



Responses guide attention

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ABSTRACT

Internalizing regularities between motor responses and stimuli is crucial for adaptive functioning. However, the influence of these regularities on attentional selection remains poorly understood. This study explored whether responses, which predict the locations of search targets, direct attention toward these associated locations, a phenomenon termed *response-induced attention*. The experiments consist of acquisition and test phases. In the acquisition phase, participants performed a dual task involving an identification task followed by a search task. In the identification task, participants responded to the color of an object presented at the center. Immediately after this response, a search target appeared on either the left or right side. Critically, the response for the identification target predicted a more probable location of the search target. Faster responses for search targets were observed at the response-cued location than the other location, suggesting an attentional bias toward the response-cued location. In the test phase, the colors of identification targets were changed, and the responses for the identification targets were no longer informative about the search target locations. Nevertheless, search remained faster when targets appeared at the response-cued location, suggesting that responses, not colors, guided attention. This response-induced attention effect was observed in Experiment 1, where responses predicted spatially compatible target locations, as well as in Experiments 2 and 3, where they predicted incompatible locations. Experiment 4 confirmed that the observed effects resulted from the spatial distribution of attention. These findings provide new insights into the ability to learn response-stimulus regularities for the intelligent allocation of attention, demonstrating the significant role of the motor dimension in attentional selection.

1. Introduction

Due to limited attentional resources, the human cognitive system selects only a few stimuli from numerous objects and events in the visual environment (Broadbent, 1958; James, 1890; Posner, 1980). However, these objects and events are often predictable. For instance, a chair is commonly found near a table, exemplifying a stimulus-stimulus regularity, and the act of pressing a light switch consistently activates the corresponding light, illustrating a response-stimulus regularity. The cognitive system encodes such meaningful regularities for predicting upcoming sensory inputs, as sensitivity to these patterns enhances adaptive functioning (Friston, 2005; Hebb, 1949; Rao & Ballard, 1999). Consistent with this, research has demonstrated that humans use stimulus-stimulus regularities to efficiently allocate attention (Chun & Jiang, 1998). However, it remains unclear whether response-stimulus regularities are used to guide attention. The current study aims to address this gap by investigating whether responses, which predict

target locations, direct attention toward the response-predicted locations for efficient search, which is termed *response-induced attention*.

1.1. Attentional guidance by stimulus-stimulus regularity

Chun and Jiang (1998) demonstrated humans' capacity to implicitly acquire meaningful regularities for intelligently allocating attention. In their experiments, participants performed a visual search task under two conditions. In the repeated display condition, the locations of a target and distractors were consistently repeated across trials, establishing a predictive relationship between the invariant configuration of the distractors and the target location. In the variable display condition, however, the locations of a target and distractors were novel, making the distractors' configuration non-predictive of the target location. Search was faster in the repeated than variable display condition although participants were unaware of the repeated configurations. These findings suggest that participants implicitly learned associations between

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configurations and target locations, and they leveraged this implicit knowledge for efficiently allocating attention toward targets (Jiang et al., 2019; but see also Vadillo et al., 2022). This phenomenon is known as contextual cueing (Chun & Jiang, 1998).

Contextual cueing has had a seminal impact on cognitive psychology because, as Chun and Jiang (1998, p. 67) stated, it represents “the beginning of a query into the broader issue of how perceivers internalize meaningful regularities and covariations between objects and events in the visual world.” However, the regularities explored in Chun and Jiang and subsequent studies primarily focused on associations between stimuli rather than associations between responses and stimuli (Chun & Jiang, 1999; Endo & Takeda, 2004; Kim & Beck, 2020a; Olson & Chun, 2001; see Sisk et al., 2019, for reviews). Regularities between stimuli and responses are also encoded to improve adaptive functioning, like stimulus-stimulus regularities, as they are essential for body movement and physical interactions with the environment (Hommel et al., 2016; James, 1890). Furthermore, a growing body of recent research emphasized the importance of brain connectivity between motor-related areas, such as motor cortex and cerebellum, and sensory-related areas, such as occipital lobe, in attentional processes (Rosenberg et al., 2016; Rosenberg et al., 2017; Rosenberg & Chun, 2020). However, the role of response-stimulus regularities in attentional selection remains unclear.

1.2. Perception and action

Relationships between stimuli and responses, crucial processes for the present topic, have been actively explored in the perception and action literature, rather than in the attention literature. Findings from the perception and action literature also provide a valuable insight into the concept of response-induced attention.

Perception and action are suggested to be tightly bound, mutually influencing each other (Hommel, 2019; Prinz, 1990; Shin et al., 2010). Therefore, research on the relations between perception and action can be categorized into stimulus-response compatibility (SRC) and response-stimulus compatibility (RSC). SRC refers to the phenomenon wherein perceiving stimuli directly influences action control (Kornblum et al., 1990), while RSC involves the phenomenon wherein action controls influence the perception of stimuli (Kunde, 2001). Although research on SRC and RSC has not examined the mechanisms of attentional allocation, it does hint at the potential for attention being guided by responses.

1.3. Stimulus-response compatibility

A classic illustration of SRC is the Simon effect (Simon, 1990). In a typical Simon task, participants are instructed to press a left key for a red target and a right key for a green target irrespective of whether the target appears on the left or right side. Despite the spatial information being entirely irrelevant to the task, responses are faster when the locations of the response and target coincide (left-left, right-right) than they do not (left-right, right-left), suggesting that the perception of the target automatically facilitates a response that is spatially compatible with the target location. Interestingly, as detailed in the following sections, the mechanisms underlying the Simon effect suggest that attention can be guided by responses (Hommel et al., 2001; Nicoletti & Umiltà, 1989; Tagliabue et al., 2000).

Attention in SRC. Attentional orienting is suggested to play an important role in the occurrence of the Simon effect (Nicoletti & Umiltà, 1989; Proctor & Lu, 1994; Stoffer, 1991; but see also Hommel, 1993). In the Simon task, attention is shifted from the center of the screen toward a target to perceive it. This attentional shift has been observed to facilitate spatially compatible responses, resulting in the occurrence of the Simon effect. However, no Simon effect was found when attention was maintained at one location (Nicoletti & Umiltà, 1989; Umiltà & Liotti, 1987; Umiltà & Nicoletti, 1992). These findings suggest that the direction of the attentional shift determines the spatial representation of target perception, influencing motor responses.

Bidirectionality in SRC. The Simon effect occurs from perception to action (SRC), counter to the direction of response-induced attention. However, traditional and contemporary theories on action and perception, such as ideomotor theory, embodied cognition, and theory of event coding, suggest a bidirectional link between action and perception (Hommel, 2015; Hommel et al., 2001; James, 1890). For instance, acquiring associations between piano keys and their corresponding sounds leads the act of pressing a piano key to facilitate the perceptual representations of the expected sound, even in the absence of physical sounds. Furthermore, hearing piano sounds itself facilitates the action of pressing keys associated with those sounds (Hommel et al., 2016). Considering this bidirectional relationship, the finding that attentional orienting determines which responses are facilitated suggests that responses might guide attention.

