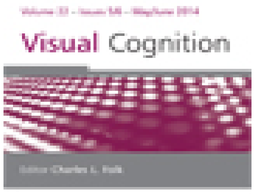

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Eye movement indices of memory reveal re-processing of visual information: Evidence from Chinese characters

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Eye movement indices of memory reveal re-processing of visual information: Evidence from Chinese characters

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ABSTRACT
This study examined the nature of the memory effect revealed in eye movements. Chinese characters were processed visually, phonologically or semantically during the study phase. The proportion of viewing time during the subsequent recognition test was compared between characters associated with different types of encoding. To eliminate the influence of response selection on eye movements, participants were asked to select the unstudied character and make the selection after the viewing period ended. Results showed that the proportion of viewing time in the recognition test was larger for visually encoded characters than it was for semantically (Experiment 1) and phonologically encoded (Experiment 3) characters, even after the participants had presumably made the decision. Moreover, there was no significant difference in the proportion of viewing time between phonologically and semantically encoded characters (Experiment 2). These findings suggest that the viewing time change in eye movements during the recognition test is an obligatory consequence of re-processing the visual information encoded during the study phase.

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Viewing time; recognition memory; levels of processing; visual priming

Past experiences can influence human behaviour in many ways. Memory alters how we process new information, changes neurophysiological responses (Tulving & Craik, 1990), and even affects where and what we look at (Althoff & Cohen, 1999; Hannula et al., 2010). Typical measures of memory require special instructions with certain response rules and introspective judgments with verbal or nonverbal responses from participants. This type of measurement relies on participants' ability to understand specific instructions and articulate answers or follow response mapping rules. Eye movement measures, which require neither special instructions nor explicit reports, have been found to reflect the influences of past experiences, even in the absence of explicit awareness of these influences (for a review, see Hannula et al., 2010). In particular, previous studies have found that viewing time and pupil dilation can provide sensitive measures of memory (e.g., Laeng, Sirois, & Gredebäck, 2012; Ryan, Hannula, & Cohen, 2007).

Viewing patterns have been demonstrated to reflect the influences of item, spatial, and temporal memory (Hannula, Ryan, Tranel, & Cohen, 2007; Ryan et al., 2007). An early study found that participants fixated earlier on the altered regions of previously observed scenes rather than on the unchanged regions of the same scenes (Parker, 1978). More recent studies have shown that participants looked longer at the regions in which the relations among the elements in the observed scene were altered (Althoff & Cohen, 1999; Ryan, Althoff, Whitlow, & Cohen, 2000; Smith, Hopkins, & Squire, 2006) and made fewer fixations on the previously observed items than on the new ones (Althoff & Cohen, 1999; Ryan et al., 2000). Regarding relational memory, participants' viewing time has been found to be longer when looking at faces that appeared in the matched observed scenes, regardless of their familiarity with the face or the face's location (Hannula et al., 2007; Hannula & Ranganath, 2009). Eye movements are also sensitive to temporal memory. Participants have been found to inspect objects that were simultaneously presented in an order that matched the originally observed temporal sequence (Ryan & Villate, 2009). Moreover, even when the information

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is no longer visible during memory retrieval, participants look at spatial locations where the information was originally presented (e.g., Richardson & Spivey, 2000). Some studies further suggest that eye movements can facilitate memory retrieval (Bochynska & Laeng, 2015; Johansson & Johansson, 2014; Laeng, Bloem, D'Ascenzo, & Tommasi, 2014; Scholz, Mehlhorn, & Krems, 2016).

Several studies have suggested that the influences of memory on eye movements can be implicit and involuntary. First, the influences of memory on eye movements occurred independent of explicit selection (Chen & Lee, 2015). The pattern of viewing time distinguished faces that were studied from faces that were incorrectly endorsed as having been observed (Hannula, Hannula, Baym, Warren, & Cohen, 2012). Unselected known and unknown target faces were shown to have a different pattern of viewing time (Schwedes & Wentura, 2012). Moreover, the influence of memory on eye movements occurred before, or in the absence of, conscious awareness of past experiences (Hannula et al., 2007; Ryan et al., 2007, 2008; Warren, Duff, Tranel, & Cohen, 2010). Hannula et al. (2007) found that the influence of memory on viewing time happened more than 1 second before the overt behavioural response. Holm, Eriksson, and Andersson (2008) demonstrated that participants looked more at fragmented target objects inserted in distracter displays as many as 25 fixations before explicit identification of the object. Both Hannula and Ranganath (2009) and Hannula et al. (2007) demonstrated that participants' eyes fixated longer on the studied face as fast as 500–750 ms after presentation of the test display. Finally, participants looked longer at altered regions of scenes even when they were unaware of such manipulations (Ryan et al., 2000).

