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ORIGINAL ARTICLE

Learned cognitive control counteracts value-driven attentional capture

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Abstract

Stimuli formerly associated with monetary reward capture our attention, even if this attraction is contrary to current goals (so-called value-driven attentional capture [VDAC], see Anderson (Ann N Y Acad Sci 1369:24–39, 2016), for a review). Despite the growing literature to this topic, little is known about the boundary conditions for the occurrence of VDAC. In three experiments, we investigated the role of response conflicts and spatial uncertainty regarding the target location during the training and test phase for the emergence of value-driven effects. Thus, we varied the occurrence of a response conflict, search components, and the type of task in both phases. In the training, value-driven effects were rather observed if the location of the value-associated target was not predictable and a response conflict was present. Value-driven effects also only occurred, if participants have not learned to deal with a response conflict, yet. However, the introduction of a response conflict during learning of the color-value association seemed to prevent attention to be distracted by this feature in a subsequent test. The study provides new insights not only into the boundary conditions of the learning of value associations, but also into the learning of cognitive control.

In today's society, money can act as a mediator or a substitute for achieving a satisfaction of particular needs (Oleson, 2004). Thus, effort was put into investigating how monetary rewards affect different aspects of human behavior such as attention (see Chelazzi et al., 2013, for a review). Hübner and Schlösser (2010), for instance, showed that the expectation of reward alone can influence performance in a specific task by increasing attentional effort. But reward can also interfere with performance: Under the expression 'value-driven attentional capture' (VDAC), the distracting effect of reward- (or *value-*) associated stimuli on attention recently became a hot topic (e.g., Anderson et al., 2011a, 2012; Marchner & Preuschhof, 2018; Mine & Saiki, 2015, 2018; Roper et al., 2014; Theeuwes & Belopolsky, 2012). VDAC is considered to be a subcategory of *selection history* —a superordinate term for different phenomena where the allocation of attention is influenced by stimuli due to previous selection experiences with them (Awh et al., 2012; Failing & Theeuwes, 2018).

VDAC is mostly examined in training-test paradigms (e.g., Anderson et al., 2011a; Theeuwes & Belopolsky, 2012; see Anderson, 2016). In the *training*, a neutral stimulus (feature) is associated with a monetary value via reward learning, and in the *test*, this value-associated stimulus (feature) is used to evaluate its distracting effects on attention. In most studies (e.g., Anderson et al., 2011a, b; Roper et al., 2014), the emphasis was on the distracting effect of already *existing* stimulus- or feature-value associations on attention. Little is known, though, whether VDAC depends on specific aspects of the *learning* of these associations (but see Anderson, 2015), although such knowledge could enlighten underlying mechanisms. In this study, we are interested in a not fully understood aspect of VDAC: Whether response conflicts influence the learning of feature-value associations as well as the occurrence of VDAC and which role spatial uncertainty plays in this context.

This study is also part of the thesis of author Annabelle Walle.

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Response conflict and conflict adaptation

We focus on research, where the Eriksen flanker task (Eriksen & Eriksen, 1974; see Merz et al., 2021, for a review) was used in at least one phase of the training-test approach. The flanker task requires reacting to a central target stimulus, which is flanked by other task-irrelevant stimuli (*flankers*). In the *congruent* condition, the target and the flankers are mapped to the same response category, whereas in the *incongruent* condition, they are mapped to a different category. Participants usually respond slower in incongruent than in congruent trials, which is considered to reflect a response conflict in incongruent trials. We will use the term 'response conflict' for exactly this case, where target and distractor stimuli are associated with different mutually competing responses as it is commonly used in the flanker effect literature (e.g., Hübner & Többel, 2019; Yeung et al., 2004). To be able to choose the correct response in such situations *cognitive control* is necessary (see, e.g., Verguts & Notebaert, 2008). The term broadly encompasses different cognitive processes adjusting our performance to sustain goal-directed behavior in such ambiguous contexts (Abrahamse et al., 2016; Botvinick et al., 2001). It is assumed that differences in control are reflected by different magnitudes of the congruency effect (Verguts & Notebaert, 2008). Most research focused on the sequential adaptation of cognitive control by showing that the congruency effect is attenuated following an incongruent trial (e.g., Gratton et al., 1992). However, Goschke and Dreisbach (2008) showed that even in the conflict trial itself, cognitive control is adapted in a way that current task goals are shielded from other information. Such shielding might be based on the presence of task representations resulting in the attentional focus being constricted on these stimulus features which help to distinguish the correct from the wrong response (Dreisbach & Haider, 2009). Note that these necessary task representations can also develop over time by associative learning (Dreisbach & Haider, 2009, Experiment 3).

Evidence suggests that associative learning might play an even more crucial role in the adaptation to conflicts (see Abrahamse et al., 2016, for a review), which is reflected in the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009; see also Abrahamse et al., 2016): In its core, the model assumes that the occurrence of response conflicts can modulate associative learning, which in turn affects cognitive control. But how does this modulation take place in more detail? In the following, this will be illustrated in the context of the incongruent trials of the flanker task. In these trials, a conflict monitoring system registers the occurrence of response conflicts signaling the need to adapt cognitive control and subsequently forwards this information to a neuromodulatory system. The system in turn sends an arousal response which consequently leads to improved associative learning within the active representations of the current task. According to Verguts and Notebaert (2009; see also Braem et al., 2014a) the active representations especially contain but are not limited to the task-relevant representations. Thus, in our flanker task example, the active representations might, for instance, contain the representation of the task demands, the target, and the corresponding response. The improvement in associative learning is achieved by strengthening the bindings of the mostly task-relevant representations, resulting in increased cognitive control and, thus, less interference by conflicting information, i.e., in case of the flanker task less interference by the distractors.

Given the relevance of associative learning in VDAC (see Chelazzi et al., 2013), it seems reasonable to assume that occurring response conflicts might influence the learning of the value association and later VDAC. Therefore, an integration of the two lines of research seems crucial, which is the aim of the present study. In the following, we review the few studies already combining the two research lines. However, in most of them the authors did not take an integrative perspective on the mechanisms of VDAC and conflict adaptation.

Conflict tasks in VDAC training-test paradigms

When focusing on training-test paradigms and how response conflicts might influence the learning of the value association and VDAC, three scenarios are conceivable: First, a non-conflict task is used in the training, and a conflict task in the test. Anderson et al. (2012) used a non-conflict-search task in the training and a flanker task in the test, where the flankers were shown in formerly value-associated colors. They found no value-driven effects in the training, but a larger congruency effect in the high value relative to the low value condition in the test. Second, a conflict task is used in the training, and a non-conflict task in the test. Mine and Saiki (2018, Experiment 1) showed VDAC in a non-conflict-search task in the test following learning of the value association in a flanker task. In the training, no value-driven effects were found (see also Mine & Saiki, 2015, Experiment 1, Experiment 2, and Experiment 4). Third, conflict tasks are used in the training *and* the test. An example of such a setup is the study of Sha and Jiang (2016, Experiment 2) although these authors might have inadvertently introduced a response conflict in the two phases: In their training, participants looked for a colored circle among other circles and categorized a line within this circle as horizontal or vertical. The target color was associated with a high or low value in Experiment 2a and with a high value or no value in Experiment 2b. In the test, participants looked for a specific form among other forms and also categorized the line within regarding its orientation. The value color was now part of a distractor. Crucially, the distractors in the training and the test also contained lines. But contrary to most VDAC studies (e.g., Anderson et al., 2011a, b; Marchner & Preuschhof, 2018), where the lines in the distractors differed in orientation (tilted) from the target line orientations (horizontal or vertical), Sha and Jiang (2016, Experiment 2) presented distractors also containing horizontal or vertical lines. With this setup, a response conflict was introduced in each trial, since at least some of the lines within the distractors (horizontal or vertical) were associated with the opposite response than the line within the target (also horizontal or vertical; see Becker et al., 2020, for a similar reasoning). They observed that the value association influenced attention in the training, but not in the test. This is opposite to the results of most studies, in which often no value-driven effects were observed in training but in test (e.g., Anderson et al., 2011b, 2012; 2013a, b; Anderson & Halpern, 2017, Experiment 1; Kim & Beck, 2020; Miranda & Palmer, 2014; Roper et al., 2014; but see Anderson & Yantis, 2012; Marchner & Preuschhof, 2018).

Interpretation of the study results

Sha and Jiang's (2016, Experiment 2) results have been discussed regarding whether learned value associations even drive VDAC in the test at all (Sha & Jiang, 2016), or whether the lack of VDAC results from differences in the experimental procedure, or is simply an expression of a Type-II error (Anderson & Halpern, 2017). But from a response conflict perspective, there is an alternative explanation: In Sha and Jiang's (2016, Experiment 2) training and test, a response conflict emerged on every trial (Becker et al., 2020). In the training, the value-associated color was part of the target and thus, an integral part of resolving the conflict, since participants searched for this specific colored circle. Consequently, the value-associated color was also part of the active task-relevant representations. Following the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009), the continuous detection of a response conflict in combination with the possibility to earn a specific reward should result in a strengthening of the associations between the different elements of the active task representations and, therefore, also of the color-value association. The strengthened color-value association should be more strongly associated to the other task-relevant representations (e.g., the perceptual representation of the target), too. In consequence of these stronger associations, improved attentional prioritizing of the different value colors might have taken place, leading to rather observable effects of value associations on attention in the training relative to training search tasks without response conflicts (e.g., Anderson et al., 2011b). In the test, the value color emerges in a new context (being part of a distractor). At the same time, although the target is now characterized by a different form, the associations between task-relevant representations (such as the perceptual representation of the target line or the corresponding response association) might be highly strengthened due to the conflict training. As a result, cognitive control might already be highly efficient and protect the processing of goal-relevant information from interferences (the value distractor) in a similar way as it was proposed by Goschke and Dreisbach (2008; see also Dreisbach & Haider, 2009) in their shielding assumption. Consequently, no VDAC should be observable.

