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Uncertainty as a determinant of attentional control settings

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Abstract

Previous studies have demonstrated that attentional capture occurs based on attentional control settings. These settings specify what features are selected for processing as well as what features are filtered out. To examine how attentional control settings are flexibly constructed when target and/or distractor features are uncertain, the current paper presents four experiments in which the numbers of target and distractor features were manipulated. The results showed that attentional control settings were configured in terms of a fixed feature when either the target or the distractor feature was uncertain and the other was fixed over trials. In addition, attention was tuned towards the specific target feature based on attentional control settings when both target and distractor features were either fixed or uncertain. The selectivity of the target or distractor feature in the attentional control setting depended on which of the target and distractor features were defined with uncertainty. These results indicate that attentional control settings are flexibly determined by given task demands, especially including the predictability of target and distractor features.

Keywords Attentional control settings · Attention capture · Spatial attention · Spatial cueing · Visual attention

Introduction

For human beings to select relevant information in environments that are overflowing with information, attention plays an important role in enhancing the processing of task-relevant information as well as screening out task-irrelevant information, based on the representations of the task goal (Desimone & Duncan, 1995). It has been suggested that visual attention is oriented both voluntarily and involuntarily (Jonides, 1981). Voluntary attentional shift or *endogenous orienting* is regarded as the top-down and goal-dependent allocation of attention. In contrast, involuntary attentional shift or *exogenous orienting* refers to the bottom-up and stimulus-driven allocation of attention. Much research has shown that an abrupt onset or salient feature attracts attention automatically, even against task goals (Jonides & Yantis, 1988; Schreij, Owens, & Theeuwes, 2008; Theeuwes, 2004).

However, there is much evidence showing that top-down attentional control overrides bottom-up salience (Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). Based on findings that only task-relevant features attract attention while salient task-irrelevant features did not, Folk et al. (1992) proposed an account known as the *contingent attentional capture*. According to this account, attentional control settings determine target-defining features and guide attention to items that contain the specified target features. In contrast, some other researchers argued that this contingent attentional capture occurs because attention is rapidly disengaged from a task-irrelevant item when the selected item does not match the target features, even though any salient stimulus can capture attention (Theeuwes, Atchley, & Kramer, 2000; Theeuwes & Godijn, 2002). Although there is a long-standing controversy regarding the stage in which attentional control settings select target-defining features, most researchers emphasize the role of attentional control settings in attentional processes, at least in some way.

Much research on attentional control settings has been conducted to examine how attention is tuned. In early studies, it was suggested that attentional control settings are configured as a function of *dynamic discontinuity* or *static discontinuity* (Folk, et al., 1992; Folk, et al., 1994). Here, discontinuity refers to changes in a local feature or luminance within a given space. When a task requires a performer to attend to the motion of a stimulus, such as an abrupt onset or apparent motion, an attentional control setting for *dynamic discontinuity* is established such that a stimulus having dynamic properties captures attention. Meanwhile, when a task has a performer

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search for a certain static property, such as color or shape, an attentional control setting for *static discontinuity* is established so that any stimulus sharing that property captures attention. However, in later studies, it was found that attentional control settings can be configured in terms of a specific value of a feature, such as the color "red." In a series of experiments, Folk and Remington (1998) showed that a red cue captured attention only when the target was defined as a red object but not when it was defined as a green object. Meanwhile, a green cue only captured attention when the target was defined as a green object but not when it was defined as a red object, regardless of whether the target was presented in the form of a singleton or it was presented with a distractor colored in another. These results indicate a narrowly tuned attentional control setting for a specified target value: the selectivity of a single feature value.

However, there is another line of research showing that attentional allocation is not solely determined in terms of target defining features, but that non-target features also influence how attentional control settings are configured. In some studies, attention was tuned towards the direction of target features from non-target features (Becker, Folk, & Remington, 2010; Schönhammer, Grubert, Kerzel, & Becker, 2016). For example, Becker et al. (2010) found that a cue more red than the target color, as well as the target color cue, captured attention when participants were asked to search for an orange target among yellow-orange non-targets, whereas a cue more yellow than the target color, as well as the target color, captured attention when they were asked to search for a yellow-orange color target among orange color non-targets. According to Becker et al., these results were due to relation-based attentional control settings. Conversely, attentional control settings have been found to be constructed in a way so to inhibit a salient non-target item (Anderson & Folk, 2012; Theeuwes & Burger, 1988). For example, when a target letter was presented in one of two colors on some trials and a no-go colored letter was presented on the other trials, the cue validity effect was observed for the target colors but not for the no-go color. Anderson and Folk (2012) insisted that a location-specific inhibitory set was made to suppress the no-go feature for selecting go features when the color of the go target was uncertain.

Although those studies showed that attentional control settings were configured differently according to given task demands, it is still unclear how attentional control settings are flexibly formed for the facilitation and/or inhibition of certain features. In Anderson and Folk's (2012) Experiment 6, the no-go color cue showed a negative cue validity effect, implying the inhibition of attentional allocation, while the target color cue showed a positive cue validity effect. However, one might propose the alternative explanation that attention is always guided to enhance the processing of task-relevant features rather than to suppress the processing of task-irrelevant features (e.g., Irons, Folk, & Remington, 2012). Irons et al. argued that unpredictable target features are enhanced through multiple attentional control settings, like a top-down control setting for a single feature (Wolfe, 1994, 2007), rather than an inhibitory attentional control setting towards a non-target feature. Thus, to re-examine whether multiple target features are maintained in attentional control settings or whether non-target features, such as distractor features, can play a role as a reference point for the inhibition of attention, in this study the uncertainties of the target and distractor features were manipulated and cue validity effects were observed as an index of attention capture.