Previous studies examining the effect of memory on eye movements has typically used pictorial materials, such as objects (e.g., Holm et al., 2008), faces (e.g., Hannula et al., 2007, 2012; Hannula & Ranganath, 2009; Schwedes & Wentura, 2012), and scenes (e.g., Ryan et al., 2000). For example, studies have found that prior experience with a face affects subsequent eye movements during a recognition test (Althoff & Cohen, 1999; Hannula et al., 2010; Ryan et al., 2007; Stacey, Walker, & Underwood, 2005). Chen and Lee (2015) is the first study to use verbal materials examining whether memory of past events can influence viewing time. In particular, Chinese characters, instead of faces or scenes, were used to investigate whether the results can be generalized to verbal materials. In their study, participants studied a list of Chinese characters and then performed a recognition memory test. During each recognition memory test trial, participants had to select the character they had studied from one studied character and two unstudied homonyms. Participants' eye movements were recorded while they were viewing the three-character test display. Both the time-course and response-locked measures indicated that participants viewed the studied character longer than they viewed the unstudied character. More importantly, this pattern was found regardless of participants' explicit response.

From the above reviews, eye movements can be used as a temporally sensitive measure of memory. However, it remains unclear whether the memory effect found in Chen and Lee (2015) came from prior exposure to the surface structure or the meaning of the studied character. The purposes of the present study are to examine the nature of the eye movement-based memory effect found in Chen and Lee (2015) and to control for the influence of response selection.

We compared viewing time during the recognition test between visually, phonologically, and semantically encoded Chinese characters. The Chinese language is a logographic system. The graphemes are symbols that typically represent the basic unit of meaning and do not map directly into phonological units. This is different from alphabetic writing systems, such as English, in which symbols more or less correspond to the basic unit of pronunciation. Because of the weak link between orthography and phonology, using Chinese characters allows us to examine independently the effect of visual and phonological encoding on subsequent eye movements. The eye movement-based memory effect can be a result of semantic processing of the studied item. On the other hand, according to the assertion that visuospatial working memory is an essential element of the eye movement system (Van der Stigchel & Hollingworth, 2018), it is also possible that the memory effect comes from visual processing of the studied item. If the viewing time change reflects semantic processing during study, then semantically encoded items should produce a larger effect than non-semantically encoded items. Moreover, because semantic processing leads to better memory performance than non-semantically processing, there should be a positive association between the eye movement effect and memory performance. If, on the other hand, the eye movement-based memory effect comes from visual processing of the studied item, then visual encoding should produce a larger effect on viewing time as compared to non-visual encoding, regardless of the memory performance. Three experiments were designed to examine this question. The phonological encoding condition was included to rule out alternative hypotheses.

In Ryan et al. (2007), participants saw three-face displays, with either all of the faces being unknown to participants or one of the faces being a known face. Participants had to select the known face in a display. The results showed that the known selected faces were viewed for a longer duration than were the unknown selected faces. This result was replicated in Chen and Lee (2015) with Chinese characters using a different design. In both studies, the viewing time of the selected studied item was influenced by both prior exposure, a memory effect, and the intention and execution of the selection, a response selection effect, whereas the unstudied selected item was driven only by the response selection effect. The difference in the viewing time between the studied selected and unstudied selected items reveals a memory effect. However, there may be an interaction between these two effects. Specifically, the basis of response selection may differ between the studied and unstudied selected items. For example, participants' selection of the unstudied item was based on guessing, which led to a weaker response selection effect on the viewing time, as compared with the effect produced by the studied item. To eliminate the influence of response selection, participants in the present study were instructed to select the *unstudied* item, instead of the studied item. We compared the viewing time of the two non-selected targets before a selection was made. This design allowed us to measure the eye movement-based memory effect without confounding associated with any response effect.

To further examine the possibility that the viewing time changes occurred involuntarily, the time course of the viewing pattern of the two non-selected targets was also analyzed. The 2-second viewing time used in the present study during the recognition memory test was determined based on the result of a similar procedure used in Chen and Lee (2015), in which there was no required time limit during the recognition test and participants took about one to two seconds to make a choice among the three testing items. The 2-second time frame allows us to examine whether the viewing time pattern changes after participants have presumably made the recognition decision. A change of the viewing pattern indicates that eye movements are influenced by participants' recognition decision, suggesting a possibility of strategic control. No changes in the viewing pattern suggest that the eye movements during the recognition test may occur involuntarily.