Associative Learning for SRC. SRC develops through associative learning, creating a link between action and perception. This process is based on long-term based learning, such as a lifetime of real-world experiences, and short-term based learning, such as practice in experiment settings like contextual cueing (Bae et al., 2009; Elsner & Hommel, 2001; Hommel et al., 2016; Tagliabue et al., 2000; Tagliabue et al., 2002; Vu et al., 2003). Specifically, the Simon effect results from a lifetime of real-world experiences where spatially compatible mappings between stimuli and responses prevail (Hommel et al., 2016). That is, we naturally acquire SRC based on these compatible mappings. Consequently, the Simon effect can occur naturally without explicit associative learning of the compatible mappings between stimulus and response locations during an experiment. On the other hand, SRC can also be acquired through short-term practice (Tagliabue et al., 2000). For example, following practice of spatially compatible associations between stimuli and responses in an SRC task (e.g., when a target is presented on the left, a correct response is a left response key), the Simon effect is evident. However, with practice of incompatible associations (e.g., when a target is presented on the left, a correct response is a right response key), the Simon effect is found to be weakened or even reversed, showing faster responses for the incompatible mappings due to the practice overriding the long-term-based Simon effect (Bae et al., 2009; Tagliabue et al., 2000). That is, the occurrence of the Simon effect or the reversed Simon effect depends on whether previous experiences were aligned with the compatible or incompatible mappings (Hommel et al., 2016; Tagliabue et al., 2000; Tagliabue et al., 2002; Vu et al., 2003). These findings suggest that response-induced attention might be more likely when responses and stimuli are spatially compatible, reflecting our natural tendency toward such mappings.

1.4. Response-stimulus compatibility

RSC refers to a phenomenon wherein action control influences the perception of stimuli. In comparison to SRC, RSC is more closely related to response-induced attention in terms of the direction of processing. However, the information-processing approach, a traditional yet still influential framework in cognitive psychology, conceptualizes cognition as a sensory-to-motor processing sequence, which has contributed to the relative neglect of RSC compared to SRC (Proctor & Vu, 2006). Therefore, responses have often been considered merely as products of perceptual processes. Furthermore, most studies on RSC have primarily focused on how responses influence the identification or perceptual sensitivity of stimuli linked to those responses (e.g., Cardoso-Leite et al., 2010; Schwarz et al., 2018; Yon & Press, 2017; see Hommel et al., 2016, and Shin et al., 2010, for reviews). Expanding upon this body of research, the present study suggests a novel type of RSC by demonstrating that motor responses can guide spatial attention toward locations associated with the responses. Although several studies have examined aspects related to response-induced attention (Pfeuffer et al., 2016; Wirth et al., 2018; Ziessler, 1998), they have some limitations which preclude a definitive conclusion regarding whether responses themselves directly guide attention, as they were not primarily designed

to investigate response-induced attention.

For example, [Ziessler \(1998\)](#) investigated whether the acquisition of response-stimulus regularities occurs implicitly during a serial search-and-reaction task, where participants could predict the target location based on their previous responses because the target location of the present trial was determined by the participant's response on the previous trial. The study observed that after approximately 9,000 trials, when the established regularities were suddenly broken, search performance significantly slowed down. This slowdown could have occurred because participants quickly located targets based on the learned response-stimulus regularities until these patterns were broken. However, the identity of targets also predicted the locations of following targets. The author attempted to examine the influences of these stimulus-stimulus regularities with a between-subject factor, but as the author noted, sampling errors occurred, with some participants showing exceptionally slow search performance. Therefore, it remains unclear whether the observed effect was driven by responses or stimuli. Additionally, it has been suggested that regularities may enhance search performance not only during attentional selection but also in later stages, such as identification and response selection ([Kunar et al., 2007](#); [Schankin et al., 2011](#)). In the serial search-and-reaction task ([Ziessler, 1998](#)), various cognitive stages, including attentional selection and response selection, were involved. Therefore, methods that effectively and specifically isolate attentional selection are crucial for examining response-induced attention. Furthermore, the delayed search performance might have been a consequence of uncertainty-related processes. It is well established that the brain continuously generates predictions through a generative model to anticipate upcoming sensory inputs ([Friston, 2005](#); [Rao & Ballard, 1999](#)). When actual inputs deviate from these predictions, the discrepancies (e.g., prediction errors, free energy, uncertainty, surprise) are used to update the model, reducing uncertainty and improving future predictions. These processes of information updating and uncertainty management are suggested to demand attentional resources, potentially interfering with other attention-demanding tasks, such as visual search ([Friston, 2009](#); [Le Pelley et al., 2016](#)). Therefore, the reduced search performance observed in [Ziessler's](#) study could have stemmed from these uncertainty-driven processes rather than response-induced attention.

To control for the influences of stimulus-stimulus regularities, RSC research often employs free response-selection methods, allowing participants to choose their responses independently of target identity (e.g., [Pfeuffer et al., 2016](#)). For example, [Pfeuffer et al. \(2016\)](#) found that when participants freely selected responses (pressing the left or right key to the same target stimulus) and these responses triggered visual effects at locations predicted by the responses, attention was biased toward the predicted locations before the visual effects appeared on the screen. In this design, participants had full control over the spatial locations of action consequences by freely choosing their response key. However, this introduces a potential confound in investigating response-induced attention: attentional shifts toward predicted locations might stem from actors' intentions rather than being driven by motor responses themselves. This confounding arises because the predictive responses and attentional orienting share a common goal: responses are executed to produce an intended effect, and attention is directed to confirm whether the desired effect occurs. For example, when turning on a television (a common goal), attention naturally shifts to the screen after pressing a remote control button to check whether the television successfully turns on. Similarly, [Wirth et al. \(2018\)](#) found that monitoring of response-triggered effects was slower when the effects appeared at spatially incompatible locations compared to compatible ones. Although this finding suggests a response-effect compatibility advantage, it remains unclear whether the effect primarily reflects attentional mechanisms or other processes ([Kunar et al., 2007](#)). Moreover, as in [Pfeuffer et al. \(2016\)](#), the responses and the attention to the effects shared a common goal, making it difficult to definitively determine whether the responses themselves guide attention.

To address these limitations, the present study employed the Posner spatial cueing task ([Posner, 1980](#)), which is known to effectively and specifically measure the spatial distribution of attention. Moreover, potential influences of stimulus-stimulus regularities were controlled within participants to ensure a focus on response-stimulus relationships. Additionally, motor responses and attentional orienting were separated into distinct tasks: an identification task for motor responses and a search task for attentional orienting. This design ensured that the two processes did not share a common task goal, minimizing potential confounds.

2. Present study

The Posner spatial cueing task is a neuropsychological test designed to assess attentional orienting ([Posner, 1980](#)). In a typical Posner spatial cueing task, two boxes appear on the screen, one on the left and the other on the right side. Immediately following the brief flashing of one box, a search target is presented either in the cued (flashed) or uncued location. The target at the cued than uncued location is detected more rapidly, which is a phenomenon called a cueing effect. In this case, the cueing effect implies that attention is drawn to the flashed cue due to its physical saliency. To investigate whether responses play a role in guiding attention, the present study modified the Posner spatial cueing task, so that a response serves as a cue.

Specifically, the experiments of the present study comprised acquisition and test phases. In the acquisition phase, participants performed a dual task, involving an identification task followed by a search task. In the identification task, participants were instructed to identify the color of a target presented in the center, pressing a left response key for red and a right response key for green. Immediately after the response for the identification, two search items were presented on the left and right sides. One of these items had a small gap on either the left or right side of it, while the other did not. Participants were to search for the target item having the gap and to respond to the location of the gap. Importantly, the responses for the identification task and the locations of the search targets were spatially compatible on 80 % of trials (left-left, right-right) and incompatible on 20 % of trials (left-right, right-left). For example, when participants pressed the left key in the identification task, a search target was more likely to appear on the left (80 %) than on the right (20 %). If participants incidentally acquire spatial associations between the identification responses and the search target locations and use them for efficient search, their responses will guide attention toward the response compatible locations (locations cued by responses), leading to faster responses for the targets presented in the compatible than incompatible locations.