In the present study, a spatial cueing paradigm, in which the target was defined in terms of color(s), was used. Before the onset of the target display, a non-informative color spatial cue was presented at one of four possible target locations. The allocation of attention was measured with the cue validity effect. If a color cue captures attention, the response to the target would be faster when it is presented at the cued location (valid) than at an uncued location (invalid). The cue was inked in one of the target, distractor, and neutral colors. It is important to note that the neutral color was unrelated to either target or distractor, which enabled us to see how attentional control settings were formed in a given task situation. If the attentional control setting is specified in terms of the target color, the neutral cue would elicit either a no cue validity effect or a negative cue validity effect in a given situation because the attentional control setting successfully ignores or suppresses everything other than the target color and activates only the target color. However, if the attentional control setting is specified in terms other than the target color, such as a distractor color, the neutral color cue would elicit a positive cue validity effect because the attentional control settings failed to select the target color separately from the neutral color.

The task situation was manipulated by varying the number of distractor colors or the number of target colors. Experiments 1 and 2 examined the specification of the target color value in the attentional control setting when the number of possible distractor features was one or two. Theeuwes and Burger (1998) suggested that the target value is specified in attentional control settings only when both target and distractor values are certain. Accordingly, the existence of distractor uncertainty may interrupt the specification of the target value in the attentional control setting. Moreover, the experiments also intended to test whether the attentional control setting could be formed to selectively ignore the given values of distractors when it was fixed or uncertain. Thus, the target color was certain across trials, but the presence of distractor uncertainty was added in Experiment 2, while the distractor color was fixed over all trials in Experiment 1. Experiment 3 was conducted to observe how target uncertainty affects how attentional control settings are configured. The target was defined as a blue or yellow letter and the distractor was defined as a red letter. It is important to note that the task environment was similar to Irons et al.'s (2012) Experiments 2 and 3, with the exception of the presence of a neutral color cue (green), and enabled us to see how attentional control settings may selectively specify multiple target values even in the presence of target uncertainty. Experiment 4 examined the specificity of attentional control settings in the existence of both target and distractor uncertainties, which is similar to Irons et al.'s Experiment 5, which showed no cue validity effect with the neutral color cue when both target and distractor features were uncertain.

Experiment 1

The goal of Experiment 1 was to examine how attentional control settings are configured when the features of the target and distractor are certain. Under this task context, attentional control settings are possibly determined in terms of the target feature, distractor feature, or both features. To examine these possibilities, participants were asked to perform an exogenous cueing task in which the target letter was always presented in blue and the distractor letter was presented in red simultaneously in a search display. A non-informative spatial cue, which was presented at one of the four possible target locations before the onset of the search display, was inked in the target color (blue), distractor color (red), or neutral color (green) to investigate the specificity of the attentional control settings by examining the patterns of the cue validity effects by these color cues.

If attentional control settings are determined in terms of the target feature, only the target color cue would capture attention, resulting in a cue validity effect, and the other cues would be ignored regardless of whether they were inked in either a distractor or a neutral color, as Folk and Anderson (2010) suggested. However, because the distractor color was also fixed over trials as the target color, it is possible that the attentional control settings include distractor features as well as target features, as Theeuwes and Burger (1998) suggested. Thus, if attentional control settings are determined in terms of the target and distractor features, a cue validity effect would be evident with the target color cue, but a negative cue validity effect would be present with the distractor color cue because it had to be suppressed, while the neutral color cue would show no cue validity effect.

Method

Participants Sixteen undergraduate students at Korea University participated in exchange for KRW 5,000 (approximately US$4). All participants had normal or corrected-to-normal visual acuity and color vision by self-report and were familiar with English alphabets. The current and following experiments were approved by the Institutional Review Board at Korea University (KU-IRB-16-138-A-1).

Apparatus A 17-in. CRT monitor was used to present visual stimuli with an approximately 60-cm viewing distance. The experiment was programmed and controlled by MATLAB (The Mathworks, Inc., Natick, MA, USA) via Psychtoolbox (Brainard, 1997; Pelli, 1997a, 1997b). Responses were collected using a standard keyboard.

Stimuli A fixation display, a cue display, and a target display were presented in each trial (Fig. 1). The fixation display consisted of a white fixation cross (RGB: 255, 255, 255; CIE color coordinates: x = .27, y = .30) located in the center of the display and four white placeholders (RGB: 100, 100, 100; CIE color coordinates: x = .28, y = .30) positioned diagonally in a black background. The placeholders (2.39° × 2.39°) were located at the top left, top right, bottom left, and bottom right 7.66° from the fixation cross. The cue display consisted of four sets of four circles (1.4° in diameter) surrounding each placeholder in a diamond array. A set of the circles colored in red (RGB: 255, 0, 0; CIE color coordinates: x = .58, y = .35), green (RGB: 0, 255, 0; CIE color coordinates: x = .28, y = .60), or blue (RGB: 0, 0, 255; CIE color coordinates: x = .15, y = .08) was presented in one of the placeholders as a color cue and the other sets of circles was colored in white (RGB: 255, 255, 255; CIE color coordinates: x = .27, y = .30). The target display was same as the fixation display, except that each placeholder contained the alphabet letter T or L. The blue-colored letter (RGB: 0, 0, 255; CIE color coordinates: x = .15, y = .08) appearing inside one of the four placeholders was the target to respond to and the red-colored letter (RGB: 255, 0, 0; CIE color coordinates: x = .58, y = .35) appearing inside one of the remaining three placeholders was the distractor to ignore. Each of the two remaining placeholders contained a white letter (RGB: 255, 255, 255; CIE color coordinates: x = .27, y = .30).