Experiment 1

The purpose of Experiment 1 was to examine the nature of the memory effect as measured by eye movements. Chinese characters were processed visually or semantically during the study phase. The viewing time during the subsequent recognition test was compared between characters associated with these two types of encoding. Moreover, to eliminate the influence of response selection on eye movements, participants were asked to select the *unstudied* item and make the selection after the viewing period ended. If the change in viewing time is more sensitive to levels of processing, then sematic encoding should produce a larger memory effect than visual encoding does. If visual memory produces changes in viewing time, then visually encoded characters should produce a larger memory effect as compared to semantically encoded characters.

Method

Participants

Twenty-four university students (15 females) with an age range of 17–24 years ($M = 20.96$, $SD = 1.78$) were recruited for this experiment. They were all native Chinese speakers from Taiwan and participated voluntarily and received payment equivalent to 3 USD for their participation. Sample size was determined a priori to be 24 participants. This sample size provided .86 power to detect an effect size of .5, equivalent to that of a similarly designed experiment (Chen & Lee, 2015).

Materials and apparatus

One hundred eight Chinese characters were selected and divided into 36 sets, each of which included three unrelated characters. The 36 sets were further divided into three groups and assigned to the visual processing, semantic processing, and unstudied conditions. The assignment of the three groups of characters to the three study conditions was counterbalanced completely to create six versions of the test materials. The materials for the recognition test consisted of all 36 sets.

The Chinese characters were presented on a computer monitor using E-Prime. Eye position was measured using a FaceLab 5 eye tracker (Seeing Machines Inc., Tucson, AZ, USA) controlled by EyeWorks 3.2 software (EyeTracking Inc., San Diego, CA, USA) that recorded binocularly at 60 Hz with a spatial resolution of 5 pixels. After informed consent was obtained, and prior to the presentation of the study items, participants' eye position was calibrated using a 3×3 spatial array. The size of the character, used in both study and test trials, subtended approximately a horizontal visual angle of 8.5° (266 pixels) and a vertical visual angle of 6.2° (193 pixels). The viewing distance was 60 cm. The font of the characters was DFKai-SB. Responses to the recognition test were recorded by E-Prime using a standard keyboard.

Design

This experiment was a 3×8 within-subjects design. The two independent variables were encoding condition (visual vs. semantic vs. unstudied) and time bin (time bin: 0–250 ms, 250–500 ms … , and 1750–2000 ms). The dependent variable was the percentage of viewing time directed to the character of interest among the total viewing time directed to the three test characters.

Procedure

Participants were tested individually. Each experimental session consisted of a study phase and a testing phase. Eye position was monitored throughout the entire experiment, but only the recordings of the recognition tests were analyzed and reported. During the study phase, the participants had to make either a visual or a semantic judgment for each character. For each type of judgment, the 36 characters were presented in succession. A fixation cross was presented for 500 ms before the presentation of each character. The character remained on the screen until participants made a response. For the visual encoding condition, participants had to judge whether the character can be divided into two separate left/right parts. The character 邪 was an example of having separable left/right parts, whereas the character 正 was an example of not having separable left/right parts. For the semantic encoding condition, participants had to judge whether a fifth grader would know the meaning of the character. Participants pressed the "Z," marked as "Yes," and "M," marked as "No," keys to indicate their answer. Both answers and response times were recorded. Within the same encoding condition, the presentation order of the character was randomly determined. The two encoding conditions were run in blocks and the order of the two blocks was counterbalanced across participants. The memory test was conducted after participants completed the two encoding blocks.

During the recognition memory test, 36 trials were presented to the participants in random order. A three-character display was presented for each trial (see Figure 1). The display comprised one unstudied character and two studied characters, one visually and one semantically encoded. Each type of the character had an equal chance of appearing in each of the three locations. For each trial, the participants had to indicate which character they had *not* studied by pressing the corresponding key. Participants did so

