Research Article

Investigating Object Files in Spatial Cueing

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Abstract. In spatial cueing, cues presented at target position (valid condition) can capture visual attention and facilitate responses to the target relative to cues presented away from target position (invalid condition). If cues and targets carry different features, the necessary updating of the object representation from the cue to the target display sometimes counteracts and even reverses facilitation in valid conditions, resulting in an inverted validity effect. Previous studies reached partly divergent conclusions regarding the conditions under which object-file updating occurs, and little is known about the exact nature of the processes involved. Object-file updating has so far been investigated by manipulating cue–target similarities in task-relevant target features, but other features that change between the cue and target displays might also contribute to object-file updating. This study examined the conditions under which object-file updating could counteract validity effects by systematically varying task-relevant (color), response-relevant (identity), and response-irrelevant (orientation) features between cue and target displays. The results illustrate that object-file updating is largely restricted to task-relevant features. In addition, the difficulty of the search task affects the degree to which object-file updating costs interact with spatial cueing.

Keywords: object-file updating, spatial cueing, selective visual attention, event-file coding, contingent capture, visual search

OPEN DATA

Visual attention allows selecting a subset of the available stimuli from the environment so that objects relevant for an ongoing task can be efficiently detected and processed. Spatial cueing experiments aim to investigate factors influencing attentional selection of visual information. Trials of such experiments consist of an initial cueing and a subsequent target display, and participants are instructed to search in the target display for a task-relevant target that is presented at one of multiple potential positions, while ignoring any irrelevant distractor stimuli. However, the visual relations between cueing and target displays affect how quickly and accurately participants identify and report the target. Therefore, systematically manipulating these relations opens a window to understanding the factors that contribute to attentional selection of relevant visual information.

In valid conditions of a cueing experiment, cues and targets appear at the same position, and typical search and response times (RTs) are lower compared to invalid conditions, where the cue is presented away from the target (Posner et al., 1980). This holds true even when the peripheral cues are uninformative about the upcoming target's position. This "classical" cue validity effect occurs when the cue captures attention, which then already is at the target's position at the time of its appearance in valid conditions, but attention has to be first shifted to the target's position in invalid conditions (Posner et al., 1980).

While the spatial relationship between cues and targets often creates an advantage for valid conditions, the validity effect also depends on the similarity between cue and target. As a consequence, even spatially valid cues do not always facilitate target responses. The reason why validity effects are sometimes absent could be that target-dissimilar cues do not capture attention (cf. Folk et al., 1992), but also that information from the cue and the target displays is represented in joint object files and processing costs occur whenever this representation has to be updated (here: from cue features to different target features; Carmel & Lamy, 2014).

Object-File Updating Can Cause Same-Location Costs

Although researchers often conceptualize the stimuli presented in the cueing and the target display as distinct

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objects (i.e., one as the "cue" object and the other as the "target" object), this might not reflect how the human visual system processes information from these sequential displays. The spatial overlap between the stimuli presented in the cueing and the target display and their close temporal proximity might entail an integration into joint object-file representations. In general, with intervals of up to several hundred milliseconds between successive stimuli, humans can integrate these stimuli into one joint object file, as long as the stimuli are presented at the same or overlapping positions (e.g., Gordon & Irwin, 1996; Hollingworth & Rasmussen, 2010; Kahneman et al., 1992). Object-file representations are transient, and there is an upper limit (probably corresponding to the limit of visual short-term memory) on the number of objects that can be represented in object files at the same time (Kahneman et al., 1992). However, as attention is a favorable side condition for the integration of successive events into one joint object file, researchers argued that valid cues can incur processing costs if participants need to update a representation of the cue into a representation of the target at the same position (e.g., Carmel & Lamy, 2014).

The integration of cueing- and target-display features into a shared object file probably depends on the similarity of task-relevant features between cue and target. This has been shown in the contingent-capture protocol, where participants had to search for targets of a particular color (e.g., search for the red stimulus and report its orientation), and two types of cues were presented: matching cues with the same color as the target and nonmatching cues with a color different from the target (cf. Folk et al., 1992; Folk & Remington, 1998). In general, cueing effects seem to be weaker if the cue does not match the current attentional control settings. However, if stimulus color at target location is different in the cueing and target display, a "same-location cost" can be observed. Most likely, updating the object representation contributes to this cost.

Currently, it is unknown if features beyond the searched-for target feature contribute to an object file and, hence, to object-file updating costs. This question is interesting for a number of reasons. First, many results demonstrate contingent capture with little evidence for bottom-up capture by salient but nonmatching cues (Büsel et al., 2018). However, some results deviate from this picture (Gaspelin et al., 2016; Lamy et al., 2018). Gaspelin et al. demonstrated that during search for a color target, a nonmatching onset cue leads to a cueing effect. Such cueing effects by nonmatching cues occurred when the search task was difficult, such that attention could not be immediately shifted away from a cued distractor relatively similar to the target (e.g., when distractors and targets had similar colors).

Object-File Updating Beyond Same-Location Costs

At first glance, the results of Gaspelin et al. (2016) are puzzling, as they found no evidence for object-file updating costs in the form of same-location costs. However, object-file updating costs do not have to show up as same-location costs only. To the degree that cues capture attention, with advantages in valid relative to invalid conditions, and, at the same time, incur object-file updating costs, with disadvantages in valid relative to invalid conditions, the resulting net validity effect could still show advantages in valid compared to invalid conditions (i.e., if object-file updating costs are lower than attention capture effects). To see if this is the case, one would need to compare the validity effects in nonmatching conditions (where both capture of attention and object-file updating occur) to that of conditions in which a cue captures attention but does not incur an object-file updating cost. Typically, these conditions are the top-down matching conditions. Yet, Gaspelin et al. did not include a top-down matching cueing condition for comparison to their nonmatching condition. Thus, it is unclear if their validity effect in nonmatching conditions was as strong as in top-down matching conditions or if an object-file updating cost could have counteracted the capture of attention by the nonmatching cues in valid conditions, so as to decrease net validity effects in nonmatching as compared to matching conditions. Here, we investigated this possibility.

Additionally, in Gaspelin et al. (2016), the difficult search task might have prevented object-file updating costs for different reasons: As long as participants had not decided on whether they identified the target correctly, the cue-induced object file could not be updated by the target features. Possibly, by the time participants found the target, they had already suppressed cue-induced feature representations so that object-file updating costs would no longer occur. The absence of object-file updating costs under difficult search conditions might also be related to why no validity effects of nonmatching onset cues occurred during easier color searches (Gaspelin et al., 2016): During easier color searches, participants might have been able to immediately disengage attention from the distractor that was clearly different from the target, and identifying the actual target could have been fast enough to allow object-file updating costs in valid conditions. Consequently, object-file updating costs could have masked attention capture by nonmatching onset cues to create a net cueing effect of zero in easy color-search conditions.

Object-File Updating and the Theory of Event Coding

The principle behind the costs related to cue-to-target feature transitions could be more general than the object-file updating hypothesis suggests, however. A similar, yet more general theory is provided by the Theory of Event Coding (TEC). In some situations, predictions by TEC are similar to that of object-file encoding, for example, if a single searched-for feature repeats or changes from one stimulus to the next. More interestingly, however, according to TEC, interactions between successive stimuli are not restricted to relevant searched-for feature dimensions. Instead, changes of features in response-relevant as well as response-irrelevant features could contribute to overall costs (cf. Hommel, 2004). Several features of an object, including features of responses given to an object, constitute an event representation. According to TEC, updating costs should mainly be driven by *partial* unbinding and rebinding processes. For example, if two events within a sequence are the same in *all* their features (e.g., their colors, locations, and the required responses) or if two objects in a sequence differ in all their features, no unbinding of features of the event file of the first event for the rebinding with different features for the representation of the second event is necessary. However, if only part of the features repeat and part of the features change during the transition from the first to the second event, unbinding and rebinding costs incur (Hommel, 2004). This alternative theoretical view of the interactions between cue and target displays suggests that (1) if costs occur, they should be a function of several features, not only of the searched-for feature, and (2) spatial relations of cues and targets (with positions as one of the objects' features) might merely be one contribution to these more general effects. In cueing experiments, this could mean that validity (i.e., the position relation) could interact with updating requirements of other features (e.g., searched-for colors), providing an alternative explanation for same-location costs, namely the partial unbinding and rebinding of location and color information that is necessary in nonmatching valid conditions.