Procedure Participants performed the experiment individually in a dimly lit, sound-attenuated chamber. A trial began with the fixation display for 1,000 ms, 1,100 ms, 1,200 ms, 1,300 ms, or 1,400 ms, and participants were asked to stare at the fixation cross. The cue display then appeared for 50 ms, followed by another fixation display for 100 ms. Participants were informed that the location of the color cue would not provide any information about the upcoming target location and they were told to ignore this cue. After the fixation display, the target display was presented for 120 ms and again followed by a fixation display, which remained until a response was made.

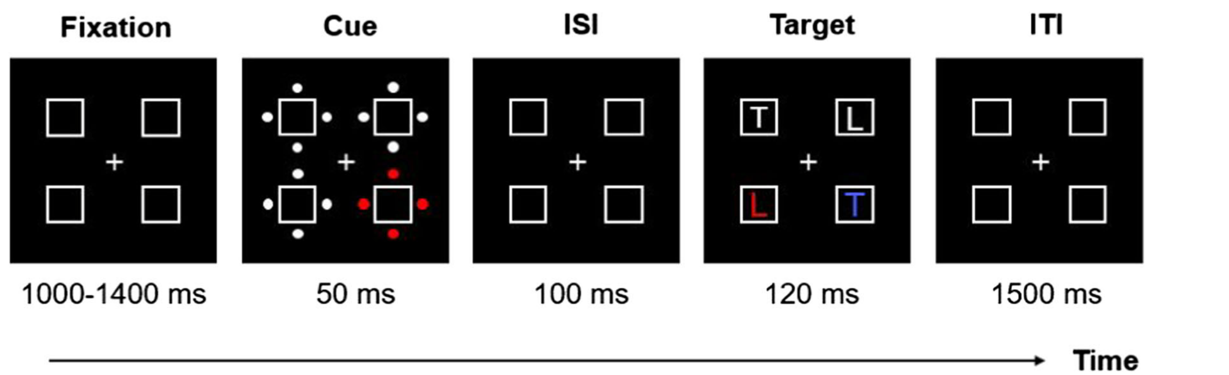

Fig. 1 Example of a trial sequence in Experiment 1. Cue display contained either target color, distractor color, or neutral color cue. Target display contained target and distractor simultaneously. *ISI* interstimulus interval, *ITI* inter-trial interval

Participants were instructed to respond to the blue target letter by pressing the "f" key on the standard keyboard with their left index finger when the target letter was T or the "j" key with their right index finger when the target letter was L. They were asked to make a response as rapidly and accurately as possible. A feedback beep-tone was presented for 150 ms if the response was incorrect, or if no response was made within 1,500 ms. The fixation display for the next trial appeared 1,000 ms after the correct response or error feedback.

Before data were collected, 16 practice trials, which were randomly chosen from all trial types, were completed. If errors occurred over 75% of the practice trials, another set of 16 practice trials was conducted again. A total of 1,152 test trials, which were divided into three 384-trial blocks with a 1-min rest period between them, were completed. Within each block, both the color cue and the target appeared equally often at all locations. For each cue-target pairing, the target was presented at the cued location on 25% of the trials (valid) and at one of the uncued locations on 75% of the trials (invalid). The two target letters, T and L, were shown equally as often. On each trial, two "T"s and two "L"s were presented in the target display. Thus, this experimental design generated 288 trials of three different cue colors (red, green, and blue) × four cue locations (top left, top right, bottom left, and bottom right) × four target locations (top left, top right, bottom left, and bottom right) × three distractor locations (other three locations except for the target location) × two target identities (T and L).

Results

Response times (RTs) of less than 200 ms and more than 1,000 ms were excluded from analyses as outliers (4.21%). Mean correct RTs and percentage of errors (PEs) were calculated for each participant as a function of cue color (red, green, or blue) and validity (valid or invalid). Repeated measures analyses of variance (ANOVAs) were conducted on the mean correct RT and PE data, with those variables as within-subject factors.

Response time The main effect of validity was significant, $F(1, 15) = 13.68$, $p = .0021$, $MSe = 282$, $\eta_p^2 = .477$. The mean RT was shorter when the target letter was presented at the cued location ($M = 384$ ms) than at an uncued location ($M = 396$ ms). The main effect of cue color was not significant, $F(2, 30) = 1.3$, $p = .2884$. The interaction between validity and cue color was significant, $F(2, 30) = 91.5$, $p < .0001$, $MSe = 124$, $\eta_p^2 = .8592$ (see Fig. 2). The cue validity effect was greater for the target color cue (56 ms), $F(1, 15) = 92.22$, $p < .0001$, $MSe = 273$, $\eta_p^2 = .8601$, than for the neutral color cue (-9 ms), $F(1, 15) = 3.04$, $p = .1019$, and the distractor color cue (-10 ms), $F(1, 15) = 13.16$, $p = .0025$, $MSe = 53$, $\eta_p^2 = .4674$, which induced a negative cue validity effect. Separate analyses showed that the magnitude of the cue validity effect was significantly different between the neutral and target color cues, $F(1, 15) = 134.58$, $p < .0001$, $MSe = 125$, $\eta_p^2 = .8997$, but not between the neutral and distractor color cues, $F(1, 15) < 1$.

Percentage of errors Neither the main effect of validity, $F(1, 15) < 1$, nor the interaction of validity with cue color, $F(2, 30) < 1$, was significant. However, the main effect of cue color was significant, $F(2, 30) = 3.97$, $p = .0296$, $MSe = 4$, $\eta_p^2 = .2092$. The mean PE was higher for the target color cue (5.11%) than for the neutral color (4.10%) and distractor color cues (3.66%).