Thus, in training-test paradigms including response conflicts, if participants have not learned how to deal with a conflict yet, results might be explainable within the adaptation-by-binding model. If, however, participants have already learned how to perform efficiently despite the presence of a conflict, shielding might take place due to that preceding learning experience.

Does this explanation also fit the results of other studies, in which a flanker task was used either in test (Anderson et al., 2012) or training (Mine & Saiki, 2018, Experiment 1)? In the first case with a non-conflict training and a conflict test (Anderson et al., 2012), based on the results of previous studies (e.g., Anderson et al., 2011b; Kim & Beck, 2020; Roper et al., 2014),[1] a value effect was rather not to be expected and indeed not observed in the training. In the test, the value-associated color was presented in the flankers and the magnitude of the value association modulated the congruency effect, indicating that especially the color associated with high value acquired attentional priority. In the beginning of the test phase, it can be assumed that the value-associated flanker was part of the active mental representation. Simultaneously, participants were confronted with a response conflict. Since the occurrence of a conflict should act like a learning signal for conflict adaptation (Verguts & Notebaert, 2008, 2009), associations between the active mental representations might be strengthened. Consequently, the color-value association might also be further reinforced and accidentally bound more strongly to the other active mental representations thereby affecting cognitive control.

In the second case with a conflict training and a non-conflict test (Mine & Saiki, 2018, Experiment 1), there was no value-driven effect in the training, contrary to Sha & Jiang's (2016, Experiment 2) results. A reason for this difference might be that Mine & Saiki (2018, Experiment 1) used rather hypothetical values for the association with the colors, which might have resulted in weak color-value associations:

[1] Note that from a theoretical perspective, a value effect should also be found in this kind of task (see, e.g., Sha & Jiang, 2016). Nevertheless, often no such effect is observed (e.g., Anderson et al., 2011b; Kim & Beck, 2020; Roper et al., 2014). One reason could be a ceiling effect. Alternatively, participants could use other features than the value color to find the target (Walle & Druey, 2021).

Participants received value-related feedback during training, but actually did not earn the total generated (see Anderson & Halpern, 2017, for a critical discussion of payoff schemes). In the test, the value-associated feature was presented as part of a distractor in a new task without conflict. Consequently, this distractor might have attracted attention and produced observable VDAC. Simultaneously, no response conflict signaled the need to further adjust cognitive control.

The present study

Despite the studies discussed, any systematic investigation of the interplay between VDAC and conflict adaptation is lacking. This study provides a first step in this direction, by combining conflict and non-conflict tasks along the scheme outlined above and testing the derived assumptions. To anticipate some results, our findings suggest that besides response conflicts, spatial uncertainty about the target location could also play a role for VDAC. Therefore, across three experiments, we varied whether response conflicts and spatial uncertainty (i.e., search components) were present in training and/or test.

In Experiment 1, we aimed at conceptually replicating and extending the results of Anderson et al. (2012) by using a non-conflict-search task during training, and a flanker task during test. The main difference to the original study was the integration of two additional conditions not associated with a response (neutral and no flankers). They served to investigate whether VDAC also occurs in such conditions. In Experiment 2, comparable with Experiment 1 of Mine and Saiki (2018, see also 2015), we used a flanker task in the training. However, different from that study, a flanker task was also used in the test. This enabled us to examine whether Mine and Saiki's (2018, Experiment 1) result in their training can be conceptually replicated, if participants gain the value used to establish the color-value association. Moreover, we examined the role of response conflicts during training for the occurrence of VDAC in the test. In Experiments 3a and 3b, we used a training similar to Sha and Jiang (2016, Experiment 2; see also Walle & Druey, 2021) and manipulated task structure (search or flanker task) in the tests. By doing so, we (a) investigated whether Sha and Jiang's (2016, Experiment 2) results can be conceptually replicated and (b) tried to separate processing mechanisms responsible for the occurrence of VDAC, specifically, conflict-based and search-based mechanisms.

Experiment 1

The experiment consisted of two phases. In the training, participants had to search for a circle in one out of two possible colors, and then categorize a line within this circle regarding its orientation. Each of the colors was associated with either a low or a high reward in case of a correct response. In the test, we used a flanker task with letters as stimuli. Different from Anderson et al. (2012), we established four conditions of response association by manipulating the type of flanking letters accordingly. This was done to investigate value effects if no response was associated to the flankers. The flanking letters were either associated with a response (congruent/incongruent) or with no response (neutral/no flankers). With no flanker letters being present in the flanker-absent trials, it would not have been possible to present the value-associated color had it been bound to the flanker letter as in the study of Anderson et al. (2012). Thus, we separated the value-associated color from the letters by presenting a colored frame around the flanker letters in all conditions. As in the Anderson et al. (2012) study, we expected no value effects in the training, but a modulation of the congruency effect during the test. For the neutral and the no flanker condition, the expectations were not as clear. No VDAC in these conditions would indicate that the response associations of the flankers have an influence on the occurrence of VDAC in this task setup.

Methods

Participants

The final sample[2] consisted of 25 participants (15 female, 10 male), from which one participant was excluded due to non-compliance with the task instructions. The sample was recruited via the online recruitment platform "SONA" of the University of Konstanz. Participants were 24.21 years in average (range 19–30 years) and had normal or corrected-to-normal vision and no color blindness by self-report. All participants took part in the study in exchange for a payment which consisted of 6 € and a varying additional 0 to 6 € related to the performance in the training (average earnings: 11.66 €). The study was in agreement with the ethical standards of the 1964 Declaration of Helsinki and its later amendments as well as the ethics and safety guidelines of the University of Konstanz. All participants were informed about being able to abort the experiment at any time without any negative repercussions and provided informed consent by checkmarking a box. Without this checkmark, the experiment did not start.

[2] Initially, we recruited 24 participants. However, we did not establish a uniform payment for those participants, meaning they could choose to receive either the full amount of money earned, or course credit in exchange for 10 € of the amount earned, plus the remaining entitlement. Due to discussion and suggestions in literature relating to the appropriate payment in tasks of this type (Anderson & Halpern, 2017), we excluded the 17 participants with the "hybrid" payment and replaced them with new participants.

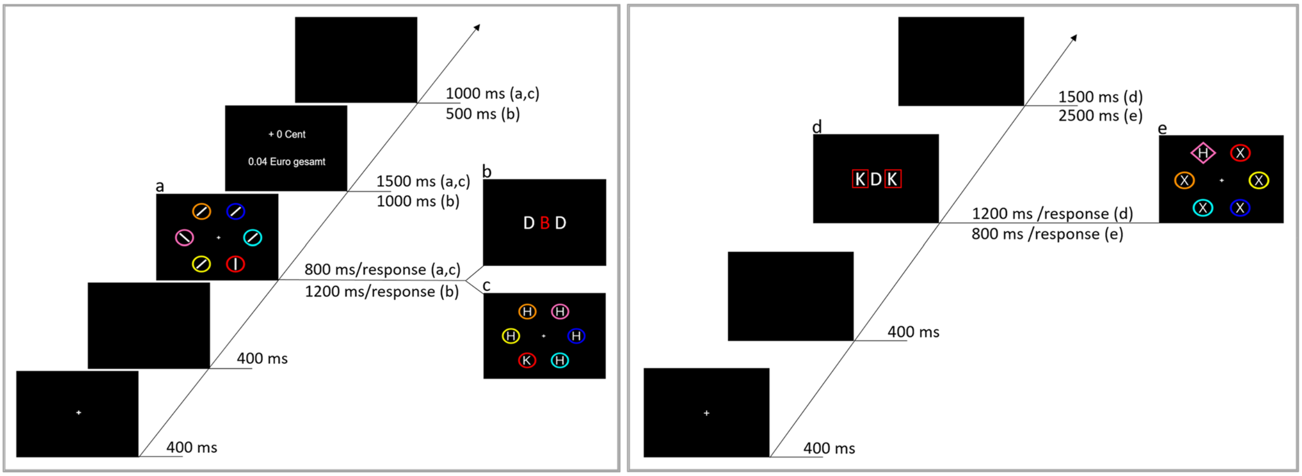

Fig. 1 Task and procedure of a trial within the experiments. Note: Left panel: Trial sequences in the training phases in Experiment 1 (**a**), Experiment 2 (**b**), and Experiment 3a and 3b (**c**). In the example, the red circle or letter is the target. Right panel: Trial sequences in the test phases of Experiments 1, 2 and 3b (**d**), and Experiment 3a (**e**). The letters in parentheses indicate, to which experiment the respective timings belong. 800 ms/response means that the display disappeared after 800 ms or earlier if a response was entered

Apparatus and software

Stimuli were presented on a 23.8-inch color monitor (Fujitsu B24-8TE Pro), with a resolution of 1920 × 1080 pixels and a refresh-rate of 60 Hz. Viewing distance was approximately 60 cm. PCs running on a Windows 10 Pro operating system were used for stimulus presentation. The experiment was programmed in JavaScript, HTML/CSS, and ran in Google Chrome (versions 62–63). A German QWERTZ-keyboard was used for response recording. The experiment took place in a group laboratory with up to nine spaces.

Materials and task

All instructions were displayed against a light blue background, whereas training and test tasks were displayed against a black background.

