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(Citation)
Japanese Psychological Association.,59(1):49-57

(Issue Date)
2016-12-18

(Resource Type)
journal article

(Version)
Accepted Manuscript

(URL)
https://hdl.handle.net/20.500.14094/90006438

Japanese Psychological Research　Volume59, Issue1　Pages 49-57
https://doi.org/10.1111/jpr.12141

Title:

Cognitive Control of Attentional Guidance by Visual and Verbal Working Memory Representations

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Japanese Psychological Research　Volume59, Issue1　Pages 49-57
https://doi.org/10.1111/jpr.12141

Abstract

Both visual and verbal information in working memory guide visual attention toward a memory-matching object. We tested whether: (a) visual and verbal representations have different effects on the deployment of attention; and (b) both types of representations can be used equally in a top-down manner. We asked participants to maintain a visual cue or a verbal cue at the beginning of each trial, and ended with a memory task to ensure that each cue was represented actively in working memory. Before the memory task, a visual search task appeared where validity was manipulated as valid, neutral, or invalid. We also manipulated the probability of valid trials (20%, 50%, and 80%), which had been told to the participants prior to the task. Consistent with earlier findings, attentional guidance by visual representations was modulated by the probability. We also found that this was true for verbal representations, and that these effects did not differ between representation types. These results suggest that both visual and verbal representations in working memory can be used strategically to control attentional guidance.

Key words: attention, working memory, cognitive control, visual search

Working memory has an influential role in guiding visual attention (Soto, Hodsoll, Rotshtein, & Humphreys, 2008; Soto & Humphreys, 2014). For example, in Soto, Heinke, Humphreys, and Blanco (2005), each trial started with the presentation of a colored shape that participants had to hold in working memory. After a delay, a visual search task appeared where the memorized item contained a target (valid trial), a distractor (invalid trial), or did not reappear (neutral trial). Each trial ended with the memory task in which participants were asked to answer whether the presented item was the same as the memorized item: that is, participants had to perform a visual search task while holding a visually encoded item in working memory. Results showed that reaction times (RTs) in the visual search task were faster in the valid trial than in the neutral trial (RT benefits), and slower in the invalid trial than in the neutral trial (RT costs). Further, Olivers, Meijer, and Theeuwes (2006) showed that an item that matched visual information in working memory attracted rapid eye movement. These results show that attention was automatically captured toward the item that matched the visual representation in working memory (i.e., memory-driven attentional capture).

While these studies have examined the role of visual representations in guiding attention, some studies have also shown that more abstract information in working memory can also determine the locus of visual attention (Balani, Soto, & Humphreys, 2010; Grecucci, Soto, Rumiati, Humphreys, & Rotshtein, 2010; Soto & Humphreys, 2007). For example, Soto and Humphreys (2007) asked participants to perform a visual search while holding either a visual object or a verbal description of an object (e.g., a red square or the words “red square”). For word cue, participants were asked to report whether the word was the same or not in their memory task. This means that they had no need to visualize the words. Nevertheless, reaction times were delayed: attention was

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captured to the semantically related item when they held the words in working memory (e.g., visual attention was captured toward a red square when participants held the words "red square"). Thus, not only visually encoded but also verbally encoded items in working memory can guide visual attention. Soto and Humphreys (2007) also showed that there was no difference in the RT costs between visual and verbal cues, indicating that the effects each type of representation has on the deployment of attention are equivalent.

Balani et al. (2010) have argued that these observations consist of the multiple component model of working memory (Baddeley, 2003). According to this model, working memory is composed of three slave systems and a central executive. The slave systems include the visuospatial sketchpad, which is involved in the storage of visual information, and the phonological loop, which is involved in the storage of verbal information. Thus, different types of information (e.g., visual vs. verbal) are represented in different ways, but both representations have an equally influential role in the deployment of attention.