During the acquisition phase, however, not only was the response linked to the identification target, but also the color of the identification target was associated with the search target location. Therefore, attention toward a response-compatible location in the acquisition phase might be due to colors (stimulus-stimulus regularity), responses (response-stimulus regularity), or a combination of both. To eliminate the potential influence of the stimulus-stimulus regularity, in the test phase, the colors of the identification targets were changed to black and white instead of red and green. Additionally, no association was established between identification responses and search target locations, resulting in a distribution of 50 % compatible and 50 % incompatible locations. It has been commonly found that learned regularities are not quickly erased but persist for a period to influence behavior ([Chun & Jiang, 1998](#); [Kim et al., 2022](#); [Kim & Beck, 2020b](#)). Therefore, if the response-stimulus regularities of the acquisition phase are learned, they will be transferred to the test phase. As a result, response-induced attention observed in the acquisition phase will remain evident in the test phase, leading to faster responses for search targets appearing at the response cued (compatible) than uncued (incompatible) locations.

Experiment 1 investigated whether responses guide attention when they predicted search target locations spatially compatible with the

responses. Experiment 2 explored response-induced attention in the incompatible mapping between responses and stimuli. Experiment 3 was conducted to provide a strong demonstration of response-induced attention with the incompatible mapping. Experiment 4 examined whether the cueing effects obtained in the present Posner spatial cueing paradigm were due to the spatial distribution of attention.

3. Experiment 1

Experiment 1 aimed to explore response-induced attention with the compatible mapping. In the acquisition phase, search targets were more likely to appear at the locations spatially compatible with the responses for the identification targets. If these response-stimulus regularities are used to guide attention, search targets will be found more rapidly when they are presented at the response cued (compatible) than uncued (incompatible) locations in the acquisition phase. Furthermore, this attentional bias will remain evident in the test phase, where the colors of the identification targets are different from those of the acquisition phase, and responses for the identification targets no longer predict the locations of the search targets.

3.1. Method

Participants. Twenty participants (mean age = 24.15, SD = 1.35, 11 women) with normal or corrected-to-normal visual acuity and color vision participated for a compensation of KRW 10,000 (about \$9). An analysis in G*Power (Faul et al., 2020) suggested a minimum sample size of 19, with 0.79 for effect size (Cohen's *d*), 0.05 for alpha, and 0.90 for power in *t*-tests (within-subject factor). The effect size was estimated based on contextual cueing effects in the Chun and Jiang's (1998) study. All experiments in this study were approved by the institutional review board of Korea University (KU-IRB-16-142-A-1).

Apparatus. Visual stimuli were displayed on a 24-in. (16:9) LED monitor. The experiment was programmed and administered using MATLAB R2020b and Psychophysics Toolbox Version 3 software. The viewing distance was approximately 60 cm but was not constrained.

Responses were collected using a standard 101-key keyboard. The experiment was conducted individually in a dimly lit, sound-attenuated room.

Stimuli and procedure. The experiment consisted of the acquisition phase, the test phase, and the post-question for awareness check. All stimuli were displayed against a light gray background ($R = 120$, $G = 120$, $B = 120$). In the acquisition phase, each trial sequentially presented a placeholder display, an identification-task display, and a search-task display (Fig. 1). In the placeholder display presented for 2000 ms, two placeholder boxes ($2.0^\circ \times 2.0^\circ$, $R = 180$, $G = 180$, $B = 180$) were presented on the left and right sides of the center (the distance between the center of each box and the center of the screen was 6.6°) with a fixation cross mark (0.3° in length for each line) at the center. The identification-task display, presented until a response, included the two placeholders and a randomly chosen red ($R = 210$, $G = 0$, $B = 0$) or green ($R = 0$, $G = 210$, $B = 0$) circle (1.6° in diameter) at the center of the screen. Participants were instructed to accurately respond to the color of the circle by pressing the 'z' key for red with their left index finger and the 'm' key for green with their right index finger (reverse color-key associations for half of participants). In the search-task display presented until a response, each placeholder contained a gray filled square ($1.0^\circ \times 1.0^\circ$, $R = 180$, $G = 180$, $B = 180$). One of the squares had a small gap either on the midpoint of the left or right side. Participants were instructed to respond to the location of the gap quickly and accurately by pressing the 'z' key for the left-side gap and the 'm' key for the right-side gap. In both tasks, if incorrect and/or slow (over 2000 ms) responses were made, a beep sound was presented immediately. During the experiment, participants were asked to always fixate their eyes on the center fixation mark.

The test phase was identical to the acquisition phase with the following exceptions. In the identification task, the target colors were black ($R = 0$, $G = 0$, $B = 0$) and white ($R = 255$, $G = 255$, $B = 255$), instead of red and green used in the acquisition phase. At the beginning of the test phase, instructions were given to inform the color changes (e. g., the 'z' key for white and the 'm' key for black for half of participants and its reverse for the other half). Subsequently, for an awareness check,

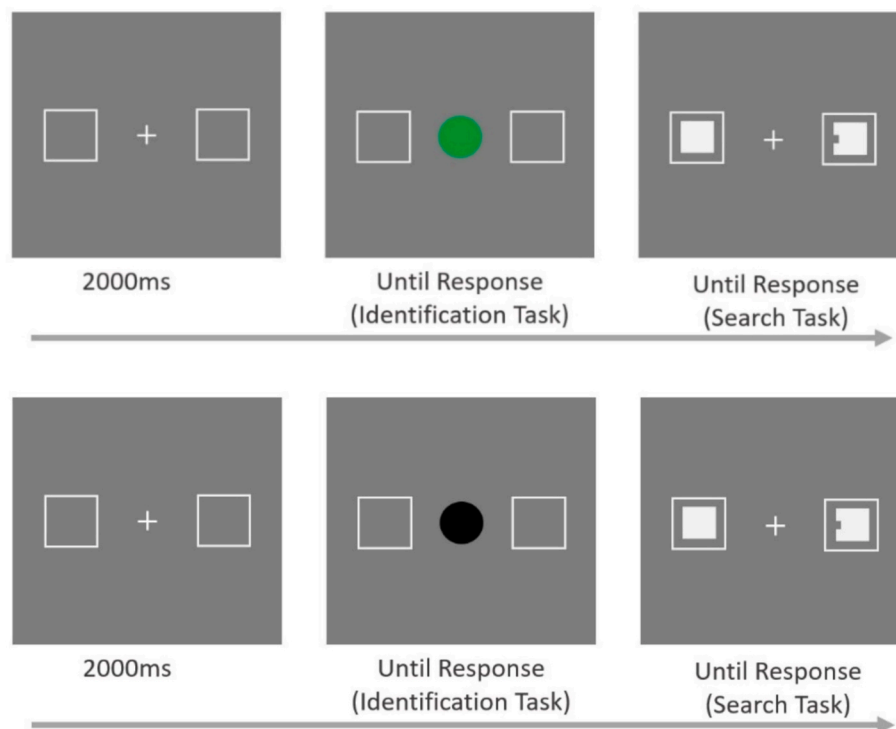


Fig. 1. Top is an example of the trial for the acquisition phase and bottom for the test phase.

participants were questioned about whether they had thought or noticed that there were patterns or rules other than the given instruction during the experiment. They were also asked to provide a detailed description of all the search strategies they employed. Finally, they were informed about the regularities and questioned whether they were aware of them during the experiment.