Training

We used a visual search task, with the search display containing six colored circles at equal distances from one another on an imaginary circle with midpoint at the center of the screen, which was marked by a white fixation cross (see Fig. 1). The fixation cross was about 0.39° in width and height. The distance between the midpoint of each circle and the midpoint of the display was 3.90°. Each circle had a diameter of 1.97°. The circles could be separated in targets and distractors according to the color of their border. Distractors could be displayed in the colors yellow (rgb: 255, 255, 0), hotpink (rgb: 255, 105, 180), darkorange (rgb: 255, 140, 0), blue (rgb: 0, 0, 255) or cyan (rgb: 0, 255, 255), and each distractor had a different color within a trial. Within each distractor, a line (width: 0.21°, height 1.55°) was displayed, which was tilted 45° to the left or to the right. Distractor colors and line orientations were chosen randomly. Targets had a lime (rgb: 0, 255, 0) or red (rgb: 255, 0, 0) colored border, and the line in these circles was either horizontally or vertically aligned. Each combination of target color and line orientation was presented equally often, but order of appearance was randomized. The participants' task was to look for the lime or red circle and categorize the line orientation within that circle by pressing the "Y"- or "M"-key on the keyboard. The response mapping to each orientation was counterbalanced across participants.

Test

We used a flanker task, in which the letters "H", "K", "B", "D", "X", and "S" served as stimuli. Their size was approximately 1.84° (width) by 2.49° (height). The flanker display consisted of three letters—one central target and two identical flankers—with identically colored rectangles around both flankers. The center-to-center distance (eccentricity) from one letter to next was 3.41°. Participants had to categorize the middle letter into the two categories [B, K] or [D, H] by clicking either the left or the right mouse key. The mapping of each category to both keys was counterbalanced across participants. We used different response sets for the training (keys on the keyboard) and the test (keys on the mouse) to avoid any indirect response-color association to emerge between tasks. There were four congruency conditions: In the *congruent* condition, target and flankers were mapped to the same response key (e.g., B K B). In the *incongruent* condition, the flankers and the target letter were mapped to different response keys (e.g., D K D). In the *neutral* condition, the flankers were not mapped to any response key (e.g., X K X) and in the *no flanker* condition, no flankers were shown.

The outline rectangles around the flanking letters were shown in one of the two former target colors from the training, with each color presented equally often (see Fig. 1). Their size was 3.67° (width) and 3.80° (height). All possible combinations of the various congruency and color conditions were mixed in each block and presented in a randomized order. The white fixation cross was presented in a size of about 1.31° (width) by 1.31° (height).

Procedure

Training

The training consisted of four blocks of 60 trials each. Participants could take a short rest between the blocks. A trial consisted of the following sequence of events (see Fig. 1a): First, a fixation cross was presented at the display center for 400 ms, followed by a blank screen for another 400 ms. This blank screen was replaced by the search display, which remained on screen until the participants responded or 800 ms passed. If no response was registered within these 800 ms, a blank screen was presented until response. After a response was registered, a feedback display appeared for 1500 ms, accompanied by a short sound presented for 100 ms in case of an erroneous response. The feedback consisted of the reward gained in the current trial and the total earnings so far. Participants could gain either 1 or 4 eurocents on each trial, depending on the color of the target circle and their performance. Each of the two target colors served as either a high or a low value color counterbalanced across participants. In the case of a high value color, the participants won 4 cents in 80 percent of the trials, and 1 cent in the remaining 20 percent, and vice versa for the low value color. The association of color with both values was counterbalanced across participants. In the case of an erroneous response, an "earning" of zero cent was displayed. Each trial ended with a blank display presented for 1000 ms.

Test

The test consisted of eight blocks of 80 trials each. Participants practiced the task in ten additional trials at the beginning. A trial (see Fig. 1d) started with a fixation cross presented at the center of the screen for 400 ms, followed by a blank screen for another 400 ms. Then, the flanker display appeared and remained on screen either until the participants responded, or a duration of 1200 ms was exceeded. If no response was registered within these 1200 ms, a blank screen was presented until response. In the case of an incorrect response, a feedback sound was presented for 100 ms. At the end of each trial, a blank display appeared for 1500 ms before the next trial started.

Data preparation

For the RT analyses, only correct trials were considered. Trials with RTs shorter than 150 ms or more than three standard deviations above the RT mean of the correct trials (separately for each condition and participant) were considered outliers and excluded. To evaluate the probability that there is a VDAC effect and an interaction of congruency by value association relative to the corresponding null hypotheses, we conducted Bayesian analyses (see Kass & Raftery, 1995; Wagenmakers et al., 2018 for reviews) in all experiments. In simple terms, the Bayes factor (BF) can be seen as a plausibility index, i.e., it indicates how plausible the observed data are, given a specified model relative to the null model or any other model. For instance, the first model could be the alternative hypothesis and the latter the null hypothesis. In this example, a BF of 4 indicates that the data is four times as probable under the alternative hypothesis than under the null hypothesis. Using Bayesian analyses also allows to provide support for the null hypothesis, which is indicated by a BF below 1. For instance, a BF of 0.25 means that under the current data the null hypothesis is four times as probable than the alternative hypothesis. For clarity, we report the BFs always in the direction of the alternative hypothesis. To classify the results, we use the nomenclature adapted by Wetzels and Wagenmakers (2012) from Jeffreys (1961). We only considered BFs, which were at least substantial as supportive evidence (BFs > 3 or BFs $< \frac{1}{3}$).

We used the "BayesFactor" package in R statistics (Morey & Rouder, 2018; R Core Team, 2019) with its default settings, if not stated otherwise. Thus, all Bayesian *t* tests (Rouder et al., 2009) were conducted with a default prior of $r = 0.707$. For the Bayesian ANOVAs (Rouder et al., 2012) *r* was set to 0.5 for fixed effects and the prior for the random effect to "nuisance". Bayesian *t* tests and ANOVAs were conducted with 1.000.000 iterations. Our strategy of analysis for Bayesian ANOVAs was based on the approach used by Souza and Oberauer (2015).

Results

Training

The trim procedure resulted in excluding 1.91% of the data. The overall accuracy was 93.86%. To investigate, whether

Table 1 Results of the Bayesian ANOVA for the RTs in the test phases of Experiments 1, 2, 3a and 3b

	Model			
	cong + id	val + id	cong + val + id	cong + val + cong × val + id
Exp. 1				
Each model/null model	19,027,098 ± 0.2%	0.87 ± 1.96%	45,788,781 ± 0.44%	25,321,121 ± 0.48%
Best model/each model	2.41 + 0.48%	52,645,522 ± 2.00%	1	1.81 ± 0.65%
Exp. 2				
Each model/null model	236,413 ± 0.35%	0.31 ± 1.24%	87,023.57 ± 0.44%	29,488.35 ± 0.87%
Best model/each model	1	760,607.8 ± 1.29%	2.72 ± 0.56%	8.02 ± 0.94%
Exp. 3a				
Each model/null model	0.23 ± 0.36%	0.27 ± 0.26%	0.06 ± 0.48%	0.02 ± 0.90%
Best model/each model	4.42 ± 0.36%	3.71 ± 0.26%	16.52 ± 0.48%	57.42 ± 0.90%
Exp. 3b				
Each model/null model	45.16 ± 0.29%	0.21 ± 0.46%	9.77 ± 0.38%	3.24 ± 0.67%
Best model/each model	1	210.85 ± 0.54%	4.62 ± 0.48%	13.92 ± 0.73%

The first line refers to the comparison between the specified model and the null model (i.e., a model with only the random participant variable). The second line refers to the comparison between the best model and the specified model. For each model, we report the BF and an additionally estimate how stable the results are, given the algorithm used to calculate it

cong congruency (congruent vs. incongruent), *val* value (high vs. low), *id* participant

responses to high versus low value targets differed, separate Bayesian dependent *t* tests were conducted for the RTs and the error data. We found evidence for the null hypothesis, i.e., there was no difference between high (M_{high} = 718 ms, SD_{high} = 145 ms) versus low value targets (M_{low} = 730 ms, SD_{low} = 148 ms) in the RTs, BF_{H1} = 0.43 ± 0%. For the error data, there was support for the null hypothesis, BF_{H1} = 0.22 ± 0.03%, (M_{high} = 6.22%, SD_{high} = 4.44%, M_{low} = 6.07%, SD_{low} = 4.50%).

Test

Due to the trim procedure, 1.76% of the data were excluded. The accuracy in the remaining data was 93.57%.

Response times

Data were analyzed by means of a two-way repeated measures Bayesian ANOVA with the factors value (high vs. low) and congruency (congruent vs. incongruent). We only included the response-related congruency conditions in this analysis to be able to compare our results with those of Anderson et al. (2012). The analysis revealed that by comparing all possible models to the null model, the model with the two main effects outperformed the other models, BF_{H1} > 100. Moreover, this model was about 1.81 times more probable than the next best model (full model, see Table 1). Visual inspection of the data showed that participants were slowest in the incongruent trials, and fastest in the congruent ones (see Fig. 2).