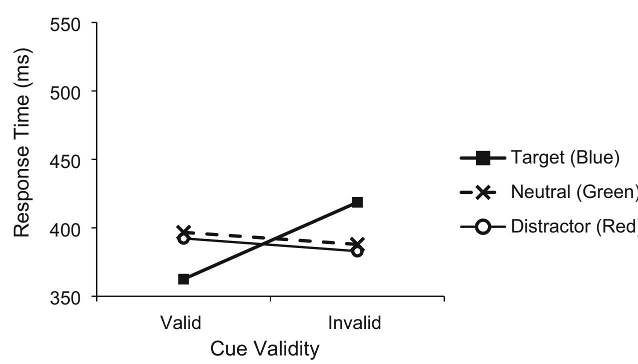

Fig. 2 Mean response time as a function of cue color and validity in Experiment 1

Discussion

In Experiment 1, in which the colors of the target and the distractor were fixed throughout the experiment, the mean RT was shorter for the target letter at the cued location than at an uncued location when the target color cue was presented, indicating a 56-ms cue validity effect, which was significantly greater than the magnitude of the cue validity effect for the neutral color cue. In contrast, a negative cue validity effect was obtained when the distractor or neutral color cue was presented. Although this negative cue validity effect suggests the possibility of the use of an inhibitory attentional set, the magnitudes of the cue validity effects for distractor (-10 ms) and neutral color cues (-9 ms) did not statistically differ, indicating that attentional control settings classified the distractor and neutral colors identically. Thus, these results suggest that the distractor and neutral colors were specified identically in the attentional control setting such that only the region occupied by the target color was selected and the regions occupied by others than the target color were inhibited. That is, the attentional control setting was specifically determined in terms of the target color when the target color was certain, as Folk and Anderson (2010) suggested. However, it is still unclear whether the attentional control settings are always determined in terms of the target feature regardless of task context. Thus, in Experiments 2 and 3, the uncertainty of either target or distractor features was manipulated.

Experiment 2

Experiment 2 examined how attentional control settings are configured when the target feature is fixed over trials but the distractor feature is uncertain. As in Experiment 1, participants were asked to respond to the identity of the letter colored in blue color, but to ignore a distractor that was colored either in red or yellow. The color cue was inked in the target color (blue), one of distractor colors (red and yellow), or neutral color (green). As mentioned above, Theeuwes and Burger (1998) argued that attentional control settings successfully select target features and filter out distractor features only when both features are fixed throughout an experiment. However, when either target features or distractor features are unpredictable, attentional control settings fail to filter out task-irrelevant features. If attentional control settings are determined in terms of fixed single target and distractor features, as Theeuwes and Burger suggested, the neutral and distractor color cues, as well as the target color cue, would capture attention because distractor features are unpredictable. Alternatively, it is possible to classify objects into target and others so that objects having features other than the target features are treated as a group of features to ignore in the attentional control setting, implying contingent attentional capture. If so, a significant cue validity effect would be observed only with the target color cue while no effect with the distractor and neutral color cues.

Method

Participants Sixteen undergraduate students from the same participant pool but who had not participated in Experiment 1 took part in Experiment 2.

Apparatus and stimuli

Apparatus and stimuli were identical to those of Experiment 1 with the following exceptions. The number of distractor colors was two, so that its color on each trial was either red, as in Experiment 1, or yellow (RGB: 255, 255, 0; CIE color coordinates: x = .39, y = .51). The color of the cue on each trial was red, green, blue, or yellow. The other stimuli were identical to those of Experiment 1.

Design and procedure

A total of 1,152 trials divided into three 384-trial blocks were completed. The experimental design consisted of four cue colors (red, green, blue, and yellow), four cue locations, four target locations, two distractor colors (red and yellow), two target letters, and three distractor locations. In Experiment 2, the distractor, which was inked in either red or yellow, was presented with the target letter inked in blue in the target display. Participants were asked to ignore the yellow or red distractor. The remaining procedure was identical to that of Experiment 1.

Results

RT and PE data were trimmed using the same criteria used in Experiment 1, resulting in the exclusion of 4.08% of all trials. Mean correct RTs and PEs were calculated for each participant as a function of cue color (red, green, blue, or yellow) and validity (valid or invalid). Repeated ANOVAs were conducted on the mean correct RT and PE data with those variables as within-subject factors.

Response time The main effect of validity was significant, $F(1, 15) = 4.82$, $p = .0443$, $MSe = 119$, $\eta_p^2 = .2432$. The mean RT was shorter when the target letter was presented at the cued location (M = 396 ms) than at an uncued location (M = 401 ms). Additionally, the main effect of cue color was significant, $F(3, 45) = 5.94$, $p = .0017$, $MSe = 101$, $\eta_p^2 = .2837$ (see Fig. 3). The mean RT was greater when the cue color was blue (M = 404) and green (M = 400 ms) than when it was yellow (M = 394 ms) and red (M = 382 ms). A significant interaction of

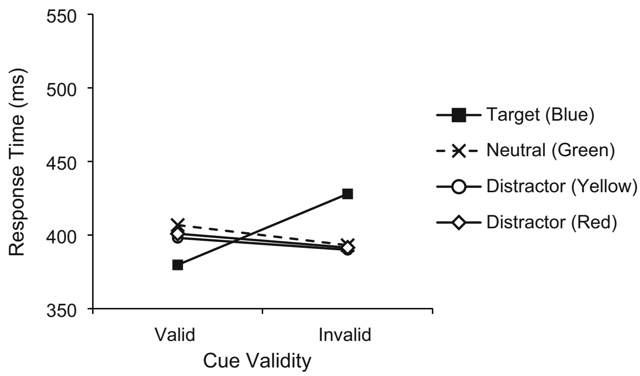

Fig. 3 Mean response time as a function of cue color and validity in Experiment 2