Although Soto and Humphreys (2007) reported equal magnitude of attentional guidance by visual and verbal representations, some studies have shown that visual cue has an advantage in guiding visual attention over word cue (Knapp & Abrams, 2012; Schmidt & Zelinsky, 2009; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). Wolfe et al. (2004) presented a target cue visually (e.g., exact copy of the target) or verbally (e.g., "Black Vertical") before a visual search task. They found that target-detection was faster when the target was visually cued than when verbally cued. In addition, Knapp and Abrams (2012) observed the search time difference even under longer SOA (stimulus onset asynchrony) between cue and search task (~3200 ms), concluding that there were fundamental differences in guiding attention between visual and verbal cues. Thus, visual representations would have an advantage in guiding visual attention, which is inconsistent with the results from Soto and Humphreys (2007).

The discrepancy about cue type effect on the guidance of visual attention may be caused by the task requirements. Unlike Soto and Humphreys (2007), studies showing visual cue advantage had no memory test for the cue at the end of each trial (Knapp & Abrams, 2012; Schmidt & Zelinsky, 2009; Wolfe et al., 2004). It is thus possible that observers had less incentive to hold visual and verbal representations actively in working memory. In addition, although there were only valid trials in these studies (e.g., both visual and word cue always described the property of the target), Soto and Humphreys (2007) used neutral and invalid trials. These differences in task requirement might lead to the differences in the cue effects. The first aim of the current study was therefore to reassess the effects of visual and verbal cues on guiding visual attention by using the same task (Figure 1).

According to recent studies investigating the role of visual representations in guiding visual attention, individuals can strategically control the attentional guidance toward an object that matches visual representation in working memory in a goal-directed manner (Carlisle & Woodman, 2011; Kiyonaga, Egner, & Soto, 2012; Kuo, Chao, & Yeh, 2013). Using similar designs to those of Soto et al. (2005), Carlisle and Woodman (2011) asked participants to perform a visual search while holding a colored square in working memory. Importantly, when they told participants the probability of valid trials (20%, 50%, or 80%) before the task, they found that the RT costs and benefits were larger when the probability was high (80%) compared to when it was low (20%). These results demonstrate that the effects that working memory has on the guidance of visual attention can be controlled. Thus, individuals can strategically avoid or enhance attentional allocation toward the item that matches the visual content in working memory.

Ansorge and Becker (2012) showed that a color word cue led to attentional capture not in a strategic manner but in an automatic fashion. They presented a word cue at the beginning of all trials, followed by a visual search task where the target appeared against a cued or uncued color disk. In their Experiment 1, the probability of valid trials was manipulated as 75% (informative) and 50% (uninformative), which participants were informed about before the task. Results showed that attention was captured to the color disk similar to the word cue irrespective of probability, indicating that the word cue was not used strategically. Although they determined the automaticity of the effects of the word cue on guiding visual attention, the qualitative and quantitative differences between the representation types were unclear because they did not use a visual cue to compare the effects. Dombert, Fink, and Vossel (2016), on the other hand, examined the effects of cue type on the deployment of attention by manipulating the probability. They presented visual, word, and two-letter (e.g., the abbreviation of the words) cues at the beginning of each trial. The validity was manipulated as valid and invalid, the subtraction of which was used as a validity effect. The probability of the valid trials was manipulated as 50%, 70%, and 90%, which participants were informed about prior to the task. Results showed that all types of the cue caused the validity effect, but its modulation by probability depended on cue types: the modulatory effect in the two-letter cue was observed only in the first half of the trials while such effect in the visual and word cue was found solely in the second halves of the trials. Dombert et al. (2016) concluded that probability information is processed differently based on the cue

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types. Neither of these studies, however, included neutral trials, making it difficult to evaluate effects of each type of cue on the deployment of attention with top-down knowledge about probability. In addition, and as mentioned above, neither of these studies included a memory test to ensure that observers held a cue actively in working memory, which leads to the difficulties in comparing these results directly with those of others (Carlisle & Woodman, 2011; Kiyonaga et al., 2012; Kuo et al., 2013). Therefore the second aim of this study was to investigate the role of the nature of representations in guiding visual attention strategically by directly comparing the magnitude of RT costs and benefits using the same experimental methods. We included neutral trials where a cued color did not appear in a visual search, which were used as a baseline to assess the effects of attentional guidance. The probability of valid trials was manipulated as 20%, 50%, and 80%. The procedure was similar to that of Carlisle and Woodman (2011) as illustrated in Figure 1, where we used both visual and verbal cues. We presented each cue for a different group to avoid the potential carryover effects resulting from any strategy to hold a cue (i.e., not to hold both cue types in the same manner). This approach allowed us not only to compare directly the cue effect in guiding attention but also to examine whether the influence of top-down knowledge on the interaction between attention and working memory would be different qualitatively or quantitatively among representation types.