Design. The acquisition phase consisted of a total 320 trials, 4 blocks of 80 trials each. A self-paced break, lasting less than 60 s, was given between blocks. The test phase had a total of 80 trials. Importantly, in the acquisition phase, unbeknownst to participants, the response for the identification task was informative of whether the target for the search task was presented in the left or right placeholder. For instance, when participants pressed the left key ('z' key) in the identification task regardless of the response correct or incorrect, the search target was more likely to appear in the left placeholder (80 %) than the right placeholder (20 %). In contrast, when they pressed the right key ('m' key), the search target was more likely to appear in the right placeholder (80 %) than the left placeholder (20 %). The spatially compatible mapping (left-left, right-right) was referred to as the *compatible condition*, while the spatially incompatible mapping (left-right, right-left) was referred to as the *incompatible condition*. Consequently, the acquisition phase included 256 compatible and 64 incompatible trials, with 64 compatible and 16 incompatible trials in each of the four blocks. In the test phase, such asymmetry was no longer present. For each of the left and right keys in the identification task, the search target had an equal chance of appearing in the left (50 %) or right placeholder (50 %). Therefore, the test phase comprised 40 compatible and 40 incompatible trials.

In both compatible and incompatible conditions, all possible combinations of colors (red and green during the acquisition phase and black and white during the test phase) and gap locations (left and right) were equally distributed. Specifically, in each block of the acquisition phase, each of the four combinations had 16 compatible and 4 incompatible trials. In the test phase, each combination included 10 compatible and 10 incompatible trials. This design ensured that during the acquisition phase, the frequency of the compatible trials (80 %) was higher than the frequency of incompatible trials (20 %), while all other factors remained consistent between the compatible and incompatible conditions. In the test phase, all factors including the equal numbers of the compatible (50 %) and incompatible (50 %) trials, were controlled across the conditions.

Moreover, in the identification task, color-response mappings were controlled across participants. For instance, five of twenty participants pressed the left key for red in the acquisition phase and black in the test phase and the right key for green in the acquisition phase and white in the test phase. The other three combinations of the color-response mappings were evenly allocated to the remaining fifteen participants.

Data availability. All data in this study are publicly available at the OSF (<https://osf.io/atbzzr>).

3.2. Results

In the present study, compatibility, the variable of interest, showed no correlation with performance in the identification task. Specifically, across all experiments in the study, there was no significant effect of compatibility in RT ($ps > 0.37$) or error rate ($ps > 0.48$) in the identification task. Therefore, the analyses and discussion were focused on the search task. Additionally, the first trial of each block in the acquisition phase and the first trial of the test phase were excluded from RT and error rate analyses in this and subsequent experiments.

RT. Trials with RTs shorter than 250 ms (none of trials) and RTs

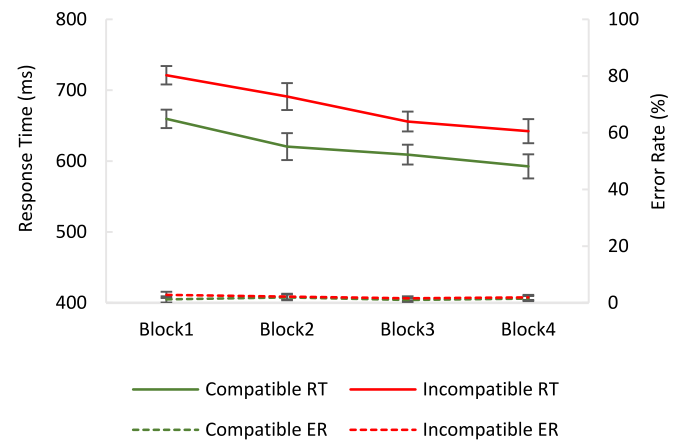


Fig. 2. Results of the acquisition phase in Experiment 1. Error bars represent 95 % confidence intervals.

longer than 1, 250 ms (0.16 %) as outlier and trials with incorrect responses (1.62 %) were excluded from the analyses.

In the acquisition phase, a repeated-measure analysis of variance (ANOVA) was conducted on the mean of response times (RTs) with blocks (4 blocks) and compatibility (compatible and incompatible target locations) as within-subjects variables (Fig. 2). The overall mean RT was 648 ms. The block factor was included to observe the development of response-induced attention. There were significant main effects of block, $F(3, 57) = 19.85, p < .001, \eta_p^2 = 0.51$, and compatibility, $F(1, 19) = 17.14, p = .001, \eta_p^2 = 0.47$. The interaction between block and compatibility was not significant, $F(3, 57) = 1.18, p = .33, \eta_p^2 = 0.06$. In the test phase, search was faster in the compatible than incompatible condition, $t(19) = 3.49, p = .002$, Cohen's $d = 0.78$ (Fig. 3).

Error rate. In the acquisition phase, ANOVAs were conducted on the mean of error rates with blocks and compatibility as within-subjects variables. The overall mean error rate was 1.8 %. None of the main effects or interaction were significant, $F_s < 1, ps > 0.33$ (Fig. 2). In the test phase, the simple main effect of compatibility was not significant, $t(19) < 1, p = .35$ (Fig. 3).

Post-question for awareness. When participants were questioned if they had noticed or thought that there was a pattern or rule during the experiment, two out of the twenty participants reported perceiving the compatibility asymmetry, while the remaining eighteen reported no awareness of any patterns. When asked to describe all search strategies they used, the two participants who identified the patterns mentioned that they appeared to focus on the search target locations associated with their responses in the identification task. In contrast, the eighteen participants who did not notice the patterns described that they followed only the instructed search strategy or sometimes used strategies unrelated to the regularities, such as scanning from left to right. When limiting the analysis of the eighteen participants who were unaware of the compatibility asymmetry, search was faster under the compatible than incompatible condition in the acquisition phase, $t(17) = 3.77, p = .002$, Cohen's $d = 0.89$, and the test phase, $t(17) = 3.05, p = .007$, Cohen's $d = 0.72$.

3.3. Discussion

In the acquisition phase, search performance was faster when search targets were presented at locations predicted by responses to identification targets than the other location. Moreover, the magnitude of this

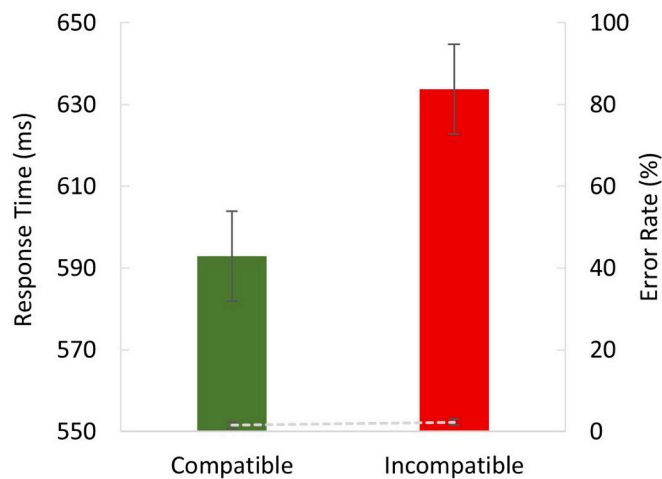


Fig. 3. Results of the test phase in Experiment 1. Error bars represent 95 % confidence intervals.

cueing effect remained consistent across four blocks, indicating that participants rapidly internalized and used the compatible regularities to optimize search efficiency. This early effect may also partially arise from a natural tendency to favor compatible mappings (Bae et al., 2009; Tagliabue et al., 2000; Tagliabue et al., 2002; Vu et al., 2003).