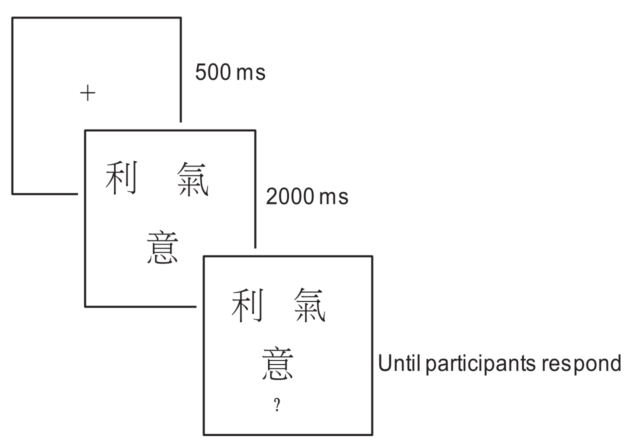

Figure 1. Schematic representations of the test trial events and their respective timings in Experiments 1–3. On each test trial, a three-character display was presented for 2 s. The three characters included an unstudied character and two studied characters that were associated with two different types of encoding. Participants had to identify the unstudied character in the display by selecting one of the three character once the question mark appeared.

Table 1. Mean encoding times (in millisecond) and mean selection rates during the recognition test as a function of encoding condition in Experiments 1–3 (Standard Errors in Parentheses).

Experiment 1			
Encoding condition	Visual	Semantic	Unstudied
Encoding time	962 (34)	1261 (92)	
Selection rate	.115 (.01)	.050 (.01)	.834 (.02)
Experiment 2			
Encoding condition	Phonological	Semantic	Unstudied
Encoding time	994 (42)	1293 (83)	
Selection rate	.134 (.02)	.034 (.01)	.832 (.02)
Experiment 3			
Encoding condition	Phonological	Visual	Unstudied
Encoding time	1053 (62)	969 (60)	
Selection rate	.117 (.01)	.058 (.01)	.826 (.02)

by entering a number (2, 4, or 6) on the standard numeric keypad on the far right of the computer keyboard. Each three-character display was presented for 2000 ms before a question mark appeared in the bottom of the screen. Participants were instructed to respond to the question mark as quickly as possible once it appeared. Prior to the experiment, participants were provided with practice trials to familiarize themselves with the encoding conditions. The procedure for the practice trials was the same as the one for the experiment. For each encoding condition, four characters that were not presented in the experiment were used in the practice trials. Participants were given feedback to ensure that they understood the judgment rule.

Data analyses

For all the experiments reported in the present study, the regions of interest (ROIs) were the areas occupied by the three characters located in the left, right, and bottom of the test displays. The ROI for each character was a rectangle area subtended a horizontal visual angle of 9.1° (285 pixels) and a vertical visual angle of 7.2° (225 pixels). The proportion of viewing time directed to the ROI during the recognition test trial was examined for each of the 8 successive (250 ms) time bins, starting from the onset of the test display and continuing over the course of the entire (2000 ms) test trial. The proportions were calculated by dividing the total amount of viewing time directed to the character of interest by the total amount of time directed to the ROIs.

The mean encoding times for the two encoding conditions and the mean selection rates for the three types of characters are presented in Table 1. The mean proportions of viewing time as a function of encoding condition and time bin are presented in Figure 2. There were large variations in the first bin because of participants' delay of focused attention and/or timing limitations of the display and recoding. To examine the difference in proportion of viewing time between different types of encoded characters without the influence of response selection, the analyses focused on the studied characters, and not the unstudied characters, in all the experiments. Moreover, we reported the viewing time analysis that included only the *non-selected studied characters*. Selection of the studied character during the recognition test was considered as a false alarm. Because the selection (false alarm) rate for the studied character was low, the analysis that included both selected and non-selected studied characters yielded the same pattern of results.

Results

Encoding time and recognition performance

The encoding time for the semantic encoding condition was longer than was that for the visual encoding condition, $F\ (1, 23) = 18.43$, $MSe = 57{,}924$, $p < .001$, $\eta_p^2 = .44$. Regarding performance on the recognition test, a one-way ANOVA revealed a significant effect of encoding condition on the selection rate, $F\ (2, 46) = 625.91$, $MSe = .007$, $p < .001$, $\eta_p^2 = .96$. Unstudied characters had a higher selection rate than did both the visually and semantically encoded characters, $F\ (1, 23) = 659.92$, $MSe = .009$, $p < .001$, $\eta_p^2 = .97$, and $F\ (1, 23) = 831.94$, $MSe = .009$, $p < .001$, $\eta_p^2 = .97$, respectively. More importantly, the selection (false alarm) rate for the semantically encoded characters was lower than was that for visually encoded characters, $F\ (1, 23) = 13.87$, $MSe = .004$, $p < .01$, $\eta_p^2 = .38$.

