	7478.078	7528.105	7534.556	7530.296	7478.166
BIC	7563.388	7601.782	7608.233	7603.973	7571.232
RMSEA (90% CI)	0.055 (0.028, 0.082)	0.102 (0.081, 0.124)	0.103 (0.083, 0.136)	0.100 (0.080, 0.121)	0.057 (0.028, 0.086)
SRMS	0.041	0.084	0.083	0.083	0.033

Abbreviations: SRD, sensory representation decay; SA, sustained attention; AOE, attentional orienting efficiency; CEP, central executive part; CFI, comparative fit index; TLI, Tucker-Lewis index; AIC, Akaike information criterion; BIC, Bayes information criterion; RMSEA, root mean square error of approximation; 90% CI, 90 percent confidence interval; SRMR, standardized root mean square residual.

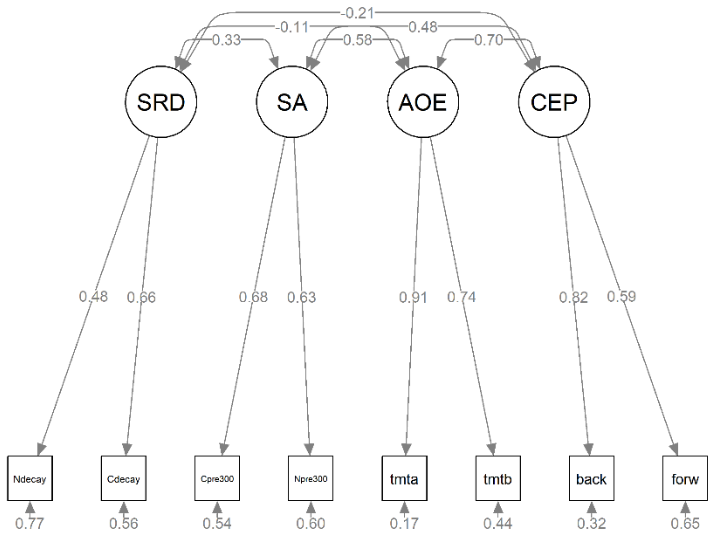

Figure 4. Diagram of the model A. Abbreviations: SRD, sensorial representation decay; SA, sustained attention; AOE, attentional orienting efficiency; CEP, central executive part; Cdecay, a difference of report accuracy in color between −100ms SOA and 100ms SOA; Ndecay difference of report accuracy in number between −100ms SOA and 100ms SOA; Cpre300, report accuracy of color condition at SOA −300ms; Npre300, report accuracy of number condition at SOA −300ms; tmta, time to complete TMT type a; tmtb, time to complete TMT type b; back, maximum number length in DST backward condition; forw, maximum number length in DST forward condition

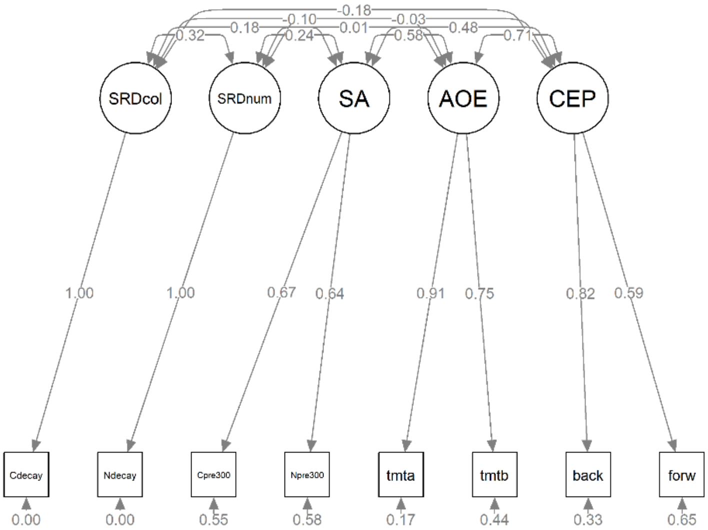

Figure 5. Diagram of the model I. Abbreviations: SRDcol, sensory representation decay of color; SRDnum, sensory representation decay of number; SA, sustained attention; AOE, attentional orienting efficiency; CEP, central executive part; Cdecay, a difference of report accuracy in color between −100ms SOA and 100ms SOA; Ndecay difference of report accuracy in number between −100ms SOA and 100ms SOA; Cpre300, report accuracy of color condition at SOA −300ms; Npre300, report accuracy of number condition at SOA −300ms; tmta, time to complete TMT type a; tmtb, time to complete TMT type b; back, maximum number length in DST backward condition; forw, maximum number length in DST forward condition

The results of the CFA without Cdecay reproduced that the best model supports IM decay as decay of sensory representation. Table 4 shows the fit indices of each model. Although All models showed RMSEA of good fit, other indices indicated model E as the best model. Fig 6 show the diagram of model E.

Table 4. Fit indices of the four models allocating Ndecay as an indicator of potential factors.

Model	E(SRD)	F(SA)	G(AOE)	H(CEP)
Chi (df)	24.110 (9)	29.456 (11)	33.016 (11)	32.879 (11)
CFI	0.962	0.953	0.944	0.945
TLI	0.911	0.911	0.894	0.895
Robust CFI	0.972	0.964	0.955	0.955
Robust TLI	0.934	0.932	0.914	0.915
AIC	6512.503	6515.652	6521.686	6521.721
BIC	6586.180	6581.573	6587.607	6587.643
RMSEA (90% CI)	0.069 (0.038, 0.100)	0.069 (0.041, 0.097)	0.075 (0.049, 0.102)	0.075 (0.049, 0.102)
SRMS	0.036	0.045	0.054	0.055

Abbreviations: SRD, sensorial representation decay; SA, sustained attention; AOE, attentional orienting efficiency; CEP, central executive part; CFI, comparative fit index; TLI, Tucker-Lewis index; AIC, Akaike information criterion; BIC, Bayes information criterion; RMSEA, root mean square error of approximation; 90% CI, 90 percent confidence interval; SRMR, standardized root mean square residual.

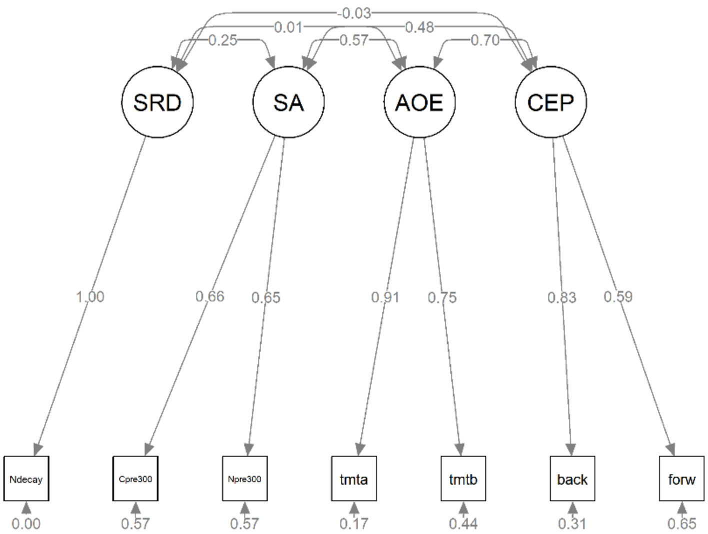

Figure 6. Diagram of the model E. Abbreviations: SRD, sensorial representation decay; SA, sustained attention; AOE, attentional orienting efficiency; CEP, central executive part; Cdecay, a difference of report accuracy in color between −100ms SOA and 100ms SOA; Ndecay difference of report accuracy in number between −100ms SOA and 100ms SOA; Cpre300, report accuracy of color condition at SOA −300ms; Npre300, report accuracy of number condition at SOA −300ms; tmta, time to complete TMT type a; tmtb, time to complete TMT type b; back, maximum number length in DST backward condition; forw, maximum number length in DST forward condition

The result that analyzed the fit indices of model J was described in Table 5. All values of RMSEA indicated good fit, model J showed the highest RMSEA. However, models other than model J had a low factor loading value regarding the indices about IM decay. Fig 7 shows the diagram of model J.

Table 5. Fit indices of the models with the difference of decay rate between number and color.

Model	J (SRD)	K (SA)	L (AOE)	M (CEP)
Chi (df)	23.872 (9)	24.923 (11)	26.979 (11)	27.232 (11)
CFI	0.963	0.965	0.960	0.959
TLI	0.913	0.933	0.923	0.922
Robust CFI	0.971	0.973	0.968	0.968
Robust TLI	0.933	0.949	0.939	0.938
AIC	6520.004	6517.246	6520.992	6521.179
BIC	6593.681	6583.168	6586.914	6587.100
RMSEA (90% CI)	0.068 (0.038, 0.100)	0.060 (0.030, 0.089)	0.064 (0.036, 0.092)	0.064 (0.037, 0.092)
SRMS	0.035	0.037	0.045	0.046

Abbreviations: CFI, comparative fit index; TLI, Tucker-Lewis index; AIC, Akaike information criterion; BIC, Bayes information criterion; RMSEA, root mean square error of approximation; 90% CI, 90 percent confidence interval; SRMR, standardized root mean square residual.

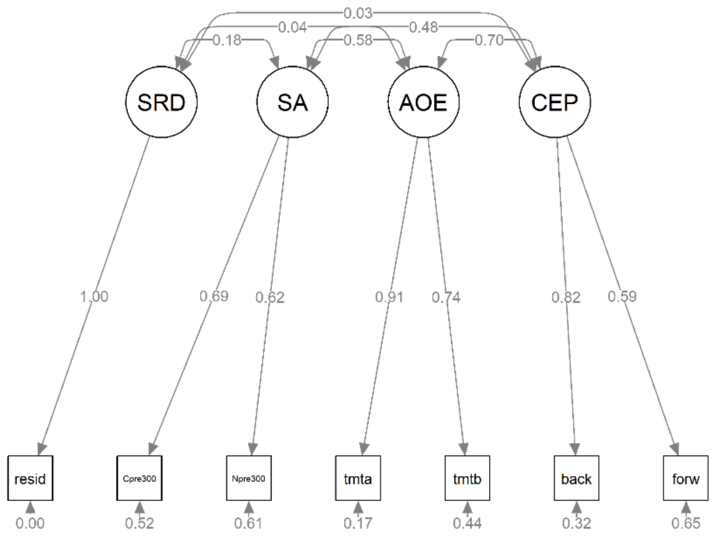

Figure 7. Diagram of the model J. Abbreviations: SRD, sensorial representation decay; SA, sustained attention; AOE, attentional orienting efficiency; CEP, central executive part; resid, residuals of regression on Cdecay with Ndecay; Cpre300, report accuracy of color condition at SOA −300ms; Npre300, report accuracy of number condition at SOA −300ms; tmta, time to complete TMT type a; tmtb, time to complete TMT type b; back, maximum number length in DST backward condition; forw, maximum number length in DST forward condition

2.4. Discussion

A comparison of models using CFA reveals two main points. First, the determining factor influencing the partial report task was the decay of sensory representation, regardless of the visual stimulus complexity. Second, the model that explained the different decay rates of color and number as a consequence of the SRD, SA, AOE, and CEP hypotheses did not indicate good fit indices.

Regarding the first result, it did not deny that the process of partial report task demanded attention and the executive part of working memory function, but affirmed that most variance of the outcome can be explained by the SRD rather than AOE and CEP. These results thus restored the validity of previous studies using partial report tasks without considering the confounding effects of attention and working memory factors.

To reinforce the validity of the above argument, we considered the possibility that the name of the latent variable was a misnomer. Particularly in the case of TMT, the visuomotor speed of senile participants could have been the main cause of performance variance. However, according to a previous study, the factor that explained most of the performance variance in type A TMT was visual searching (Crowe, 1998). In addition, the type B TMT used in the present study minimized the confounding of visual sequencing ability because participants connected the triangle and square in an alternating order instead of connecting numbers in increasing order. Therefore, naming the latent variables of TMTa and TMTb as AOEs was plausible in our case.

The next concern about the validity of the model was that the CEP was not a critical variable. The failure of conscious access could be a matter of retaining visual information in the modality-specific part of working memory, such as the visual sketchpad. However, DST did not primarily measure the visuospatial element of working memory, which is an important factor affecting the capacity of visual working memory (Baddeley, 2000). The decreased accuracy in the number condition, which is more visually complex than color, aroused suspicion about the participation of the modality−specific part of the working memory. Regarding the complexity of visual stimuli, the results of previous studies on working memory capacity are inconsistent. One study found that the capacity of visual working memory is not influenced by complexity (Awh, Barton & Vogel, 2007). However, other studies have observed that the complexity of visual features affects the storage limit of visual working memory (Eng, Chen & Jiang 2005; Song & Jiang, 2006).

Although the capacity of visual working memory may not be affected by stimulus complexity, the independent loss of visual features in visual working memory can influence the identification of numbers. From the perspective of visual attributes, the complexity of a visual stimulus is related to the amount of information necessary to identify objects. A conjunction of multiple visual features could have been necessary when categorizing the number, whereas this was not necessary for the color. For example, the identification of the number 2 is not possible if participants remember just a round part of the form. In contrast, color can be identified without a combination of several visual features. In the case of numbers, retention of more information could have been necessary for the identification task, thus exerting a higher load on visual working memory. Therefore, the decreased accuracy of the number condition could have reflected the capacity of the visuospatial part in working memory, which was not reflected in our models.