validity and cue color was obtained, $F(3, 45) = 74.25$, $p < .0001$, $MSe = 93$, $\eta_p^2 = .8319$. A significant 48-ms cue validity effect was obtained when the cue color was blue, $F(1, 15) = 167.97$, $p < .0001$, $MSe = 111$, $\eta_p^2 = .918$, which was the target color. However, a negative cue validity effect was obtained when the cue color was green (-14 ms), $F(1, 15) = 11.69$, $p = .0038$, $MSe = 128$, $\eta_p^2 = .4381$, which was the neutral color, yellow (-8 ms), $F(1, 15) = 6.07$, $p = .0263$, $MSe = 87$, $\eta_p^2 = .2881$, and red (-9 ms), $F(1, 15) = 9.76$, $p = .007$, $MSe = 73$, $\eta_p^2 = .3941$, which were the distractor colors. Separate analyses showed that the magnitude of the cue validity effect was significantly different between the neutral color cue and the target color cue, $F(1, 15) = 97.27$, $p < .0001$, $MSe = 178$, $\eta_p^2 = .8664$, but not between the neutral color cue and the neutral color cue, $F(2, 30) = 1.05$, $p = .3637$, $MSe = 66$.

Percentage of errors The main effect of validity, $F(1, 15) = 3.21$, $p = .0932$, or cue color, $F(3, 45) = 1.49$, $p = .231$, was significant. The interaction of validity with cue color was not significant, $F(3, 45) = 1.11$, $p = .3544$.

Discussion

In contrast to Theeuwes and Burger's (1998) idea, even with the uncertainty of distractor color, the target color cue produced a significant cue validity effect (48 ms), whereas a significant negative cue validity effect was obtained when any one of the distractor color cues (-14 ms) or the neutral color cue was presented (-9 ms). The significant negative cue validity effect with the distractor color cue was possibly due to an independent inhibitory attentional set. If so, however, this inhibitory set should have classified the distractor color separately from the neutral color. These results suggest that the attentional control setting successfully filtered out the regions occupied by colors other than the target color. As in Experiment 1, the neutral color was categorized as one of the distractor colors in the attentional control setting. That is, when the target feature was fixed over trials but the distractor features were uncertain, the attentional control settings were adopted for the activation of the fixed target value and the inhibition of the remaining values.

Experiment 3

The results of Experiments 1 and 2 indicated that when the target feature is fixed over trials, the attentional control setting is configured in a way to activate it while suppressing or ignoring the others. If the number of possible target-defining features is more than one, however, it is difficult to specify these multiple features in the attentional control setting. Folk and Anderson (2010) demonstrated that significant cue validity effects were obtained with all color cues, including the target color cue, when target uncertainty existed. These results imply that the attentional control setting for a color singleton, rather than only for the target features, was adopted. In contrast, when multiple target colors and a single distractor color were used in Irons et al.'s (2012) Experiments 2 and 3, only the target color cue captured attention, supporting the availability of multiple attention control settings. However, the findings were not conclusive enough to confirm that multiple attentional control settings were formed in terms of target features because they examined the cue validity effects only with target and distractor color cues and not with a neutral color cue. There is a possibility that an attentional control setting was established to specify features to ignore rather than those attended to. Experiment 3 examined how an attentional control setting is formed when the target values are uncertain but the distractor value is fixed by using a neutral color cue, as well as the target and distractor color cues. The target was defined as a yellow or blue letter and the distractor was a red letter. An uninformative cue was presented in a target color (blue, yellow), distractor color (red), or neutral color (green).

If attentional control settings selectively specify the target features, as found in Experiments 1 and 2, and as suggested by Iron et al. (2012), the target color cue would elicit a cue validity effect, but the neutral color cue, as well as the distractor color cue, would not. However, if attentional control settings are determined in terms of any fixed feature, rather than the varied target features, such as ignoring the distractor feature and attending to the other features, a positive cue validity effect would be obtained for the neutral color cue, as well as the target color cues, and a negative or no effect for the distractor color cue.

Method

Participants A newly recruited group of 16 undergraduate students from the same participant pool as that in the previous experiments participated.

Apparatus and stimuli Apparatus and stimuli were identical to those of Experiment 2 with the following exceptions. The color of the target on each trial was either blue or yellow (RGB: 255, 255, 0; CIE color coordinates: x = .39, y = .51) and the color of the distractor was always red. As in Experiment 2, the color of the cue on each trial was red, green, blue, or yellow.

Design and procedure In total, 768 trials equally divided into three 256-trial blocks were completed. There were four cue colors (red, green, blue, and yellow), four cue locations, four target locations, two target colors (blue and yellow), two target letters, and three distractor locations. In Experiment 3, participants were asked to respond to the target letter inked in yellow or blue, which was presented with a red distractor letter and two white letters in the target display. The remaining procedure was identical to that of Experiment 1.

Results

Based on the same exclusion criteria used in the previous experiments, 7.38% of the trials were excluded from the analyses. Mean correct RTs and PEs were calculated for each participant as a function of cue color (red, green, blue, or yellow) and validity (valid or invalid). Repeated measures ANOVAs were conducted on the mean RT and PE data, with those variables as within-subject factors.