Present Study

We investigated the influences of feature changes versus repetitions from cue to target display, regarding (1) task-relevant target-matching colors (vs. nonmatching colors), (2) response-relevant shapes (i.e., cue–target compatibility effects), and (3) response-irrelevant orientations. In Experiments 1 and 2, we used a variant of the protocol of Gaspelin et al. (2016) – that is, difficult color search with targets and search-display distractors of target-similar colors. As these authors used only nonmatching onset cues, we first replicated their protocol: In one ("pure onset-cue") block, only nonmatching/onset cues were presented during difficult color search. In another ("mixed-cue") block, we intermixed nonmatching/onset cues and matching/color cues for our test of the influence of object-file updating costs.

If object-file updating can be explained by TEC, we expected costs in conditions in which features between cueing and search display partly change, but not when no or all features change. Furthermore, by varying not only searched-for features between cueing and search display (cue vs. target colors), but also response-relevant features (letters) and response-irrelevant features (letter orientations), we examined which features contribute to an object file or event file.

We investigated our hypotheses by conceptualizing compatibility across time as in Schoeberl et al. (2020), who found that object-file updating occurs whenever the target had a different color than the stimulus in the cueing display preceding the target at its location. Hence, we defined compatibility as feature repetitions between the stimulus at the target location in the cueing display and the target following at the same location, irrespective of the cue's location (see Figure 1, Panel A).

Under the object-file updating hypothesis, we expected stronger validity effects by target-matching color cues than by nonmatching color cues. However, under this hypothesis, we did not predict any influence of response-compatibility. An open question we addressed is whether response-relevant and irrelevant feature similarities at the target location contribute to object files and facilitate processing of validly cued targets even further. Based on TEC, we hypothesized that the strongest facilitation should occur in trials where all features (colors, positions, and response-relevant and response-irrelevant features) either repeated or all features changed from cueing to target display. In contrast, based on TEC, costs should only occur in trials where some of these features changed while others repeated due to the assumed partial unbinding and rebinding processes.

In a complementary analysis, we took the approach of Zivony and Lamy (2018) to investigate if attention dwelled at cued locations under nonmatching onset-cueing conditions during difficult color search. These authors measured dwelling through response (in)compatibility effects based on the (dis)similarity between response-relevant features at the invalidly cued location in the target display and the actual target. Note that only invalid trials can be analyzed in this way (as response-relevant information at the target location is always compatible; see Figure 1, Panel B). Following Gaspelin et al. (2016), we expected

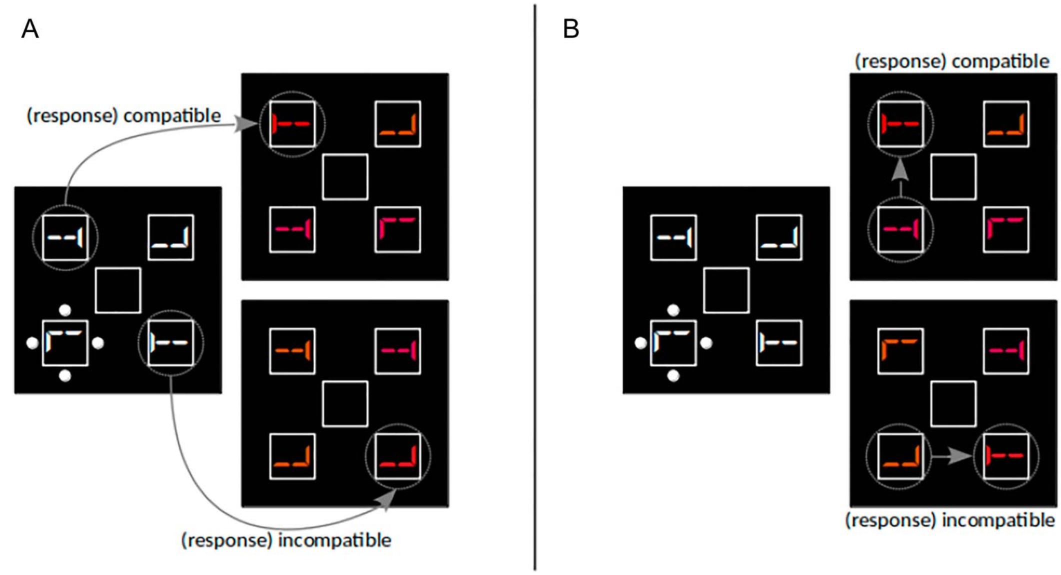

Figure 1. Depicted is the same cueing display (in Panels A and B) of the nonmatching conditions used in Experiment 1 preceding two potential target displays, with red targets among differently tinted red and pink distractors; difficult color search. This figure explains how object-file updating costs (Panel A) and dwelling at cue locations (Panel B) were investigated. (A) (In)compatibility as the (dis)similarity between features at the target's position between cueing and search display (cf. Schoeberl et al., 2020). (B) (In)compatibility as the (dis)similarity between features at the invalidly cued position in the target display and the actual target. Dwelling at a cue's location is measured via (in)compatibility in invalid trials (cf. Zivony & Lamy, 2018). See online version of this article for the colored version of this figure.

dwelling at all cued locations – resulting in a response-compatibility effect not only with matching but also with nonmatching cues.

Assuming that the object-file updating hypothesis does not predict an influence of response-compatibility, RTs should only vary as a function of validity and cue match. Under TEC, however, all features of an event (position, search relevant, and response relevant features) are represented in a single event-file. If none (leftmost condition) or all (rightmost condition) of the features within this event file change, faster RTs (*y* axis) are to be expected. In contrast, if one or more features change, this leads to partial unbinding and rebinding processes which, in turn, increase RTs. (Here, we assumed similar costs by each additional feature that needs to be unbound and rebound, but this might actually not be the case.)

Experiment 1

Methods

Participants

Twenty participants (12 females) from the University of Innsbruck participated (M_{age} = 22.7, SD_{age} = 3.16). All except one participant reported normal or corrected-to-normal vision. One participant without binocular vision did not alter the overall results and was therefore included. Our sample size is identical to Zivony and Lamy's (2018) Experiment 2 and, hence, should be sufficient to detect compatibility effects as a function of cue match.

Apparatus and Stimuli

Stimuli were presented on a 24-inch LCD monitor with a screen resolution of 1,920 × 1,080 pixels and a refresh rate of 60 Hz. Viewing distance was stable at 57 cm.

The fixation display consisted of five squares (each 2.5° × 2.5° of visual angle): one at the screen center serving as a fixation area and the remaining four at the corners of an imaginary square (9.2° × 9.2°) serving as placeholders for the possible target locations. In the cueing display, four dots with a diameter of 0.5° positioned around the placeholders served as cues. In the nonmatching/onset-cue condition, a single set of four white dots appeared at one of the four possible target locations. In the matching/color-cue condition (in mixed-cue blocks only; see below), dots appeared at each position, with one set of dots being colored red and the remaining three sets of dots being white. Within the placeholders in the cueing display, white *T*s and *L*s (2° × 1.3°) appeared with equal frequency. They were rotated left or right by 90° (with always two left-oriented and two right-oriented *T*s and *L*s). The blank between cue and target displays was identical to the fixation display. In the target display, one red target (RGB values: 255, 0, 0), at least one orange (220, 80, 0), and one pink (220, 0, 80) distractor were presented. Which distractor color was used twice in the target-display distractors was randomly chosen in each trial. Colors and fonts were chosen to mimic Gaspelin et al.'s (2016) Experiment 4, but, of course, they were likely not identical to those used by Gaspelin et al.