The concern about the capacity of visual working memory is plausible, but our focus was on the function of the central executive part of working memory, which is related to information transfer. Previous studies on the different decay rates of IM between the colors and numbers suggested that the capacity of VWM could have been determined by the speed of information transfer from IM to VWM (Yi, Kang & Lee, 2018). If the information transfer was slower in more complex visual stimuli, the IM could have decayed before the completion of the transfer.

We postulated that this role relied more on the CEP of working memory since it played a role in controlling information flow to the modality-specific part (D'esposito et al., 1995). Additionally, the transfer of sensory information into a more durable form of visual memory, including visual working memory and visual short-term memory, was not significantly different in the senile group with varying cognitive aging (Lu, Neuse, Madigan & Dosher, 2005), which makes the confounding of the modality-specific capacity of working memory unlikely. Based on these observations, we focused on the CEP of the working memory and the function can be measured with DST. In addition, if the decay rate of IM had been determined by the central executive part of the working memory, the variance of the results would have been similar to the variance of the results of DST. The tendency could have been captured by the CFA.

Lastly, the indicators of the latent variable SRD could have been confounded with the attentional orienting factors since the −100ms SOA condition could not completely rule out the performance variance caused by the attentional orienting efficiency difference. However, a −100ms SOA was selected to maximally include the performance variance originating from the IM decay because voluntary orienting of attention required approximately 300 ms. Although there would be an individual difference in orienting efficiency, the confounding effect of the attentional orienting factor would have been relieved by the inclusion of an additional performance variance originating from SRD.

Regarding the second result, the decay of sensory representation did not sufficiently explain the different decay rates between color and number reporting conditions. Although model J showed the good fit indices, the results suggested that factors other than SRD, SA, AOE, and CEP could be responsible for the different IM decay rates between color and number. Potentially, the factor causing the different decay rates between color and numbers could be the difference in the participation of top−down factors because a number is a symbol that needs to be learned unlike color.

In conclusion, we found that the results of the partial report task could restore the validity of the method to examine the properties of IM despite the interplay of attention and working memory factors during the task. The results of the CFA imply that an adequate explanation of accuracy decline requires factors other than attention and the central executive part of working memory to be considered. It is plausible that the SRD is an additional factor that must be considered. The confounding effect of more durable visual memory, such as visual short-term memory and the attentional orienting factor, was found to be unlikely.

However, the results of the current study are limited in that the number of SOA conditions in the IM task were not sufficient to capture the exact decay rate. The index of decay rate was the difference in report accuracy between the two SOA conditions (-100ms SOA, 100ms SOA) in the experiment. Although the index can capture the crude tendency of the decay rate, more data points with location cue that appears after the offset of the visual stimulus are necessary to find the starting point of the asymptotic line in the report accuracy graph.

3. Experiment 2

3.1. Participants

Thirty-one right-handed participants (mean age = 23.6 years; standard deviation = 4.5; 16 females, 15 males) without a recorded history of psychiatric or neurological disorders were recruited from the community website of Seoul National University (SNUlife). The collection of data was approved by the Institutional Review Board of Seoul National University and conducted in accordance with the Declaration of Helsinki (Association, G. A. o. t. W. M., 2014).

Four participants were excluded from the analysis because of frequent movement during the experiment. In addition, screening criteria were applied to minimize the possibility of careless responding. Participants whose correct rate was under 0.9 in color condition or under 0.8 in number condition when SOA was 0ms were excluded from the final analysis. As a result, a total of twenty-three participants in color condition and twenty-four participants in number condition were included in the analysis.

3.2. Methods

3.2.1. Iconic Memory Test

The test procedure stayed the same with Experiment 1 except for a few changes in parameters. Participants watched a visual stimulus on the screen and reported the number or color of the number at the cued location by pressing the keyboard. The visual stimulus consisted of eight colored numbers located at eight cardinal points at equal distances from the center of the monitor (radius = 3.34°). Four numbers (2, 4, 7, and 8) with four colors (red: RGB(255, 0, 0), blue: RGB(0, 0, 255), gray: RGB(0.7, 0.7, 0.7), and yellow: RGB(255, 255, 0)) are shown in a black background (0.5 cd/m2). The numbers were selected to avoid shape similarity. For each presentation of the visual stimulus, the number and color were randomly combined.

Before starting the experiment, participants were instructed to fix their gaze at the fixation point located at the center of the monitor. The fixation point was a small white box (0.40° × 0.40°). Four different SOAs were introduced between the onset of the target cue and the visual stimulus (0 ms, 200 ms, 500 ms, and 1000ms). There was no pre-cue condition. The duration between fixation point onset and the location cue onset was 2000 ms. The inter-trial interval was randomized between 1000 to 1500 ms to ensure the minimum interstimulus interval of 3 seconds in single-pulse TMS (Rothwell et al., 1999) although there is a report that interstimulus interval difference in the second-scale did not induce a significant change in individual motor-evoked potentials amplitudes (Julkunen, Säisänen, Hukkanen., Danner & Könönen, 2012). The stimulus duration was adjusted to 100 ms.

Participants went through 24 trials for each SOA condition, and 96 trials consisted of one block of the IM task. Four different SOA conditions were randomly distributed across each block. During the experiment, two blocks of IM tasks were performed for each TMS stimulation condition. In the number block, participants reported the target number, whereas, in the color block, they reported the color of the target number. The order of the blocks was randomized between the participants. It took approximately 10 minutes to complete one block of IM task.

3.2.2. Transcranial Magnetic Stimulation

TMS was performed with a Magpro R30 stimulator (Magventure, Denmark) connected to a butterfly coil (MC-P-B70, 53mm). A single biphasic pulse was delivered at a specific time point after the appearance of the visual stimulus according to the experiment condition. The pulse was delivered at 100% of the motor threshold (MT) over the target site (V1, left FEF, and vertex). The MT was used instead of the phosphene threshold which is usually applied when stimulating V1. The application of MT, which is usually less than phosphene threshold (Deblieck, Thompson, Iacoboni & Wu, 2008), would cause little problem since the purpose of the experiment is to apply sub-threshold stimulation to the V1 area to facilitate the activity (Abrahamyan, Clifford, Arabzadeh & Harris, 2015; Silvanto & Cattaneo, 2017).

To determine the intensity of individual MT, single-pulse TMS was applied at increasing intensities starting from 40% of the maximum stimulator output. MT was defined as the lowest TMS intensity capable of evoking a dorsal interosseous muscle twitch in the contralateral hand in more than 5/10 consecutive trials (inter-trial interval = 10s) (Rossini et al., 2015). The intensity of the TMS was increased by 5% of the maximum stimulator output until the first observation of muscle twitch. The lowest TMS intensity was determined through decreasing the intensity by 1% of the maximum stimulator output until the twitch at a dorsal interosseous muscle was observed in 5/10 trials.

TMS was applied over the V1, FEF, and the vertex (sham condition). The Cz site is the most widely used control site for TMS studies because the auditory and somatosensory activations caused by vertex TMS can be equivalent to those of real TMS (Sandrini, Umiltà & Rusconi, 2011). The choice of V1 as the target area is to test the influence of early sensory representation of visual information. V1 is responsible for the gatekeeping of incoming visual information and the site of iconic storage (Hubel, 1982; Nikolić, Häusler, Singer & Maass, 2009; Tootell et al., 1998). In the case of FEF, the area generates saccade on the contralateral side and plays a central role in the allocation of spatial attention in humans (Kincade, Abrams, Astafiev, Shulman & Corbetta, 2005; Muggleton, Juan, Cowey & Walsh, 2003; Tehovnik, Sommer, Chou, Slocum & Schiller, 2000; Thompson, Biscoe & Sato, 2005). The left frontal eye field was targeted as the area which is related to the visual attention orienting (Chica, Valero−Cabré, Paz−Alonso & Bartolomeo, 2014; Smith, Jackson & Rorden, 2005).

The location of V1 was determined by the average scalp site from the results of the functional localization method commonly used in studies investigating phosphenes (Walsh & Pascual−Leone, 2003). The location of FEF was determined based on a previous study which elicited significant modulation of FEF (Ronconi, Basso, Gori & Facoetti, 2014). The site of V1 was set to 2cm above inion (Fumal et al., 2006; Lang et al., 2007; Silvanto, Lavie & Walsh, 2005; Silvanto & Muggleton, 2008), which corresponds to the approximate location of Oz in 10−20 system. The coil' s handle was pointing upward (Bona, Herbert, Toneatto, Silvanto & Cattaneo, 2014; Ptito et al., 2008). The left FEF was localized by moving the coil 3cm rostral from individual motor hotspots and 5cm laterally of the sagittal midline (Ronconi, Basso, Gori & Facoetti, 2014). The variance of FEF location between individuals could be the possible source of error. However, multiple TMS studies have been successfully employed similar localization procedure (Leff, Scott, Rothwell, & Wise, 2001; O'Shea, Muggleton, Cowey & Walsh, 2006). The coil' s handle was pointing posterior and the was approximately 45° to the sagittal midline (Marshall, O'Shea, Jensen & Bergmann, 2015; Nuding et al., 2009)

3.2.3. Procedure

The experiment was a 2×3 factorial, with a within group design consisting of factors about TMS site (sham, V1, and FEF) and reporting visual attributes (color and number). Participants were sat comfortably on an armchair in a quiet room at a distance of 75cm from a computer screen. First, the purpose and procedure of the experiment were explained. After the explanation, participants underwent the MT calibration process with a white cap on. The location of M1, V1, left FEF, and vertex was marked with a red color pencil. Calibration of MT took approximately 30 minutes including explaining time.

The experimental procedure was divided into two sessions by the reporting condition of IM task. In the first session, participants performed three blocks of IM task with the same reporting condition (either color or number) according to the TMS site (V1, FEF, and vertex). The order of stimulation sites was randomized among the participants. The second session started after five minutes of break time. The procedure remained the same as the previous session except for the reporting condition of IM task. The order of reporting conditions was also randomized. Each session lasted about 30 minutes including one practice IM task consisting of 50 trials. The total experiment time was about 90 minutes including the MT calibration procedure.

Single-pulse TMS was applied during IM task. Participants received TMS after 100ms from the onset of visual stimulus in the V1 condition. The timing of TMS was chosen not to disturb the encoding of visual information to V1. It was reported that early visual perception started at 75–80 ms after stimulus onset (VanRullen & Thorpe, 2001). During the FEF stimulating condition, TMS was delivered at the time of cue onset without delay since the voluntary allocation of attention would start after the onset of the location cue. The timeline and diagram of the experiment procedure are presented in figure 8 and figure 9 respectively.

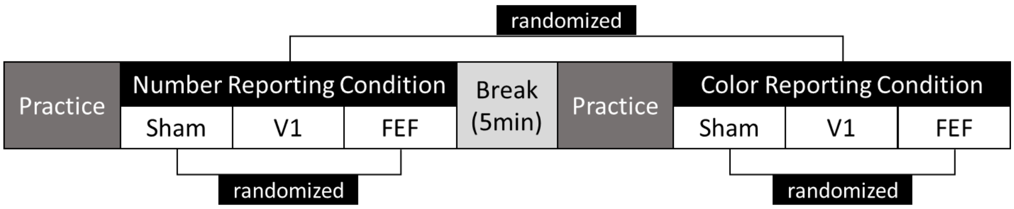

Figure 8. The procedure of the TMS experiment. Abbreviations: Sham, TMS sham stimulation; V1, TMS V1 stimulation; FEF, TMS FEF stimulation

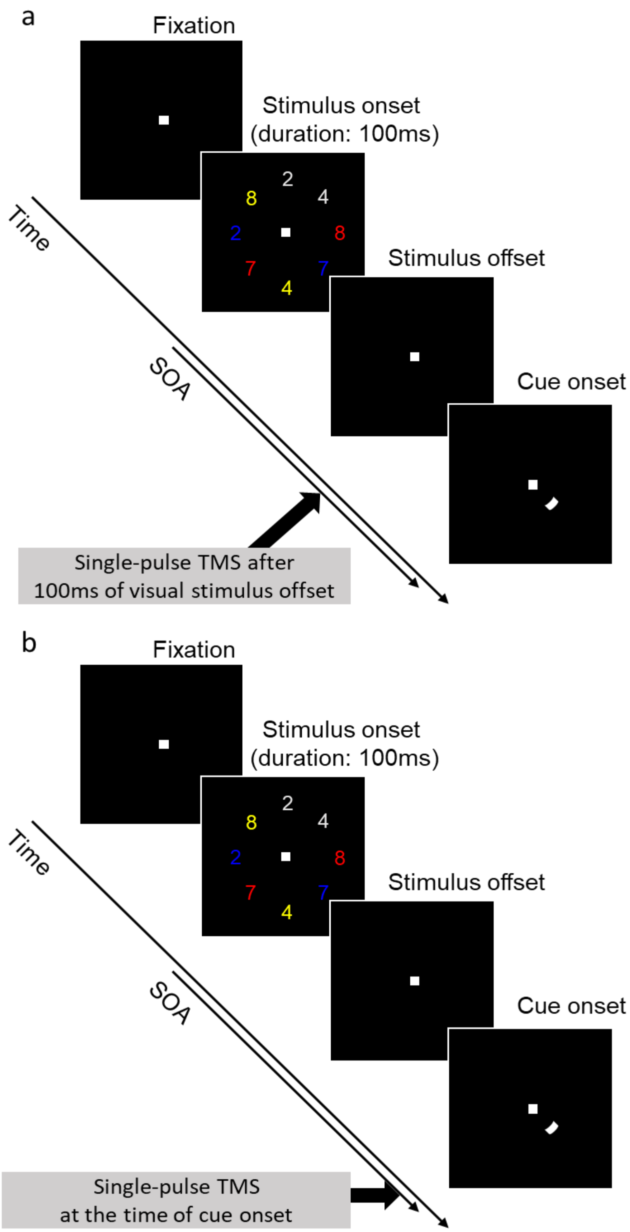

Figure 9. Timeline of single−pulse TMS experiment. (a) The procedure of IM task and the timing of stimulation at V1 stimulation condition. (b) The procedure of IM task and the timing of stimulation at the FEF stimulation condition

3.2.4. Statistical Analysis

The difference of report accuracy at each SOA condition between color and number was analyzed using Wilcoxon signed-rank test to confirm that the color and number decay in different rate. The analysis was conducted on participants included in both color and number reporting condition. The sample size was eighteen.