During the acquisition phase, however, the colors of the identification targets also predicted the locations of the search targets. Consequently, it was possible that the observed cueing effect during the acquisition phase was due to stimulus-stimulus regularities rather than response-stimulus regularities. To eliminate this potential confounding, in the subsequent test phase, the colors for the identification targets were changed, and responses to the identification targets no longer predicted the search target locations. Despite this change, search performance remained faster for the search targets appearing at locations spatially compatible with the responses to the identification targets than incompatible ones. This finding suggests that the cueing effect observed during the acquisition phase was, at least in part, attributable to the acquisition of the response-stimulus regularities, with the memory of these regularities persisting to guide attention during the test phase. Furthermore, eighteen out of twenty participants were unaware of the patterns but still demonstrated cueing effects in both phases, suggesting that response-induced attention can occur independently of awareness of the regularities. Taken together, these findings indicate that humans possess the ability to learn response-stimulus regularities and use this knowledge to allocate limited attentional resources more efficiently.

4. Experiment 2

Experiment 1 demonstrated response-induced attention in compatible regularities, where search targets were expected to appear at locations compatible with the responses for the identification task. However, previous studies on SRC have revealed the internalization of both compatible and incompatible regularities, with the compatible regularities being acquired more readily than the incompatible ones (Bae et al., 2009; Tagliabue et al., 2000; Tagliabue et al., 2002; Vu et al., 2003). The purpose of Experiment 2 was to investigate response-induced attention in incompatible regularities. During the acquisition phase, search targets appeared more frequently at the locations incompatible with the responses for identification targets than compatible ones. Accordingly, if these incompatible regularities are used to guide attention, attention would be biased more toward the locations incompatible with the responses rather than compatible ones. Consequently, search would be faster when the search targets are presented in the response-cued (incompatible) locations than uncued (compatible) locations.

4.1. Method

The method for Experiment 2 was identical to those employed in Experiment 1, with the following modifications. Twenty new participants (mean age = 22.5, SD = 2.45, 11 women) were recruited. The acquisition phase comprised 256 incompatible and 64 compatible trials. Consequently, when participants pressed the left key ('z' key) in the identification task, the search target was more likely to appear in the right placeholder (80 %) than the left placeholder (20 %). In contrast, when participants pressed the right key ('m' key), the search target was more likely to appear in the left placeholder (80 %) than the right placeholder (20 %).

4.2. Results

RT. As in Experiment 1, trials with RTs shorter than 250 ms (none of trials), trials with RTs longer than 1,250 ms (0.03 %), and trials with incorrect responses (1.91 %) were excluded in the analyses.

In the acquisition phase, the overall mean RT was 636 ms, and a repeated-measures ANOVA with blocks and compatibility revealed that the main effect of block was significant, $F(3, 57) = 23.33, p < .001, \eta_p^2 = 0.55$ (Fig. 4). The main effect of compatibility was not significant, $F(1, 19) = 3.95, p = .061, \eta_p^2 = 0.17$. The interaction between block and compatibility was not significant, $F(3, 57) = 2.22, p = .095, \eta_p^2 = 0.10$. In the test phase, search performance was faster when search targets appeared at the incompatible location than the compatible location, $t(19) = 2.15, p = .044$, Cohen's $d = 0.48$ (Fig. 5).

Error rate. In the acquisition phase, the overall mean error rate was 1.8 %, and a repeated-measures ANOVA with blocks and compatibility showed that none of the main and interaction effects were significant, $F_s < 1, p_s > 0.79$ (Fig. 4). In the test phase, error rate was not significantly different between the incompatible condition and the compatible condition, $t(19) = 0.67, p = .50$, Cohen's $d = 0.15$ (Fig. 5).

Post-question for awareness. None of the twenty participants explicitly noticed the compatibility asymmetry. They reported adhering to only the instructed search strategy or occasionally using strategies unrelated to the regularities, such as scanning from left to right or from right to side.

4.3. Discussion

The purpose of Experiment 2 was to explore response-induced attention with the incompatible mappings, when responses to identification targets predicted search target locations spatially incompatible with the responses. During the acquisition phase, search performance was faster for the targets presented in the response-cued (incompatible) locations than uncued (compatible) locations, although this difference

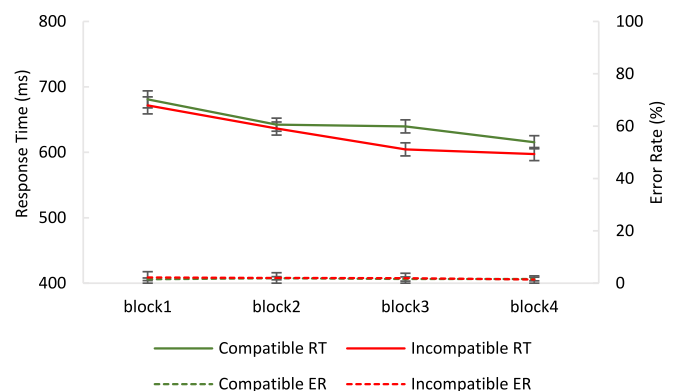


Fig. 4. Results of the acquisition phase in Experiment 2. Error bars represent 95 % confidence intervals.

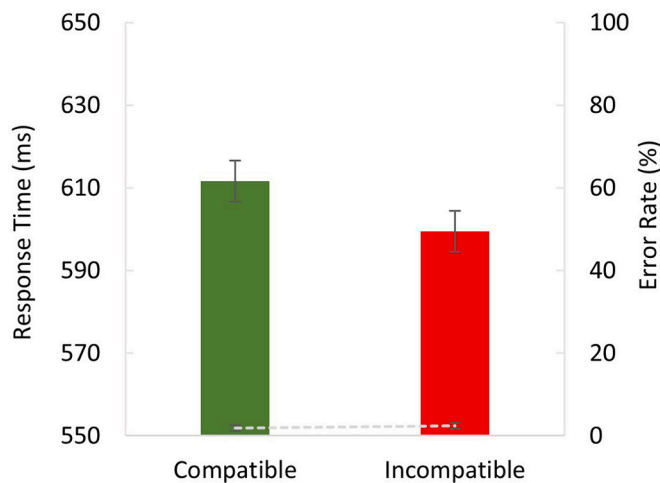


Fig. 5. Results of the test phase in Experiment 2. Error bars represent 95 % confidence intervals.

was not statistically significant ($p = .061$). Based on a visual inspection of the results (Fig. 4), which showed that the cueing effect began to emerge from block 3, the lack of significance in the cueing effect appeared to be primarily due to slow learning of the incompatible regularities rather than an inability to learn the incompatible regularities. Previous research consistently demonstrated less robust learning of incompatible regularities than compatible regularities, suggesting a natural disparity as the long term-based learning of compatible regularities may interfere with the short term-based learning of incompatible ones (Bae et al., 2009; Hommel et al., 2016; Tagliabue et al., 2000; Tagliabue et al., 2002; Vu et al., 2003).

During the test phase, search performance was faster when search targets appeared at the locations incompatible with the responses to identification targets than compatible ones. Importantly, the identification targets' colors differed from those used in the acquisition phase, and there was no contingency between responses and stimuli. Therefore, the response-induced attention effect in the test phase suggests that participants acquired the incompatible regularities during the acquisition phase. This finding supports the idea that the insignificant cueing effect during the acquisition phase involved slow learning of incompatible regularities, rather than an inability to learn them. Furthermore, none of the participants were aware of the incompatible regularities. Taken together, the results of Experiment 2 suggest that participants are capable of internalizing incompatible regularities and allocating attention effectively, despite the slow learning process for these incompatible regularities.

5. Experiment 3

The less robust response-induced attention effect for the incompatible than compatible patterns appears to be due to the potentially slower learning process associated with incompatible patterns than compatible ones (Bae et al., 2009; Hommel et al., 2016; Tagliabue et al., 2000; Tagliabue et al., 2002; Vu et al., 2003). Thus, Experiment 3 was conducted to validate and replicate the response-induced attention effect with the incompatible regularities, when the learning process for incompatible regularities could be enhanced compared to in Experiment 2. During the acquisition phase, the probability of the incompatible trials was increased to 90 %. Additionally, the number of acquisition trials was increased to 640 trials.