1. Experiment

1.1. Methods

1.1.1. Participants.

Twenty-three undergraduate and graduate students participated in the experiment: 13 participants were presented a visual cue (eight females and five males, mean age = 23.6 years) and 10 participants were presented a word cue (seven females and three males, mean age = 22.7 years, native Japanese speakers). All participants reported normal or corrected-to-normal visual acuity, and normal color vision. All participants gave informed consent.

1.1.2. Apparatus.

Stimuli were presented on a 19-in. display monitor using PsychoPy 1.76 (Peirce, 2007). The viewing distance was fixed to approximately 57 cm with a chin rest. RTs were collected using a numeric keypad.

1.1.3. Stimulus.

Figure 1 illustrates a trial sequence and the stimulus arrangement. All stimuli were presented on a gray background. A black fixation cross (0.3° × 0.3°) was present at the center of the screen throughout the trial. The memory item was presented 1° above the fixation cross. As a visual cue, five distinguishable colors were used: red, green, blue, yellow, and magenta. As a word cue, five white words (0.9° × 0.9°) were used: “red,” “green,” “blue,” “yellow,” and “magenta” (note: the experiment used Japanese equivalents). Items in the search array consisted of four Landolt squares (0.9° × 0.9°, line thickness = 0.18°, gap = 0.36°), presented at each corner of an imaginary square with a diagonal of 14.32° in length passing the center of the screen. The location of the gap distinguished a target from distractors: the target had gaps on the top or bottom, and those of the distractors were left or right. The target appeared randomly in one of the four locations. Each Landolt square was unique in color: red, green, blue, yellow, or magenta.

1.1.4. Design.

We used a within-subject factorial design for each cue type separately with the following two factors: Validity (valid, neutral, invalid) and Probability (20%, 50%, and 80%). In valid trials, the target was the same color as the description of the memory item. In neutral trials, no item had the same color as the description of the memory item. In invalid trials, one of the distractors was the same color as the description of the memory item. Probability conditions were blocked, and each participant was told the probability of the next blocks before practice trials.

1.1.5. Procedure.

Each trial began with the presentation of a fixation cross for 800 ms. A memory item was then presented for 100 ms, followed by a 900-ms delay, followed by the search array, which appeared for 3000 ms. The task was to search for a target and report the location of its gap (top or bottom) as quickly as possible using a numeric keyboard (top = the eight key, bottom = five key). After a 500-ms delay, a memory test appeared for 2000 ms. Participants used the numeric keypad to indicate whether the presented item was the same as the one presented at the beginning of the trial (same = the four key, different = the six key).

The three probability blocks (20%, 50%, and 80%) were pseudo-counterbalanced across participants. Each block consisted of 80 trials (240 trials in total), and the number of trials in each condition was as follows: 20% (valid: 8 trials, invalid: 32 trials, neutral: 40 trials), 50% (valid: 20 trials, invalid, 20 trials, neutral: 40 trials), and 80% (valid: 32 trials, invalid: 8 trials, neutral: 40 trials). Trials for validity (valid, invalid, and neutral) were randomized for each block and for each participant. There were 10 practice trials before each block. Approximately 5 min of rest time was given to participants between the blocks.

1.2. Results

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1.2.1. Search task performance.

RTs greater than 2000 ms were excluded from the analysis (0.8% of data for visual cue and 1.1% of data for word cue). Accuracy in the search task was high for both cue type (*M* = 99.1% for visual cue, *M* = 99.4% for word cue), therefore we analyzed the mean RTs of the correct response for each cue type.