In addition, one-sided Wilcoxon signed-rank test was performed to observe the significant increase/decrease in report accuracy of IM task with four different SOA conditions (0ms, 200ms, 500ms, 1000ms). Specifically, changes in report accuracy at 200ms SOA and 500ms SOA indicate the change in IM decay rate since IM lasts about 500ms after stimulus onset. The changes in report accuracy at SOA conditions of 0ms and 1000ms indicate changes in sustained attention level and working memory capacity respectively.

Since the data did not satisfy the normality assumption, Wilcoxon signed-rank test was used instead of the student's t-test or ANOVA. Bonferroni correction was applied to the comparison made with report accuracy at SOA 200ms and SOA 500ms because those two conditions test the same hypothesis that there is a change in IM decay. The significance level was set at $p<0.025$. Bonferroni correction was not applied in the case of comparison with SOA 0ms and SOA 1000ms since those two conditions test different hypotheses that there are changes related to the participants' sustained attention level and working memory capacity.

3.3. Results

The results of the Wilcoxon signed-rank test of report accuracy between color and number showed faster decay rate in number reporting condition than color reporting condition at SOA larger than 0ms in general. There was a significant difference in report accuracy at SOA of 0ms only when TMS was applied to V1 (Wilcox V = −2.208, p−value = 0.27). In addition, the index of visual working memory capacity (report accuracy at SOA 1000ms) was significantly different between color and number regardless of TMS site. The detailed results are described in table 6.

Table 6. Results of the Wilcoxon signed-rank test between number and color report accuracy in Experiment 2. The sample size is eighteen.

SOA	Wilcox V	P-value
Sham stimulation		
0ms	-1.746	0.081
200ms	-2.382**	0.017
500ms	-2.916**	0.004
1000ms	-3.201**	0.001
V1 stimulation		
0ms	-2.208*	0.027
200ms	-2.796**	0.005
500ms	-3.204**	0.001
1000ms	-2.893**	0.004
FEF stimulation		
0ms	-0.763	0.446
200ms	-2.893**	0.004
500ms	-3.336**	0.001
1000ms	-2.898**	0.004

* p-value<0.05 ** p-value<0.025

The results of the one-sided Wilcoxon signed-rank test showed that there was a significant increase in report accuracy at SOA 200ms when TMS is applied to the V1 (Wilcox v = 39, p-value = 0.021) in the color reporting condition. There was no significant increase in report accuracy with other SOA conditions. When the stimulation site was left FEF, no significant increase in report accuracy was observed.

In the case of number reporting condition, the results of the one-sided Wilcoxon signed-rank test showed a significant decrease in report accuracy at SOA 500ms (Wilcox v = 189, p-value = 0.020). There was no significant change in the performance level of IM task when the stimulation was applied to FEF. The detailed results are described in figure 10 and table 7.

Table 7. Results of the one-sided Wilcoxon signed-rank test in Experiment 2.

Color Condition			
SOA	**TMS site**	**Wilcox V**	**P-value**
0ms	V1	68.5	0.5034
	FEF	65.5	0.5567
200ms	V1	39*	0.021*
	FEF	77.5	0.7587
500ms	V1	86	0.5181
	FEF	103.5	0.2232
1000ms	V1	145	0.7293
	FEF	76	0.3495
Number Condition			
SOA	**TMS site**	**Wilcox V**	**P-value**
0ms	V1	136.5	0.125
	FEF	61	0.6502
200ms	V1	126.5	0.2171
	FEF	103.5	0.1033
500ms	V1	189*	0.020*
	FEF	176.5	0.051
1000ms	V1	147.5	0.5303
	FEF	116	0.4977

*. p-value<0.025

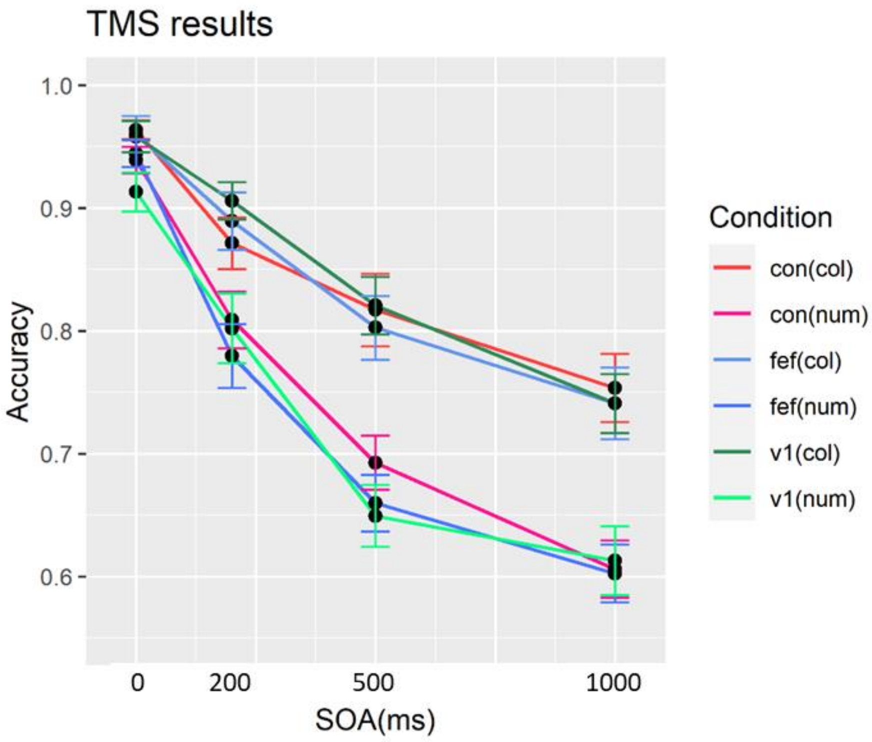

Figure 10. Graphs describing the results of TMS experiment by reporting visual attributes. Error bars represent standard errors. Abbreviations: con, sham stimulation condition; fef, frontal eye field stimulation condition; v1, primary visual cortex stimulation condition; col, color; num, number.

3.4. Discussion

Experiment 2 reproduced the same results as the first experiment: AOE did not significantly determine the decay rate of IM. The application of TMS to the left FEF to disturb the attention orienting process did not produce a significant decrease in report accuracy of IM task in either color or number reporting conditions. However, in the condition which required the reporting of number, the report accuracy tended to decrease at 500ms of SOA (Wilcox's $V = 176.5$, $p = 0.051$). When TMS was applied to V1 to facilitate neural activity, report accuracy increased at 200ms SOA in the condition which required the reporting of color and decreased at 500ms SOA in the number reporting condition. These two significant changes at the 200ms SOA and 500ms SOA conditions indicate that the IM decay rate changed significantly.

Regarding the insignificant results of the FEF stimulation condition, the lack of a neuronavigation system and individual MRI scans could have decreased the accuracy when locating the target area. The location of left FEF was determined by using the average scalp location reported in previous studies (Ronconi, Basso, Gori, & Facoetti, 2014). The location is reported to vary fairly among individuals (Ro, Farnè & Chang, 2002). In addition, the relatively deep location of FEF (Vernet, Quentin, Chanes, Mitsumasu & Valero-Cabré, 2014) could have weakened the effect of TMS. However, some studies reported significant manipulation of FEF activity (O'Shea, Muggleton, Cowey, & Walsh, 2006; Ronconi, Basso, Gori, & Facoetti, 2014) and the intensity of 1.0 MT is used in FEF stimulation (Ronconi, Basso, Gori, & Facoetti, 2014). Although the possibility of a decrease in statistical power due to the increased variance in location determination cannot be eliminated, this possibility is minimal considering the results of previous studies.

In the case of V1, the area is located closer to the scalp than FEF, which adds stability to the stimulation (Razi et al., 2017). However, it was unclear why the effect of TMS appeared in opposite directions between the color reporting condition and the number reporting condition. It was also unclear why the effect of TMS appeared at an SOA of 200ms in the color reporting condition and at an SOA of 500ms in the number reporting condition.

The difference in the time points of the TMS effect between the color and number conditions could be explained by considering the competition between the facilitating effect of V1 and the inhibiting effect on feedback necessary for feature grouping. According to the results of the color reporting condition, the single-pulse TMS applied 100ms after the offset of the visual stimulus exerted a significant facilitation effect on the V1 until SOA reached 200ms but not 500ms. In the case of the number reporting condition, the facilitation effect at an SOA of 200ms could have been canceled out because of the inhibition of the feature grouping process. When the SOA between the visual stimulus and location cue reached 500ms, the facilitation effect of V1 could have weakened which was not sufficient to cancel out the inhibition effect.

Regarding the different directions of the TMS effect between the two cases, it is possible that the use of MT instead of the phosphene threshold resulted in the difference. Although the MT is generally lower than the phosphene threshold (Deblieck, Thompson, Iacoboni & Wu, 2008), there are exceptions. In addition, even if MT can be considered to be of a subthreshold intensity to V1, the mechanism of the TMS effect on the visual cortex is complicated. The factors that influence the direction of TMS effect to V1 are still an ongoing issue due to the interplay between V1 and other areas in the visual cortex (Sparing et al, 2005).

However, the significantly increased report accuracy in the color condition indicates that V1 activity is facilitated by the TMS application. fMRI studies have shown that color perception is related to an increased V1 response (Engel, Zhang & Wandell, 1997; Gegenfurtner, 2003). In this case, the decreased report accuracy in the number condition can be interpreted as inhibition of the grouping process which is necessary for number perception. There is a study that showed a reciprocal relationship between V1 activity and grouping of visual features (Lerner, Hendler, Ben-Bashat, Harel & Malach, 2001; Murray, Kersten, Olshausen, Schrater & Woods, 2002). Feedback from the lateral visual complex, responsible for feature grouping, induces a decrease in V1 activity. In contrast, V1 activity increased and the activity of the lateral visual complex decreased when participants focused on individual features instead of grouping. This reciprocal relationship can be explained by the "explaining away" of the higher visual areas. The higher visual areas gave feedback to V1, which narrowed the possible shape of the stimulus. The results of Experiment 2 on V1 stimulation can be explained by the inhibition of those explaining away the feedback due to TMS.

The results of V1 stimulation indicated that the grouping process of visual features significantly affected the IM decay rate in the partial report task. Therefore in the case of numbers, the decrease in the decay rate can be the result of the inhibited feature grouping process and loss of independent features due to the delay instead of faster decay in the sensory representation of independent features. The present study provides TMS evidence of consideration in an earlier study (Yi, Kang & Lee, 2018). These results suggest that visual stimuli with multiple features should be used with caution when a partial report task aims to measure the decay rate of sensory representations.

Lastly, unlike an earlier study (Yi, Kang & Lee, 2018), the capacity of working memory between color and number appeared significantly different. The capacity of working memory was larger with color than with the numbers. Therefore, the possibility of a capacity difference at the working memory level arises again. Despite the confounding of working memory capacity between IM of color and number, the different directions of the TMS effect on color and number accuracy support that the grouping process can be another factor influencing the IM decay rate in the number reporting condition.

4. Experiment 3

4.1. Participants

Thirty right-handed participants (mean age = 22.6 years; standard deviation = 2.1; 23 females, 7 males) without a recorded history of psychiatric or neurological disorders were recruited from the community website of Seoul National University. Among thirty participants, fourteen participants and sixteen participants were randomly assigned to the anodal stimulation group and cathodal stimulation group respectively. The collection of data was approved by the Institutional Review Board of Seoul National University and conducted in accordance with the Declaration of Helsinki (Association, G. A. o. t. W. M., 2014). Among thirty participants, fifteen participants who did not wear glasses or contact lenses recorded their eye movements using an eye tracker.

Participants whose report accuracy was under a certain level (color condition: 0.85, number condition: 0.7) in sham condition at 0ms SOA were excluded from the tDCS results analysis. In the eye tracker analysis, three participants who showed low recording quality were excluded from the final analysis.

4.2. Methods

4.2.1. Iconic memory task

The procedure of IM task was the same as Experiment 2. Participants watched a visual stimulus via a 24" monitor placed 75cm ahead. They reported the number or color of the number at the cued location by pressing the keyboard. The visual stimulus consisted of eight colored numbers located at eight cardinal points at equal distances from the center of the monitor (radius = 3.34°). Four numbers (2, 4, 7, and 8) with four colors (red: RGB(255, 0, 0), blue: RGB(0, 0, 255), gray: RGB(0.7, 0.7, 0.7), and yellow: RGB(255, 255, 0)) are shown in a black background (0.5 cd/m2). The numbers were selected to avoid shape similarity. For each presentation of the visual stimulus, the number and color were randomly combined.