5.1. Method

The method for Experiment 3 was the same as in Experiment 2 except

for the following changes. Twenty new participants (mean age = 23.25, SD = 2.16, 8 women and 12 men) participated for payment of KRW 12,000 (about \$11). The acquisition phase had 576 incompatible and 64 compatible trials (8 blocks of 80 trials). Therefore, when participants pressed the left key (z-key) in the identification task, the search target was more likely to appear in the right placeholder (90 %) than the left placeholder (10 %). In contrast, when participants pressed the right key (m-key), the search target was more likely to appear in the left placeholder (90 %) than the right placeholder (10 %).

5.2. Results

RT. As in the previous experiments, trials with RTs shorter than 250 ms (none of trials), trials with RTs longer than 1,250 ms (0.35 %), and trials with incorrect responses (2.21 %) were excluded from the analyses.

In the acquisition phase, the overall mean RT was 610 ms, and a repeated-measures ANOVA with blocks and compatibility showed that the main effect of block was significant, $F(7, 133) = 4.09, p < .001, \eta_p^2 = 0.17$ (Fig. 6). The main effect of compatibility was significant, $F(1, 19) = 15.69, p = .001, \eta_p^2 = 0.45$. The interaction between block and compatibility was not significant, $F(7, 133) = 1.87, p = .078, \eta_p^2 = 0.09$. In the test phase, the mean RT was shorter for the incompatible than compatible condition, $t(19) = 2.28, p = .034$, Cohen's $d = 0.51$ (Fig. 7).

Error rate. In the acquisition phase, the overall mean error rate was 2.9 %, and a repeated-measures ANOVA with blocks and compatibility was conducted. The main effect of block was insignificant, $F(7, 133) = 0.54, p = .79, \eta_p^2 = 0.028$. The main effect of compatibility was significant, $F(1, 19) = 14.14, p = .001, \eta_p^2 = 0.42$. The interaction between block and compatibility was not significant, $F(7, 133) < 1, p = .74$ (Fig. 6). In the test phase, the simple main effect of compatibility was not significant, $t(19) = 1.63, p = .12$, Cohen's $d = 0.36$ (Fig. 7).

Post-question for awareness. Three out of the twenty participants explicitly noticed the compatibility asymmetry, while the remaining seventeen participants reported no awareness of any pattern or rule other than the given instruction. The three participants who identified the regularities reported that they tended to first check the search target locations predicted by their identification task responses. The seventeen participants who did not notice the patterns reported following the instructed search strategy and did not use any additional strategy. Analyses were conducted on the 17 participants who were unaware of it. Results revealed significant compatibility effects in the acquisition phase, $t(16) = 2.97, p = .009$, Cohen's $d = 0.72$, and the test phase, $t(16) = 2.16, p = .047$, Cohen's $d = 0.52$.

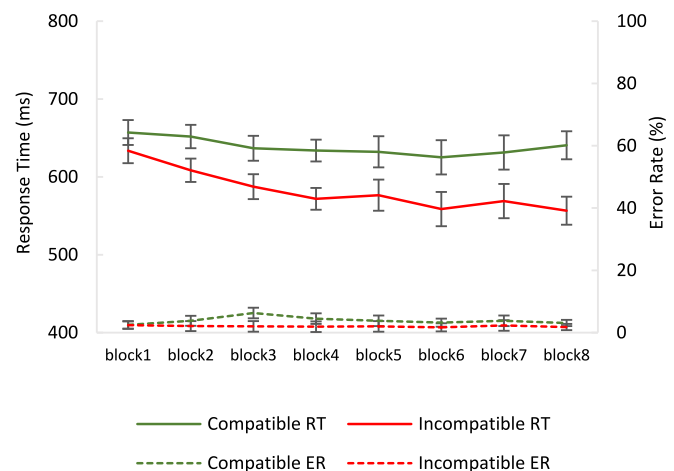


Fig. 6. Results of the acquisition phase in Experiment 3. Error bars represent 95 % confidence intervals.

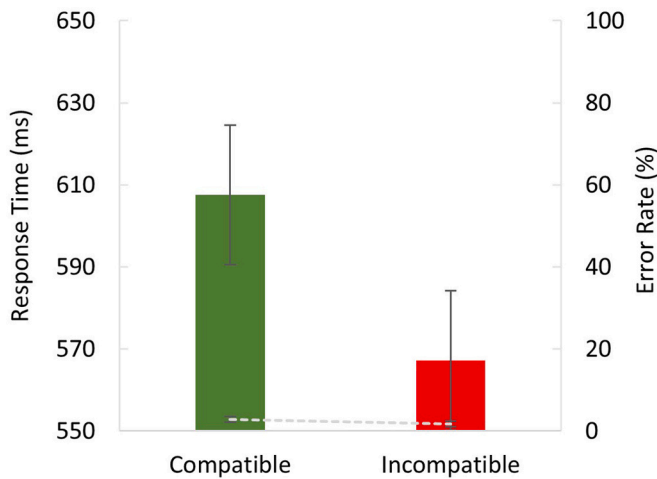


Fig. 7. Results of the test phase in Experiment 3. Error bars represent 95 % confidence intervals.

5.3. Discussion

Experiment 3 confirmed response-induced attention with the incompatible mappings. During the acquisition phase, faster search performance was observed when search targets appeared in the incompatible location than the compatible one, with this cueing effect persisting into the test phase. These findings suggest that responses for the identification targets effectively directed attention toward the incompatible locations. Furthermore, the magnitudes of the response-induced attention effects in both phases were numerically increased compared to those observed in Experiment 2. This enhancement indicates that the increased contingency and the greater number of acquisition trials facilitated the learning of the regularities as predicted.

6. Experiment 4

The present study utilized the Posner spatial cueing paradigm for its effectiveness in measuring the spatial distribution of attention. However, the current version introduced a novel aspect, as motor responses served as cues. Thus, it is crucial to verify whether the cueing effects in this version pertained to the spatial distribution of attention. Experiment 4 was designed to address this verification. Specifically, it replicated the acquisition phase of Experiment 1 but included intermittent catch trials. In these catch trials, two search targets were presented on the left and right sides, each with a gap. However, the positions of the gaps were always different, enabling the identification of whether participants responded to the left or right target (e.g., Kim et al., 2023). If participants more frequently attended to search targets at locations cued by their responses in the identification task, they would be more likely to respond to targets at the cued location than at the uncued location in catch trials.

6.1. Method

To effectively measure the underlying mechanism of the cueing effect using catch trials, it is essential to establish a condition in which the cueing effect is robust. Furthermore, across Experiments 1 to 3, a strong correlation was found between the cueing effects observed in the acquisition and test phases ($r(58) = 0.59, p < .001$). This robust relationship suggests that the cueing effects observed during the acquisition phase reliably reflect the learned response-stimulus regularities. Therefore, this experiment replicated the acquisition phase of Experiment 1, where the most robust cueing effect was observed, with the following changes. Sixty-four catch trials were intermittently presented, so that each of 4 blocks contained 64 compatible trials, 16 incompatible

trials, and 16 catch trials. Unlike compatible and incompatible trials, which had a single search target at either the left or right location, catch trials had two search targets at both locations. That is, each square had a gap on catch trials. The gaps were positioned differently: One square had a gap on the left, and the other had a gap on the right, ensuring that correct responses to the left and right targets were distinct. Participants were instructed that search targets were usually presented on one side but rarely on both sides simultaneously. In cases where participants encountered two targets before response, they were instructed to make a response based on the target they first attended to. Thirty-two new participants (mean age = 23.88, SD = 2.23, 18 women and 14 men) participated. The increased sample size was due to the small number of catch trials compared to compatible and incompatible trials, potentially requiring a larger sample to detect response-induced attention in catch trials.