Viewing time analyses

A 2 (encoding condition: visual vs. semantic) by 8 (time bin: 0–250 ms, 250–500 ms … , and 1750–2000 ms) repeated measures ANOVA was performed to examine the effect of encoding condition and time course on the proportion of viewing time of the non-selected studied character. The results revealed significant main effects of encoding condition, $F\ (1, 23) = 10.36$, $MSe = .01$, $p < .01$, $\eta_p^2 = .31$, and time bin, $F\ (7, 161) = 2.69$, $MSe = .01$, $p < .05$, $\eta_p^2 = .10$. The

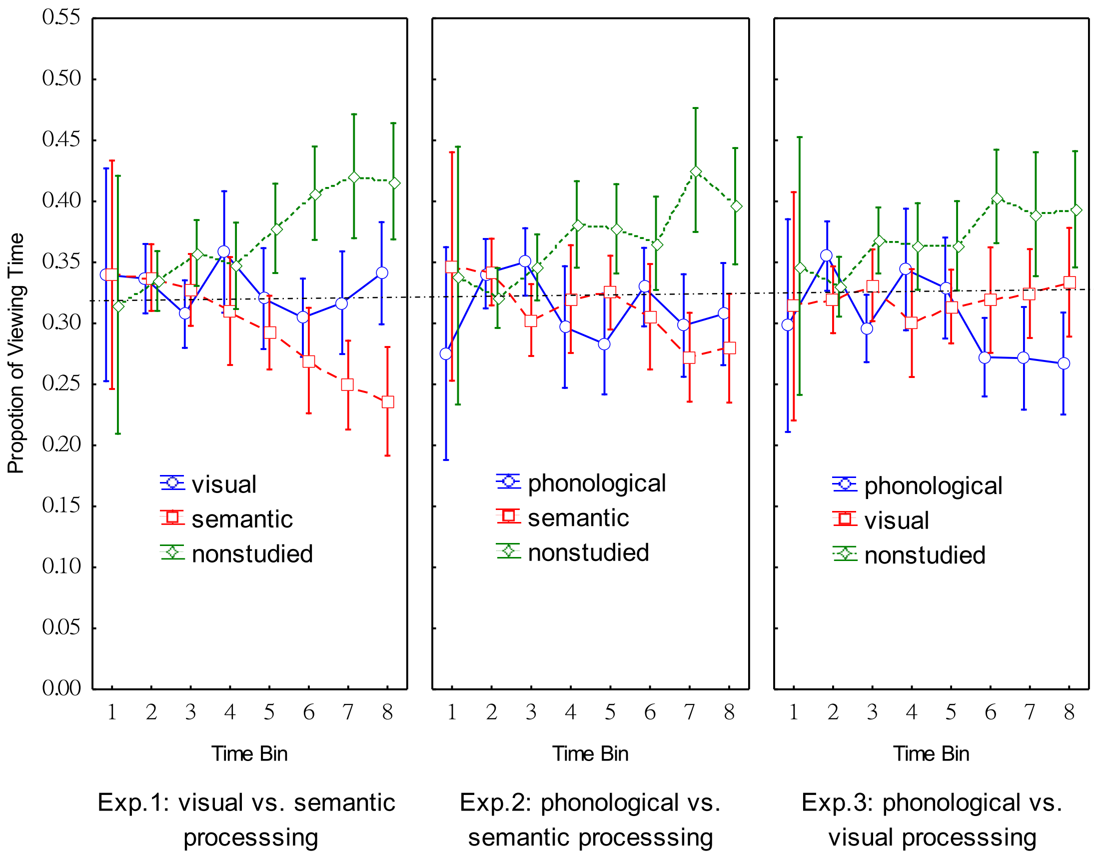

Figure 2. Proportion of total viewing time directed to regions of interest as a function of time bin and encoding conditions in Experiments 1–3. The error bars represent the standard errors. The dotted line indicates the chance level. It is important to note that participants were asked to select the unstudied item and the focus of the comparison was on the two studied items.

interaction effect was not significant, $F(7, 161) < 1$. The proportion of viewing time was larger for the visual than it was for the semantic encoding condition. Evidence for the lack of the interaction effect was further investigated by computing the Bayes factor using Bayesian Information Criteria (Kass & Raftery, 1995; Masson, 2011; Wagenmakers, 2007). An estimated Bayes factor (BF01), comparing the fit of the data under the null hypothesis and the alternative hypothesis, suggested that the data were 2.98:1 in favour of the null hypothesis.