Before starting the experiment, the participants were instructed to fix their gaze at the fixation point located at the center of the monitor. The fixation point was a small white box (0.40° × 0.40°). Four different SOAs were introduced between the appearance of the target cue and the visual stimulus (0 ms, 200 ms, 500 ms, and 1000ms). The duration between fixation point onset and the location cue onset was 2000 ms. The inter-trial interval was randomized between 1000 to 1500 ms. The duration of the visual stimulus was adjusted to 100 ms.

Participants went through 24 trials for each SOA condition, and 96 trials consisted of one block of the IM task. Four different SOA conditions were randomly distributed across each block. In the number block, participants reported the target number, whereas, in the color block, they reported the color of the target number. The order of the blocks was randomized between the participants. It took approximately 10 minutes to complete one block of IM task.

4.2.2. Transcranial Direct Current Stimulation

Stimulation was delivered by a battery−driven transcranial electrical stimulator which provides constant current stimulation (Soterix medical, New York, United States) using a pair of sponge electrodes (5×7cm) with conductive rubber inserts. The sponge electrodes were soaked in a saline solution (0.9% NaCl) and applied to the scalp.

For the stimulation of V1, the electrode was placed over the Oz position according to the international 10/20 electroencephalogram system (Lang et al., 2007). The reference electrode was located at the Cz position. The selection of reference site was based on a previous study that showed Cz as the preferable site to induce changes in visual cortex stimulation (Antal, Kincses, Nitsche, Bartfai & Paulus, 2004). Figure 11 depicts the placement of electrodes.

Participants received a constant current of 1.0 mA (current density: 0.029 mA/cm2) for 20 minutes. The intensity of the stimulation was reported to be sufficient in inducing the observable change in performance level (Ellison, Ball & Lane, 2017).

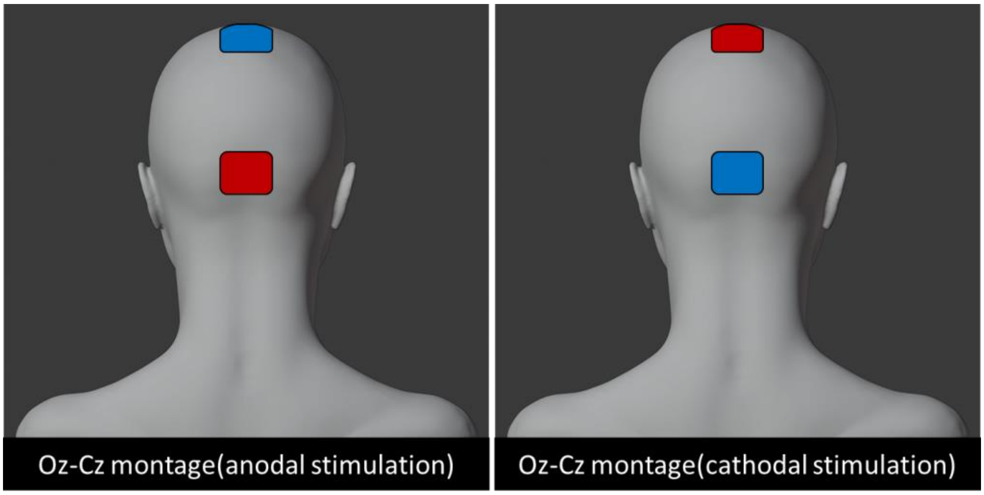

Figure 11. Placement of tDCS electrodes. The location of anode and cathode are illustrated as red and blue round patches respectively.

Participants were assigned to either group A or group B according to the type of tDCS stimulation. Group A received anodal stimulation and group B received cathodal stimulation to V1. Both groups received sham stimulation as a control condition. For the Sham stimulation, the current ramped up to 1.0mA in 30 seconds and ramped down in 30 seconds at the beginning of stimulation to induce the sense of stimulation. The ramp-up and ramp-down of current were repeated at the end of stimulation and there was no stimulation in between.

4.2.3. Eye Tracker

Eye movement was recorded using TRACKPixx3 (Vpixx Technologies, Quebec, Canada) which is a binocular eye tracker with a 2 kHz sampling rate. Visual stimuli were presented on a 24” screen with a resolution of 1920 × 1080. The monitor was placed 75cm ahead of the eyes of the participants. The recording was performed in a dark room. Before the recording, pupil size and gaze calibration processes were performed using the software (DATAPixx3) included in the eye tracker system.

4.2.4. Procedure

The experiment was a mixed design consisting of within group factors about the presence of tDCS stimulation (sham stimulation and tDCS stimulation), reporting visual attributes(color and number) and a between group factor about the type of tDCS stimulation (cathodal and anodal). The experiment consisted of two sessions. Each session delivered tDCS(anodal/cathodal) stimulation or sham stimulation in random order. The stimulation started at the beginning of the session and lasted for 20 minutes. Participants performed two blocks of IM tasks for number reporting condition and color reporting condition 10 minutes after the stimulation onset and 10 minutes after the stimulation offset to observe if there is any performance difference originating from the stimulation duration. Therefore, a total of four blocks of IM task were performed in each session. An eye tracker recorded the eye movement during the IM task in the sham condition. Calibration of the eye tracker was performed at the start of each session.

There was a 30-minute break time between the sessions to assure a 60-minute washout period for the purpose of preventing the carry-over effect of constant current stimulation on V1(Antal, Kincses, Nitsche, Bartfai & Paulus, 2004). The procedure was described in figure 12.

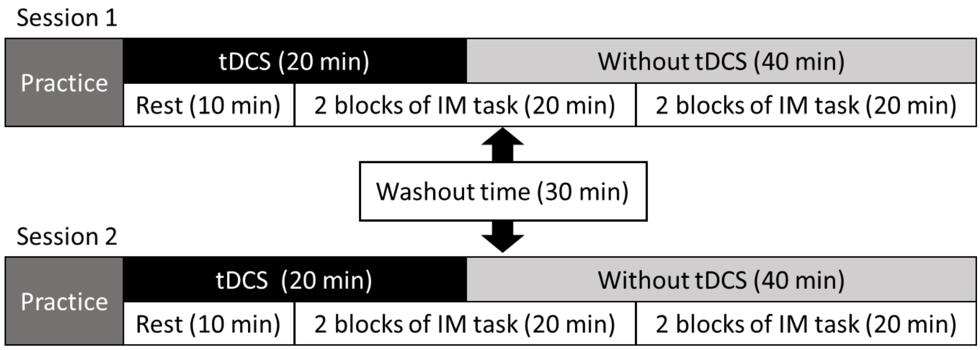

Figure 12. Procedure of tDCS experiment. The order of anodal/cathodal stimulation and sham stimulation was randomized across sessions.

4.2.5. Statistical Analysis

Statistical analysis was performed with IBM SPSS statistics 25. Since the data did not satisfy the normality assumption, nonparametric analysis was performed.

The Wilcoxon signed-rank tests were performed to analyze the difference in report accuracy in IM task between sham condition and tDCS (anodal/cathodal) stimulation condition. the results of IM task during and after the offset of tDCS stimulation were averaged since there were no significant differences in reporting accuracy.

The correlations between the report accuracy of IM task with four different SOAs (0ms, 200ms, 500ms, 1000ms) and the eye movement indices were calculated using the Spearman's rank correlation coefficient. A p-value under 0.05 was considered significant.

4.2.6. Eye Movement Analysis

An eye movement was classified as fixation when the velocity was under 10.1° /s and the duration was over 50ms. To avoid the over-segmentation of one fixation due to the noise occurring randomly with large velocity, fixation segments separated within 75ms were regarded as continuous fixation (Olsen, 2012). Among the segments which were not classified as fixation, the segments with maximum velocity under 300°/s were regarded as microsaccades (Martinez-Conde, Macknik, Troncoso & Hubel, 2009). The segments over 300°/s of maximum velocity were classified as saccades. However, the segments classified as microsaccades and saccades would contain other eye movements since they were a complementary set of fixation segments. Therefore it would be more appropriate to regard them as segments containing microsaccades and saccades.

The selection of maximum velocity of fixation was based on the results of the receiver operating characteristic (ROC) curve with six threshold points (figure 13). Eye tracker data were classified using each velocity threshold and the maximum velocity of the segments was calculated. The maximum velocity over 100°/s was considered as true saccade as saccade amplitude during the IM task would occur approximately as a radius of visual stimulus (3.34˚). The results showed that the velocity threshold of 10.1˚/s showed the highest Youden index which is the vertical distance from the curve to the diagonal.

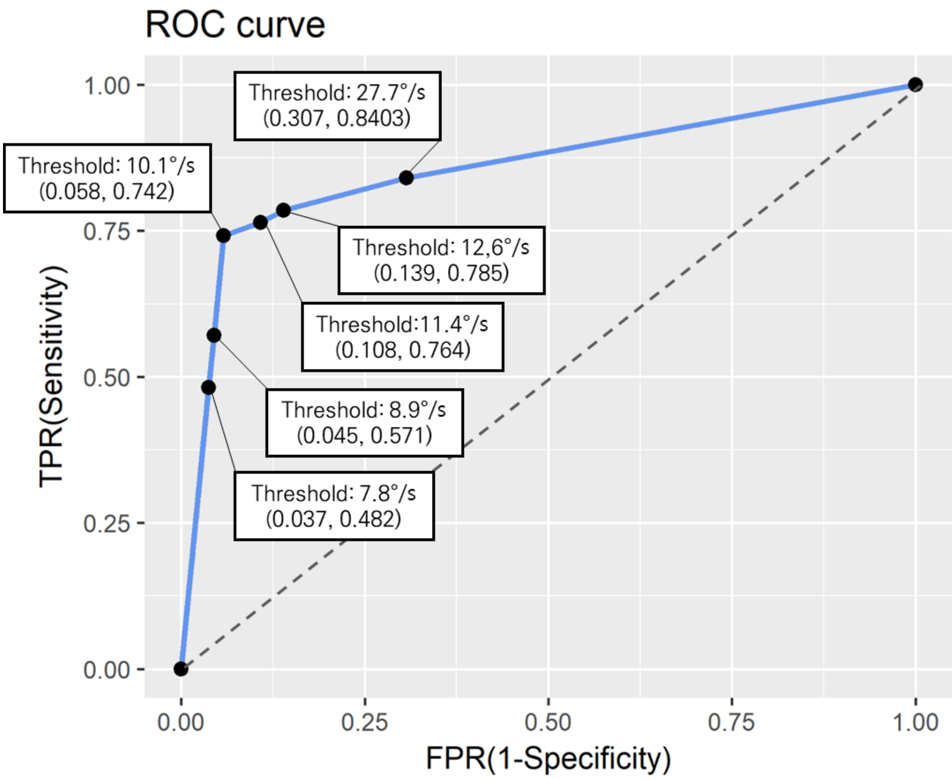

Figure 13. ROC curve with six velocity thresholds regarding fixation classification. Abbreviation: TPR, true positive rate; FPR, false positive rate.

A previous study showed considering the velocity of saccade offset as 10° /s was plausible, which is lower than the maximum fixation velocity at 50ms of duration threshold (Manor & Gordon, 2003). The minimum duration threshold was selected to include short fixations which are reported to occur at the ambient mode of information processing (Fudali-Czyż, Francuz & Augustynowicz, 2018; Inhoff, Topolski & Wang, 1992).

The indices of fixation stability (average fixation duration, standard deviation of fixation coordinates) were calculated from the raw data using Matlab based algorithm provided by DATAPixx. The standard deviations of coordinates related to microsaccades and saccades are also calculated as indices of the prevalence of each eye movement relative to fixation. The duration was excluded from the index since the segments would overestimate the duration of microsaccades or saccades.

4.3. Results

4.3.1. Iconic Memory and tDCS

The results of Wilcoxon signed-rank tests showed significant differences of report accuracy at different SOA conditions between color and number in general. The detailed results are described in table 8.

Table 8. Results of Wilcoxon signed−rank tests in Experiment 3.

SOA	Wilcox V	P-value
Control (anodal group)		
0ms	-1.754	0.080
200ms	-3.297**	0.001
500ms	-3.297**	0.001
1000ms	-3.297**	0.001
tDCS stimulation (anodal group)		
0ms	-2.518**	0.012
200ms	-3.108**	0.002
500ms	-3.297**	0.001
1000ms	-3.297**	0.001
Control (cathodal group)		
0ms	-2.295**	0.022
200ms	-2.658**	0.008
500ms	-3.297**	0.001
1000ms	-2.968**	0.003
tDCS stimulation (cathodal group)		
0ms	-1.510	0.131
200ms	-3.041**	0.002
500ms	-3.046**	0.002
1000ms	-2.921**	0.003

*p−value<0.05, **p−value<0.025

However, The results of Wilcoxon signed-rank tests showed no significant differences between sham condition and anodal/cathodal condition in the decay rate of IM either in color and number reporting conditions. The results are described in table 9 and figure 14.

Bonferroni correction was applied to the comparisons with report accuracy of IM task at SOA 200ms and SOA 500ms conditions since those two comparisons test the same hypothesis that there is a change in the decay rate of IM. The significance level was set at $p<0.025$.

Table 9. Results of Wilcoxon signed-rank tests between report accuracy of number and color in Experiment 3.