6.2. Results

RT in compatible and incompatible trials. Trials with RTs shorter than 250 ms (none of trials), trials with RTs longer than 1, 250 ms (0.49 %), and trials with incorrect responses (2.93 %) were excluded from the analyses.

The overall mean RT was 641 ms, and a repeated-measures ANOVA with blocks and compatibility showed that the main effect of block was significant, $F(3, 93) = 11.71, p < .001, \eta_p^2 = 0.27$. The main effect of compatibility was significant, $F(1, 31) = 16.77, p < .001, \eta_p^2 = 0.35$, replicating the cueing effect of response-induced attention. The interaction between block and compatibility was not significant, $F(3, 93) = 2.44, p = .07, \eta_p^2 = 0.07$ (Fig. 8).

Error rate in compatible and incompatible trials. The overall mean error rate was 3.5 %. A repeated-measures ANOVA with blocks and compatibility revealed that the main effect of block was insignificant, $F(3, 93) = 0.82, p = .48, \eta_p^2 = 0.03$. The main effect of compatibility was significant, $F(1, 31) = 9.57, p = .004, \eta_p^2 = 0.24$. The interaction between block and compatibility was not significant, $F(1, 31) = 1.55, p = .21, \eta_p^2 = 0.05$ (Fig. 8).

Target selection ratio in catch trials. This measurement assessed whether participants more frequently selected (attended to) response-cued targets or response-uncued targets. The overall mean selection ratio was naturally 50 %. A repeated-measures ANOVA with blocks (4 blocks) and compatibility (selection of compatible or incompatible search targets) showed that the main effect of block was insignificant (50 % for each block). The main effect of compatibility was significant, $F(1, 31) = 22.57, p < .001, \eta_p^2 = 0.42$, indicating that participants more

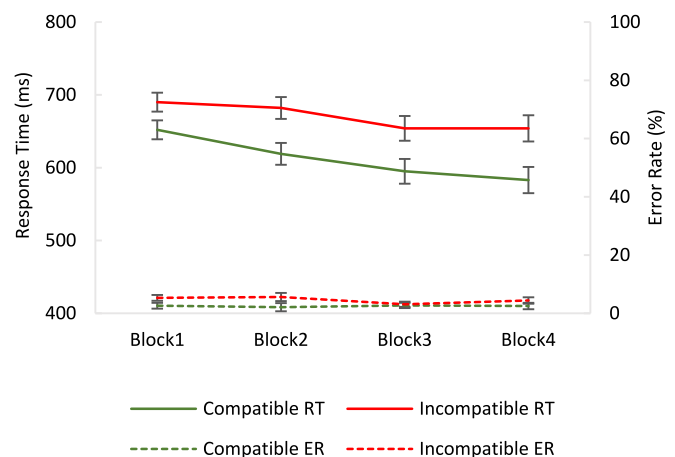


Fig. 8. Results of the compatible and incompatible trials in Experiment 4. Error bars represent 95 % confidence intervals.

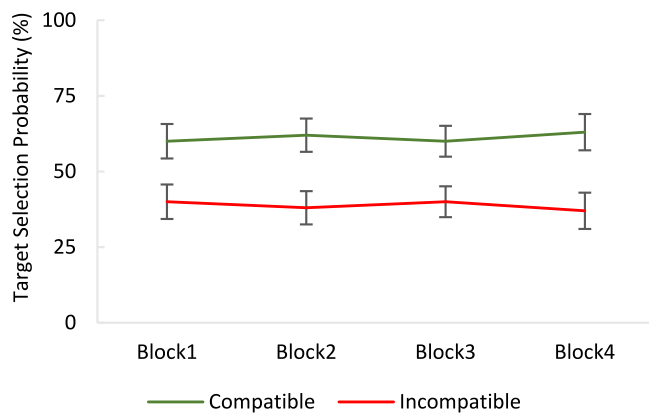


Fig. 9. Results of the catch trials in Experiment 4. Error bars represent 95 % confidence intervals.

frequently selected targets at the compatible than incompatible location. The interaction between block and compatibility was not significant, $F(3, 93) = 0.62, p = .61, \eta_p^2 = 0.02$ (Fig. 9).

Correlation analysis. The results from the cueing effect and the target selection ratio indicated attention toward response-cued locations. To further confirm this idea, a correlation analysis was conducted between the magnitude of the cueing effect (incompatible RT - compatible RT) and the selection probability of the compatible target. A strong positive correlation was found, $r(30) = 0.89, p < .001$ (Fig. 10). This finding suggests that participants with a larger cueing effect more frequently selected (attended to) targets at the compatible than incompatible location.

Post-question for awareness. Three participants reported explicitly noticing the response-stimulus regularities and exploited them to locate search targets quickly. The remaining 29 participants reported not noticing any pattern or rule other than the given instruction and following only the instructed search strategy or occasionally using strategies unrelated to the regularities, such as scanning from left to right and right to left. The 29 participants unaware of the regularities showed a significant 35-ms cueing effect in compatible and incompatible trials, $t(28) = 4.71, p < .001$, Cohen's $d = 0.87$, a significant selection bias to the compatible targets (58.10 %) compared to the incompatible targets (41.90 %) in catch trials, $t(28) = 4.64, p < .001$, Cohen's $d = 0.86$, and a significant correlation between these cueing effect and selection bias, $r(27) = 0.75, p < .001$.

6.3. Discussion

In the compatible and incompatible trials, a significant cueing effect was observed, with faster search performance for the response-cued location compared to the uncued location, replicating findings from the previous experiments. The results from the catch trials further support the interpretation that these cueing effects reflect the spatial allocation of attention toward the cued locations. Specifically, targets presented at the response-cued location were reported more frequently than those at the uncued location, indicating enhanced attention to the cued locations. Moreover, a correlation analysis revealed that participants with larger cueing effects also exhibited stronger selection biases. This finding suggests that both measures reflect a common underlying mechanism: the spatial allocation of attention to the response-cued location. Accordingly, Experiment 4 confirmed that the response-induced attention effects observed in the present Posner spatial cueing paradigm reflect spatial attention.

7. General discussion

The four experiments in this study demonstrate that responses

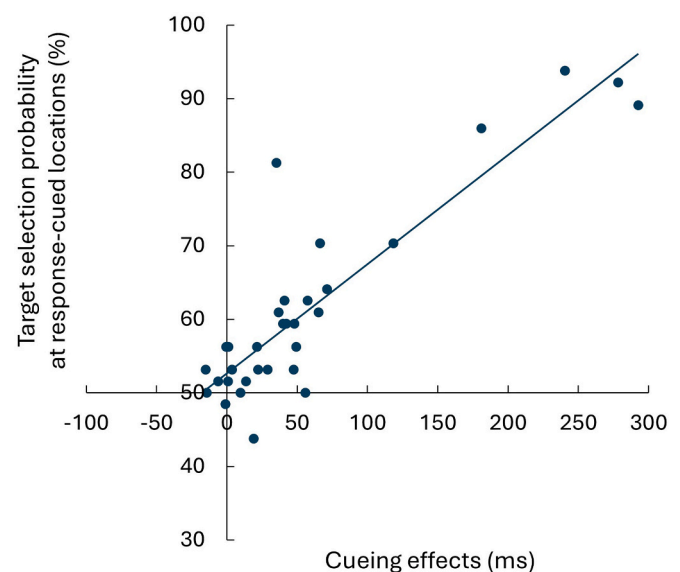


Fig. 10. A correlation between the cueing effect (uncued location RT - cued location RT) and the selection probability of the target at the cued location.

influence perception by directing attention to the locations associated with the responses. Manual responses to the identification targets predicted the more probable locations of the search targets, and these associations were incidentally encoded to guide attention efficiently. As a result, target localization improved when targets appeared at response-cued locations compared to uncued locations. This phenomenon is referred to as the response-induced attention effect.