Design and Procedure

Figure 2 shows example trials. The experiment consisted of two blocks: one pure onset-cue block and one mixed-cue block, with top-down matching red cues and top-down nonmatching (white) onset cues. Block order was counterbalanced across participants. The cueing display remained visible for 100 ms. After a 50-ms fixation screen, the target display appeared and remained visible until a response was given or up to a maximum of 2 s. In case of a time out, participants were instructed to respond faster.

Across trials, cue and target positions, cue and target identities, cue and target orientations, target-display distractor colors and their locations, and cue types/colors (in mixed-cue blocks only) were all equally frequent, selected in a pseudorandom fashion, and realized in a pseudorandom sequence. Accordingly, cues were nonpredictive of the target locations. Letters and orientations could change between cue and target displays.

As in Gaspelin et al. (2016), participants were instructed to search for the red target letter and report its identity (i.e., *T* or *L*), rendering the letters' orientations task irrelevant. Participants responded on a conventional (German QWERTZ layout) computer keyboard (keys *m* and *y*). Participants were also asked to keep their eyes fixated on the screen center. This instruction was not enforced by eye-tracking. However, as the interval between cue and target was short, such that not too many saccades to the cue could be conducted before the target appeared, and as covert shifts (of attention only) and overt shifts (of the eyes) of attention are tightly coupled (cf. Deubel & Schneider, 1996), we do not think that contributions by eye movements have played a major role for the conclusions of the current study.

Participants completed 400 trials in the pure onset-cue block and 800 trials in the mixed-cue block. Before the first block of each trial type, participants completed 16 practice trials, which were excluded from subsequent analyses. The experiment lasted for approximately an hour, and participants were able to take self-paced breaks every 100 trials.

Results

Only RTs from correct trials were analyzed. RTs deviating more than 2.5 *SD*s from each participant's condition mean were excluded, leading to a loss of 2.4% of the data. Overall accuracy was 96%. In the analyses of error rates (ERs), the arcsine-transformed ERs were used.

Compatibility as Letter and Orientation Similarity at the Targets' Position

Compatibility of response-relevant letter identities and irrelevant letter orientations was defined as repetitions

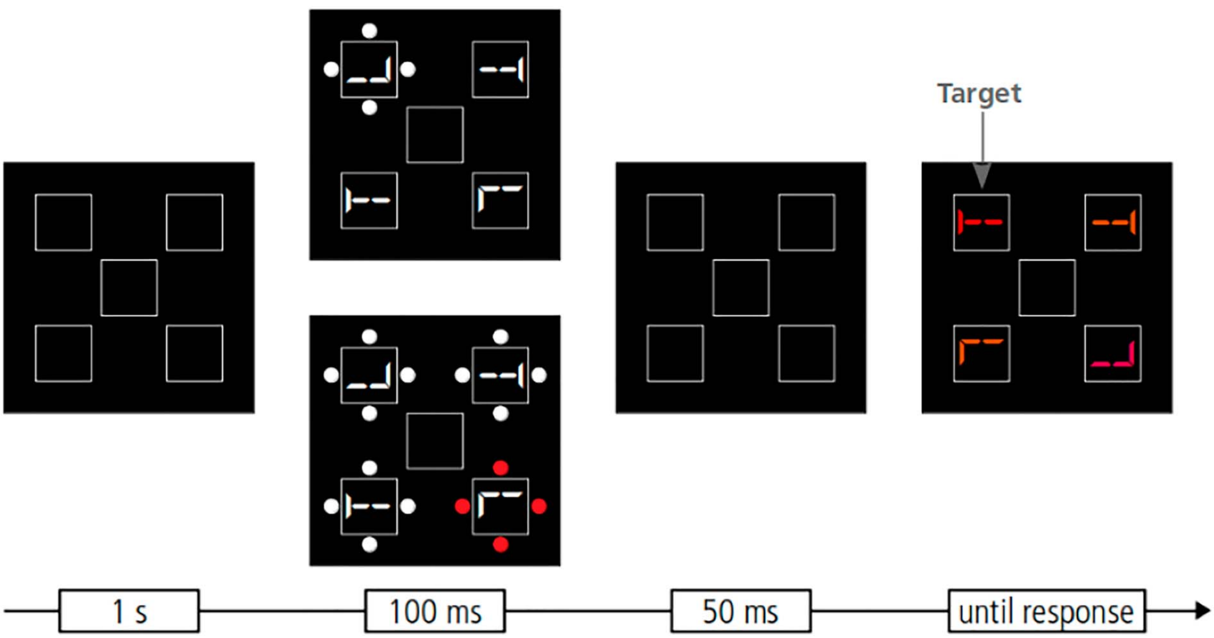

Figure 2. Example trials of Experiment 1. Cues were presented at one of the potential target locations. These cues could either be nonmatching white onset cues (upper panel; valid cue) or matching red cues (lower panel; invalid cue). See online version of this article for the colored version of this figure.

versus changes from cue to target display at target position. This conceptualization of compatibility follows Schoeberl et al.'s (2020) notion that object files are updated from distractor stimuli in the cueing display (to the targets following at these distractors' positions).

Pure Onset-Cue Blocks

Response Times

A repeated-measurements ANOVA, with the factors validity (valid, invalid), relevant repetition (of letter identity at target location; change, repetition), and irrelevant repetition (of letter orientation at target location; change, repetition), yielded a significant main effect of relevant repetition, $F(1, 19) = 6.92$, $p = .016$, $\eta_p^2 = .27$, which was further modulated by its interaction with validity, $F(1, 19) = 6.04$, $p = .024$, $\eta_p^2 = .24$. Paired t tests revealed a significant relevant-repetition (of letter identity) effect of 23 ms in valid trials (identity repetition: 772 ms vs. identity change: 795 ms), $t(19) = 4.07$, $p < .001$, $d = 0.25$, but not in invalid trials ($p = .92$).

Error Rates

No significant effects were found.

Interim Discussion

The finding is more in line with the object-file updating hypothesis than with the predictions of TEC. According to TEC, valid relevant-repetition (response-compatible) trials would have been partial repetitions, as these were all nonmatching cues, with a different color than the following targets. The absence of any relevant-repetition effect under invalid conditions could be due to attention capture by the onset cues corrupting the influence of preceding letter identities at target locations. This capture of attention might have gone unnoticed, as color-based object-updating costs under valid conditions could have counteracted the facilitation by bottom-up capture.

Mixed-Cue Blocks

Response Times

A repeated-measurements ANOVA, with the factors cue match (matching, nonmatching), validity (valid, invalid), relevant repetition (of letter identity at target location; change, repetition), and irrelevant repetition (of letter orientation at target location; change, repetition), was calculated.

We found a main effect of cue match, $F(1, 19) = 58.59$, $p < .001$, $\eta_p^2 = .76$. Validity was modulated by cue match, $F(1, 19) = 121.91$, $p < .001$, $\eta_p^2 = .87$. Top-down matching cues led to a validity effect of 99 ms (valid: 727 ms vs. invalid: 826 ms), $t(19) = 10.34$, $p < .001$, $d = 0.96$, while onset cues did not ($p = .32$).

Error Rates

Main effects were found for cue match, matching: 4.2% versus nonmatching: 3.5%, $F(1, 19) = 5.08$, $p = .036$, $\eta_p^2 = .21$, and validity, valid: 3.7% versus invalid: 4.1%, $F(1, 19) = 28.74$, $p < .001$, $\eta_p^2 = .60$.