Color Condition			
SOA	**Comparison**	**Wilcox V**	**P-value**
0ms	Sham/Anodal	1.016	0.310
	Sham/Cathodal	0.220	0.825
200ms	Sham/Anodal	-0.629	0.529
	Sham/Cathodal	0.118	0.905
500ms	Sham/Anodal	-0.157	0.875
	Sham/Cathodal	1.086	0.278
1000ms	Sham/Anodal	0.175	0.861
	Sham/Cathodal	-0.251	0.802
Number Condition			
SOA	**Comparison**	**Wilcox V**	**P-value**
0ms	Sham/Anodal	-1.102	0.270
	Sham/Cathodal	1.455	0.146
200ms	Sham/Anodal	0.456	0.648
	Sham/Cathodal	0.188	0.851
500ms	Sham/Anodal	-0.503	0.615
	Sham/Cathodal	1.610	0.107
1000ms	Sham/Anodal	-1.428	0.153
	Sham/Cathodal	2.437*	0.015

*p<0.025

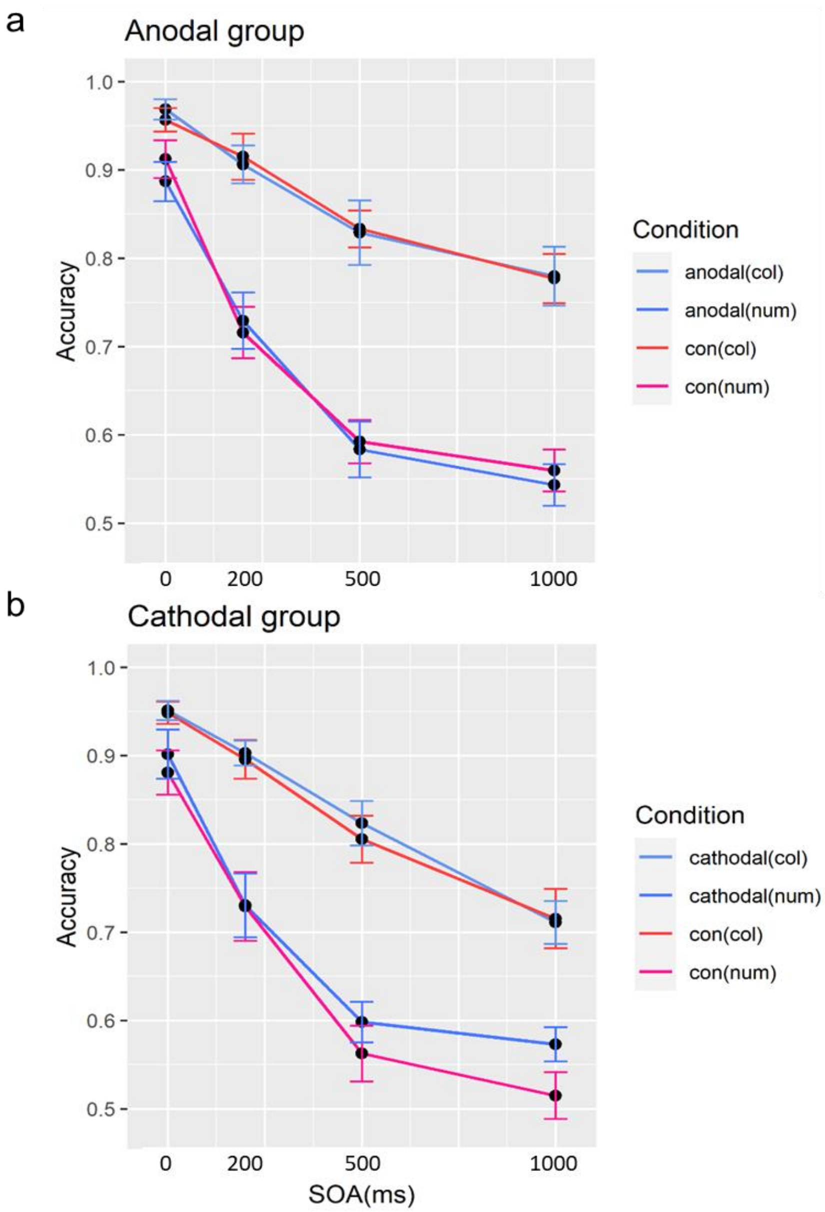

Figure 14. Graphs of IM task−accuracy according to conditions by tDCS stimulation. (a) The graphs of the anodal stimulation group. (b) The graphs of the cathodal stimulation group.

4.3.2. Iconic memory and Eye Movements

One participant was excluded from the analysis of Spearman correlation between color report accuracy and microsaccades as an outlier. As a result, there were no significant correlations between the report accuracy of IM task and the indices of fixation stability, microsaccades, and saccades (Table 10, Table 11).

Table 10. Spearman's rho between fixation stability and report accuracy of IM task. SD of fixation refers to the standard deviation of fixation coordinates.

Color Condition		
SOA	**SD of fixation**	**Fixation Duration**
0ms	0.020	0.100
200ms	0.345	-0.029
500ms	0.325	0.139
1000ms	0.279	0.350
Number Condition		
SOA	**SD of fixation**	**Fixation Duration**
0ms	0.228	-0.327
200ms	0.241	-0.028
500ms	-0.300	<0.000
1000ms	0.198	-0.109

*$p<0.05$

Table 11. Spearman's rho between the coordinate standard deviation of microsaccades (saccades) and report accuracy of IM task.

Color Condition		
SOA	**SD of microsaccades**	**SD of saccades**
0ms	-0.178	-0.175
200ms	0.515	0.506
500ms	0.449	0.354
1000ms	0.479	0.468
Number Condition		
SOA	**SD of microsaccades**	**SD of saccades**
0ms	0.360	0.307
200ms	0.311	0.032
500ms	0.224	0.416
1000ms	0.032	-0.047

*p<0.05

4.4. Discussion

The anodal and cathodal stimulations of V1 did not induce significant changes in the IM decay rate. There were no significant differences in report accuracy at 200ms SOA and 500ms SOA between the sham and tDCS conditions. However, report accuracy at 1000ms SOA in the number condition significantly increased when participants received cathodal stimulation.

Before concluding that V1 activity is not significantly related to IM decay rate, the results of tDCS had to be compared with the TMS results, which induced a significant change in the IM decay rate. There are two mechanisms of brain stimulation. TMS creates a magnetic field that penetrates the skull up to a depth of 3cm. Stimulation induces an electrical current to neurons in the target area, which is sufficient to depolarize neuronal membranes and generate action potentials (Rossi et al., 2009). Compared to TMS, tDCS is not sufficient to instantly induce action potential. It modulates membrane potential to increase or decrease cortical excitability (Torres, Drebing & Hamilton, 2013). It takes a few minutes for tDCS to induce significant changes in cortical excitability of the visual cortex (Antal, Kincses, Nitsche, Bartfai & Paulus, 2004).

However, considering that Experiment 2 used a subthreshold intensity of TMS and 20 min of tDCS is sufficient to induce a change in excitability of the visual cortex, other factors could have resulted in the difference.

TMS and tDCS have different spatial and temporal resolutions. In general, TMS has a higher spatial and temporal resolution than tDCS. The relatively low spatial resolution of tDCS could have modulated the excitability of other visual areas, which canceled out the effect of V1 on the IM decay rate. In addition, the absence of a specific temporal window in tDCS could have resulted in its insignificance. It has been reported in single-pulse TMS studies that the timing of stimulation influences the magnitude the effect on specific visual information processing (Fierro, Brighina, Piazza, Oliveri & Bisiach, 2001). Therefore, the change in the membrane potential in a broad temporal window could have been insufficient to induce significant changes in the IM decay rate.

In the case of a significant increase in report accuracy at 1000ms SOA in the number condition while receiving cathodal stimulation to V1, the results can be interpreted as the consequence of anodal stimulation on FEF, which is close to a vertex. Considering that anodal stimulation facilitates neuronal activity at the stimulated location, attentional orienting may have been facilitated resulting in an increase in working memory capacity. Provided that this is true, the insignificant change in the IM decay rate suggests that the efficiency of attentional orienting does not influence the IM decay rate. In addition, the insignificant changes in working memory capacity in the color condition could be the result of a ceiling effect. In contrast, the orienting of attention appeared to influence the working memory capacity with respect to numbers implying working memory capacity regarding numbers demanded more attentional resources than color.

Regarding report accuracy, the larger working memory capacity in the color reporting condition compared to the number reporting condition was reproduced. Therefore, the possibility that the capacity of visual working memory influences the IM decay rate and induces a difference between color and number must be considered.

The results related to eye movement, fixation stability, and the prevalence of microsaccades or saccades did not correlate with the report accuracy of the IM task at any SOA. These results suggest that in the group without significant problems with eye movement, individual accuracy differences were not sufficiently explained in terms of eye movement differences related to AOE. Fixation stability has been regarded as an index for suppressing unwanted saccades and microsaccades, which is related to the efficient functioning of the FEF (Krauzlis, Goffart & Hafed,2017). In addition, it is broadly considered an index of attention control ability (Unsworth, Robison & Miller, 2019). In this experiment, fixation stability was measured to determine the degree of instability of attentional control, which is related to AOE. Microsaccades have been reported to be related to the orientation of covert attention (Eng, Chen & Jiang, 2005; Kang, Kim & Lee, 2017). The prevalence of regular saccades indicates disengagement of spatial attention, since the IM task instructed participants to fixate on the center of the screen.

Therefore the results of eye movement indices provide converging evidence that the AOE did not determine IM decay rate. The report accuracies at variable SOAs were not exact indices of IM decay rate because they were not compared between groups. However, strong negative correlations (Spearman' s rho < −0.77) existed between the report accuracy at 200ms, 500ms SOA, and the difference in report accuracy from SOA 0ms which suggests lower report accuracy at a specific SOA, indicated a more pronounced decrease in report accuracy by SOA.

The prevalence of microsaccades also did not correlate with the report accuracy at 0ms SOA or 1000ms SOA. Considering previous studies that reported a correlation between attentional orienting and microsaccades, the results seemed inconsistent. The insignificant correlation could have been caused by microsaccades irrelevant to the task because the prevalence index did not account for the relevance to the task. Previous studies have shown that only microsaccades made in the direction of relevant items increase performance (Lara & Wallis, 2012). In addition, a previous study has also indicated that gaze shifts do not serve as an index to measure working memory storage or the performance level of detection tasks (Kang & Woodman, 2014).

5. General Discussion

Three experiments were conducted to investigate the neural mechanisms underlying IM decay rate to explain the different decay rates in color and number. In addition to the existing hypothesis that the IM decay rate was determined by the decay of sensory representation stored at V1 (SRD hypothesis), efficiency in attentional orienting (AOE hypothesis) and information transfer speed from IM to working memory (CEP hypothesis) were considered potential neural mechanisms influencing the IM decay rate of color and number. The results are discussed below along with their limitations.

5.1. Attentional Orienting Efficiency and Decay Rate of Iconic Memory

AOE was considered a potential neural mechanism determining IM decay rate because participants had to voluntarily orient their attention to the cued location to produce an accurate report in a partial report task. If attention was not immediately focused on the cued location, a participant reported it inaccurately, although the decay rate of sensory representation remained the same. However, the results showed that AOE did not significantly affect the IM decay rate in terms of either color or number.

Experiment 1 conducted confirmatory factor analyses to evaluate the fit indices of the models about the SRD, AOE, and CEP hypotheses. Additionally, the model which explained IM decay rate as being a result of sustained attention level was also included in this analyses. The fit indices showed that the IM decay rate was best explained by the decay of sensory representation in both color and number.

Experiment 2 modulated the AOE directly by single-pulse TMS on the left FEF, which played a central role in the orienting of spatial attention in humans (Kincade, Abrams, Astafiev, Shulman & Corbetta, 2005; Muggleton, Juan, Cowey & Walsh, 2003; Tehovnik, Sommer, Chou, Slocum & Schiller, 2000; Thompson, Biscoe & Sato, 2005). The modulation did not induce significant changes in the IM decay rate for either color or numbers. Although the absence of individual MRI and neuronavigation could be possible sources of error, the use of average scalp locations based on previous studies have successfully yielded signification modulations at FEF in multiple TMS studies (Leff, Scott, Rothwell, & Wise, 2001; O'Shea, Muggleton, Cowey & Walsh, 2006; Ronconi, Basso, Gori & Facoetti, 2014), making the possibility unlikely.

In Experiment 3, although the possible anodal stimulation of FEF using tDCS induced a significant increase in working memory capacity of number, the IM decay rate remained unchanged. These results suggest the possibility that the working memory capacity of numbers could be influenced by the AOE, while the IM decay rate was not. It is also interesting that the working memory capacity of color remained unchanged, unlike those of number. This difference implies that the facilitation of efficiency in attentional orienting improves the retention of information with higher visual complexity. Considering the results of a study that showed the independent loss of visual features in working memory (Fougnie & Alvarez, 2011), modulation of AOE could have increased working memory capacity by capturing the information before the loss.

Finally, there were no correlations between individual IM report accuracy and eye movement indices, such as fixation stability, the prevalence of microsaccades, and the prevalence of regular saccades. The results of eye movement indices provide converging evidence that AOE does not determine IM decay rate.

5.2. Central Executive Part and Decay Rate of Iconic Memory

The possibility that CEP significantly affects the IM decay rate was first reported in a study that showed different decay rates between number and color stimuli (Yi, Kang & Lee, 2018). The report accuracy of the partial report task decreased faster when participants reported the number than the color of the number.

