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„Value-driven attentional capture is based on a fit with a top-down relevant search criterion."

verfasst von / submitted by

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Evgenia Yurchuk, Oktober 2023

Content

Introduction

How does reward affect our attention? Do we find it harder to ignore stimuli we have learned are associated with reward? The current study investigates the possible effect of reward on visuospatial attention.

Visuospatial attention refers to the process of orienting oneself according to visual information. This can be achieved by overt selection, such as looking in a particular direction, or by covert selection, such as looking at someone out of the corner of your eye (Posner et al., 1980). We can watch someone covertly out of the corner of our eye, just as we can look at someone directly with our gaze.

What we pay attention to can be either top-down guided or determined by the environment itself and therefore be bottom-up guided (e.g., Connor et al., 2004; Folk et al., 1992; Yantis & Egeth, 1999). Top-down attention is also referred to as endogenous orienting or goal-directed attention and bottom-up as exogenous orienting or stimulus-driven attention. Distinguishing between these two different types of visual selection can be rather challenging. In visual search tasks, we can observe a mixture of top-down and bottom-up processing (Awh et al., 2012; Desimone et al., 1995). A red spot on a white shirt captures our attention since the red is easily distinguished and conspicuous in contrast to the white colour of the rest of the shirt. The red spot is particularly salient and captures attention in a bottom-up way. The term salience describes the conspicuousness of a stimulus (Itti & Koch, 2001). The salience of a stimulus can be high or low, depending on the stimulus context. A red spot on a red shirt would be less noticeable as it blends into the background, making it less salient.

As a top-down effect, the so-called *contingent-capture* effect can be observed (Folk et al., 1992). The contingent-capture hypothesis states that only stimuli which match our top-down set of attention control catch our attention. In experimental conditions where participants must single out a predefined stimulus amongst distractors, it was observed that only stimuli matching the searched-for target feature capture attention. When participants are presented with a cueing display before the target display, they manage to localise the target quicker if the cueing display contains an item matching both the searched-for feature as well as the position of the target in the target display. Hence, attention is only captured by stimuli that are relevant to the task or salient in a specific manner. Without any distinct feature to serve as a searching criterion, stimuli that lack relevance or salience fail to attract attention. Other stimuli, albeit being salient, fail to elicit this behaviour (Folk et al., 1992).

Anderson et al. (2011) made an observation that does not fit into the dichotomy of a bottom-up versus a top-down paradigm for allocating attention. They observed that task-irrelevant but reward-associated stimuli produced a significant distractor effect in a singleton search paradigm even though they were not physically salient. The term "singleton" denotes a stimulus that is unique among other stimuli. For instance, a circle amidst square shapes would be considered a singleton.

Their two-phased study consisted of a training phase and a test phase. In the former, a six-item display was shown with all items containing a line and each item having a unique colour. The participants were instructed to search for the red or green target. Participants had to report the orientation of the line inside the target by pressing a certain keyboard key. Upon successful response, they received a monetary reward. The amount of money rewarded depended on the colour of the target, e.g., a low reward when the target was red and a high reward when the target was green. In the test phase, the participants were instructed to search for the item that has a unique shape, the diamond among circles or a circle among diamonds. All the items were differently coloured than they had been in the training phase. Again, participants had to report the orientation of the line inside the target. In some trials, a distractor was present that was either in a colour that was associated with a high or a low reward during the training phase, either red or green. The target was never in a previously rewarded colour.

When one of the high or low-reward distractor items was present a longer reaction time was measured in comparison to trials in which no reward-associated distractor items were present. Salience-driven attentional capture cannot account for this observation as the saliency of the stimuli was equal unless one assumes that reward increases bottom-up salience (e.g. Bachman et al., 2020; Henschke et al., 2020; Hickey et al., 2010; Hickey & Peelen, 2015; Robinson & Berridge, 2008). Goal-driven attentional capture also fails to explain the observation, as the colour of the distractors was task-irrelevant. Anderson et al. concluded that the reward association established in the training phase leads to involuntary attention capture. This specific type of attentional capture is termed value-driven attentional capture (VDAC) and is considered to be part of a broader class of attentional capture effects that are referred to as *selection history effects* (for reference see e.g., Anderson et al., 2021).