First, we assessed the effect of validity of each memory item on search performance. Analysis of the data for visual cue showed that a significant main effect of Validity, $F(2, 24) = 55.37$, $MSe = .013$, $p < .001$, $\eta_p^2 = .82$, 95% CI [0.63, 0.90], and no main effect of Probability, $F(2, 24) = 1.04$, $MSe = .023$, $p = .369$, $\eta_p^2 = .08$, 95% CI [0.00, 0.25], and significant interaction between Validity and Probability, $F(4, 48) = 5.87$, $MSe = .006$, $p < .001$, $\eta_p^2 =.33$, 95% CI [0.05, 0.54]. Further analysis of the simple main effects revealed a significant effect of Validity for all probability conditions, 20%: $F(2, 24) = 15.13$, $MSe = .008$, $p < .001$, $\eta_p^2 = .56$, 95% CI [0.21, 0.76]; 50%: $F(2, 24) = 43.07$, $MSe = .005$, $p < .001$, $\eta_p^2 = .78$, 95% CI [0.62, 0.88]; 80%: $F(2, 24) = 41.98$, $MSe = .112$, $p < .001$, $\eta_p^2 = .78$, 95% CI [0.62, 0.86]. Shaffer's Bonferroni test showed that in all probability conditions, RTs of valid trials were faster than those of neutral trials and that RTs of invalid trials were slower than those of neutral trials (all *p*s < .05), indicating that visual representation in working memory captured attention.

Analysis of the data for word cue showed a significant main effect of Validity, $F(2, 18) = 44.77$, $MSe = .006$, $p < .001$, $\eta_p^2 = .83$, 95% CI [0.74, 0.89], no main effect of Probability, $F(2, 18) = 0.36$, $MSe = .03$, $p = .706$, $\eta_p^2 = .04$, 95% CI [0.00, 0.12], and significant interaction, $F(4, 36) = 13.94$, $MSe = .002$, $p < .001$, $\eta_p^2 = .61$, 95% CI [0.33, 0.76]. Analysis of the simple main effects revealed that there was a significant effect of Validity for each Probability condition, 20%: $F(2, 18) = 8.89$, $MSe = .002$, $p = .002$,

η_p^2 = .50, 95% CI [0.20, 0.81]; 50%: $F(2, 18) = 49.60$, $MSe = .002$, $p < .001$, η_p^2 =.85, 95% CI [0.75, 0.90]; 80%: $F(2, 18) = 34.84$, $MSe = .006$, $p < .001$, η_p^2 = .79, 95% CI [0.65, 0.88]. Shaffer's Bonferroni test showed that for the 50% and 80% conditions, RTs in neutral trials were slower than those in valid trials and faster than those of invalid trials, indicating that verbal representation in working memory captured attention (all *p*s < .05). We found no attentional capture in the 20% condition ($p = .076$ for valid vs. neutral trials, and $p = .094$ for neutral vs. invalid trials).

Second, to compare the degree of RT costs and benefits among cue types, we used between-subject analyses of variance (ANOVAs) for RT costs and benefits, with Probability (20%, 50%, and 80%) and Cue (visual, word) as the between-subject factors. Notice that RT costs were calculated by subtracting mean RTs of neutral trials from mean RTs of invalid trials, and that RT benefits were calculated by subtracting mean RTs of valid trials from mean RTs of neutral trials.

Figure 2a shows the mean RT costs for all conditions. We found no main effect of Cue, $F(1, 21) = 1.17$, $MSe = .008$, $p = .291$, η_p^2 = .05, 95% CI [0.00, 0.31], and a significant main effect of Probability, $F(2, 42) = 20.33$, $MSe = .0076$, $p < .001$, η_p^2 = .33, 95% CI [0.07, 0.53]. Shaffer's Bonferroni test showed that RT costs in the 80% condition were larger than in the 20% condition, $t(21) = 3.62$, $p = .002$, and in the 50% condition, $t(21) = 2.98$, $p = .007$, and that RT costs did not differ between the 50% and 20% conditions, $t(21) = 1.61$, $p = .123$. The interaction was not significant, $F(4, 42) = 0.18$, $MSe = .0076$, $p = .835$, η_p^2 = .01, 95% CI [0.00, 0.04].