Two explanations for these results are discussed in this study. The first explanation is that the color information persisted longer than the number information at the sensory representation level. The second explanation considers the difference in the transfer speed of information regarding color versus numbers from the IM to visual working memory, which is the role of CEP (Imbo & Vandierendonck, 2007) as a possible cause of the phenomenon. Because the partial report task required conscious reporting in the process, the confounding of the CEP of working memory could not be eliminated.

The hypothesis that CEP of working memory is a neural mechanism underlying the IM decay rate was investigated in Experiment 1 using CFA. Comparisons of the models showed that the report accuracy of partial report tasks was better explained by the decay of sensory representation instead of the efficiency of information transferring processes to working memory, which is related to CEP, regardless of visual complexity in color and numbers. The model that assigned the report accuracy of the partial report task as an indicator of CEP showed less adequately-fit indices than the model that allocated the report accuracy of the partial report task as an indicator of SRD. Although the experiment used the DST, which measures verbal working memory, the efficiency of CEP can be measured through the task because it is modality-free (Baddeley, 1992). If the information transfer speed from IM to working memory was the main neural mechanism determining IM decay rate and resulted in different decay rates in number and color, the model that considered report accuracy of the IM task as a measurement of CEP would have resulted in the best fit indices.

The results of CFA did not eliminate the possibility that the partial report task demanded CEP participation. The results must be interpreted in such a way that the CEP of working memory, which was responsible for the information transfer speed from IM to working memory, is not concluded to be the main neural mechanism determining the IM decay rate for both number and color. CEP participation would be necessary because the partial report task demands a conscious report. However, it may not be concluded that this factor was significantly involved in the determination of the decay rate since that would not account for the different decay rates in color and number.

Meanwhile, in Experiment 2 and Experiment 3, the capacity of working memory turned out to be different with respect to color and numbers. Although the information transfer speed did not appear to be a significant factor determining the IM decay rate, the possibility of capacity differences in visual working memory needs further investigation. Regarding capacity difference, a previous study showed that visually complex stimuli had encoding limitations in visual working memory. The influence of visual complexity decreases considerably when encoding limitations are minimized by increasing the duration of the visual stimulus to 3000 ms (Eng, Chen & Jiang, 2005). Considering that the duration of the visual stimulus was 100 ms in Experiment 2 and Experiment 3 while the duration was 180 ms in Experiment 1, a longer duration of visual stimulus could have reduced the influence of encoding efficiency.

5.3. Sensory Representation Decay and Decay Rate of Iconic Memory

The results from Experiment 1 supported the SRD hypothesis that decay of sensory representation mainly determined IM decay rate instead of AOE or CEP factors. One study showed that persisting neural activity of V1 after the disappearance of a visual stimulus predicted accuracy in macaque monkeys (Teeuwen, Wacongne, Schnabel, Self, & Roelfsema, 2021). In addition, the results of Experiment 2, which used TMS to modulate V1 activity, support the SRD hypothesis. When single-pulse TMS was applied to V1, the report accuracy increased at 200ms SOA in the color reporting condition, which indicated the decrease in the IM decay rate.

However, the results of TMS showed another possibility regarding the number reporting condition. When single-pulse TMS was applied to V1, report accuracy increased at 200ms SOA in the color reporting condition and decreased at 500ms SOA in the number reporting condition compared to sham stimulation. These two significant changes in report accuracy indicated that the IM decay rate changed significantly after TMS application to V1.

A significant decrease in the IM decay rate under the color condition indicated that V1 activity was facilitated by the TMS application. fMRI studies have shown that improvement in color perception is related to an increased V1 response (Engel, Zhang & Wandell, 1997; Gegenfurtner, 2003). In this case, the decreased report accuracy, or increased IM decay rate in the number condition can be interpreted as the result of an activity increase in V1.

Regarding the results of number reporting condition, some studies showed a reciprocal relationship between V1 activity while grouping process of individual features into shapes (Lerner, Hendler, Ben-Bashat, Harel & Malach, 2001; Murray, Kersten, Olshausen, Schrater & Woods, 2002). The feedback from the higher visual area, in this case, the lateral visual complex which was responsible for feature grouping induced a decrease in V1 activity. In contrast, V1 activity increased while activity lateral visual complex decreased when participants focused on individual features instead of shape perception. This reciprocal relationship was explained by the "explaining away" of visual shape ambiguity by feedback from the higher visual area. In other words, the higher visual area gave feedback to V1 which narrowed down the possible shape of the incoming sensory stimulus to reduce the ambiguity (Kersten & Yuille, 2003). Therefore, the decreased report accuracy in number reporting condition could be interpreted as the inhibition of that feedback explaining away visual ambiguity due to TMS on V1.

The reciprocal relationship between V1 activity and report accuracy in number reporting condition was not observed by tDCS application to V1. Considering the absence of change in IM decay rate in color reporting condition after tDCS application, it could be the case that tDCS did not sufficiently modulate V1 activity to induce changes in IM decay rate. In general, TMS has higher spatial and temporal resolution compared to tDCS. The relatively low spatial resolution of tDCS could have modulated the excitability of other visual areas which canceled out the effect on V1. In addition, TMS was executed in a specific temporal window according to the onset of visual stimulus while tDCS was not. It was reported in single-pulse TMS studies that the timing of stimulation influenced the size of the effect on specific visual information processing (Fierro, Brighina, Piazza, Oliveri & Bisiach, 2001). In addition, the change at the level of membrane potential could have been insufficient to induce significant changes in IM decay rate.

Based on the results of TMS, it seems plausible to consider the involvement of the grouping processes to explain the faster decay rate of IM in the number reporting condition. Unlike color, a number requires feature grouping to be identified correctly. This possibility was discussed in a previous study on different IM decay rates in color and number reporting conditions (Yi, Kang & Lee), and the present study showed TMS evidence that the IM decay rate of numbers significantly increased when the grouping process was interrupted. In this case, the difference in IM decay rate between color and number reporting conditions could have been caused by the independent loss of visual features essential in identifying the shape of numbers.

However, there are ongoing debates regarding the necessity of feature grouping in meaningful, familiar objects.

The first point of debate is whether the perception unit of meaningful, familiar symbols, such as letters, is based on independent features or whole objects. Although, independent elementary features are regarded as intermediate representations that lead to object identification (Gibson, 1969), the unit of elementary features is not clear. For an experienced reader, an entire letter could be an elementary feature for letter identification.

Regarding the issue, a previous study investigated whether letter identification occurred in letter-specialized mechanisms which regarded the whole letter as an elementary unit of perception by comparing the response of experts and novices in specific languages (Pelli, Burns, Farell & Moore-Page, 2006). The results showed a reciprocal relationship between identification efficiency and complexity, indicating that letter identification occurred in an independent feature detection method rather than the whole letter being used as an elementary feature. Another study showed that the grouping process is involved in letter identification by showing that letter identifiability obeys the Gestalt law of good continuation (Pelli et al., 2009). In addition, a recent study found that people identified letters better by using general object-based features as opposed to specialized letter features through the use of deep convolutional neural networks (Janini, Hamblin, Deza & Konkle, 2021). Although the studies mainly used letters instead of numbers, the underlying mechanisms could be compatible because numbers are one example of meaningful, familiar symbols that are highly trained due to everyday use.

The debate concerning the point at which feature grouping occurs is intertwined with the debate on the independent loss of visual features in the IM and working memory. An earlier study that discussed the possibility of an independent loss of visual features in IM (Yi, Kang & Lee, 2018) was based on yet another previous study that advocated the feature-based model of information storage in working memory instead of an object-based model by observing the independent loss of visual features rather than dependency on the objects (Fougnie & Alvarez, 2011). Based on the properties of working memory which is a later stage of visual memory as compared to IM, it seems plausible that IM stores visual information according to a feature-based model if working memory stores information in a feature-based model. If this is the case, we may conclude that the grouping process occurs at the working memory level.

In other studies, object-based storage of visual working memory was observed instead of feature-based storage (Hakim, Adam, Gunseli, Awh & Vogel, 2019; Luck & Vogel, 1997). Yet another study found that object-based storage occurs in the case of basic features while detailed information needs additional effortful processing (Gao, Gao, Li, Sun & Shen, 2011). If this is the case, the grouping process could occur at the IM level before the information is encoded into the working memory. According to the previous studies, then, there is no consensus about the grouping of independent features occurring at the level of IM or working. In the current study, there was a significant difference in report accuracy between color and number at an SOA of 0ms only when TMS was applied to V1. The results could be interpreted as implying that the inhibition of the grouping process occurs not at the level of IM but the level of working memory.

To summarize, the results regarding TMS suggest that when the visual stimulus has multiple features, the IM decay rate can be changed, although the decay rate of individual features remains unchanged. Therefore, the grouping process should be considered a potential factor influencing the IM decay rate in the case of visual stimuli with multiple features.

Lastly, since one of the visual stimuli was a number, which is a symbol that has meaning and needs to be learned unlike color, some additional top-down processing related to semantics could be considered as a possible factor inducing differences in the IM decay rates between color and numbers. Although, the involvement of additional top-down factors could not be eliminated and needs further investigation, this concern could be mitigated by the following two points.

First, during the experiment, participants reported the color by pressing the assigned keyboard. This process may have demanded that participants process the color at the level of semantics.

Specifically, after the perception of the color yellow, it was likely to be converted to the concept of yellow to match the right keyboard. Contingency learning between color and word has been reported to occur at the semantic level (Geukes, Vorberg & Zwitserlood, 2019).

In addition, the identification of numbers could be considered a highly trained and automated process since participants of the experiment are likely to have performed the task for many years. According to the case of the Stroop effect (MacLeod, 1991), a highly trained process can be automated to a level of competing to the color perception.

5.4. Limitations of the Study

Our study has certain limitations that must be noted. First, the insignificant results of the experiments indicate several limitations. In Experiment 1, the introduction of a brief overlap of visual stimulus and the cue occurred for 80 ms in the 100 ms SOA condition to adjust the difficulty level, which could have led some participants with sufficient AOE to perform the volitional attentional orienting task instead of a partial report task. In the experiment, confounding was minimized by selecting 80ms of overlap no not disturb the participation of IM. It is reported that the time gap was too short for the volitional orienting of attention (Carlson, Hogendoorn & Verstraten, 2006; Fuentes & Campoy, 2008; Müller & Rabbitt, 1989). In addition, the number of SOA conditions in IM task was not enough to capture the exact decay rate. The index of decay rate was the difference of report accuracy between two SOA conditions (−100ms SOA, 100ms SOA) in the experiment. Although the index can capture the crude tendency of the decay rate, more data points with different SOA under 500ms would improve the process of finding the start point of the asymptotic line in the accuracy graph.

In Experiment 3, the different spatial and temporal resolutions of tDCS could be the factor causing insignificant results regarding V1 activity modulation. In addition, the eye movement indices for microsaccades and saccades do not account for the direction of each eye movement. Although a previous study indicaed that gaze shifts did not serve as an index to measure working memory storage or performance level of detection tasks (Kang & Woodman, 2014), this point can be considered a possible contributor to insignificant results.

Finally, the absence of visual masking during the IM task allowed the confounding of the prolonged visual afterimage which had significant results. Despite this possibility, the differences in the decay rate of IM with respect to color and numbers were reproduced after the backward masking experiment (Yi, Kang & Lee, 2018). In addition, the different directions of the TMS effect on color and number stimulation seemed unlikely to be the result of the prolonged duration of the visual afterimage.

6. Conclusion

Three experiments were conducted to investigate the neural mechanisms underlying the IM decay rate which could explain the different decay rates in color and number. In addition to the existing hypothesis that the IM decay rate was determined by the decay of sensory representation stored at V1 (SRD hypothesis), efficiency in attentional orienting (AOE hypothesis) and information transfer speed from IM to working memory (CEP hypothesis) were considered potential neural mechanisms influencing the IM decay rate of color and number.

The converging evidence lowered the possibility that AOE and CEP are neural mechanisms that determine the decay rate of IM in both number and color. The results of the confirmatory factor analysis showed that the most determining factor in the IM decay rate was not likely to be the AOE or CEP. In addition, the modulation of AOE and CEP factors induced no significant changes in the IM decay rate.

Instead, the TMS results suggested that the additional process of visual feature grouping during number shape perception could be a significant factor that induced different IM decay rates between color and numbers. The involvement of the grouping process could have resulted in different IM decay rates, although the decay of the sensory representations of individual visual features remained the same. In addition, the difference in visual working memory capacity between color and number appeared to be another possible factor inducing the different IM decay rates between color and number reporting conditions.

In conclusion, the present study provides evidence that the decay rate of an IM with multiple visual features could be the result of factors such as the grouping process of visual features and capacity of visual working memory, rather than only being the result of the decay of sensory representation.

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Appendix A
Diagrams and CFA results of the models from Experiment 1

This appendix consists of the nine diagrams of models from confirmatory factor analyses, which are based on SA, AOE, and CEP hypotheses (model B, C, D, F, G, H, K, L, and model M) and tables describing detailed numerical values of the models from Experiment 1. The following describes abbreviations used in the diagrams.

Abbreviations: SA, sustained attention; AOE, attentional orienting efficiency; CEP, central executive part; Cdecay, a difference of report accuracy in color between −100ms SOA and 100ms SOA; Ndecay difference of report accuracy in number between −100ms SOA and 100ms SOA; Cpre300, report accuracy of color condition at SOA −300ms; Npre300, report accuracy of number condition at SOA −300ms; tmta, time to complete TMT type a; tmtb, time to complete TMT type b; back, maximum number length in DST backward condition; forw, maximum number length in DST forward condition.