Discussion

It took participants longer to perform semantic encoding than it did to perform visual encoding. Furthermore, the selection (false alarm) rate was higher for the visual than it was for the semantic encoding condition. This result is consistent with the levels-of-processing framework (Craik & Lockhart, 1972). During the 2-second period of the recognition test, as expected, participants spent most of the time viewing the to-be-selected unstudied character (see Figure 2) because they were instructed to select the unstudied target. The focus of this study was to examine the viewing time difference between the two non-selected studied characters without the confounding effect of response selection. The proportion of viewing time during the recognition test was larger for the visually encoded characters than it was for the semantically encoded characters. This finding suggests that visual processing produced a larger memory effect on subsequent viewing time than did semantic processing. Moreover, because neither type of character was the target and only the non-selected characters were analyzed, the viewing time difference found was not only free of the influence of response selection, but also unlikely to occur voluntarily. Especially, the difference remained after participants had presumably made their decision.

The visual and semantic encoding differed in both the type and depth of processing performed. It is possible that visually encoded characters were viewed longer during the recognition test was a result of shallow processing. Shallow processing might have created a weaker memory trace, which reduced participants' confidence during the recognition test and in turn increased the viewing time. In other words, participants looked longer at the visually encoded characters possibly because the other semantically encoded characters had already been rejected. Experiment 2 was conducted to examine this possibility.

Experiment 2

The purpose of Experiment 2 was to determine whether visual processing or shallow processing, relative to semantic processing, at the study phase increased the proportion of view time during the recognition test. Visual encoding was replaced with phonological encoding in Experiment 2. If it was the visual memory that increased the viewing time, then phonological processing would not produce such an effect. If, on the other hand, the effect could be explained by the shallow processing of visual encoding producing weak memory and low confidence during the recognition test, then phonological encoding should produce an effect similar to that of visual encoding. In other words, phonologically encoded characters should be more difficult to reject and result in a longer viewing time than semantically encoded characters.

Method

Twenty-four university students (20 females) with an age range of 19–27 years (M = 20.25, SD = 1.67) were recruited for this experiment. They were all native Chinese speakers from Taiwan and participated voluntarily and received payment equivalent to 3 USD for their participation. None had participated in Experiment 1.

There were two differences between Experiments 2 and 1. First, the visual encoding condition was replaced by a phonological encoding condition in which participants had to judge whether the character was pronounced with a falling tone (the fourth tone) in Mandarin. Second, to generalize the finding to a different type of semantic encoding, participants in the semantic encoding condition had to judge whether the character could be used as a verb.

Results

Encoding time and recognition performance

The encoding time of the semantic encoding condition was longer than that of the phonological encoding condition, $F\ (1,\ 23) = 13.66$, $MSe = 78{,}605$, $p < .01$, $\eta_p^2 = .37$. Regarding the selection rate in the recognition test, there was a significant effect of encoding condition, $F\ (2,\ 46) = 421.42$, $MSe = .011$, $p < .001$, $\eta_p^2 = .95$. Unstudied characters had a higher selection rate than did both phonologically and semantically encoded characters, $F\ (1,\ 23) = 297.67$, $MSe = .020$, $p < .001$, $\eta_p^2 = .93$, and $F\ (1,\ 23) = 869.90$, $MSe = .009$, $p < .001$, $\eta_p^2 = .97$, respectively. The selection (false alarm) rate for semantically encoded characters was lower than was that for phonologically encoded characters, $F\ (1,\ 23) = 31.32$, $MSe = .004$, $p < .001$, $\eta_p^2 = .58$.

Viewing time analyses

A 2 (encoding condition: phonological vs. semantic) by 8 (time bin: 0–250 ms, 250–500 ms … , and 1750–2000 ms) repeated measures ANOVA revealed that neither the main effect of encoding condition, $F\ (1,\ 23) < 1$, nor the main effect of time bin, $F\ (7,\ 161) = 1.82$, $MSe = .008$, $p = .086$, was significant. The interaction effect was also not significant, $F\ (7,\ 161) = 1.41$, $MSe = .014$, $p = .207$. Evidence for the lack of both main effects and the interaction effect was further investigated by computing the Bayes factor. An estimated Bayes factor (BF01), comparing the fit of the data under the null hypothesis and the alternative hypothesis, suggested that the data were 4.87:1 for the encoding main effect, 1.96:1 for the time bin main effect, and 2.42:1 for the interaction effect in favour of the null hypothesis.