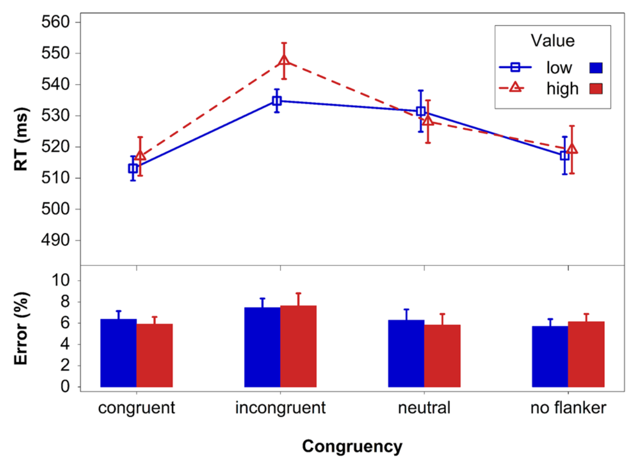

Fig. 2 Mean RT and error rates for the four congruency conditions in the test of Experiment 1. Note: Error bars represent the within-subject confidence intervals as recommended by Morey (2008)

Next, we focused on the effects of value in general by conducting Bayesian *t* tests separately for each of the four congruency conditions. These revealed an effect in the incongruent trials: high value resulted in slower responding compared to low value, BF_{H1} = 4.60 ± 0%. In other words, it was 4.60 times more probable that high and low value differed in the incongruent condition relative to the assumption according to the null hypothesis that there is no difference. However, there was no support for an effect of value in the other congruency conditions, range BF_{H1} = 0.22–0.29, range error estimate: 0.03–0.04%.

Table 2 Results of the Bayesian ANOVA for the error data in the test phases of Experiments 1, 2, 3a and 3b

	Model			
	cong + id	val + id	cong + val + id	cong + val + cong × val + id
Exp. 1				
Each model/null model	2.33 ± 0.25%	0.22 ± 0.23%	0.53 ± 3.11%	0.16 ± 0.43%
Best model/each model	1	10.67 ± 0.34%	4.41 ± 3.12%	14.43 ± 0.5%
Exp. 2				
Each model/null model	3.85 ± 0.2%	0.21 ± 0.35%	0.84 ± 1.65%	0.25 ± 1.51%
Best model/each model	1	17.98 ± 0.4%	4.58 ± 1.66%	15.33 ± 1.52%
Exp. 3a				
Each model/null model	1.28 ± 0.2%	0.24 ± 0.24%	0.30 ± 0.60%	0.10 ± 6.42%
Best model/each model	1	5.45 ± 0.31%	4.21 ± 0.63%	13.39 ± 6.42%
Exp. 3b				
Each model/null model	0.89 ± 0.22%	1.64 ± 0.69%	1.58 ± 0.55%	0.45 ± 0.58%
Best model/each model	1.84 ± 0.73%	1	1.03 ± 0.89%	3.64 ± 0.90%

The first line refers to the comparison between the specified model and the null model (i.e., a model with only the random participant variable). The second line refers to the comparison between the best model and the specified model. For each model, we report the BF and an additionally estimate how stable the results are, given the algorithm used to calculate it

cong congruency (congruent vs. incongruent), *val* value (high vs. low), *id* participant

Error data

We analyzed the error data by means of a Bayesian repeated measures ANOVA with the two factors value (high vs. low) and congruency (congruent vs. incongruent) first. As can be seen in Table 2, the congruency-only model fitted the data best relative to the null model, which was the next best model. However, the BF in favor of the congruency model was only anecdotal ($BF_{H1} = 2.33$). Error rate was the highest in the incongruent condition.

Separate Bayesian *t* tests for each of the four congruency conditions revealed that there was no value effect in any congruency condition, range $BF_{H1} = 0.22$–0.28, range error estimate: 0.03%–0.04%.

Discussion

We used a training-test paradigm similar to Anderson et al. (2012) with a search task in the training and a flanker task in the test. As in many training-test studies (e.g., Roper et al., 2014), we did not observe any value effect in the training. In the test, we observed VDAC only in the incongruent trials indicated by increased RTs for high value relative to low value flankers. Although we did not find a reliable interaction, we replicated the basic pattern Anderson et al. (2012) observed, however slightly shifted: Whereas in their data, high value (compared to low value) produced a benefit in congruent trials and only a small disadvantage in incongruent ones, we observed no benefit in congruent trials, but substantial costs in incongruent ones. In the Anderson et al. (2012) study, the value-associated color was integrated into the flankers. Thus, in the congruent condition, if the value flanker attracted attention, the correct response might be primed stronger, resulting in faster RTs in the high value than the low value condition. In our experiment, the value-associated color was spatially separated from the flanker, making such priming rather unlikely.

Our results can be interpreted with the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009): If the value-associated color is attentionally prioritized (see Anderson, 2016, for a review), the color-value association should also be actively represented in incongruent trials. The occurrence of a response conflict in these trials results in binding the elements of the active task representation stronger together. Thus, there might also be a strengthened linkage between the color-value association and the other elements actively represented, i.e., also the elements necessary to solve the conflict. For instance, the value-associated rectangles could be bound stronger to the mental representation of the target, resulting in the flankers within the rectangles increasingly interfering with response selection. In conditions, where no conflict occurred, the color-value association should not be associated as strongly with other elements of the active task representation. Moreover, top-down control might more easily counteract interferences by the distractors in these conditions (e.g., by suppressing the distractor so that it does not attract attention, see Gaspelin & Luck, 2018; Sawaki & Luck, 2010) resulting in rather less observable value effects.

However, there are also alternative explanations: Our results could simply mirror little generalization of the learned value associations to the test if different tasks are used. But since a transfer of value associations has been observed from one task to another in previous studies (e.g., Anderson et al., 2012; Mine & Saiki, 2015, 2018), we considered this explanation as unlikely. Moreover, it is also conceivable that there might have been a transfer of the color-value association from the training to the test phase, but VDAC was only observable in the incongruent trials, since in the other conditions a ceiling effect occurred.

Experiment 2

In Experiment 1, a response conflict occurred for the first time in the test phase and VDAC emerged only in the incongruent condition. However, Sha and Jiang (2016, Experiment 2) did not find VDAC in a test phase with conflicts, if the conflicts were already part of the training. This might indicate that cognitive control was already highly efficient in the test due to the conflict adaptation learning (Verguts & Notebaert, 2008, 2009) in the training. Since the value association was now presented in a new context (as part of a distractor), attention might be shielded from the interferences of this association (see Dreisbach & Haider, 2009; Goschke & Dreisbach, 2008). In Experiment 2, we examined this assumption by using a flanker task in both phases and, thus, integrating the conflict already in the training.

In the training, in line with the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009), value-driven effects should emerge, at least in the incongruent trials. However, with a similar training task, Mine and Saiki (2015, 2018, Experiment 1) did not find value-driven effects in four out of five experiments. It is though possible that their results are due to them providing only hypothetical values for the color-value association. Our experimental design enabled us to examine the replicability of their results if participants indeed earn the instructed rewards.

In the test phase, three outcomes are conceivable: First, in line with the shielding assumption, VDAC does not emerge in any condition. Second, VDAC only occurs in the incongruent trials, replicating the findings of Experiment 1. While this result would be explainable in the context of the adaptation-by-binding model, it would not support the shielding assumption. Third, VDAC emerges in every condition, indicating that the results in Experiment 1 were caused by little generalization of the value association from training to test.

Methods

Participants

Twenty-four new participants (19 women and 5 men) took part in the study. The average age was 22.62 years (range 19–30 years). The participants received a payment, which consisted of 6 € (for the test) plus up to 6.40 € performance-contingent (for the training). The average payment was 11.99 €. All other conditions participants had to meet were identical to Experiment 1.

Apparatus, software, material, task, and procedure

The same apparatus and software were used as in Experiment 1. We used a flanker task in each phase. The test phase was identical to the one of Experiment 1, with the exception that we removed the practice trials, because the participants were already familiar with the task from the training. The task comprised 640 trials which were divided into 10 blocks. For the training, we adapted the flanker task: To create associations between specific colors and values, similarly as in the search task of Experiment 1, the corresponding value color was integrated in the target. Participants made the categorization task by pressing the "Y"- or "M"-key. The mapping was counterbalanced across participants, where the side of a response key corresponding to a particular response remained the same between test and training within one participant. We removed the practice trials to make the training comparable to the one in Experiment 1. Other changes concerned the trial procedure and the payoff scheme: Instead of a blank display after a registered response, a feedback display was presented, which informed about the money earned in the current trial and the total earnings up to now. The timing of the different displays mirrored the timing of the flanker task in the test (see Fig. 1b). Thus, the task display was presented for 1200 ms, the feedback for 1000 ms, and the blank between trials for 500 ms. We raised the trial number in the training to 256, which led to 128 trials per block, to ensure that all targets were combined with every flanker stimulus equally often. The payoff scheme was the same as in Experiment 1 with one exception: Due to the slightly higher number of trials, the probabilistic reward scheme had to be adapted. Instead of an 80/20 scheme for the respective high/low or low/high payment of each color, we implemented a 75/25 scheme as otherwise not every target-flanker-color-combination would have been presented with the rarer reward with equal probability. Trim and exclusion procedures were identical to Experiment 1.

Table 3 Results of the Bayesian analyses of variance for the RT and error data in the training phases of Experiments 2 and 3ab

	Model cong + id	val + id	cong + val + id	cong + val + cong × val + id
Exp. 2				
RT				
Each model/null model	3.56 ± 0.35%	0.25 ± 0.41%	0.90 ± 0.35%	0.28 ± 0.9%
Best model/each model	1	14.15 ± 0.54%	3.97 ± 0.5%	12.61 ± 0.96%
ER				
Each model/null model	14.17 ± 0.19%	0.22 ± 0.31%	3.12 ± 0.55%	1.22 ± 0.49%
Best model/each model	1	64.67 ± 0.36%	4.55 ± 0.58%	11.64 ± 0.53%
Exp. 3ab				
RT				
Each model/null model	10.59 ± 0.26%	126.43 ± 0.72%	2063.92 ± 0.60%	870.99 ± 0.92%
Best model/each model	194.82 ± 0.65%	16.32 ± 0.93%	1	2.37 ± 1.09%
ER				
Each model/null model	1,178,939,975 ± 0.91%	0.16 ± 0.25%	186,729,731 ± 0.54%	54,453,917 ± 2.54%
Best model/each model	1	7,406,680,352 ± 0.95%	6.31 ± 1.06%	21.65 ± 2.7%

The first line refers to the comparison between the specified model and the null model (i.e., a model with only the random participant variable). The second line refers to the comparison between the best model and the specified model. For each model we report the BF and an additional estimate how stable the results are, given the algorithm used to calculate it

cong congruency (congruent vs. incongruent), *val* value (high vs. low), *id* participant, *RT* response time, *ER* error

Results

Training

Overall, 1.87% of the data were excluded. The accuracy in the remaining data was 93.80%.