Response time A 22-ms significant cue validity effect was obtained, $F(1, 15) = 38.05, p < .0001, MSe = 413, \eta_p^2 = .7173$. The main effect of cue color was also significant, $F(3, 45) = 6.89$, $p = .0006$. $MSe = 317$, $\eta_p^2 = .3148$. The mean RT was shorter when the red cue ($M = 474$ ms) was presented than the blue cue ($M = 477$ ms), the yellow cue ($M = 489$ ms), and the green cue ($M = 490$ ms). The interaction of validity and cue color was significant, $F(3, 45) = 9.37, p < .0001, MSe = 182$, $\eta_p^2 = .3844$ (see Fig. 4). Importantly, a significant cue validity effect was obtained not only when the cue color was blue (35 ms), $F(1, 15) = 25.89, p = .0001, MSe = 370, \eta_p^2 = .6332$, and yellow (35 ms), $F(1, 15) = 47.35, p < .0001, MSe = 203, \eta_p^2 = .7594$, which were the target colors, but also when it was green (12 ms), .$F(1, 15) = 11.86, p = .0036, MSe = 104, \eta_p^2 = .4415$, which was the neutral color. However, no cue validity effect was obtained when it was red (7 ms), $F(1, 15) = 1.36, p = .2615$, which was the distractor color. Separate analyses showed that the magnitude of the cue validity effect with the neutral color cue was significantly different from that with the target color cues, $F(2, 30) = 7.63, p = .0021, MSe = 172, \eta_p^2 = .3372$, while it was not from that with the distractor color cue, $F(1, 15) = 1.11, p = .3087, MSe = 206$.

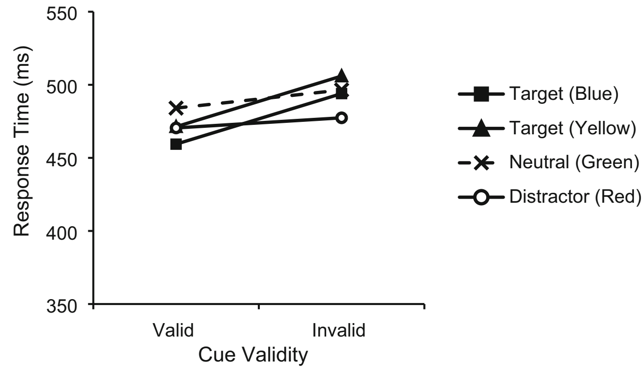

Fig. 4 Mean response time as a function of cue color and validity in Experiment 3

Percentage of errors Neither the main effect of validity, $F(1, 15) < 1$, nor the main effect of cue color, $F(3, 45) = 2.29$, $p = .0914$, was significant. The interaction of validity and cue colors was also not significant, $F(3, 45) = 1.25$, $p = .3025$.

Discussion

Unlike the previous experiments, in which the target feature was fixed over trials, a significant positive cue validity effect was obtained when the neutral color cue (12 ms), as well as the target color cue (35 ms), was presented. However, the distractor color cue did not yield a significant cue validity effect (7 ms). These results imply that the attentional control settings were specified in a way to ignore the distractor features and to attend to other features when the target defining feature was uncertain but the distractor feature was certain. This is inconsistent with the idea that attentional control settings always specify only task-relevant target features regardless of task demands. However, the magnitudes of the cue validity effect of the target and neutral color cues were significantly different, but those of the distractor and neutral color cues were not, implying that the attentional control setting was not fixed throughout the tasks. The larger cue validity effect for the target color cues than found for the neutral color cue suggests that the target features or color singleton features were contained in the attentional control settings in some occasions, possibly because of the task instruction described in terms of the target colors, which is partly consistent with Irons et al.'s (2012) idea that multiple target colors can be simultaneously specified in an attentional control setting.

Experiment 4

The previous experiments reported here showed that attentional control settings specified the target-defining feature when it was fixed across trials. However, when the target-defining feature was uncertain but the distractor feature was fixed over trials, they could specify features other than the target features, including the distractor-defining feature to ignore, resulting in a significant cue validity effect with the neutral color cue. Thus, the purpose of Experiment 4 was to examine how attentional control settings are configured when both target and distractor features are uncertain. In Experiment 4, the possible target colors were blue and red, and the possible distractor colors were yellow and purple. A non-informative cue presented before the onset of the target display was inked in one of the target (blue, red), distractor (yellow, purple), or neutral (green) colors. In Irons et al.'s (2012) Experiment 5, in which target and distractor colors were uncertain, they found significant cue validity effect with the target color cue but no cue validity effect with the neutral color cue, suggesting multiple attentional control settings for both target colors. Thus, if attentional control settings specify only the target colors preferentially, as suggested by Irons et al., no cue validity effect would occur when the neutral color cue was presented. However, if the attentional control settings specify the features of distractors to ignore (as in Experiment 3), a positive cue validity effect would be obtained when the neutral color cue or one of the target color cues was presented. Lastly, if participants fail to construct attentional control settings because there is no fixed feature, all color cues would show positive cue validity effects.

Method

Participants Sixteen newly recruited undergraduate students from the same participant pool as in the previous experiments participated.

Apparatus and stimuli The same apparatus as used in the previous experiments was used. The stimuli were identical to those of Experiment 3 with the following exceptions. The number of the target colors was two, blue and red, and the number of the distractor colors was also two, yellow and purple, (RGB: 255, 0, 255; CIE color coordinates: x = .26, y = .15). The color of the cue on each trial was red, green, blue, yellow, or purple.

Design and procedure A total of 640 trials divided into two 320-trial blocks were completed. The experiment consisted of five cue colors (red, green, blue, yellow, and purple), four cue locations, four target locations, distractor colors (yellow and purple), and two target colors (blue and red). The location of the distractor was randomly distributed across trials. Participants were asked to respond to the blue or red target letter, and to ignore the purple or yellow distractor letter presented in each target display. The remaining procedure was identical to that of Experiment 3.

Results

With the same exclusion criteria as in the previous experiments, 6.43% of the trials were excluded from the analyses. RTs and PEs were calculated for each participant as a function of cue color (red, green, blue, yellow, or purple) and validity (valid or invalid). Repeated measures ANOVAs were conducted on the mean RT and PE data with those variables as within-subject factors.