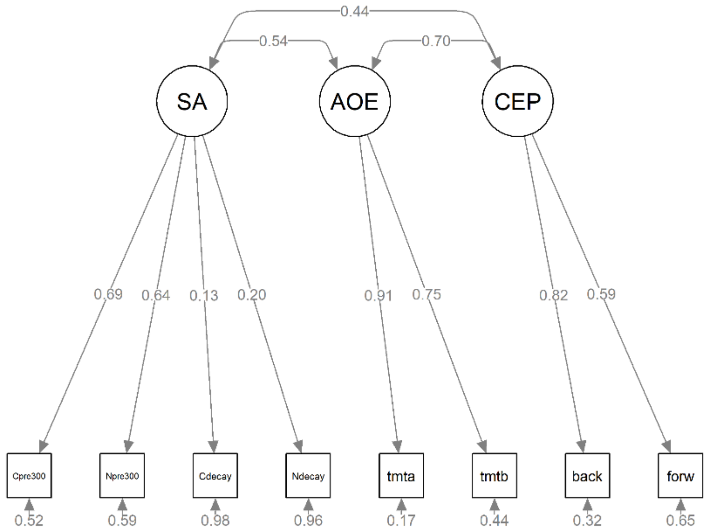

Figure 1. Diagram of model B. The model is based on the SA hypothesis.

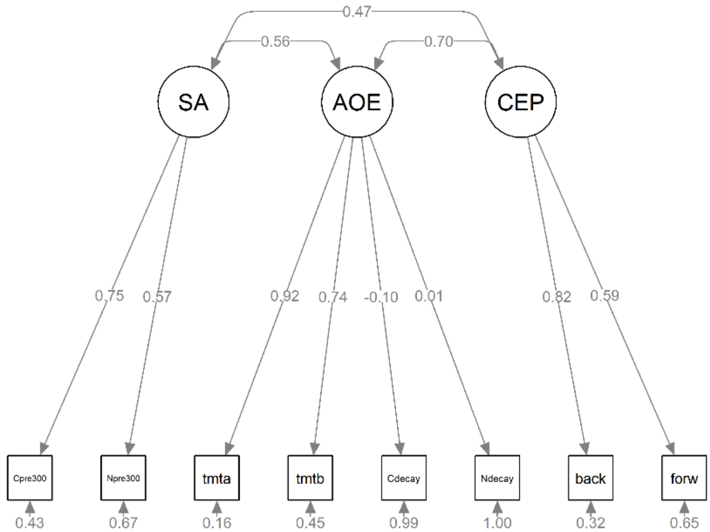

Figure 2. Diagram of model C. The model is based on the AOE hypothesis.

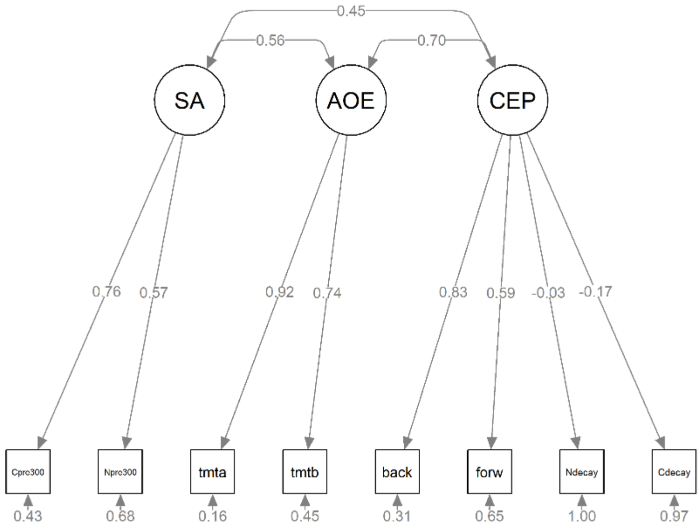

Figure 3. Diagram of model D. The model is based on the CEP hypothesis.

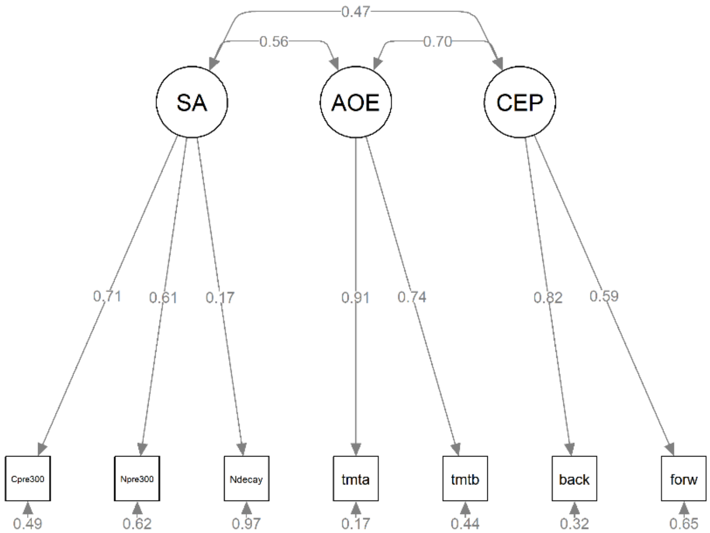

Figure 4. Diagram of model F. The model is based on the SA hypothesis.

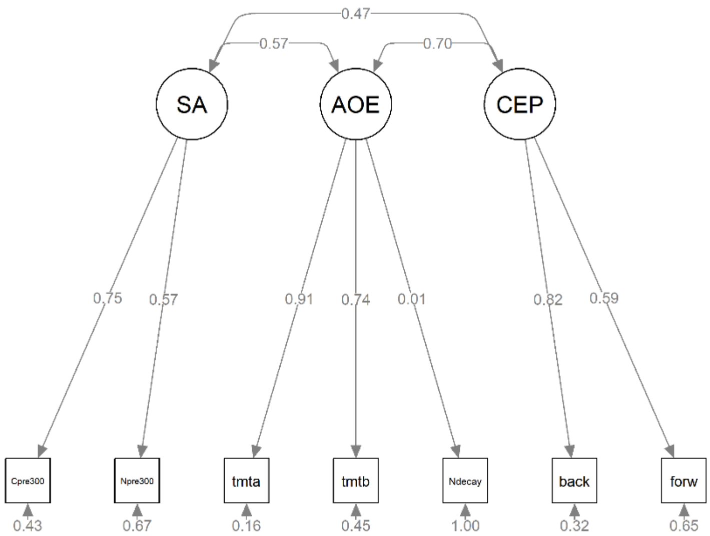

Figure 5. Diagram of model G. The model is based on the AOE hypothesis.

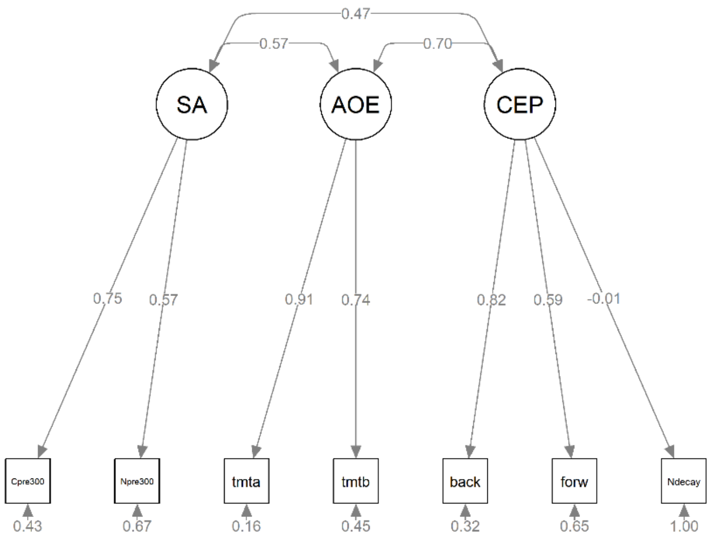

Figure 6. Diagram of model H. The model is based on the CEP hypothesis.

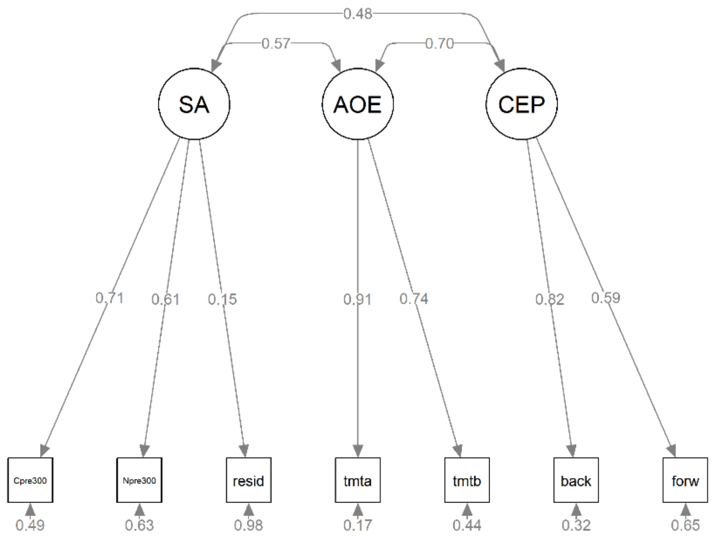

Figure 7. Diagram of model K. The model is based on the SA hypothesis.

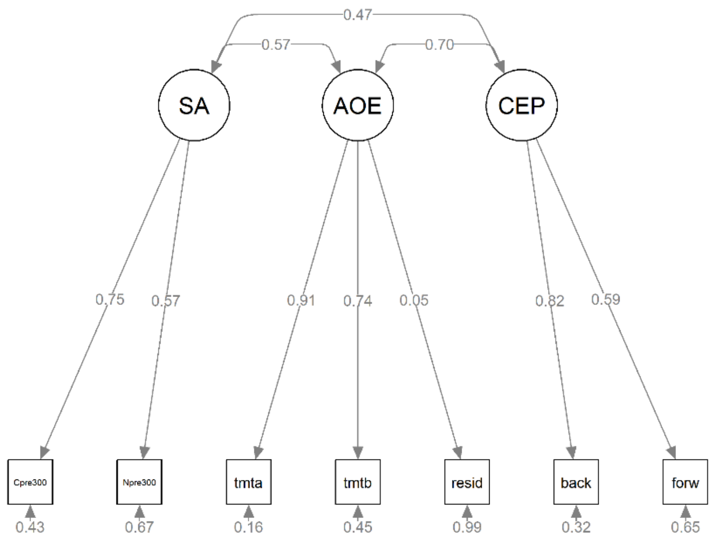

Figure 8. Diagram of model L. The model is based on the AOE hypothesis.

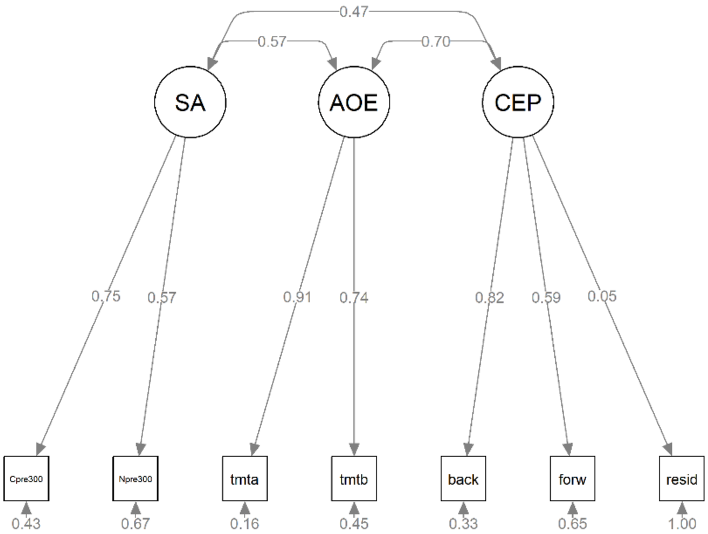

Figure 9. Diagram of model M. The model is based on the CEP hypothesis

Table 1. CFA results of model A

Model A			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SRD	Ndecay	0.481**	<0.001
	Cdecay	0.662**	<0.001
SA	Cpre300	0.680**	<0.001
	Npre300	0.630**	<0.001
AOE	tmta	0.910**	<0.001
	tmtb	0.744**	<0.001
CEP	Back	0.823**	<0.001
	forw	0.590**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SRD	SA	0.326**	0.001
	AOE	-0.108	0.196
	CEP	-0.212*	0.014
SA	AOE	0.577**	<0.001
	CEP	0.483**	<0.001
AOE	CEP	0.703**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
Ndecay		0.766**	<0.001
Cdecay		0.559**	<0.001

Cpre300	0.535**	<0.001
Npre300	0.600**	<0.001
tmta	0.169**	0.001
tmtb	0.443**	0.004
back	0.320**	<0.001
forw	0.649**	<0.001