Figure 2b shows the mean RT benefits for all conditions. We found no main effect of Cue, $F(1, 21) = 3.25$, $MSe = .021$, $p = .086$, η_p^2 = 13, 95% CI [0.00, 0.35], and a significant main effect of Probability, $F(2, 42) = 9.58$, $MSe = .005$, $p < .001$, η_p^2 = .31, 95% CI [0.13, 0.46]. Shaffer's Bonferroni test showed that RT benefits in the 80% condition were larger than in the 20% condition, $t(21) = 4.00$, $p < .001$, and in the 50% condition, $t(21) = 2.21$, $p = .038$, and that RT benefits in the 50% condition were larger than in the 20% condition, $t\,(21) = 2.38$, $p = .027$. The interaction was not significant, $F(2, 42) = 0.63$, $MSe = .005$, $p = .536$, $\eta_p^2 = .03$, 95% CI [0.00, 0.13].

In addition to null hypothesis testing, we further evaluated the effects of Cue types on RT costs and benefits by running a Bayesian analysis using the anovaBF function in the BayesFactor package (Morey & Rouder, 2014) in R. We computed Bayes factor (BF) for each combination of the main effects and interaction in our ANOVA model, and then compared BF to determine the best model based on the evidence provided by the data (as implemented in Blanc-Goldhammer & Cohen, 2014; Morey & Bieler, 2013). The BF represents the ratio with which the alternative hypothesis is favored over the null hypothesis. BF > 1 indicates that the data are more likely under the alternative hypothesis, while BF < 1 supports the null hypothesis. Jeffreys (1961) suggests that a BF < 0.33 indicates support for the null hypothesis and a BF > 3 indicates support for the alternative hypothesis.

For RT costs, models with the Probability condition were preferred (*BF* = 1057.24). Models including both main effects showed a BF of 545.38, following the models with the interaction (*BF* = 107.21), and the models with the Cue condition (*BF* = 0.40). The comparable BF analysis for RT benefits showed that models including both main effects were preferred (*BF* = 83.76). Models including main effect of Probability showed a BF of 66.30, following the models with the interaction (*BF* = 22.48), and the models with the Cue condition (*BF* = 1.17).

1.2.2. Memory task performance.

Trials with no response were excluded from the analysis (0.4% of data for visual cue and 0.4% of data for word cue). A one-factor (Probability) repeated-measures ANOVA with mean RTs showed no main effect for either visual or word cue; visual: $F(2, 24) = 1.81$, $MSe = .005$, $p = .186$, $\eta_p^2 = .13$, 95% CI [0.00, 0.38]; word: $F(2, 18) = 0.86$, $MSe = .004$, $p = .438$, $\eta_p^2 = .09$, 95% CI [0.00, 0.26]. A comparable ANOVA with mean error rate also showed no main effect for either cue type; visual: $F(2, 24) = 0.51$, $MSe = .0006$, $p = .609$, $\eta_p^2 = .04$, 95% CI [0.00, 0.13]; word: $F(2, 18) = 0.62$, $MSe = .0008$, $p = .550$, $\eta_p^2 = .06$, 95% CI [0.00, 0.27].

2. Discussion

By using the same experimental methods, the present study: (a) examined whether visual and verbal cues have equal effects on guiding visual attention; and (b) investigated the nature of representations in guiding visual attention strategically. For both visual and word cues, we observed that attention was captured toward the memory-match item. These results are in line with the notion that both types of representations can guide visual attention (Balani et al., 2010; Grecucci et al., 2010; Soto & Humphreys, 2007). These results support the notion that visual and verbal representations have an influential role in the deployment of attention, and that the two forms of representation are represented in different ways (Baddeley, 2003). We further compared the effects of visual and verbal cues on RT costs and benefits, showing that visual representation has a weak advantage in guiding visual attention. Although the recent findings have shown that target detection can become faster by visual cue than by word cue (Knapp & Abrams, 2012; Schmidt & Zelinsky, 2009; Wolfe et al., 2004), we could not find a clear difference between cue types. One possibility is that a memory test might make the representation status equal irrespective of cue types. With a memory test, each cue would be represented actively in working memory throughout the trials. Crucially, previous studies have manipulated cue types, but have not controlled how each cue is represented. Therefore the representation status of each cue might be variable depending on participants' task set, such as motivation or difficulties to hold and use cues. Such a variability would induce the differences in their performances. We speculate that controlling the status of each representation would minimize the observed visual cue advantage.