Response time The main effect of validity was significant, $F(1, 15) = 13.01$, $p = .0026$, $MSe = 800$, $\eta_p^2 = .4645$. The mean RT of valid trials ($M = 464$ ms) was shorter than that of invalid trials ($M = 480$ ms). The main effect of cue color was also significant, $F(4, 60) = 12.94$, $p < .0001$, $MSe = 311$, $\eta_p^2 = .4631$. The mean RT was greater when the cue color was red ($M = 485$ ms) or blue ($M = 484$ ms) than when it was yellow ($M = 465$ ms), purple ($M = 463$ ms) or green ($M = 464$ ms). The interaction of validity and cue color was significant, $F(4, 60) = 16.74$, $p < .0001$, $MSe = 285$, $\eta_p^2 = .5274$ (see Fig. 5). No cue validity effect was observed when the cue color was green (1 ms), $F(1, 15) < 1$, which was the neutral color, yellow (6 ms), $F(1, 15) = 1$, $p = .3143$, and purple (-10 ms), $F(1, 15) = 2.26$, $p = .1531$, which were the distractor colors. In contrast, significant 48-ms and 35-ms cue validity effects were obtained when it was blue, $F(1, 15) = 51.22$, $p < .0001$, $MSe = 359$, $\eta_p^2 = .7735$, and red, $F(1, 15) = 13.52$, $p = .0022$, $MSe = 744$, $\eta_p^2 = .4741$, which were the target colors. Separate analyses showed that the cue validity effect for the neutral color cue was significantly different from the effect for the target color cue, $F(2, 30) = 15.82$, $p < .0001$, $MSe = 296$, $\eta_p^2 = .5133$, but not significantly different from the effect for the distractor color cue, $F(2, 30) = 2.06$, $p = .1449$, $MSe = 251$.

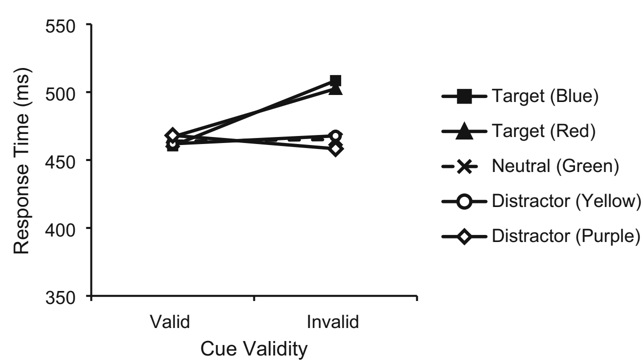

Fig. 5 Mean response time as a function of cue color and validity in Experiment 4

Percentage of errors The main effect of validity, $F(1, 15) < 1$, cue color, $F(4, 60) = 2.25$, $p = .0746$, and the interaction of validity and cue colors, $F(4, 60) = 2.07$, $p = .0955$, were not significant.

Discussion

As in Experiment 3, a significant cue validity effect was obtained when one of the target color cues was presented (48 and 35 ms). Unlike the results of Experiment 3, however, the neutral color cue showed no cue validity effect (1 ms) as found for the other distractor color cues (6 and -10 ms). Moreover, the magnitude of the cue validity effect for the neutral color cue was significantly different from that for the target color cue but not from that for the distractor color cues. These results imply that the attentional control setting specified that only the target features should be attended to preferentially when both target and distractor features were uncertain in the task environment. This is consistent with Irons et al.'s (2012) argument, which suggested that it is possible to maintain multiple target features in an attentional control setting. If the attentional control setting specified the distractor features, the neutral color cue, as well as the target color cue, should have elicited a significant cue validity effect. The results of this experiment reflect that certainty of target or distractor features is not required in the specification of the target value in attentional control settings.

Meanwhile, unlike the results of Experiments 1 and 2, in which the target feature was fixed across trials, no significant negative cue validity effect was obtained with the neutral and distractor color cues, consistent with the results obtained when the target features were not fixed across trials (e.g., Grubert & Eimer, 2016; Irons et al., 2012). For example, Irons et al. showed that the distractor color cues showed no cue validity effect when the target and distractor features were unpredictably varied across trials. These results suggest that features other than the target features are just ignored when multiple attentional control settings are adopted for multiple target colors.

General discussion

In the present study, different patterns of the cue validity effect were obtained with the neutral color cue according to the uncertainties of the target and distractor features. These results are consistent with the idea that visual selection is optimized to perform the task goal efficiently (Becker, Harris, Venini, & Retell, 2014). The attentional control settings in any circumstance should lead to effective performance with an optimal use of working memory capacity (Desimon & Duncan, 1995). To guide visual attention to a task-relevant object or location in a given circumstance, targets can be defined in different modes in attentional control settings. Irons and Leber (2016) suggested that attentional control settings are optimally configured to maximize task performance with minimal effort. Thus, when the target, which has a distinct feature, is presented with other items having a homogenous single feature, a singleton search mode is adopted to minimize effort with a low task performance cost because it requires less effort than feature search modes. For example, when no color singleton distractor was presented, all color cues were found to capture attention, indicating a singleton search mode (e.g., Bacon & Egeth, 1994; Harris, Becker, & Remington, 2015).

However, when the target, which has its defining feature fixed over trials, is presented with other items having heterogeneous different features, a feature search mode is adopted because a singleton search mode impairs the speed and accuracy of task performance, so that only objects having the target-defining features can capture attention. Accordingly, when the target, which was defined as a color, was presented with a distractor singleton, only the color target cue was found to capture attention but other color cues were not, indicating a feature search mode (e.g., Folk & Anderson, 2010; Folk & Remington, 1998). In Experiments 1 and 2 reported here, when the target feature was constant across trials, the cues colored in anything other than the target color, including the neutral color cue, did not show a positive cue validity effect. This indicates that the control setting successfully filtered out any colors other than the target-defining colors. Moreover, unlike Theeuwes and Burger's (1998) argument that the target-defining features are specified only when the target and distractor features are certain, attentional control settings were tuned towards the target feature regardless of the uncertainty of distractor features when the target feature was constant across trials. Establishing attentional control settings in terms of the target feature is the most efficient way to select the target for fast and accurate search and with minimal effort when the target, of which its feature is constant across trials, is presented with a singleton distractor.