*. p−value<0.05, **. p−value<0.01

Table 2. CFA results of model B

Model B			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SA	Ndecay	0.204**	0.008
	Cdecay	0.131*	0.028
	Cpre300	0.694**	<0.001
	Npre300	0.642**	<0.001
AOE	tmta	0.909**	<0.001
	tmtb	0.745**	<0.001
CEP	Back	0.824**	<0.001
	forw	0.590**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SA	AOE	0.540**	<0.001
	CEP	0.440**	<0.001
AOE	CEP	0.703**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
Ndecay		0.955**	<0.001
Cdecay		0.980**	<0.001
Cpre300		0.516**	<0.001
Npre300		0.586**	<0.001
tmta		0.171**	0.001

tmtb	0.442**	0.004
back	0.319**	<0.001
forw	0.650**	<0.001

*. p-value<0.05, **. p-value<0.01

Table 3. CFA results of model C

Model C			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SA	Cpre300	0.753**	<0.001
	Npre300	0.569**	<0.001
AOE	Ndecay	0.009	0.897
	Cdecay	-0.102	0.051
	tmta	0.916**	<0.001
	tmtb	0.739**	<0.001
CEP	Back	0.823**	<0.001
	forw	0.590**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SA	AOE	0.562**	<0.001
	CEP	0.469**	<0.001
AOE	CEP	0.702**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
Ndecay		0.997**	<0.001
Cdecay		0.987**	<0.001
Cpre300		0.430**	<0.001
Npre300		0.674**	<0.001
tmta		0.158**	0.002

tmtb	0.450**	0.004
back	0.320**	<0.001
forw	0.649**	<0.001

*. p−value<0.05, **. p−value<0.01

Table 4. CFA results of model D

Model D			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SA	Cpre300	0.756**	<0.001
	Npre300	0.567**	<0.001
AOE	tmta	0.915**	<0.001
	tmtb	0.740**	<0.001
CEP	Ndecay	-0.027	0.706
	Cdecay	-0.165**	0.004
	Back	0.829**	<0.001
	forw	0.590**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SA	AOE	0.565**	<0.001
	CEP	0.449**	<0.001
AOE	CEP	0.696**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
Ndecay		0.996**	<0.001
Cdecay		0.970**	<0.001
Cpre300		0.426**	<0.001
Npre300		0.676**	<0.001
tmta		0.160**	0.002

tmtb	0.449**	0.004
back	0.310**	<0.001
forw	0.649**	<0.001

*. p−value<0.05, **. p−value<0.01

Table 5. CFA results of model E

Model E			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SRD	Ndecay	0.999**	<0.001
SA	Cpre300	0.657**	<0.001
	Npre300	0.652**	<0.001
AOE	tmta	0.908**	<0.001
	tmtb	0.746**	<0.001
CEP	Back	0.828**	<0.001
	forw	0.586**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SRD	SA	0.246**	0.001
	AOE	0.007	0.913
	CEP	-0.027	0.707
SA	AOE	0.574**	<0.001
	CEP	0.480**	<0.001
AOE	CEP	0.701**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
Cpre300		0.565**	<0.001
Npre300		0.572**	<0.001
tmta		0.173**	<0.001

tmtb	0.440**	0.004
back	0.311**	<0.001
forw	0.653**	<0.001

*. p−value<0.05, **. p−value<0.01

Table 6. CFA results of model F

Model F			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SA	Ndecay	0.170*	0.028
	Cpre300	0.711**	<0.001
	Npre300	0.615**	<0.001
AOE	tmta	0.910**	<0.001
	tmtb	0.744**	<0.001
CEP	Back	0.823**	<0.001
	forw	0.590**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SA	AOE	0.563**	<0.001
	CEP	0.466**	<0.001
AOE	CEP	0.703**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
Ndecay		0.968**	<0.001
Cpre300		0.492**	<0.001
Npre300		0.619**	<0.001
tmta		0.169**	0.001
tmtb		0.443**	0.004
back		0.319**	<0.001

forw	0.649**	<0.001

*. p−value<0.05, **. p−value<0.01

Table 7. CFA results of model G

Model G			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SA	Cpre300	0.752**	<0.001
	Npre300	0.570**	<0.001
AOE	Ndecay	0.014*	0.838
	tmta	0.914**	<0.001
	tmtb	0.741**	<0.001
CEP	Back	0.823**	<0.001
	forw	0.590**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SA	AOE	0.567**	<0.001
	CEP	0.469**	<0.001
AOE	CEP	0.701**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
Ndecay		0.997**	<0.001
Cpre300		0.432**	<0.001
Npre300		0.672**	<0.001
tmta		0.162**	0.002
tmtb		0.448**	0.004
back		0.319**	<0.001

forw	0.649**	<0.001

*. p−value<0.05, **. p−value<0.01

Table 8. CFA restuls of model H

Model H			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SA	Cpre300	0.753**	<0.001
	Npre300	0.569**	<0.001
AOE	tmta	0.915**	<0.001
	tmtb	0.741**	<0.001
CEP	Ndecay	-0.009	0.896
	Back	0.824**	<0.001
	forw	0.589**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SA	AOE	0.566**	<0.001
	CEP	0.468**	<0.001
AOE	CEP	0.700**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
Ndecay		0.997**	<0.001
Cpre300		0.431**	<0.001
Npre300		0.673**	<0.001
tmta		0.161**	0.002
tmtb		0.449**	0.004
back		0.318**	<0.001

forw	0.650**	<0.001

*. p−value<0.05, **. p−value<0.01

Table 9. CFA results of model I

Model I			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SRDcol	Cdecay	0.999**	<0.001
SRDnum	Ndecay	0.999**	<0.001
SA	Cpre300	0.665**	<0.001
	Npre300	0.644**	<0.001
AOE	tmta	0.909**	<0.001
	tmtb	0.745**	<0.001
CEP	Back	0.819**	<0.001
	forw	0.593**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SRDcol	SRDnum	0.319**	<0.001
	SA	0.179**	0.002
	AOE	-0.103	0.050
	CEP	-0.182**	0.002
SRDnum	SA	0.241**	0.002
	AOE	0.007	0.915
	CEP	-0.026	0.717
SA	AOE	0.575**	<0.001
	CEP	0.484**	<0.001
AOE	CEP	0.705**	<0.001

Variances		
Indicator	**Estimate**	**P-value**
Cpre300	0.555**	<0.001
Npre300	0.582**	<0.001
tmta	0.171**	0.001
tmtb	0.442**	0.004
back	0.327**	<0.001
forw	0.646**	<0.001

*. p-value<0.05, **. p-value<0.01

Table 10. CFA results of model J

Model J			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SRD	resid	0.999**	<0.001
SA	Cpre300	0.688**	<0.001
	Npre300	0.623**	<0.001
AOE	tmta	0.910**	<0.001
	tmtb	0.745**	<0.001
CEP	Back	0.825**	<0.001
	forw	0.589**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SRD	SA	0.180*	0.022
	AOE	0.042	0.512
	CEP	0.033	0.632
SA	AOE	0.578**	<0.001
	CEP	0.483**	<0.001
AOE	CEP	0.702**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
Cpre300		0.524**	<0.001
Npre300		0.609**	<0.001
tmta		0.170**	0.001

tmtb	0.443**	0.004
back	0.317**	<0.001
forw	0.650**	<0.001

*. p−value<0.05, **. p−value<0.01

Table 11. CFA results of model K

Model K			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SA	resid	0.145	0.058
	Cpre300	0.713**	<0.001
	Npre300	0.606**	<0.001
AOE	tmta	0.911**	<0.001
	tmtb	0.744**	<0.001
CEP	Back	0.823**	<0.001
	forw	0.590**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SA	AOE	0.571**	<0.001
	CEP	0.476**	<0.001
AOE	CEP	0.703**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
resid		0.976**	<0.001
Cpre300		0.489**	<0.001
Npre300		0.631**	<0.001
tmta		0.168**	0.001
tmtb		0.444**	0.004
back		0.320**	<0.001

forw	0.649**	<0.001

*. p−value<0.05, **. p−value<0.01

Table 12. CFA results of model L

Model L			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SA	Cpre300	0.750**	<0.001
	Npre300	0.571**	<0.001
AOE	resid	0.049	0.450
	tmta	0.912**	<0.001
	tmtb	0.742**	<0.001
CEP	Back	0.823**	<0.001
	forw	0.590**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SA	AOE	0.569**	<0.001
	CEP	0.470**	<0.001
AOE	CEP	0.702**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
resid		0.995**	<0.001
Cpre300		0.434**	<0.001
Npre300		0.671**	<0.001
tmta		0.165**	0.002
tmtb		0.446**	0.005
back		0.319**	<0.001

forw	0.649**	<0.001

*. p-value<0.05, **. p-value<0.01

Table 13. CFA results of model M

Model M			
Factor loadings			
Latent variable	**Indicator**	**Estimate**	**P-value**
SA	Cpre300	0.751**	<0.001
	Npre300	0.570**	<0.001
AOE	tmta	0.914	0.450
	tmtb	0.741**	<0.001
CEP	resid	0.046	0.510
	Back	0.820**	<0.001
	forw	0.592**	<0.001
Covariances			
Latent variable	**Latent variable**	**Estimate**	**P-value**
SA	AOE	0.567**	<0.001
	CEP	0.473**	<0.001
AOE	CEP	0.703**	<0.001
Variances			
Indicator		**Estimate**	**P-value**
resid		0.995**	<0.001
Cpre300		0.433**	<0.001
Npre300		0.672**	<0.001
tmta		0.161**	0.002
tmtb		0.448**	0.004
back		0.325**	<0.001

forw	0.647**	<0.001

*. p−value<0.05, **. p−value<0.01

초 록

영상 기억이 쇠잔하는 속도는 일차 시각 피질에 저장된 감각 표상의 쇠잔 속도가 결정하는 것으로 알려져 있다. 동시에 영상 기억의 쇠잔 속도를 측정하는 부분보고법의 특성상 주의기능과 작업기억이 관여하는 것으로도 알려져 있으며, 해당 요인들은 영상 기억 쇠잔 속도를 결정하는 잠재적 요인일 가능성이 있다. 숫자가 색깔에 비해 영상 기억이 쇠잔하는 속도가 빠르다는 선행 연구는 주의기능과 작업기억 관련 요인이 잠재적 요인일 가능성을 더해주었다. 본 연구는 부분보고 과제에서 지시하는 위치로 주의를 이동하는 주의이동 속도와, 영상 기억이 작업 기억으로 전달되는 효율에 관여하는 중앙집행기를 가능한 잠재적 요인으로 두고 이를 검증하기 위한 목적으로 네 개의 실험을 진행하였다.

첫 번째 실험에서는 확인적 요인분석을 통해 부분보고 과제로 측정한 숫자와 색깔에 관한 영상 기억 쇠잔 속도 지표를 주의이동 속도 혹은 중앙집행기 기능으로 설명하는 모델이 감각 표상의 쇠잔 속도로 설명하는 모델보다 적합한 지 분석하였다. 두 번째 실험에서는 경두개자기자극기를 이용하여 감각 표상이 저장되는 것으로 알려진 일차 시각피질과 주의이동에 관여하는 전두안구영역의 신경 활성도를 변조하면서 색깔과 숫자에 관한 영상 기억 쇠잔 속도의 변화를 살폈다. 세 번째 실험은 경두개전류자극기를 이용하여 일차 시각피질의 활성도의 방향성이 숫자와 색깔에 관한 영상 기억 쇠잔 속도에 미치는 영향을 보았고, 샴 조건에서 안구 운동을 측정하여 주의이동이 숫자와 색깔에 관한 영상 기억 쇠잔 속도에 미치는 영향을 살폈다.

분석 결과, 숫자와 색깔에 관한 영상 기억 쇠잔 속도를 결정하는 신경기전으로서 주의이동 속도나 작업기억의 중앙집행기 기능은 유의미하지 않은 것으로 나타났다. 하지만 숫자와 색깔 보고 조건 사이에서 유의미한 시각 작업 기억 용량 차이가 관찰되었으며, 동시에 경두개자기자극기 결과는 숫자에 관한 영상 기억 쇠잔 속도를 결정하는데 시각적 특징의 그룹화 과정이 유의미한 신경 기전으로서 관여했을 가능성을 시사하였다. 이는 시각 작업기억 용량과 그룹화 과정이 숫자와 색깔 간 영상 기억 쇠잔 속도 차이를 설명할 수 있을 가능성을 보강하면서, 그룹화가 필요한 다수의 시각 특징을 가진 복잡한 자극을 영상 기억 과제에 활용할 경우 감각 표상 쇠잔 속도와 더불어 시각 작업 기억 용량 및 그룹화 과정을 잠재적 요인으로 고려해야 할 가능성을 시사하였다.

주요어 : 영상 기억, 영상 기억 쇠잔, 주의이동 속도, 중앙집행기, 특징 그룹화, 작업 기억

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감사의 글

본 논문을 쓰면서 정말 많은 분들께 도움을 받았습니다. 매일같이 연구실에서 함께 졸업을 준비하며, 심란할 때 힘이 되어주시고 기쁠 때 함께 마음을 나눠주신 혜연 선배, 소영 선배. 심사과정에서 논문의 학문적 완성도를 높이는 데 아낌없이 조언을 해주신 김청택 교수님, 고성룡 교수님, 강민석 교수님, 전현애 교수님. 학교를 졸업하고 각자의 길을 열심히 걸으면서도 중요한 순간을 공유하며 함께했던 민영이, 다희, 예슬이, 민하 언니. 고민이 있을 때 기꺼이 상담해주셨던 정은 선배, 은빈이. 박사로 졸업하기까지 아끼지 않고 지원해 준 가족들……. 그리고 여전히 많은 분들이 계십니다. 모든 분들께 진심으로 감사드립니다.

마지막으로, 생전에 늘 가까이에서 심도 있는 학문적 조언을 주셨으며 이 논문의 기반이 되어주신 이경민 지도 교수님께 깊은 감사의 말씀을 전합니다.

이 마음이 부디 계신 곳까지 닿기를 바라며.

2022년 8월

서민희 올림