Response times

We analyzed the data by means of a two-way repeated measures Bayesian ANOVA with the factors value (high vs. low) and congruency (congruent vs. incongruent). The congruency-only model was around 3.56 times more probable than the null model (see Table 3), which was the next best model. Visual inspection of Fig. 3 revealed that participants were slower in the incongruent relative to the congruent condition.

To further investigate whether the two value conditions differ on the four levels of the factor congruency, Bayesian *t* tests were conducted. All tests supported the null hypothesis, range $BF_{H1} = 0.22–0.64$, range error estimate: 0–0.04%.

Error data

We conducted a congruency (congruent vs. incongruent) by value (high vs. low) Bayesian repeated measures ANOVA. Again, the model with only the factor congruency outperformed the null model, being 14.17 times more probable (see Table 3). Moreover, this model was also about 4.55 times more probable than the next best model (model with both main effects). Participants made the most errors in the incongruent condition compared to the congruent one (see Fig. 3).

To further investigate, whether the two value conditions differ on the four levels of the factor congruency, Bayesian *t* tests were conducted. All tests supported the null hypothesis, range $BF_{H1} = 0.22–0.31$, range error estimate: 0.03–0.04%.

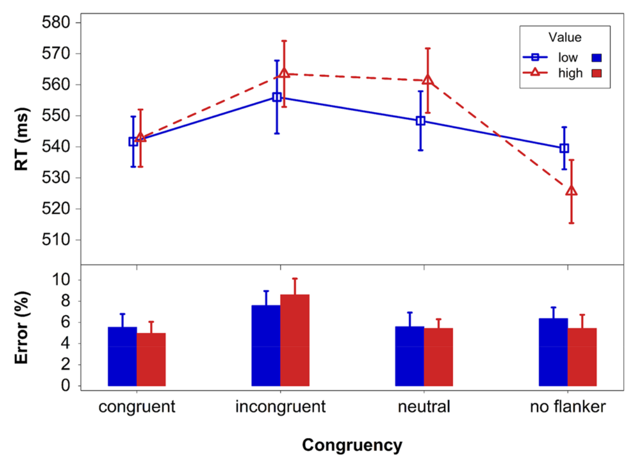

Fig. 3 Mean RT and error rates for the four congruency conditions in the training of Experiment 2. Note: Error bars represent the within-subject confidence intervals as recommended by Morey (2008)

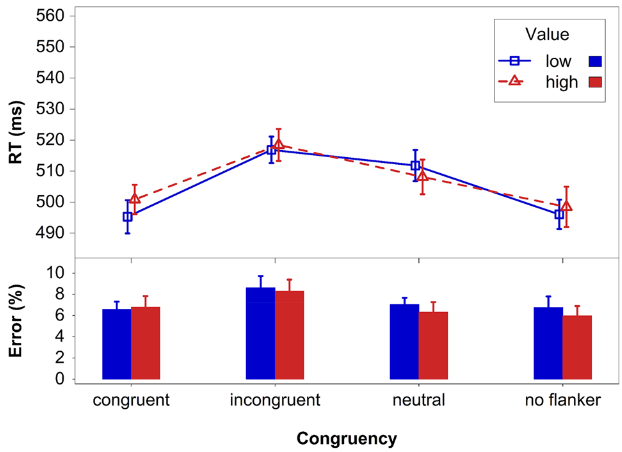

Fig. 4 Mean RT and error rates for each congruency and value condition in the test of Experiment 2. Note: Error bars represent the within-subject confidence intervals as recommended by Morey (2008)

Test

Data trimming resulted in excluding 1.70% of the data. In the remaining data, mean accuracy was 92.95%.

Response times

RTs were analyzed by means of a 2 (congruency: congruent vs. incongruent) by 2 (value: low vs. high) repeated measures Bayesian ANOVA. As can be seen in Table 1, the congruency-only model was more than 100 times more probable relative to the null model and outperformed the other models by being 2.72 times more probable than the next best model (model with both main effects). Participants were slowest in the incongruent trials (see Fig. 4).

As in Experiment 1, Bayesian *t* tests comparing the two value conditions were computed for each of the four congruency conditions. All tests supported the null hypothesis, range $BF_{H1} = 0.23–0.41$, range error estimate: 0%–0.04%.

Error data

The same Bayesian ANOVA as for the RTs was also computed for the error data. The congruency-only model was 3.85 times as probable as the null model (see Table 2), which was the next best model. Visual inspection showed that participants made most errors in the incongruent condition (see Fig. 4).

Separate Bayesian *t* tests were computed for each of the four congruency conditions to investigate possible VDAC-effects. All tests supported the null hypothesis, range $BF_{H1} = 0.22–0.32$, range error estimate: 0.03%–0.04%.

Discussion

In Experiment 2, with response conflicts occurring in the training and the test, we did not find any value-driven effect, neither in the RTs, nor the error data of both phases. These results are informative in three ways. First, they exclude the interpretation that the results of Experiment 1 were due to little generalization of the value association from training to test. This is in line with studies in which a response conflict was either part of the training *or* the test (Anderson et al., 2012; Mine & Saiki, 2018, Experiment 1) and in which VDAC occurred in the test. Moreover, it also seems rather unlikely that the results of Experiment 1 were due to ceiling effects in all conditions but the incongruent one, since it is unclear why changing the task in the training phase (Experiment 2) would result in a lack of VDAC in the incongruent trials of the corresponding test phase.

Second, in the training, we did not find value effects and thus, replicated the overall pattern observed by Mine and Saiki (2015, 2018, Experiment 1), although—in contrast to their studies—participants in our task actually earned their performance-contingent reward. This result is challenging, since, based on the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009), one would expect value-driven effects in trainings with a conflict as it was observed by Sha and Jiang (2016, Experiment 2; see also Walle & Druey, 2021). Comparing the task of Sha and Jiang (2016, Experiment 2) with our task, an obvious difference is that in their study, the conflict was part of a visual search task and the value color indicated the target location. In our task, the target was presented in the value color, but its location was always predictable. Possibly, the attentional prioritization of value-associated stimuli (see Anderson, 2016, for a review) might be especially observable in tasks, where the target location is not predictable (as in the training of Sha & Jiang, 2016, Experiment 2). If the location is predictable (as in our training), though, attentional prioritization might not be observable due to a ceiling effect. We will come to this issue in Experiment 3a and 3b again.

Third, in the test, similar to Sha and Jiang (2016, Experiment 2), we did not find value effects, if response conflicts were part of both phases. Participants have presumably already learned to deal with a conflict in the training. In the test, if the value-associated feature appeared in a new context (as part of a distractor) cognitive control might be already highly efficient, resulting in attentional shielding of disruptive information (the value-associated distractors) in line with the shielding assumption (Dreisbach & Haider, 2009; Goschke & Dreisbach, 2008). However, an alternative explanation for the results could be that the color-value association has simply not (yet) or only weakly formed in the kind of task that we used in the training phase. This might result in the color-value association being faster devalued and, thus, in the lack of VDAC in the test phase (see Milner et al., 2020, for one of the few studies examining devaluation in the training-test paradigm). We will discuss this alternative explanation in more detail in the General Discussion.

Experiment 3a and 3b

In the training of Experiment 2 (flanker task), we did not observe value effects. We speculated that this result might be due to the predictability of the target location. Thus, in Experiment 3a and 3b, we investigated the role spatial uncertainty concerning the target location plays for the occurrence of value effects on attention in conflict-training and conflict-test phases. Therefore, we used a visual search task with an integrated response conflict in the training of both sub-experiments (see Braem et al., 2014b, for a similar task). Note that in studies, in which the training was characterized by spatial uncertainty about the target location *or* response conflicts, often no value effects were found in this phase (visual search: e.g., our first Experiment; Anderson et al., 2011b; Anderson & Halpern, 2017; Anderson & Kim, 2019; flanker task: e.g., our second Experiment; Mine & Saiki, 2015, 2018, Experiment 1). From this perspective, finding value effects with this setup would indicate that it is the mixture between spatial uncertainty and the occurrence of conflicts that results in value effects being observable.

A related question is how spatial uncertainty about the target location might affect VDAC in a conflict-test phase. Our results from Experiment 1—where we found VDAC in a flanker task—suggest that spatial uncertainty might not play a role in the test phase. Nevertheless, we investigated this issue in Experiment 3a and 3b. At the same time, our study design enabled us to examine the shielding assumption (see also Dreisbach & Haider, 2009; Goschke & Dreisbach, 2008) in more detail. Experiment 3a and 3b only differed in their test. Whereas in Experiment 3a the same conflict-search task was used as in the training, a flanker task was used in Experiment 3b. If VDAC emerges in the test of Experiment 3a (in contrast to Experiment 2), this indicates that spatial uncertainty about the target location affects the influence of the value-related distractor on attention in conflict-test phases. If, however, no VDAC emerges, this is an indication that participants had learned how to deal with a conflict during the training and, therefore, are able to shield attention from distracting influences irrespective of spatial uncertainty. Analogously, if attentional shielding takes place no VDAC should occur in the flanker-test phase of Experiment 3b either. If, however, VDAC emerges in Experiment 3b, this is additional evidence that spatial uncertainty might not play a role for VDAC in conflict-test phases. However, this result would also indicate that learning of efficient control is task-specific, hence does not generalize to another task (see Braem et al., 2014a, for a review about the specificity of adapting to conflicts albeit in the context of sequential congruency effects).