Discussion

The results of encoding time and selection (false alarm) rate for the phonological and semantic encoding conditions are consistent with the levels-of-processing framework (Craik & Lockhart, 1972). During the recognition test, once again, participants spent most of the time viewing the to-be-selected unstudied target. The most important finding of Experiment 2 was that no difference was found in the proportion of viewing time between the phonologically and semantically encoded characters, suggesting that shallow processing *per se* did not increase the proportion of view time during the recognition test. Phonologically encoded characters were harder to reject than semantically encoded characters. However, this difference did not produce a change in the proportion of viewing time. If the memory effect measured by viewing time is specific to visual processing, then the viewing time difference in the recognition test should also be found between visual and non-visual shallow encoding. Experiment 3 was designed to test this prediction.

Experiment 3

The purpose of Experiment 3 was to further demonstrate that the viewing time of the studied item during the recognition test is more sensitive to visual memory, even in comparison with other types of non-semantic memory. This experiment compared the viewing time difference between visually and phonologically encoded characters. If the viewing time is more sensitive to the visual memory, then visually encoded characters should be viewed longer than the phonologically encoded characters.

Method

Twenty-four university students (18 females) with an age range of 19–25 years (M = 20.42, SD = 1.86) who did not participate in the previous two experiments were recruited for this experiment. They were all native Chinese speakers from Taiwan and participated voluntarily and received payment equivalent to 3 USD for their participation.

The method was the same as Experiments 1 and 2, except that two types of non-semantic encoding were used in this experiment. For the visual encoding condition, participants had to judge whether the character could be divided into two separate left/right parts, whereas for the phonological encoding condition, participants had to judge whether the character was pronounced with a falling tone (the fourth tone) in Mandarin.

Results

Encoding time and recognition performance

The encoding time for the phonological encoding condition was marginally longer than was that for the visual encoding condition, F (1, 23) = 4.16, MSe = 20,051, p = .053, $\eta_p^2 = .15$. Regarding the selection rate in the recognition test, there was a significant effect of encoding condition, F (2, 46) = 663.17, MSe = .007, $p < .001$, $\eta_p^2 = .97$. Unstudied characters had a higher selection rate than did both phonologically and visually encoded characters, F (1, 23) = 582.44, MSe = .010, $p < .001$, $\eta_p^2 = .96$, and F (1, 23) = 886.60, MSe = .008, $p < .001$, $\eta_p^2 = .97$, respectively. The selection (false alarm) rate for visually encoded characters was lower than was that for phonologically encoded characters, F (1, 23) = 28.22, MSe = .001, $p < .001$, $\eta_p^2 = .55$.

Viewing time analyses

A 2 (encoding condition: visual vs. phonological) by 8 (time bin: 0–250 ms, 250–500 ms … , and 1750–2000 ms) repeated measures ANOVA revealed a significant main effect of encoding condition, F (1, 23) = 4.71, MSe = .012, $p < .05$, $\eta_p^2 = .17$. The main effect of time bin and the interaction effect were not significant, F (7, 161) = 1.11, MSe = .009, p = .36, $\eta_p^2 = .10$, and F (7, 161) = 1.22, MSe = .020, p = .30, $\eta_p^2 = .05$, respectively. The proportion of viewing time was larger for the visual than it was for the phonological encoding condition. Evidence for the lack of the time bin main effect and interaction effect was further investigated by computing the Bayes factor. An estimated Bayes factor (BF01), comparing the fit of the data under the null hypothesis and the alternative hypothesis, suggested that the data were 2.78:1 for the time bin main effect, and 2.64:1 for the interaction effect in favour of the null hypothesis.

Discussion

The mean encoding time was longer in the phonological encoding condition than it was in the visual encoding condition, presumably because a tone judgement about a Chinese character was more abstract than a visual configuration judgment. For the same reason, the selection (false alarm) rate in the recognition test was higher for the phonological encoding condition than it was for the visual encoding condition. More importantly, the proportion of viewing time was larger for visually encoded characters than it was for phonologically encoded characters, suggesting that visual encoding had a larger memory effect on the proportion of view time during the recognition test than did non-visual encoding.