The present study revealed that the direction of response-induced attention effects was modulated by the regularities established during the acquisition phase. Specifically, while attention was prioritized for the response-compatible locations during the learning of compatible regularities in Experiments 1 and 4, it was prioritized for the response-incompatible locations during the learning of incompatible regularities in Experiments 2 and 3. This indicates that search processes are sensitive to the regularities between observers' actions and external stimuli. Furthermore, the acquisition of response-stimulus regularities appeared to occur without explicit awareness of the regularities, consistent with the findings and ideas of the previous studies that humans incidentally and implicitly extract and learn meaningful regularities from the environment (Chun & Jiang, 1998; Friston, 2005; Rao & Ballard, 1999; Ziessler, 1998). This adaptive mechanism optimizes crucial visual processes, such as attentional deployment, thereby enhancing our ability to efficiently navigate and interact with our surroundings (Chun & Jiang, 1998). It should be noted that the awareness test used might not have been sufficiently sensitive to detect explicit learning processes (Vadillo et al., 2022). Therefore, further investigation is necessary to elucidate whether the acquisition of regularities is primarily driven by implicit learning, explicit learning, or both.

Building upon previous findings that adaptive functioning leverages stimulus-stimulus regularities to intelligently allocate limited attentional resources (Chun & Jiang, 1998), the present study provides evidence that such adaptation also applies to response-stimulus regularities. This extension holds significance in ecological contexts, as humans are active agents who physically engage with their environment rather than remaining stationary or passively reacting to it. In the attention literature, the concept of response-induced attention deviates from traditional and current attention theories, in that they typically do not consider physical actions as potential attentional factors. However, abundant evidence in the action-perception literature supports the underlying mechanisms of response-induced attention, alluding to a

significant role of motor responses in directing attention. For example, attentional orienting was found to automatically influence motor responses, as evidenced in phenomena like the Simon effect. This effect is attributed to the shared spatial representations between action and perception, enabling mutual interactions (Hommel, 2019; Prinz, 1990). The bidirectional influences between responses and attentional orienting suggest a possibility that responses can guide attention. Moreover, response-induced attention was more pronounced in compatible mappings compared to incompatible ones, consistent with the patterns observed in Simon effects. That is, the connections between action and perception are forged through long-term (compatible mappings) and short-term (compatible or incompatible mappings) associative learning processes. As a result, SRC and RSC effects are typically more prominent with compatible mappings than with incompatible ones (Bae et al., 2009; Elsner & Hommel, 2001; Hommel et al., 2016; Tagliabue et al., 2000; Tagliabue et al., 2002; Vu et al., 2003).

7.1. Contribution of response-induced attention to attention literature

In attention theories, factors guiding attention are broadly categorized into stimulus saliency, a task goal, and a selection history (Awh et al., 2012; Wolfe, 2021). The present study controlled these factors to investigate the influence of responses on the spatial distribution of attention. The stimulus saliency factor suggests that physically salient stimuli (e.g., flashing light) attract attention (Itti & Koch, 2001; Theeuwes, 1992). In the current experiments, the same object (the square with a gap) was employed as the search targets in both compatible and incompatible conditions, ensuring equal salience. The task goal factor indicates that stimuli sharing characteristics of search targets attract attention (Duncan & Humphreys, 1989; Folk et al., 1992). For example, when observers search for friends with red shirts, red stimuli attract attention. In the current experiments, participants searched for the square with a gap in both compatible and incompatible conditions, maintaining the same task goal in both conditions. The selection history factor suggests that attention is guided based on what stimuli were recently attended or how these attended stimuli were important (Anderson, 2016; Awh et al., 2012; Kim et al., 2022; Kim et al., 2023; Maljkovic & Nakayama, 1994). In the current experiments, the features (e.g., locations, colors, shapes) of search targets and distractors in previous trials were not different between the compatible and incompatible conditions. For example, color and shape of search targets and distractors were consistent between trials in both conditions. Locations of search targets were predicted by responses for the identification task on present trials (the critical manipulation of the present study) but not locations of search targets on previous trials in both conditions. Furthermore, the importance of search targets was not different between the compatible and incompatible conditions. Therefore, little difference of the selection history was expected between the conditions. By controlling these variables, the present study demonstrated that responses can guide attention.

The primary contribution of response-induced attention lies in its emphasis on the role of motor responses in attentional selection. The concept of response-induced attention challenges traditional and existing attention theories (Broadbent, 1958; Bundesen, 1990; Chun et al., 2011; Deutsch & Deutsch, 1963; Duncan & Humphreys, 1989; Itti & Koch, 2001; Kahneman, 1973; Neisser, 1967; Norman & Shallice, 1986; Pashler, 1994; Posner, 1980; Treisman, 1964; Wolfe, 2021), as they do not consider the domain of motor responses as attentional factors. Specifically, cognitive psychologists have extensively explored various factors that guide attention, considering both external stimuli from the environment and internal activities of an observer. However, the attention literature often limits the scope of internal activities to mental processes that exclude motor functions, thereby overlooking the potential role of physical activities in guiding attention. For instance, in typical behavior experiments, observers respond to stimuli by pressing keyboard buttons. These responses have mainly been used to measure

effects induced by the stimuli rather than being considered as factors that could influence attention allocation.

7.2. Brain connectivity between action and perception

While canonical models of attention primarily focus on frontoparietal networks, emerging research increasingly underscores the critical role of connections between motor and sensory brain areas in attentional processes (Corriveau et al., 2024; Jones et al., 2024; Kardan et al., 2022; O'Halloran et al., 2018; Rosenberg et al., 2016; Rosenberg et al., 2017; Rosenberg & Chun, 2020). For instance, Rosenberg et al. (2016) demonstrated that stronger connectivity between motor and sensory networks is a significant predictor of higher attentional abilities, whereas intra-network connections within either system alone did not show such predictive power. Furthermore, this finding was supported by resting-state fMRI data, where participants remained stationary in the scanner without engaging in explicit tasks, indicating that sensory-motor connectivity reflects intrinsic brain activity rather than being driven by physical movements (Rosenberg et al., 2017). While this connectivity does not directly explain the mechanisms of response-induced attention due to inherent task differences, it aligns with the core assumption of response-induced attention and ideomotor theory. The assumption posits direct and strong connections between motor and perceptual processes, enabling humans to rapidly learn action-perception regularities and efficiently allocate attention based on them.

7.3. Ecological factor

The present research is expected to contribute to the practical application of attention studies in real-world contexts. Rather than passively adapting to the natural environment, humans actively shape their surroundings for improving physical interactions between actors and environment, creating the response-stimulus regularities. Response-induced attention suggests that such patterns are internalized to allocate attention intelligently. Future research may extend response-induced attention to various and complex body movements, and this would help understand attentional mechanisms in real-world situations where we move our body in a dynamic and complex manner. Response-induced attention represents a crucial first step in elucidating the importance of the motor dimension in attention.

CRedit authorship contribution statement

Sunghyun Kim: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yang Seok Cho:** Writing – review & editing.

Declaration of competing interest

All authors have no conflicts of interest to declare.

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Data availability

I have shared the link to data

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