Methods

Participants

In Experiment 3a, 26 new participants took part in the study. Two participants were excluded due to bad performance or not finishing the experiment. The remaining sample consisted of 16 women and 8 men. In Experiment 3b, 26 new participants took part. Two participants were excluded due to bad performance. The remaining sample consisted of 16 women and 8 men. In Experiment 3a, the average age was 23.33 years (range 20–32 years) and in Experiment 3b 23.50 years (range 18–29 years). In both experiments participants received 6 € fix (for the test) and up to 6.40 € performance-related (for the training). The average earnings were 11.91 € in Experiment 3a and 11.77 € in Experiment 3b. All other recruitment and participation criteria were the same as in the previous experiments.

Apparatus, software, material, task and procedure

The same apparatus and software were used as in the previous experiments. Google Chrome Browser (versions 71 till 76) was used for stimuli presentation.

Training

The training was similar to the one of Experiment 1, with one exception (see Fig. 1c): Letters were displayed within each circle. The letter set "H", "K", "B", "D", "X", and "S" was used, where each letter was white and 1.31° in height as well as 1.02° in width. In the target circles, one of the letters "H", "K", "B", "D" was presented. Within the distractor circles, either one letter of the full letter set, or no letter was presented. In each trial the same letter was presented within each distractor circle. Participants' task was to look for the red or lime target and categorize the letter within to the two categories [B, K] or [D, H] by pressing the "Y"- or "M"-Key on the keyboard, respectively. The response mapping was counterbalanced across participants. By presenting the letters in the target and distractor circles, a response conflict was introduced in the search task. Due to the different target and distractor letter combinations, four conditions emerge, which mirror the congruency conditions (congruent, incongruent, neutral, and no flanker) used in the previous experiments. The training consisted of two blocks with 128 trials each. The participants could rest between blocks. The procedure and timing were the same as in the training of Experiment 1, and the reward schedule mirrored the one of the training of Experiment 2.

Test

In the test of Experiment 3a, the same search task as in the training was used with three modifications: First, the target was a colored diamond, which was 2.49° in height and width. The diamond could be displayed in one of the colors yellow (rgb: 255, 255, 0), hotpink (rgb: 255, 105, 180), darkorange (rgb: 255, 140, 0), blue (rgb: 0, 0, 255), or cyan (rgb: 0, 255, 255) and never appeared in one of the value colors from the training. Second, in each trial, one of the distractors was presented in one of the two value colors from the training. The other distractors were displayed in one of the remaining colors out of the target color set. Each color could only be present once in each trial. Participants' task was to look for the diamond shape and to categorize the letter within as either [B, K] or [D, H] by pressing the left or right mouse button, respectively. The mapping was counterbalanced across participants, where the side of a response key corresponding to a particular response remained the same between test and training within one participant. Third, since participants could not earn money anymore, no feedback display was presented, but a blank lasting 2500 ms. The test consisted of 10 blocks with 64 trials each. In Experiment 3b, the test consisted of an identical flanker task as the test of Experiment 2 and comprised 10 blocks with 64 trials each. Both test phases are displayed in Fig. 1.

Data preparation

We used the same trim and exclusion procedure as in the previous experiments.

Results

Training experiment 3a and b

Since participants in Experiments 3a and 3b took part in the same training, we merged the data of both groups. 1.90% of the data were excluded due to our trim procedure. The overall accuracy was 90.68%.

Response times

We conducted a Bayesian repeated measures ANOVA with the factors value (high vs. low) and congruency (congruent vs. incongruent). The model with the main effects of congruency and value was far more than 100 times as likely as the null model (see Table 3). Moreover, this model outperformed the next best model (full model) with a BF of 2.37. Figure 5 shows that RTs were slower in the incongruent relative to the congruent condition. We conducted follow-up tests to investigate the value main effect in more

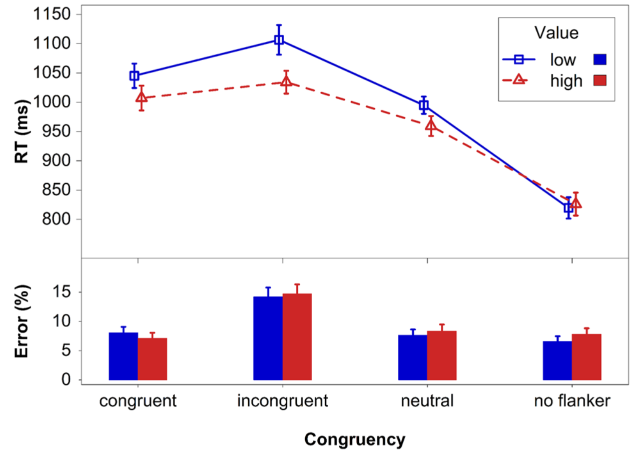

Fig. 5 Mean RT and error rates for the four congruency conditions in the training of Experiments 3a and 3b. Note: Error bars represent the within-subject confidence intervals as recommended by Morey (2008)

detail. The effect was mainly driven by the difference between high and low value in the incongruent condition, $BF_{H1} = 12.87 \pm 0\%$. In the congruent condition, there was no support for a difference between the two value conditions, $BF_{H1} = 1.01 \pm 0\%$.

Separate Bayesian *t* tests for the neutral and the no flanker conditions revealed that in the neutral condition there was anecdotal support for a value effect, $BF_{H1} = 2.25 \pm 0\%$. For the no flanker condition, the evidence supported the assumption, that RTs on high and low value trials did not differ, $BF_{H1} = 0.20 \pm 0\%$.

Error data

We calculated a Bayesian repeated measures ANOVA with the factors value (high vs. low) and congruency (congruent vs. incongruent). The model with only the main effect of congruency was far more than 100 times more likely than the null model (see Table 3). Moreover, this model outperformed the next best model (model with both main effects) by being 6.31 times as likely. Participants made more errors in the incongruent than in the congruent condition (see Fig. 5).

Bayesian *t* tests were conducted to evaluate, whether the two value conditions differ on the four congruency conditions. All *t* tests supported the null hypothesis, range $BF_{H1} = 0.17–0.50$, error estimate: 0%.

Test experiment 3a

The trim procedure resulted in excluding 1.81% of the trials. The accuracy in the remaining trials was 92.50%.

Response times

A Bayesian repeated measures ANOVA with the factors congruency (congruent vs. incongruent) and value (high vs. low) revealed support for the null model (see Table 1). To examine possible value effects, separate Bayesian *t* tests comparing high and low value were computed for each of the four congruency conditions. All tests supported the null hypothesis, range $BF_{H1} = 0.23–0.37$, range error estimate: 0–0.04% (Fig. 6 upper panel).

Error data

We calculated a Bayesian repeated measures ANOVA with the factors congruency (congruent vs. incongruent) and value (high vs. low). As can be seen in Table 2, there was low anecdotal evidence for the model with only the congruency main effect relative to the null model, $BF_{H1} = 1.28$. The next best model was the null model.

Again, separate Bayesian *t* tests comparing the two value conditions in each of the four congruency conditions revealed support for the null hypothesis, range $BF_{H1} = 0.22–0.79$, range error estimate: 0%–0.04%.

Test experiment 3b

1.96% of the data were excluded due to our trim procedure. The accuracy was 93.33% in the remaining data.

Response times

We conducted a Bayesian repeated measures ANOVA with the factors congruency (congruent vs. incongruent) and value (high vs. low). The analysis revealed that the model with the congruency main effect explained the data the best relative to the null model (see Table 1). Moreover, the congruency-only model outperformed the next best model (model with both main effects) with BF = 4.62. Participants were slower in the incongruent relative to the congruent condition (see Fig. 6, bottom panel).

To investigate possible effects of value, Bayesian *t* tests were conducted comparing high and low value in each of the four congruency conditions. Each test revealed support for the null hypothesis, range $BF_{H1} = 0.22–0.43$, range error estimate: 0%–0.03%.

Error data

A Bayesian repeated measures ANOVA with the factors congruency (congruent vs. incongruent) and value (high vs. low) revealed low anecdotal support for the model with the value main effect relative to the null model, $BF_{H1} = 1.64$. If comparing the value main effect model with the next best model (model with two main effects), the evidence was inconclusive, BF = 1.03 (see Table 2).