The interaction between relevant and irrelevant repetition was significant, $F(1, 19) = 9.03$, $p = .007$, $\eta_p^2 = .32$, which was due to selective relevant-repetition (letter-similarity) effects for conditions, in which the irrelevant feature changed, orientation repetition: 3.2% versus orientation change: 4.4%, $t(19) = 2.21$, $p = .04$, $d = 0.48$.

Interim Discussion

Figure 3 shows the results predicted by both object-file updating and TEC. Based on previous research and the unclear role of irrelevant repetitions, we limited our predictions to the interactions between the factors validity, match, and relevant repetition. Considering only these three factors, our results are more in line with the predictions from an object-file updating perspective. However, our findings are neither entirely compatible with object-file updating, nor with TEC. The facilitation by simultaneous repetitions of relevant and irrelevant features (at target position) from cueing to target display would be in line with object-file updating. However, the stronger interference by irrelevant repetitions under invalid conditions, contingent on a repetition of the relevant feature, was unexpected under the perspective of object-file updating and of TEC. According to TEC, these are partial repetition conditions as the irrelevant feature changed and the relevant feature repeated. Interestingly, irrelevant repetition had no effect in the pure-onset blocks, but in the mixed blocks.

Compatibility Between Cued Distractor and Target in Invalid Conditions

We also analyzed dwelling effects (cf. Zivony & Lamy, 2018) by defining (in)compatibility as the (dis)similarity of relevant (letter identity) or irrelevant (letter orientation) feature at the cued distractor position in the target display and the target. This was only possible for invalid trials.

Pure Onset-Cue Blocks

Response Times

We calculated a repeated-measurements ANOVA of the invalid trials, with the factors relevant (i.e., letter) similarity (similar, different) and irrelevant (i.e., orientation) similarity (similar, different). No significant main effect or interaction was found.

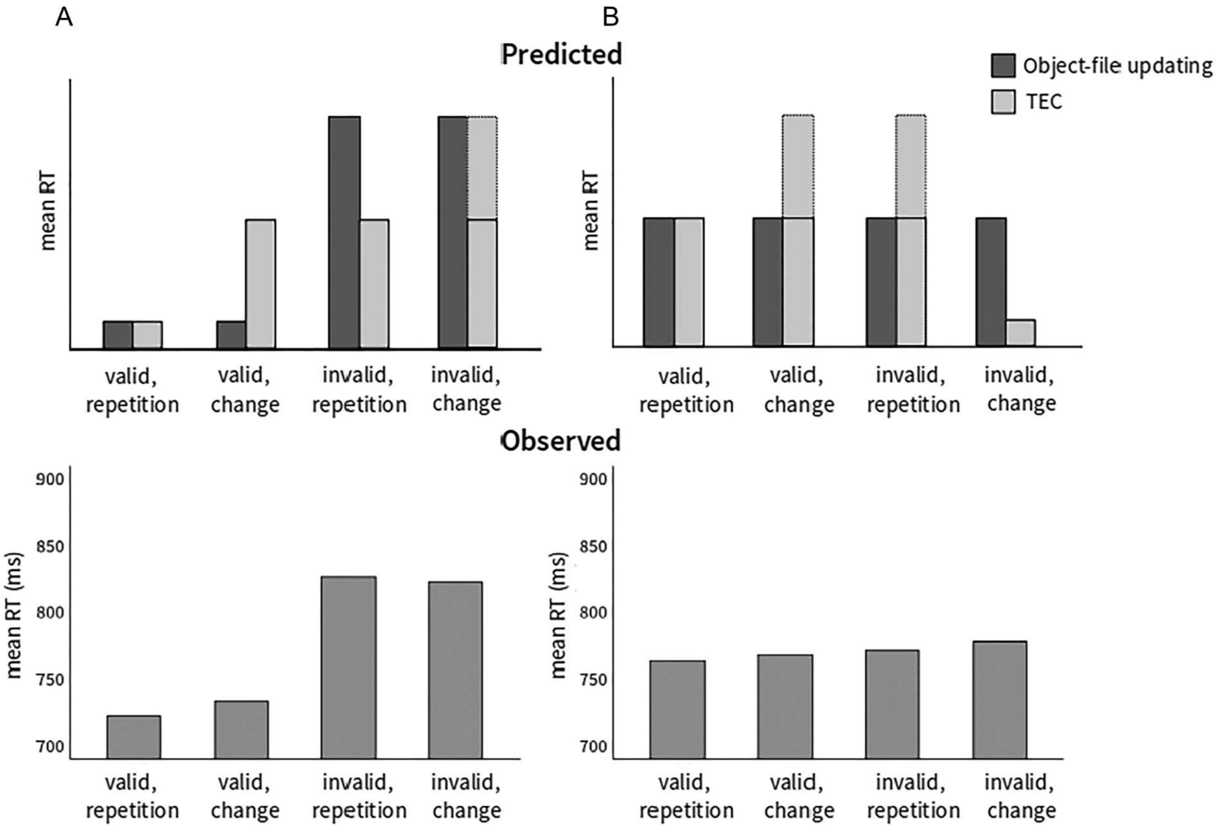

Figure 3. A comparison of the predicted pattern of results (upper row) by the object-file updating hypothesis (darker gray) and the theory of event coding (lighter gray), for both (Panel A) top-down matching color cues and (Panel B) top-down nonmatching onset cues, and the observed data in Experiment 1 (lower row). Note that the dotted bars in the upper row represent potential greater costs of unbinding and rebinding of two features as compared to one.

Error Rates

The main effect of relevant similarity was significant, relevant-similar: 3.3% versus relevant-dissimilar: 4.2%, $F(1, 19) = 8.20$, $p = .01$, $\eta_p^2 = .30$.

Mixed Cue Blocks

Response Times

We calculated a repeated-measurements ANOVA with the factors cue match (matching, nonmatching), relevant similarity (similar, dissimilar), and irrelevant similarity (similar, dissimilar). The main effect of cue match, $F(1, 19) = 129.84$, $p < .001$, $\eta_p^2 = .87$, was due to 53 ms faster RTs in trials with nonmatching cues (774 ms), compared to trials with matching cues (826 ms). Additionally, the main effect of relevant similarity (or response compatibility between cued distractor and target) of 11 ms was significant (letter similar: 792 ms vs. letter dissimilar: 804 ms), $F(1, 19) = 6.93$, $p = .016$, $\eta_p^2 = .27$.

Error Rates

No significant main effects or interactions were found.

Experiment 2

Experiment 1 had two notable caveats. First, same-location costs have hitherto only been observed in easy search conditions (e.g., Carmel & Lamy, 2014). Therefore, our difficult search conditions in Experiment 1 might not have been ideal for investigating object-file updating. Second, in Experiment 1, only the dots in the cueing display were colored while the letters at all positions were white. This might have diminished integration of letters and cues in the cueing display into one joint object file. Experiment 2 accounted for these two caveats.

Methods

Participants

Overall, 39 participants (25 females; M_{age} = 22.76, SD_{age} = 4.04) completed the experiment. Thirteen participants were tested in the laboratory at the University of Innsbruck. Due to restrictions applying during phases of the COVID-19 pandemic, 26 additional participants were tested online. Due to technical failures, only data from 19 participants could be analyzed. None of the participants participated in both versions of the experiment. All participants received course credits for their participation. Because a part of the participants was not tested under strictly standardized conditions, we increased the sample size compared to Experiment 1.

Apparatus and Stimuli

The technical equipment for the laboratory-based version of Experiment 2 was identical to that of Experiment 1. The online version of Experiment 2 was created with the OSWeb extension of OpenSesame (Mathôt et al., 2012).