For visual cues, results showed that attentional guidance was modulated by knowing the probability about valid trials, which replicates the finding of Carlisle and Woodman (2011). In contrast to their study, we manipulated probability as a within-subject factor, indicating that the control of attentional guidance by visual representations in working memory is not design-specific. As well as visual cue, attentional guidance by verbal cue was also modulated by top-down knowledge about probability. These results contradict the studies showing no modulatory effect by word cue (Ansorge & Becker, 2012) and the difference of cue types in the use of probability information (Dombert et al., 2016). One possibility is that the range of probability in previous studies was not wide enough to observe strategic control of attentional guidance. As compared with our manipulation, previous studies set the probability as 50% and 75% (Ansorge & Becker, 2012), or 50%, 70%, and 90% (Dombert et al., 2016). Participants might be confused about such a narrow range of probability condition to use it strategically. It may be interesting to examine how observers interpret and use probability information by manipulating it more continuously.

Our results also demonstrated that fully visual representations are not needed to control the working memory guidance. Until now, these control effects of working memory bias

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have been examined only using visual stimuli as a memory item (Carlisle & Woodman, 2011; Kiyonaga et al., 2012; Kuo et al., 2013). These results provide new insight into the nature of this type of modulation: in addition to visual representations, verbal representations can also be strategically used to guide visual attention. This suggests that the control of working memory guidance is not a domain-specific, but a domain-general process. That is, the common resource may be used to control the attentional guidance for both visual and verbal representations. According to Baddeley (2003), the central executive manages and allocates resources to both the visuospatial sketchpad and phonological loop. We suspect that the central executive manages information in working memory based on probability knowledge, which results in the modulation of attentional guidance. Such management is not specific to visual information: the general system may be used to control attentional deployment.

In contrast to the domain-specific view of working memory storage (Baddeley, 2003), some have argued that a unitary working memory system is involved in the maintenance regardless of stimulus types (Li, Christ, & Cowan, 2014). It is possible that such a common system might be used to represent each cue type in our study, for example, through automatic transformation from visual input to verbal code. Although our study cannot answer whether working memory storage itself is domain-specific or domain-general, our results indicate that the control of working memory is not domain-specific because both cue types can be similarly used to guide visual attention strategically.

The current results lead to some future directions. As we did not conduct a within-subject test, future work should directly examine the cue type effects. It is possible and interesting to investigate that those who use visual cues strategically can

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also use verbal cues effectively. In addition, such design allows us to obtain more power by excluding possible alternatives. In order to implement a within-subject design, future studies should develop more sophisticated ways to avoid carryover effects. Furthermore, it remains to be determined as to whether our results can be generalized to other stimuli features, such as shape or motion direction.

In summary, by using the same experimental procedure, we demonstrated that the control of attentional guidance can be modulated not only when holding visual representations but also when holding more abstract, or verbal representations in working memory. Both visual and verbal information can control the attentional guidance in a visual search. These findings shed light on how visual and verbal information are represented in working memory, both of which control the deployment of visual attention in a top-down manner.

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https://doi.org/10.1111/jpr.12141