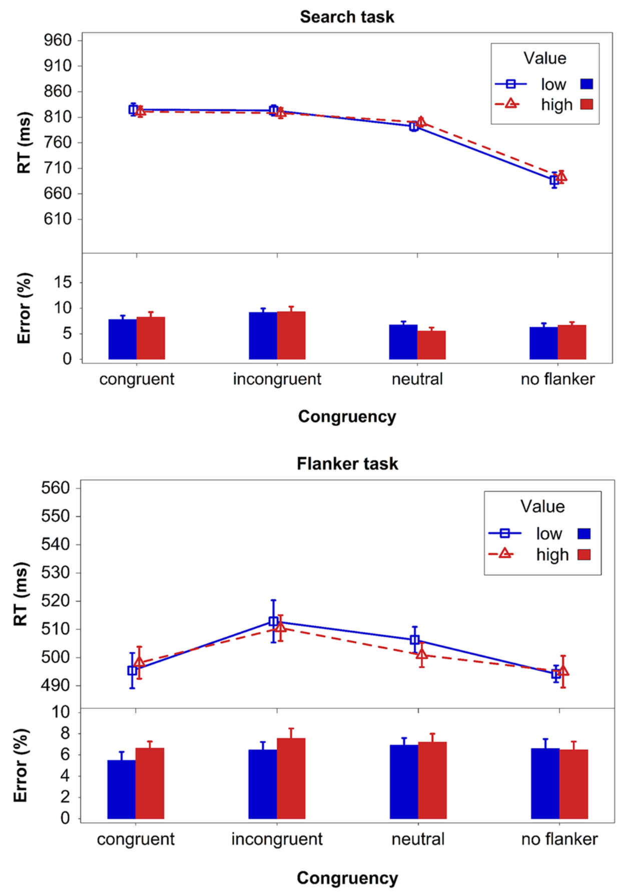

Fig. 6 Mean RTs and error rates for the four congruency conditions in the test of Experiment 3a (upper panel) and of Experiment 3b (lower panel). Note: Error bars represent the within-subject confidence intervals as recommended by Morey (2008). The *y* axes are not scaled similarly because of the data belonging to different task types

Separate Bayesian *t* tests revealed low anecdotal support for high and low value differing in the congruent condition, $BF_{H1} = 1.35 \pm 0.01\%$. However, all other *t* tests supported the null hypothesis, i.e., that high and low value did not differ in any other congruency condition, range $BF_{H1} = 0.22–0.64$, range error estimate: 0–0.03%.

Discussion

We examined the role spatial uncertainty about the target location plays for the occurrence of value effects in conflict-training and conflict-test phases. Moreover, we investigated the shielding assumption (see Dreisbach & Haider, 2009; Goschke & Dreisbach, 2008) in more detail. Hence, we used a conflict-search task in the trainings of Experiment 3a and 3b as well as the test of Experiment 3a. In the test of Experiment 3b, we used a flanker task. We found a value effect in the training phases, which was expressed above all in the incongruent trials. This indicates that the mixture of spatial uncertainty and response conflicts might lead to the occurrence of value effects. As supposed in the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009), the presence of conflicts might result in increased associative learning which strengthens the bindings between the elements of the active mental representations. Since the value color is part of the target, but also signals the possibility to earn a specific reward, the color-value association might be part of the active representations and, thus, be strengthened, too. Consequently, this strengthened color-value association might result in emphasizing the attentional prioritization of the target and, therefore, in observable value effects. This seems especially to be the case if the target location is unpredictable. If it is predictable, no effects might be observable due to a ceiling effect (see Experiment 2).

Neither in Experiment 3a, nor in Experiment 3b VDAC emerged in the test phase, which is in line with potential shielding (see also Dreisbach & Haider, 2009; Goschke & Dreisbach, 2008): If participants have learned to deal with a response conflict, they might be able to shield their attention from distracting influences. This also seems to be the case, if the conflict is part of a search task in the test (Experiment 3a). That is remarkable, since most studies found VDAC if a search task was used in the test (e.g., Anderson et al., 2011b; but see Sha & Jiang, 2016 Experiment 2, for a comparable result). From this perspective, effective conflict adaptation seems to be able to overcome the attentional prioritization of irrelevant value-associated distractors.

General discussion

In three experiments, we investigated how response conflicts and spatial uncertainty regarding the target location modulate the learning of value associations and the resulting VDAC. We assumed that results of previous research (Anderson et al., 2012; Mine & Saiki, 2018, Experiment 1; Sha & Jiang, 2016, Experiment 2) could be explained with the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009) and shielding (Dreisbach & Haider, 2009; Goschke & Dreisbach, 2008): If participants are confronted for the first time with response conflicts, these conflicts act like a learning signal resulting in all elements of the active mental representation being stronger bound. This should also result in strengthening the color-value association. However, if participants have already learned how to deal with the conflict in a previous phase, they might be able to shield attention from interfering irrelevant information, i.e., also from the color-value association.

Experiment 1 served as a conceptual replication and extension of Experiment 1 from Anderson et al. (2012), who also used a visual search task in their training and a flanker task in their test. We added two conditions to the flanker task, namely a neutral one and a condition without flankers. With these conditions, we investigated how VDAC looks like if no response was associated with the flanker letter, or the value-associated element was the only flanking element. Like Anderson et al. (2012), and in line with the adaptation-by-binding model, we found no value effects in the training, but VDAC in our test. However, whereas in the study of Anderson et al. (2012) this effect was mainly driven by a RT difference between high and low value in the congruent condition,[3] in our study a corresponding difference occurred mainly in the incongruent condition.

In Experiment 2, we investigated the shielding assumption by introducing a response conflict in both phases. For this purpose, we used a flanker task. With this manipulation, no effect of value association on attention emerged in any phase. Although the results of the test phase could be interpreted within the framework of the shielding assumption, the results of the training phase seemed to be in contrast to the adaptation-by-binding model. We speculated that the results in the training might be due to the predictability of the target location resulting in a ceiling effect.

Therefore, in Experiment 3, we examined, whether spatial uncertainty regarding the target location might play a role for the occurrence of value effects within a conflict-training and a conflict-test phase. In the trainings of Experiments 3a and 3b as well as in the test of Experiment 3a, we presented a conflict-search task. In the test of Experiment 3b, a flanker task was used. We found value effects in the incongruent condition of the trainings, which are in line with the adaptation-by-binding model and the assumption concerning spatial uncertainty. In the test phases of Experiments 3a and 3b, no value effects emerged irrespective of the predictability of the target location. These results were in line with the shielding assumption.

Adaptation by binding

VDAC only occurred in the training or test, if this was the first time the participants had to deal with response conflicts (as in the test of Experiment 1 or the trainings of Experiments 3a and b). These results can be explained with the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009). According to this model, if a response conflict is

[3] They also found a difference between high and low in the incongruent condition, but much less pronounced than in the congruent one. Since the authors did not report this comparison, it is unclear, whether it is significant.

detected, the associations between the different elements of the active mental representations are strengthened. Verguts and Notebaert (2009) assumed in this context, that mostly those representations are active, which are relevant for solving the current task. The stronger associations between relevant task elements result, in turn, in improved cognitive control.

Since in the training of Experiments 3a and 3b the target color and the associated monetary value might also be part of the active mental representation (the participants want to earn money), it is reasonable that the color-value association is strengthened as well. Moreover, it might also be more strongly bound to the elements that are necessary for an efficient conflict resolution as, for instance, the perceptual representation of the target. This should result in an attentional prioritization of the value color, even beyond the prioritization which is assumed for value-associated stimuli per se (see Anderson, 2016, for a review) and, thus, to a search benefit for the target. However, there is also an alternative explanation for the observed data pattern in the training of Experiment 3a and 3b which is not necessarily based on the adaptation-by-binding model: In the incongruent condition, the RTs were consistently slower relative to all other conditions. It is possible that a value effect is expressed only in this condition while a ceiling effect was already reached in the other conditions with faster RTs, explaining the lack of value effects. Although we cannot exclude this explanation for the present data we assume it as rather unlikely given that value effects can also be found in easy visual search tasks (pop-out search) with included response conflicts (Walle & Druey, 2021, Experiment 2): Although the reported RTs were shorter than the ones observed in Experiment 3a and 3b value-driven attentional priority for the target could still be observed, indicating that the response conflict might rather be the driving factor than the slow RTs.

The adaptation-by-binding model might also offer an explanation for the results of the test phase of Experiment 1: Since the value color was presented within a rectangle around the flankers the color-value association might have been accidently bound to the target representation. Consequently, it might have been more difficult to exert cognitive control by, for instance, narrowing the attentional focus on the target (see, e.g., Botvinick et al., 2001) resulting in increased interferences by the value color.

At this point, we focus on the training in Experiment 2. The results seem to be an exception with respect to the adaptation-by-binding model: Although participants have to deal with a response conflict for the first time, they showed no value effects, neither in the incongruent, nor in the other flanker conditions. This finding fits the results of Mine and Saiki (2015, 2018, Experiment 1), who also used a flanker task in their trainings and did not find an effect of value on attention in four out of five experiments. How can these results be explained? In the specific context of the training task in Experiment 2, the color-value association may simply not (or only weakly) have been learned. In line with this, we did not observe VDAC in the corresponding test phase. While we cannot exclude the explanation based on the observed data, it is not supported by the results from another study, in which VDAC was observed in the test phase if a very similar flanker task was used in the training phase (Mine & Saiki, 2015, Experiment 1). If one takes a more general perspective, it is also possible that the amount of trials in the training phases of our experiments and the ones of other studies (e.g., Anderson & Halpern, 2017, Experiment 1; Roper et al., 2014) might have been just too small to observe value effects in this phase. This perspective fits the results of Sha & Jiang (2016, Experiment 2), who found value effects in training phases containing a higher amount of trials than often used in studies to VDAC (e.g., Anderson & Halpern, 2017, Experiment 1; Roper et al., 2014). It is conceivable that value effects might be rather found in training phases with a high amount of trials, since the associations might be learned better (see also Sha & Jiang, 2016). Nevertheless, the results of our Experiments 3a and 3b clearly show that value effects can also be observed in training phases containing only a small number of trials.