In the laboratory conditions, display layouts and stimulus sizes were identical to those of Experiment 1. In the online version, these values were unknown. In addition, we initially planned to control for stimulus luminance in both the easy and the difficult search conditions. Therefore, we matched all stimulus colors in the laboratory-based version of Experiment 2 to approximately 20 cd/m^2 (red: x = 0.629, y = 0.364; pink: 0.551, 0.282; orange: 0.582, 0.264; blue: 0.114, 0.055; green: 0.301, 0.581; yellow: 0.404, 0.503). However, during pilot tests for the online version, these colors proved to be too difficult to distinguish even with long presentation times. Hence, for the online version, we reverted to the colors used in Experiment 1 and replaced the color values of yellow with RGB (255, 255, 0). Therefore, there was likely an additional influence due to lower search difficulty based on luminance, as the equiluminant colors were more difficult to distinguish than the color values used in Experiment 1 and the online version of Experiment 2.

The notable differences between Experiments 1 and 2 are as follows (see also Figure 4). First, we implemented an easy search condition in addition to the difficult search condition. The easy search condition was based on Gaspelin et al.'s (2016) easy search condition in their Experiment 4, in which participants searched for a red target letter among green and blue distractors. Second, letters in the cueing display were colored. If a white onset cue appeared at one location, the letter embedded in the corresponding placeholder was white. All the remaining letters were colored yellow. If a top-down matching red color cue appeared at a specific location, the letter inside the respective placeholder was also colored red. Dots appearing around the remaining placeholders were colored yellow, as were the letters at these positions. Third, only mixed blocks were realized, as the experiment was already relatively long, with its additional factor search difficulty.

Design and Procedure

Presentation times of each of the displays within one trial were identical to those in Experiment 1. Similarly, letter identities and orientations randomly changed or repeated between cueing and target displays. Again, cues were nonpredictive of the upcoming target location. Participants completed one block in the easy and the difficult search condition each, amounting to 1,600 experimental trials in total.

Laboratory-Based Version

In the laboratory-based version of the experiment, participants were tested individually in a dimly lit room. Viewing distance was kept stable at 57 cm. The order of search condition blocks (i.e., easy block first vs. difficult block first) was counterbalanced across participants. Participants completed 16 practice trials before each block. Self-paced breaks were implemented in the experiment after each 100 trials.

Online Version

An experiment consisting of more than 1,600 trials caused OSWeb to fail. Hence, we divided the experiment into four separate online experiments, each consisting of 16 practice trials and 400 experimental trials. We created two versions of the easy search condition and two versions of the difficult search condition. After providing their demographic data and consenting to participate in the experiment, participants were sent a list of links leading them to the respective online experiments. These links were ordered in a way that they would first lead participants to two easy search condition blocks and then two difficult search condition blocks, or vice versa. Participants were instructed to open the links in the correct order and to complete all four experiments within a maximum of 2 hours. Participants were asked to only participate in the experiment if they felt well rested and were in a quiet room.

Results

RTs deviating more than 2.5 *SD*s from each participant's condition mean were excluded, leading to a loss of 2.3% of the data. Overall accuracy was 95%. Note that we included the factor experiment version (laboratory-based, online version) as a between-subjects factor in our analyses to control for variance stemming from the different testing conditions. However, to increase readability and comparability of results between Experiments 1 and 2, the main effect of and interactions including experiment version are reported in ESM 1. Results indicated that search was more difficult with equiluminant stimuli in the laboratory-based version as compared to the online version of Experiment 2.

Letter and Orientation Similarity at the Targets' Position

Again, similarity of response-relevant letter identities and irrelevant letter orientations here were defined as

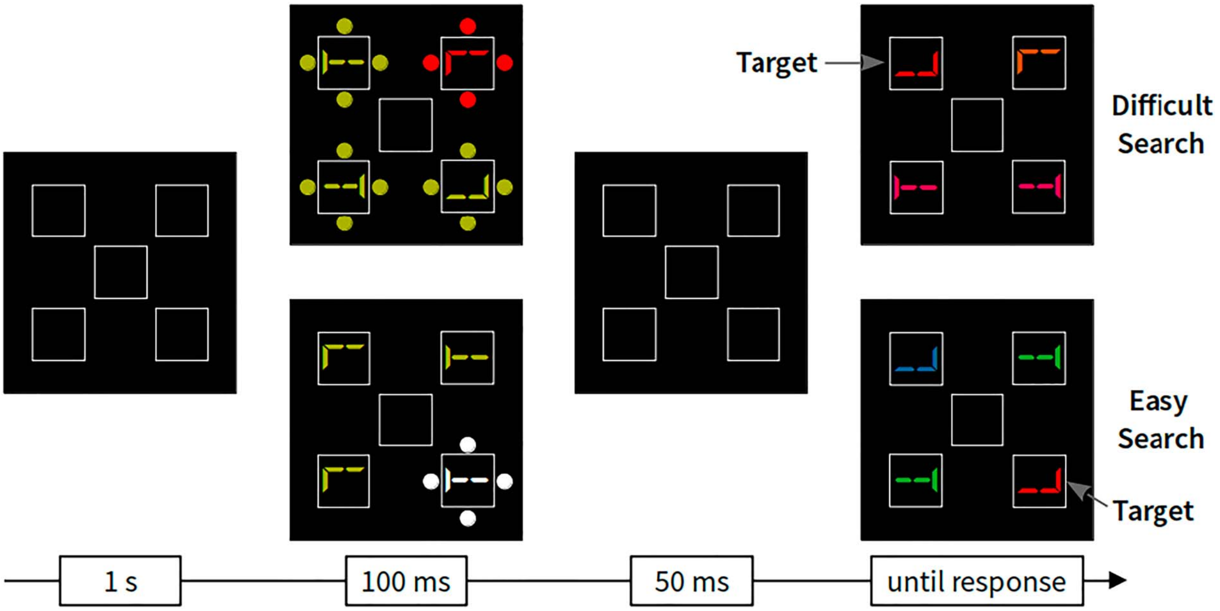

Figure 4. Example trials from Experiment 2, with an example of a top-down matching cue in the upper and an example of a nonmatching cue in the lower of the two depicted cueing displays, second from left. Nonsingleton locations in cueing displays were colored yellow, and both dots and the letters inside the placeholders within the cueing display were colored identically. Furthermore, we implemented both easy (lower right display) and difficult (upper right display) search conditions which were run in separate blocks. See online version of this article for the colored version of this figure.

repetitions versus changes from cue to target display at target position, following Schoeberl et al. (2020).

Response Times

We calculated a mixed ANOVA, with the within-participant factors validity (valid, invalid), cue match (matching, nonmatching), relevant repetition (of letter identity at target location; change, repetition), irrelevant repetition (of letter orientation at target location; change, repetition), and search difficulty (easy, difficult), and the between-participants factor experiment version (laboratory-based version, online version).