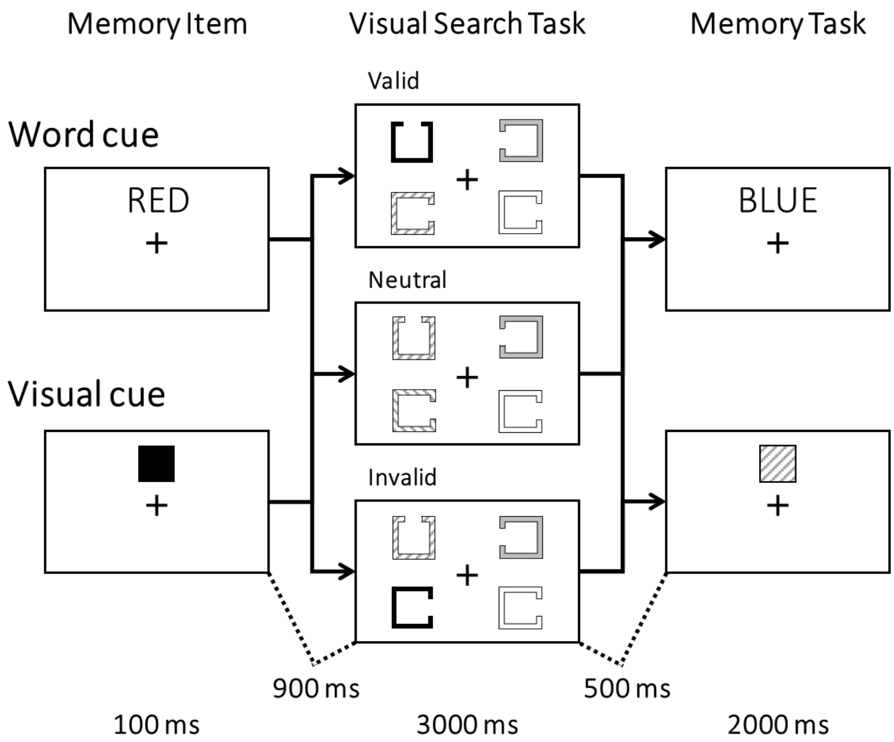

Figure 1. Example trials in different conditions (valid, neutral, and invalid) for a word cue (top) and a visual cue (bottom). Participants were asked to memorize a word or a colored square. In memory task, participants were asked to judge whether the presented item was the same as the memory item or not. In visual search task, participants made a speeded key press to target (gap on top or bottom) while ignoring distractors (gap on left or right). *Note*: The actual experiment used Japanese equivalents for word cue.

Japanese Psychological Research Volume59, Issue1 Pages 49-57
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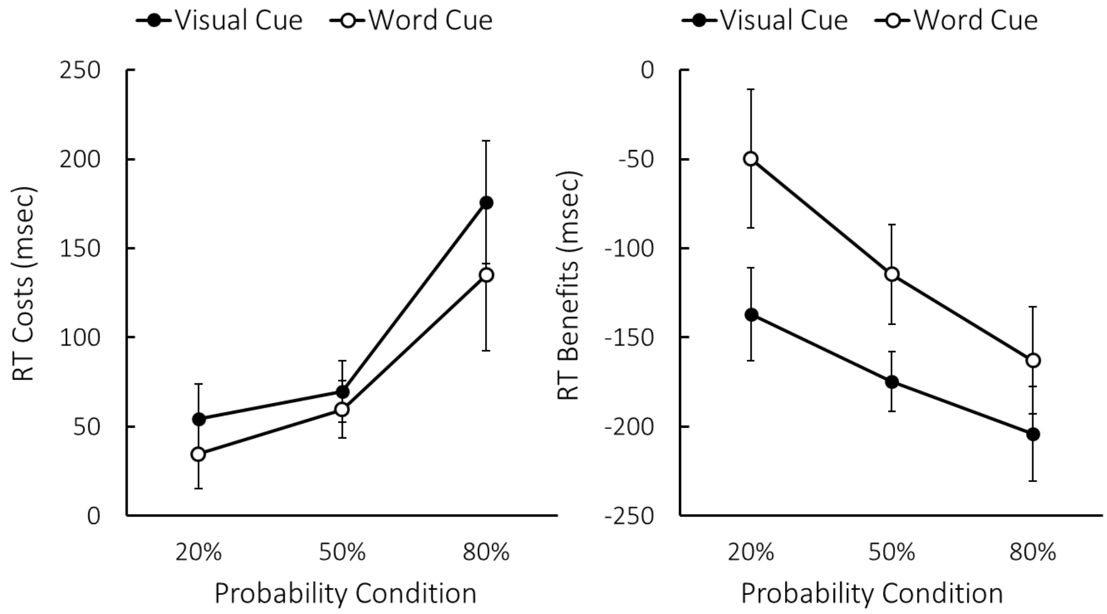

Figure 2. (a) Reaction time (RT) costs (mean RT for invalid trials − mean RT for neutral trials) and (b) RT benefits (mean RT for valid trials − mean RT for neutral trials) for the two cue types. Error bars reflect 95% confidence intervals.