An alternative explanation for the observed results in the training phase of Experiment 2 is based on the task used: One crucial difference between search tasks and flanker tasks concerns the spatial uncertainty of the target location: Whereas in search tasks the target location is unpredictable, in flanker tasks participants always know where the target will appear. Thus, the lack of value effects might simply reflect ceiling. The value-associated target might be attentionally prioritized, but this only results in an observable effect if the spatial location of the target is uncertain. This line of reasoning receives support from the result of the trainings in Experiments 3a and 3b, where a conflict-search task was used and where value effects were observed in the incongruent trials. Thus, our results suggest that in the training, where the value feature is also part of the target, value effects are observable if the task contains a response conflict *and* the target location is unpredictable. But as the results of the test of Experiment 1 (flanker task) show, this spatial uncertainty only seems to play a role, if the value association is part of the target.

Shielding

If participants experienced response conflicts in the training, no VDAC emerged in tests that also included conflicts (Experiment 2, 3a, and 3b). The results can be interpreted with shielding (Dreisbach & Haider, 2009; Goschke & Dreisbach, 2008): In the training, participants should have learned how to deal efficiently with a conflict. Thus, cognitive control in the test might have already been efficient, resulting in a shielding of attention from all distracting influences (see also Dreisbach & Haider, 2009), i.e., also from the value-associated distractor. Consequently, no VDAC should be observable. This effect becomes particularly visible when comparing Experiments 1 and 3b. Both only differed in that in Experiment 3b a response conflict was already introduced in the training, whereas in Experiment 1 it was not. However, only in the latter experiment VDAC was found.

Nevertheless, there is also an alternative explanation: The lack of value effects in the test phases of Experiment 2, 3a, and 3b could also be explained with fast devaluation of the color-value association following only weak learning of this association from the training phase, thereby mimicking shielding effects. While this explanation might fit the results of Experiment 2, where no value effect occurred in the training phase, it fits less the results of Experiment 3a: In this experiment, we used a conflict-search task in both phases and found a value effect in the training but none in the test. The results, however, fit the results of Sha and Jiang (2016, Experiment 2), who used a similar design and also found value effects in the training, but no VDAC in the test. Our Bayesian approach allowed us to rule out that Sha and Jiang's (2016, Experiment 2) results might simply be a Type-II error (Anderson & Halpern, 2017). Moreover, we showed that—from a response conflict perspective—the results in the training can be explained by the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009) and the ones in the test by shielding (see also Dreisbach & Haider, 2009; Goschke & Dreisbach, 2008) which presumably occurs due to that previous learning experience.

However, the result of one study seems to be at odds with the shielding assumption. Mine and Saiki (2015) used a flanker task in their training and a visual search task in their test. The latter required to look for a deviating number among equal distractor numbers and to categorize it as odd or even. All stimuli were white, except for one distractor, which was displayed in a former value color. Importantly, the distractors and the target were either all odd or all even or differed in this respect, introducing a response conflict. Contrary to the present study, Mine and Saiki (2015) found VDAC with this setup. However, the diverging results might be based on differences in the task. In Mine and Saiki's (2015) study, the value-associated distractor was very salient relative to the other elements of the display, whereas in the test of Experiment 3a and in Sha and Jiang's (2016, Experiment 2) study, it was not. It has been assumed that attention is attracted by the color of a stimulus and this allocation of attention is in turn modulated by the value association of this stimulus (Anderson et al., 2011b; see also Wolfe & Horowitz, 2017). From this perspective, in the study of Mine and Saiki (2015), the colored distractor might have attracted attention giving rise to the influence of its value association. Possibly, it is more difficult to shield attention from value-associated distractors if they are also salient. Although this seems to be an interesting research question, it goes clearly beyond the scope of the present study.

In sum, our results suggest that trained cognitive control mechanisms could be able to shield attention from distracting influences, such as value-associated distractors. But they also suggest that, if efficient control has not been learned before, feature-value associations could accidently be bound to the elements necessary for conflict resolution. In the following, we turn to questions and topics that have arisen from our results and their interpretation but are clearly beyond the scope of the present work.

Thoughts about the role of task relatedness and conflicts for VDAC

In Experiment 1, we partly replicated the results of Anderson et al. (2012) and found VDAC if a flanker task was used in the test phase. However, in the Anderson et al. (2012) study, VDAC occurred primarily if the flankers were congruent (see Footnote 3), whereas we only found VDAC, if the flankers were incongruent. The former result seems to be at odds with the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009) since no response conflict must be solved in the congruent condition. But the value feature in their task was an integral part of the flankers. Thus, in the congruent condition, if a high value flanker distracts attention more than a low value flanker, the correct response might be primed more strongly, resulting in a faster response, as observed by Anderson et al. (2012). In our experiment, though, the value feature was spatially separated from the flankers (colored rectangle around the flankers), making such direct priming unlikely. From this perspective, the role that integrating the value features into the distractors might play for the occurrence of value-driven effects in general—but also in the context of the flanker task—might be a promising topic for future research.

Further thoughts concern the role of response conflicts for the learning of the color-value association and occurrence of VDAC: In the adaptation-by-binding model, response conflicts lead to an adaptation of cognitive control by means of enhanced associative learning and we interpreted the results of our experiments within the framework of this model. However, the question arises whether also information that results in conflicts at other levels of processing might have a similar influence on the learning of the color-value association and VDAC. For instance, the value-associated distractor as it is used in the test phase of most VDAC studies (e.g., Anderson et al., 2011a; Mine & Saiki, 2018) could also be seen as conflictual information for task performance and for the achievement of the task objectives (see Sali et al., 2018, for a similar reasoning). Examining this topic in more detail might not only give further insights into the interplay of cognitive control and the learning of the color-value association. It might also shed light on the nature of cognitive control itself given the ongoing debate whether conflict resolution by means of cognitive control might generalize from one kind of conflict to the next or whether it even relies on different control mechanisms (Egner, 2008).

Another question refers to the influence of response conflicts, which emerge for the first time in the test phase, on the color-value association. On the basis of the adaptation-by-binding model, we assumed that the presence of response conflicts leads to the active mental representation of the color-value association being stronger bound to the other task-relevant mental representations. But how could the enhanced associative learning by virtue of a response conflict affect the color-value association in the long term? It is possible that the color-value association would be further strengthened over the course of the test phase or that the learning of the association would eventually reach a ceiling. Alternatively, since the color-value association is not relevant for performing the task, there might be a point in time when its mental representation is no longer activated and the association is slowly devalued due to the lack of reward (see also Milner et al., 2020). Giving these different possibilities, investigating this topic in more detail might give further insights into a possible interaction between cognitive control and devaluation processes.

Response conflicts and selection history effects

In the present study, we focused on the influence of response conflicts on value-driven effects and VDAC in training-test paradigms. However, the question arises whether and how response conflicts affect value-driven effects in other paradigms. One of these paradigms consists of only one phase, where the value is never associated to the target of the visual search but to a distractor instead and in which value-driven capture effects are also found (Le Pelley et al., 2015; Watson et al., 2020, Experiment 1 and 2). If a response conflict is introduced in this kind of task, value-driven effects can still be observed (Walle et al., 2021). Again, this result is in line with the adaptation-by-binding model (Verguts & Notebaert, 2008, 2009): Because of the aim to earn money and the distractor being a predictor for the specific monetary value on stake, the distractor-value association is part of the active task set. The introduction of response conflicts in this kind of task might result in an even more emphasized learning of the distractor-value association, which might also be more strongly bound to the (also active) target representation. Consequently, this distractor might interfere more with the search for the target in the presence of response conflicts—a possibility which should be examined in more detail in future studies.

Another question concerns the interaction of adaptation-by-binding (Verguts & Notebaert, 2008, 2009) and shielding (see also Dreisbach & Haider, 2009; Goschke & Dreisbach, 2008) with other selection history effects. An example is a statistical learning effect, where, for instance, salient distractors can be suppressed with regard to attention if they occur with high probability on a specific location in comparison to a less probable location (Wang & Theeuwes, 2018). It is assumed that the high probability location is suppressed before the corresponding stimuli are presented due to learning effects (Wang et al., 2019). From this point of view, if a distractor on this already learned location contains an element that produces a response conflict with respect to the target, the response conflict should be less processed, which has also been shown in a corresponding study (Ivanov & Theeuwes, 2021). At this point, we can only speculate, but associative learning in response to the less processed conflict might also be less pronounced. From our view, examining how response conflicts might affect different selection history effects might be promising to gain new insights into the learning mechanisms resulting in these effects. It is to future research to follow this path.

Summary and conclusion

In three experiments, we examined the specific roles response conflicts and spatial uncertainty regarding the target location might play for the occurrence of value-driven effects on attention. First, value effects seem to rather occur, if the location of the value-associated target is uncertain. Second, trained control mechanisms might help to shield attention from interfering stimuli (see also Dreisbach & Haider, 2009). If these mechanisms have not yet been trained, though, learned value associations may be strengthened and linked to other elements of the active task representations (see Verguts & Notebaert, 2008, 2009), resulting in observable value-driven capture effects. This seems even to be the case if these associations interfere with efficient conflict resolution.

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Availability of data and materials The datasets are available in a public repository. This repository can be found here: https://osf.io/wkqm2/.

Code availability Experiment code and code for data analyses in R are available on request. Requests should be addressed to Annabelle Walle (walle.annabelle@gmail.com) or Ronald Hübner (ronald.huebner@uni-konstanz.de).

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The study was performed in accordance with the ethical standards of the Declaration of Helsinki (1964) and its later amendments and with the ethics and safety guidelines of the University of Konstanz.

Informed consent Informed consent was provided by all participants by marking a checkbox on the computer screen. Without check marking, the experiment could not be started. Participants could abandon the experiment at any point without encountering any negative consequences.

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