We found significant main effects for cue match, $F(1, 30) = 28.60$, $p < .001$, $\eta_p^2 = .49$, validity, $F(1, 30) = 131.54$, $p < .001$, $\eta_p^2 = .81$, relevant repetition, $F(1, 30) = 46.32$, $p < .001$, $\eta_p^2 = .61$, irrelevant repetition, $F(1, 30) = 5.42$, $p = .027$, $\eta_p^2 = .15$, and search difficulty, $F(1, 30) = 132.89$, $p < .001$, $\eta_p^2 = .82$. Cue match and validity entered a two-way interaction, $F(1, 30) = 24.54$, $p < .001$, $\eta_p^2 = .45$, which reflected contingent-capture: Matching cues led to a significant validity effect of 60 ms (valid: 621 ms vs. invalid: 681 ms), $t(31) = 9.93$, $p < .001$, $d = 1.07$, whereas nonmatching cues resulted in a smaller, yet still significant validity effect of 21 ms (valid: 628 ms vs. invalid: 649 ms), $t(31) = 5.14$, $p < .001$, $d = 0.35$. Additional two-way interactions were found between validity and relevant repetition, $F(1, 30) = 23.22$, $p < .001$, $\eta_p^2 = .44$, validity and irrelevant repetition, $F(1, 30) = 4.29$, $p = .047$, $\eta_p^2 = .13$, relevant and irrelevant repetition, $F(1, 30) = 26.37$, $p < .001$, $\eta_p^2 = .47$, and validity and search difficulty, $F(1, 30) = 4.61$, $p = .04$, $\eta_p^2 = .13$. Because validity and relevant repetition, and validity and search difficulty entered further interactions (see below), we focus on the remaining two interactions first. The interaction between validity and irrelevant repetition was due to significant RT increases in valid irrelevant-change (orientation change; 628 ms) compared to valid irrelevant-repetition (orientation repetition; 621 ms) trials, 7 ms, $t(31) = 2.55$, $p = .016$, $d = 0.13$. The same did not hold true for invalid trials, $p = .48$. The two-way interaction between relevant and irrelevant repetition was due to longer RTs in relevant change trials (667 ms), compared to relevant repetition trials (646 ms), in irrelevant change trials, 21 ms, $t(31) = 8.19$, $p < .001$, $d = 0.36$, whereas no such difference was found for irrelevant repetition trials, $p = .12$.

The three-way interactions between cue match, validity, and relevant repetition, with $F(1, 30) = 13.84$, $p = .001$, $\eta_p^2 = .32$ (Figure 5), and cue match, validity, and search difficulty, $F(1, 30) = 9.21$, $p = .005$, $\eta_p^2 = .23$, were significant. The strongest relevant-repetition (letter-repetition) effect was found in valid matching cue conditions (identity repetition: 607 ms vs. identity change: 634 ms), 27 ms, $t(31) = 6.14$, $p < .001$, $d = 0.49$. The altogether smallest relevant-repetition effect was found for invalid matching cues (identity repetition: 679 ms vs.

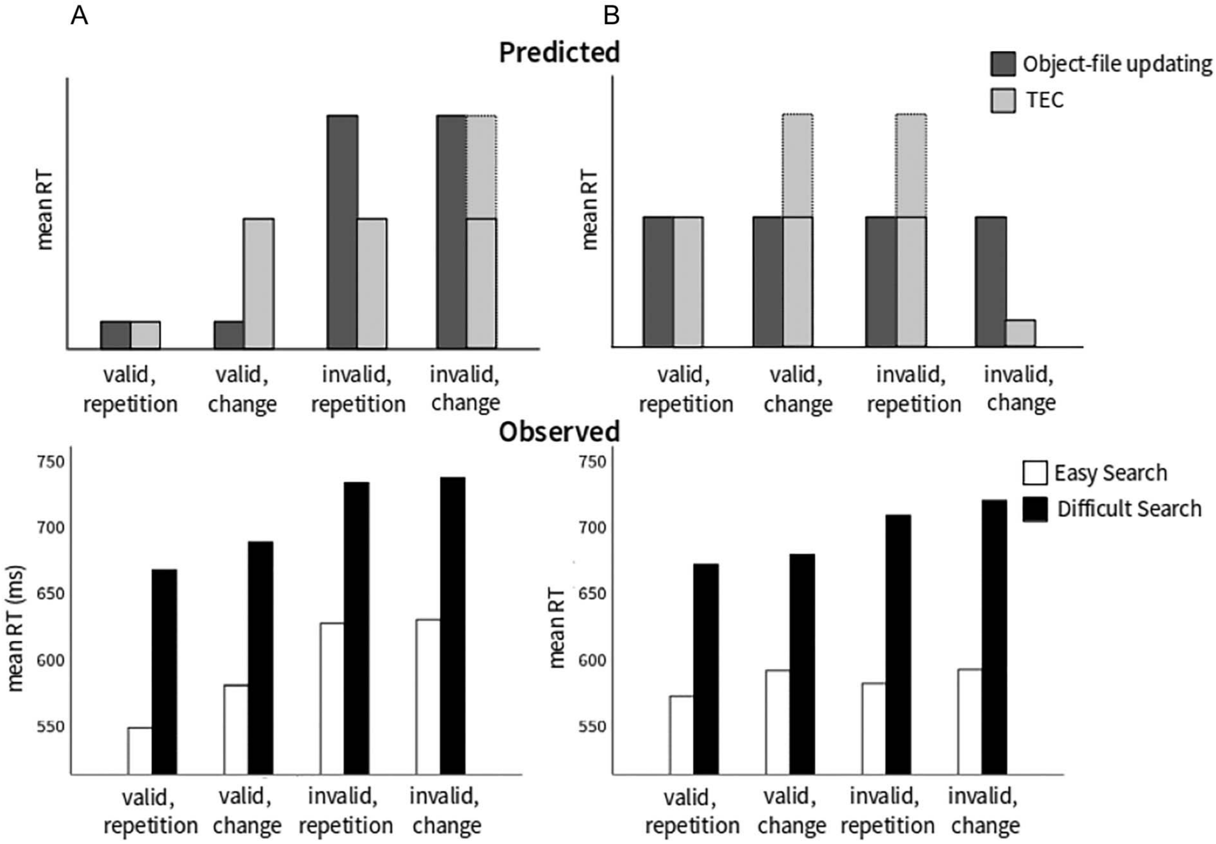

Figure 5. A comparison of the predicted pattern of results (upper row) by the object-file updating hypothesis (darker gray) and the theory of event coding (lighter gray), for both (Panel A) top-down matching color cues and (Panel B) top-down nonmatching onset cues, and the observed data in Experiment 2 (lower row) for both the easy (white) and difficult (black) search blocks. As can be seen in this figure, the influence of search difficulty was an additive one, also indicated by the nonsignificant four-way interaction between the four variables. Note that the dotted bars in the upper row represent potential greater costs of unbinding and rebinding of two features as compared to one.

identity change: 684 ms), 5 ms, $t(31) = 2.51$, $p = .018$, $d = 0.09$. For nonmatching cues, both valid and invalid trials led to a comparable relevant-repetition (i.e., letter-repetition) effect of intermediate size, with 14 ms (identity repetition: 622 ms vs. identity change: 635 ms), $t(31) = 4.16$, $p < .001$, $d = 0.24$, and 16 ms (identity repetition: 642 ms vs. identity change: 658 ms), $t(31) = 5.71$, $p < .001$, $d = 0.26$, respectively. The interaction between cue match, validity, and search difficulty was due to a typical contingent-capture effect in the easy search condition, with a validity effect of 64 ms for matching cues (valid: 565 ms vs. invalid: 629 ms), $t(31) = 17.44$, $p < .001$, $d = 1.19$, and a lack thereof for nonmatching cues ($p = .13$). Conversely, there was much more evidence for bottom-up capture by the nonmatching cues and, hence, a less pronounced contingent-capture effect in the difficult search condition, with a validity effect of 57 ms for top-down matching cues (valid: 678 ms vs. invalid: 735 ms), $t(31) = 5.38$, $p < .001$, $d = 0.72$, and a validity effect of 39 ms for nonmatching cues (valid: 676 ms vs. invalid: 715 ms), $t(31) = 5.22$, $p < .001$, $d = 0.47$.