Meanwhile, it has been demonstrated that attentional control settings can be tuned for multiple target features, especially multiple colors, simultaneously (e.g., Adamo, Pun, Pratt, & Ferber, 2008; Cho & Cho, 2018; Grubert & Eimer, 2015a, b; Irons et al., 2012; Moore & Weissman, 2010; Worschech & Ansorge, 2012). For example, in Irons et al.'s experiments, in which a red or green target was presented unpredictably, the target color cues showed cue validity effects but the distractor color cue, which was blue, did not. According to Iron et al., because attentional control settings were established for the two target colors simultaneously, only cues sharing either one of them showed a cue validity effect. Consistent with this result, in Experiment 4 of the present study, in which the target inked in one of two different colors was presented unpredictably with a distractor colored in one of other two different colors, the neutral cue, as well as the distractor color cues, showed no cue validity effect. In contrast, the target color cues did result in a cue validity effect. These findings suggest that attentional control settings were configured on the basis of the two target colors. When the colors of both target and distractor are uncertain, it may be effective for the attentional control settings to be established to attend selectively to the target color and to ignore all other colors, rather than to specify all the presented colors.

Consistent with the multiple attentional control setting account, Irons et al. (2012) found that significant cue validity effects were obtained with the target color cues but not with the distractor color cue when the target-defining feature was uncertain but the distractor feature was fixed over trials. Similarly, Anderson and Folk (2012) found that the go color cues elicited a cue validity effect but the no-go color cue did not when the color of the go target varied unpredictably across trials but that of the no-go target was certain. Interestingly, although previous studies emphasized the specificity or selectivity for the target features relevant to a task goal (e.g., Adamo, Wozny, Pratt, & Ferber, 2010; Irons et al., 2012), the specificity for the target-defining features in the attentional control setting was not obtained in Experiment 3 of the present study. As in Irons et al.'s experiments, when the color of the target varied unpredictably across trials but the distractor-defining feature was constant throughout the task, the neutral color cue, as well as the target color cues, elicited a significant cue validity effect, indicating that the attentional control setting failed to filter out the neutral color. This result implies that the attentional control setting was configured to specify the specific distractor color to be ignored and the other colors to be selected.

Even though attentional control settings for multiple target colors can be maintained simultaneously, it has been suggested that search performance based on multiple attentional control settings is impaired (e.g., Biderman, Biderman, Zivony, & Lamy, 2017; Dombrowe, Donk, & Olivers, 2011; Meneer, Cave, & Donnelly, 2009). For example, in Dombrowe et al.'s experiment, in which participants were to search for two targets presented in a target display simultaneously, target search accuracy was lower when the two targets were defined by different colors than when they were defined by a single color. This impairment is possibly due to the difficulty in maintaining multiple attentional control settings in working memory simultaneously (e.g., Biderman et al., 2017; Harris et al., 2015) or less computational efficiency when multiple attentional control settings are established than when a single attentional setting adopted (Harris et al., 2015). Thus, if the attentional control setting specifies values to ignore and other values to select when the target is defined with multiple colors and the distractor feature is certain, it is possible to maximize search performance with minimal effort. However, it is important to note that the finding of a significantly greater cue validity effect with the target color cues than with the neutral color cue and no difference between the distractor and neutral color cues in the magnitude of the cue validity effect, even though a significant cue validity effect was obtained with the neutral color cue but not with the distractor color cues, in Experiment 3 indicates that the attentional control setting specified multiple target features or color singletons in some occasions.

Importantly, multiple target colors appeared to be specified in attentional control settings even when the distractor features, as well as the target feature, varied unpredictably across trials in Experiment 4. This specificity or selectivity for the target features is due to a possibility that establishing attentional control settings specifying other than the target features has no benefit for improving task performance or minimizing cognitive effort when the values of either feature is uncertain. Moreover, the task instruction was described in terms of the target colors in Experiment 4 reported here. Thus, participants tended to maintain multiple attentional control settings for multiple target colors. However, when the value of the distractor feature is fixed but the value of the target feature is not, attentional control settings configured in terms of features other than the target values can maximize task performance with minimal effort. Taken together, the most efficient way to construct attentional control setting is to use fixed features across trials when a fixed feature exists, even though it is favorably determined in terms of the target defining features.

Conclusion

The present research measured the cue validity effect as a behavioral measure of attentional capture by a neutral cue to examine how attentional control settings are configured. The results showed that the uncertainty of either target or distractor mediated the cue validity effect of the neutral cue. Note that the nature of a task is goal-directed (Locke, Shaw, Saari, & Latham, 1981). That is, attentional control settings in any circumstances should lead to effective performance with an optimal use of limited cognitive resources (Desimone & Duncan, 1995). Thus, when a fixed value of the target or distractor is placed in the task demand, less cognitive resources are required for an attentional control setting to specify this certain defining value. Meanwhile, in the case of both target and distractor uncertainty, it may be more effective for the control setting to be determined to attend selectively to the target color and to ignore all other colors, rather than to specify all the presented values, even though target uncertainty is present. Overall, our data suggest that the processing feature values to attend to, ignore, or suppress in attentional control settings are all flexibly adjusted to given task demands for efficient target search.

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