General discussion

The present study examined the nature of eye movement-based memory effects found in previous studies (Chen & Lee, 2015; Ryan et al., 2007). Effects of different types of processing performed during encoding were compared. Results from the three experiments converged to a clear conclusion. First, the proportion of viewing time in recognition test was larger for visually encoded characters than it was for semantically (Experiment 1) and phonologically encoded (Experiment 3) characters even after the participants had presumably made the decision. Moreover, there was no significant difference in the proportion of viewing time between phonologically and semantically encoded characters (Experiment 2). Visual processing during encoding produced a larger memory effect on the subsequent viewing time than semantic and phonological processing did. In other words, visual processing facilitated the effect of previous exposure to a greater extent than non-visual processing did, suggesting that the memory effect as measured by eye movements reflected a visual re-processing effect. While all the characters were presented visually at both study and test phases, during the recognition test the eyes were more likely to move to visually than phonologically and semantically encoded items. This visual fluency effect may be supported by visuospatial working memory which is an essential element of the eye movement system (Van der Stigchel & Hollingworth, 2018).

The results from the three experiments enabled us to rule out other explanations of the memory effect revealed in eye movements. First, processing levels did not have an effect on the proportion of viewing time during the recognition test. Neither deep semantic processing nor shallow phonological processing produced a larger proportion of view times than visual processing. In addition, the finding of no difference in the proportion of viewing time between semantic and phonological processing was also inconsistent with the levels-of-processing explanation. The memory effect on viewing time did not reflect processing levels during encoding. Second, viewing time differences during the recognition test were not associated with the differences in the false alarm rate of recognition performance. Visual processing led to a larger proportion of viewing time, regardless of memory performance; semantic processing produced better memory, whereas phonological processing produced worse memory than visual processing did. In other words, visually encoded characters were viewed longer regardless of whether they were easier to reject than phonologically encoded characters or harder to reject than semantically encoded characters were. Finally, viewing time during the recognition test was independent of the encoding time. The encoding time in the phonological condition was significantly shorter than that in the semantic condition, however there was no difference in the proportion of viewing time between these two encoding conditions.

In the present study because participants were required to select the unstudied item, they may have used a novelty heuristic to select an item during the recognition test. In other words, participants were complying with the task demands and directing their viewing to the item based on the perceived novelty. This hypothesis can explain the finding that viewing time was longer for visually than semantically encoded items, because semantic encoding took longer time, involved deeper processing and produced better memory than visual encoding. However, several findings were inconsistent with this hypothesis. First, there was no difference in the viewing time between phonologically and semantically encoded items, even though semantic encoding also took longer time and produced better memory than phonological encoding. Additionally, visually encoded items were remembered better than phonologically encoded items. If participants adopted a novelty heuristic, they should have viewed the phonologically encoded items longer than the visually encoded item. However, the reversed pattern was found.

The viewing time difference between the studied characters may have occurred involuntarily, as they were not the to-be-selected target in the recognition test and the viewing time difference was not associated with the difference in memory performance. In our previous study (Chen & Lee, 2015), when there was no required time limit, participants took about one to two seconds to make a choice among the three testing items. Thus, participants in the present study should have already made the recognition decision before the response prompt appeared. The finding that toward later time bins of the 2-second recognition test, visually encoded characters were still viewed longer than the other types of studied characters also suggests the possibility that the viewing time difference occurred automatically. However, direct evidence is needed to answer the question of whether the viewing time difference occurred involuntarily.

Some studies demonstrated that a simultaneously presented spoken word could guide the eyes to move to visual, semantic or phonological competitors depending on the time-course and nature of the information in the visual environment (e.g., Huettig & McQueen, 2007). This eye movement effect was also found using printed Chinese words revealing that phonological competitors attracted more fixations than distractors during spoken word recognition (Shen, Qu, & Tong, 2018). Instead of asking participants to view an array of pictures or words while listening to spoken target words, the present study examined eye movement behaviours driven by previous experiences and demonstrated that the memory effect measured by eye movements is most evident when visual processing was performed during the study phase. Previous studies have shown this eye movement-based re-processing effect using pictorial materials based on semantic memory (e.g., Althoff & Cohen, 1999). The present study is the first to demonstrate this re-processing effect using verbal materials and testing memory episodes learned in the laboratory. Evidence of eye movement-based memory effect demonstrates that changes in overt attention to visual items can occur not only during online spoken word processing, but also during an offline memory test.

In conclusion, the present study suggests that the viewing time change in eye movements is an obligatory consequence of re-processing the visual information encoded during the study phase after ruling out alternative explanations and eliminating the influence of response selection. This is the first evidence of this effect in verbal episodic memory, and thus, it provides an important generalization with regard to using eye movements as alternative measures of the influence of past experiences.

Disclosure statement

No potential conflict of interest was reported by the authors.

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