While this is described in more detail in ESM 1, we should note at this point that experiment version seemingly influenced the results: Relevant repetition only sped up RTs in the online version of the experiment under valid cue conditions when the irrelevant feature changed, 13 ms (relevant repetition: 611 ms vs. relevant change: 624 ms), $t(18) = 3.54$, $p < .01$, $d = 0.29$, and under invalid cue conditions when the irrelevant feature changed, 15 ms (relevant repetition: 645 ms vs. relevant change: 660 ms), $t(18) = 7.14$, $p < .001$, $d = 0.28$. In the online version of the experiment, relevant repetition trials *slowed* RTs in invalid trials when the irrelevant feature repeated, −14 ms (relevant repetition: 648 ms vs. relevant change: 634 ms), $t(18) = -6.66$, $p = .001$, $d = -0.29$.

Error Rates

Main effects were observed for validity, $F(1, 30) = 45.38$, $p < .001$, $\eta_p^2 = .60$, for relevant repetition, $F(1, 30) = 9.76$, $p < .01$, $\eta_p^2 = .25$, and for search difficulty, $F(1, 30) = 20.10$, $p < .001$, $\eta_p^2 = .40$. The two-way interactions between validity and cue match, $F(1, 30) = 8.09$, $p < .01$,

$\eta_p^2 = .21$, and relevant and irrelevant feature repetition, $F(1, 30) = 7.62$, $p = .01$, $\eta_p^2 = .20$, reached significance. Significant three-way interactions were found for validity, relevant, and irrelevant repetition, $F(1, 30) = 4.22$, $p = .049$, $\eta_p^2 = .12$, and for validity, cue match, and search difficulty, $F(1, 30) = 9.57$, $p < .01$, $\eta_p^2 = .24$.

Finally, the five-way interaction between all variables was significant, $F(1, 30) = 6.51$, $p = .016$, $\eta_p^2 = .18$. Influences of relevant repetitions were found in easy search conditions for matching, invalid cues, when the irrelevant feature changed (identity repetition: 4.1% vs. identity change: 5.6%), $t(31) = 2.9$, $p < .01$, $d = 0.44$, and in the easy search condition for valid nonmatching cues, when the irrelevant feature changed (identity repetition: 2.4% vs. identity change: 5%), $t(31) = 3.25$, $p < .01$, $d = 0.73$. In the difficult search condition, effects of relevant repetitions were only found for trials with valid matching cues, again, when the irrelevant feature changed (identity repetition: 2.6% vs. identity change: 6%), $t(31) = 3.48$, $p < .01$, $d = 0.72$.

Compatibility Between Cued Distractor and Target in Invalid Conditions

Response Times

We performed a mixed ANOVA, with the within-participant factors cue match (matching, nonmatching), relevant (i.e., identity) similarity (similar, dissimilar), irrelevant (i.e., orientation) similarity (similar, dissimilar), and search difficulty (easy, difficult), and the between-participants factor experiment version (laboratory-based, online). As before, we report the influence of the experiment version in ESM 1 to increase readability and comparability of the results of Experiment 2 to those in Experiment 1.

Main effects were found for cue match (32 ms difference; matching: 681 ms vs. nonmatching: 649 ms), $F(1, 30) = 57.46$, $p < .001$, $\eta_p^2 = .66$, relevant similarity (15 ms difference; similar: 655 ms vs. dissimilar: 670 ms), $F(1, 30) = 31.38$, $p < .001$, $\eta_p^2 = .51$, and search difficulty (118 ms difference; easy: 607 ms vs. difficult: 725 ms), $F(1, 30) = 119.70$, $p < .001$, $\eta_p^2 = .80$.

Cue match entered two-way interactions both with relevant similarity, $F(1, 30) = 51.31$, $p < .001$, $\eta_p^2 = .63$, as well as with irrelevant similarity, $F(1, 30) = 4.66$, $p = .039$, $\eta_p^2 = .13$. Furthermore, we found an interaction between cue match and search difficulty, $F(1, 30) = 11.05$, $p = .002$, $\eta_p^2 = .27$. Irrelevant similarity only decreased RTs under top-down matching cue conditions, 8 ms (similar: 676 ms vs. dissimilar: 684 ms), $t(31) = 2.28$ $p = .03$, $d = 0.13$, but not under nonmatching cue conditions ($p = .4$).

Moreover, the analysis yielded a three-way interaction between search difficulty, cue match, and relevant similarity, $F(1, 30) = 11.88$, $p = .002$, $\eta_p^2 = .28$. This was due to selective response-compatibility effects for matching cues, 34 ms (similar: 605 ms vs. dissimilar: 640 ms), $t(31) = 7.89$, $p < .001$, $d = 0.59$, and a lack thereof for nonmatching cues ($p = .48$) under easy search conditions. Under difficult search conditions, response-compatibility effects were found for matching and nonmatching cues. These compatibility effects were more pronounced for matching cues, 24 ms (similar: 720 ms vs. dissimilar: 744 ms), $t(31) = 6.4$, $p < .001$, $d = 0.27$, than for nonmatching cues, 8 ms (similar: 709 ms vs. dissimilar: 717 ms), $t(31) = 2.26$, $p = .03$, $d = 0.09$.

Error Rates

Main effects were found for relevant similarity (dissimilar: 5.4% vs. similar: 4.1%) and search difficulty (difficult: 5.8% vs. easy: 3.7%), with $F(1, 30) = 31.74$, $p < .001$, $\eta_p^2 = .51$, and $F(1, 30) = 16.47$, $p < .001$, $\eta_p^2 = .35$, respectively.

Cue match and relevant similarity interacted, $F(1, 30) = 7.6$, $p = .01$, $\eta_p^2 = .20$. Relevant similarity exerted its influence only under top-down matching cue conditions, similar: 3.8% versus dissimilar: 6%, $t(31) = 6.86$, $p < .001$, $d = 0.86$. No such influence was found for top-down nonmatching cues ($p = .08$). Furthermore, we found an interaction between cue match and search difficulty, $F(1, 30) = 12.13$, $p < .01$, $\eta_p^2 = .29$. Under easy search conditions, matching cues increased ERs, compared to nonmatching cues, 4.2% versus 3.2%, $t(31) = 2.65$, $p = .01$, $d = 0.39$. No difference was found under difficult search conditions ($p = .21$). Finally, relevant similarity interacted with search difficulty, $F(1, 30) = 4.57$, $p = .041$, $\eta_p^2 = .13$. Response-compatibility effects were found both under easy search conditions, $t(31) = 5.17$, $p < .001$, $d = 0.39$, and under difficult search conditions, $t(31) = 3.89$, $p < .001$, $d = 0.37$. However, this response-compatibility effect was more pronounced under easy search conditions (similar: 2.9% vs. dissimilar: 4.4%) than under difficult search conditions (similar: 5.2% vs. dissimilar: 6.4%).

General Discussion

The present study investigated the contribution of object-file updating to validity effects in cueing experiments. Individual trials consisted of a cueing and a target display, and we investigated whether feature relations between these displays could facilitate the identification of the target. Based on object-file theory, sequential stimuli that share the spatial location between the cueing and the target displays could be integrated into common object representations. Based on this theory, feature changes between the cueing and target displays should incur object-file updating costs.

In two experiments, we found contingent-capture effects: robust validity effects only with top-down matching color cues but not or at least less so with nonmatching onset cues. In Experiment 1, no validity effect occurred during difficult color search with pure onset cues of a nonmatching color – notably. This is different from prior research that reported validity effects even with nonmatching cues under difficult search conditions (Gaspelin et al., 2016). This could be due to the counteracting effect of object-file updating costs (cf. Carmel & Lamy, 2014). In line with this interpretation, we found that attention dwelled at cued locations even under nonmatching conditions: The response-compatibility (of letter identities) between the cued distractor (in invalid conditions) and the target affected the ERs in the pure onset-cue blocks of Experiment 1 as well as the RTs in the mixed-cue blocks of Experiments 1 and 2. In addition, the difficult search conditions of Experiment 2 revealed evidence for bottom-up capture by nonmatching onset cues: Invalid nonmatching cues led to a response-compatibility effect but also created a robust validity effect. In line with Gaspelin et al. (2016), evidence for bottom-up capture by nonmatching cues was more or less absent under Experiment 2's easy search conditions. Thus, nonmatching cues' locations must have been processed at one point, leading to attention's dwelling at the cue's position and allowing participants to quickly grasp the letter identity at this position in Experiment 1 as well as in the difficult search condition of Experiment 2.

At first glance, the results in the difficult search conditions of Experiments 1 and 2 seem at odds with the results of Zivony and Lamy (2018; see also Lamy et al., 2018), as they did not observe any response-compatibility effects under nonmatching conditions (but for an exception, see Experiment 2 of Lamy et al., 2018). However, Zivony and Lamy used shorter target displays of 100 ms, whereas our target displays were presented until a response was given (>600 ms). Thus, we simply allowed more time for a longer processing of response-related information from cued distractor positions. In line with a role of time, under easy search conditions in the present Experiment 2, we also did not find any response-compatibility effects through distractors cued by a nonmatching cue, just as in the study of Zivony and Lamy. These results showed that the response-compatibility effect of distractors cued by nonmatching cues took time to build up. That the response-compatibility effect was not present under nonmatching invalid easy search conditions is, thus, also at variance with a central tenet of Gaspelin et al. (2016). Gaspelin et al. reasoned that onset cues would capture attention, but that this could be masked by a swift disengagement from the color distractor during easy color search. Based on the present results, we suggest the alternative interpretation that bottom-up capture effects of onset cues take some time to build up, such that they are not seen during easy color searches. This interpretation is also better in line with lacking behavioral evidence for capture effects with cued target-similar distractors in mixed displays of Lamy et al. (2018) and with missing electrophysiological evidence for bottom-up capture by nonmatching onset cues under easy color-search conditions (Goller et al., 2020).

The findings in Experiments 1 and 2 were generally in line with an object-file updating account if we assume that weaker validity effects in nonmatching conditions reflected a mixture of (1) bottom-up capture by the nonmatching onset cues and (2) costs incurred by feature changes from nonmatching cues to the targets under valid conditions that counteracted the capture effect and, hence, decreased net validity effects. However, the present results yielded inconsistent and, therefore, limited evidence that features beyond searched-for colors at target position contributed to object-file updating costs.[1] For example, we observed a joint facilitation of relevant (letter) and irrelevant (orientation) feature repetition from the valid cue in pure onset-cue blocks of Experiment 1. However, this facilitation did not replicate in the mixed-cue block of Experiments 1 and 2. Moreover, in the mixed-cue blocks of Experiment 1, we observed an unpredicted facilitation by relevant repetitions when irrelevant orientation changed from cueing display to target display at target position, whereas in Experiment 2, relevant-feature similarity effects were altogether less affected by irrelevant-feature similarity. One might argue that TEC allows for influences of attentional weighting and, thus, interactions of relevant and irrelevant features might not be so critical for TEC (cf. Memelink & Hommel, 2013). Importantly, however, other particular interactions that were predicted by TEC were also not found, such as the specific consistent type of interaction between repetitions versus switches of task-relevant spatial positions (corresponding to an influence of validity), task-relevant color repetitions (corresponding to an influence of top-down matching), or task-relevant letter identities. The latter were all attended-to features, but the

[1] We ran additional analyses where we defined feature repetition as feature (dis)similarity between features at the cued position in the cue display and the target features. For the sake of brevity, only the results relevant to the current research questions are reported in ESM 1.

particular forms of some of the significant interactions concerning these variables were not predicted by TEC. In addition, although some interactions were better in line with TEC, they did not occur consistently across conditions. Therefore, we remain skeptical regarding additional contributions by event files beyond those already predicted by object-file updating alone.

Overall, our results did not corroborate the more specific predictions of TEC. According to TEC, full feature repetitions from cueing to target display and full feature changes should have created advantages relative to partial repetitions of these features (cf. Hommel, 2004). Evidence for this was maybe found in the valid matching condition, where a position, letter, and color repetition facilitated target responses the most. However, under the perspective of TEC, it is difficult to say what to make of the weaker rather than inverted response-compatibility effect of nonmatching cues. In conclusion, cueing and target displays were seemingly jointly used for target object-file representations rather than as distinct event files. The latter finding dovetails with the observation that participants can treat the entire trial – consisting of cue and target – as one event (Ansorge et al., 2019). It is tempting to consider object-file updating processes to occur within visual short-term memory (cf. Scimeca et al., 2018; Teng & Kravitz, 2019) and event-file coding further up the hierarchy, at more abstract levels, encompassing motor response representations (cf. Xu, 2017). Future research is needed to look more closely into these matters.

Limitations

While we strived to closely replicate Gaspelin et al.'s (2016) Experiment 4, our research questions required adjustments of the original experiment. First, presenting onset letters already in the cueing display may have altered the top-down and bottom-up signals of the cues and reduced capture effects by onset cues.

Although we tried to facilitate encoding of stimuli in the cueing and target displays into joint event files (e.g., by increasing the color similarities between cues and letters in Experiment 2), we cannot say with certainty whether our display choices sufficed to ensure encoding of these stimuli into one event file. Consequently, the present conditions might have been suboptimal for testing specific predictions of TEC. At the same time, the present results are interesting to those who use contingent-capture protocols free of complications by partial rebinding and unbinding costs of event files.

A further limitation of the present study was the move from controlled laboratory-based experimental conditions to an online-based study format in Experiment 2. With this change of experimental conditions, we had to revert to luminance differences between colors as in Experiment 1 in the online version of Experiment 2. Findings in the online version of Experiment 2 and the laboratory-based Experiment 1 were very similar (see ESM 1). However, one should note the more different results between luminance-equated laboratory version and nonequated online version of Experiment 2. One explanation is an even higher difficulty of the already more difficult searches among equiluminant colors in the laboratory-based version and of searches among unequal luminance colors in the online version of Experiment 2 (and in Experiment 1). This was reflected in higher ERs and RTs in the difficult search conditions of the laboratory-based version than in the online version of Experiment 2.

It is possible that an increased search difficulty altered participants' integration of information across cueing and target displays. In the context of priming, for example, Meeter and Olivers (2006) found that increased ambiguity can lead participants to rely more on episodic memory than on perceptual priming when accessing information of preceding displays. However, Experiment 2 was not planned to investigate this possibility and, therefore, also not sufficiently powered to address this possibility appropriately. Thus, differences between versions of Experiment 2 could also reflect spurious interactions in underpowered mixed ANOVAs (cf. Lakens & Evers, 2014). Due to this reason, we believe that collapsing data from both versions of Experiment 2 are a more conservative approach. Nonetheless, future research should address the question of object-file representations under even more difficult search conditions as in Gaspelin et al. (2016) in an appropriately powered study.

Conclusion

We investigated the hypothesis that validity effects interact with object-file updating costs, which could occur when features at the target's location change from the cueing to target displays. Overall, the present experiments suggest that feature relationships between cueing and target displays and search difficulty jointly modulate how efficiently the target can be identified and reported. Previous studies that reached divergent conclusions regarding occurrence of object-file updating costs often differed regarding the choice of stimuli and the difficulty of the search task. The present results suggest that close scrutiny should be placed on these factors to better understand if object-file updating costs might contribute to the efficiency of target identification. In conclusion, the current findings illustrate that human perception integrates stimulus features across time, and stimuli from successive cueing and target displays are not necessarily processed as separate objects, which is important to reach a full understanding of the mechanisms that underlie spatial validity or cueing effects (cf. Carmel & Lamy, 2014).

Electronic Supplementary Material

The electronic supplementary material is available with the online version of the article at https://doi.org/10.1027/1618-3169/a000511

ESM 1. Additional analyses including the influence of experiment version (laboratory-based, online).

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