However, another explanation is possible. The participants are looking for a unique stimulus among similar stimuli. Egeth, Leonard and Leber (2010) argue in their commentary that the use of a broad search mode can be an effective strategy in visual search tasks, even though it results in some inaccuracy (see also Duncan & Humphreys, 1989). In the case of Anderson et al. (2021), participants can solve the task of finding the singleton stimulus by adopting a so-called *singleton detection mode* as the target is defined by being a singleton among non-singletons (Bacon & Egeth, 1994). The distracting effect of the reward-associated stimuli can be explained when considering the potential singleton status of those stimuli. The reward association during the training could have either, as already mentioned, induced incentive salience (e.g. Bachman et al., 2020; Henschke et al., 2020; Hickey et al., 2010; Hickey & Peelen, 2015; Robinson & Berridge, 2008) or added meaning to the rewarded stimulus, as the implicit uniqueness of rewarded stimuli in contrast to non-rewarded stimuli could be perceived as an additional feature dimension. The reward association is therefore leading to a semantic singleton status in contrast to the non-rewarded items surrounding it. Existing research supports that items semantically related to the target tend to attract visuospatial attention (Belke et al., 2008; Goodhew et al., 2014; Lupyan & Spivey, 2008; Moores et al., 2003). Given the singleton search criteria, the stimulus that is (semantically) salient fits the search template. Therefore, during the singleton search task the singleton search criterion opens up an attentional window for salient stimuli that would fit the singleton criterion and the increased salience due to the reward association and semantic singleton status attracts attention. However, the stimulus itself is task-irrelevant.

Anderson et al.'s (2011) study leaves open if the singleton status of the targets in the transfer task is critical for the found reward-based distraction. This could be the case if either visual or semantic singleton status of reward-associated features plays a role in the distraction.

The present study aims to address this research gap and provide answers to the aforementioned question. We examine whether the distractor effect of reward-associated stimuli persists when participants search for a shape feature rather than a shape singleton. Searching for a shape feature would prevent the rewarded distractor colour from matching a top-down template for singletons, provided that the rewarded colour increases the singleton status of a stimulus carrying the reward-associated colour. Under the assumption that reward associations increase feature salience or semantic singleton status, we expect longer reaction times on trials with reward-associated distractors during the singleton search task. In the feature search task, we expect no attentional capture by reward-associated distractors, since they do not match with the specific shape search criterion.

Methods

Participants

Forty-five participants (29 female) between 19 and 39 years old (M_{age} = 22.98 years, SD_{age} = 4.11, Mdn_{age} = 23 years) took part in the experiment. Most of them were students at the University of Vienna.

All participants self-reported normal or corrected visual acuity. A red-green deficiency was ruled out with Ishihara colour plates. In addition, all participants had consented to participate in the experiment. Participants were compensated for their participation with course credits. Furthermore, participants were treated by the ethical standards of the Helsinki Declaration as well as national and institutional ethical standards.

Since chance level performance was already 50%, two participants were excluded due to an error rate above 45% in at least one of the two tasks. Therefore, data analysis was conducted with forty-three participants.

Design and Procedure

The present study consists of a training block, a singleton search task and a feature search task. All three blocks were forced choice tasks and all participants started with the training block. Whether the singleton search task or the feature search task followed the training block was randomly balanced between the participants. The design and procedure of the experiment is demonstrated in Figure 1.

The experiment was conducted in a quiet, dimly lit room in the faculty of psychology of the University of Vienna.

Training Block

The training block followed the design of Anderson et al. (2011) but was not identical. Several changes to the original design were introduced.

The training was preceded by a pre-training session to familiarise participants with the task. The pre-training was designed in the same way as the training, but participants only received feedback on whether the answer they gave was correct or incorrect until 80% of the 20 trials were correct. The pre-training therefore consisted of at least 20 trials. The training block started with a fixation display, with a duration of 400 ms, 500 ms or 600 ms at random, followed by the target display with six items arranged in a circle, all items being circles for 800 ms. Afterwards, the feedback display was presented for 1000 ms.

The target items were defined by their colour. The target was either green or red, all other items were yellow, blue, cyan, magenta, grey or violet. Different to Anderson et al. (2011), where there was one high-value and one low-value target, only one target colour was rewarded in our design. The no-reward target colour was only followed by visual feedback that the answer was correct upon a correct response. Which colour was the rewarded colour was randomly balanced among the participants**.** Participants were not explicitly informed of the reward contingency.

In each item, there was a line. Participants had to report the correct orientation of the cardinal line, either horizontal or vertical, inside the target by key press. The response keys were 'F' for the line in horizontal orientation and 'J' for the line in vertical orientation, with the assignment of the response key to orientation balanced across participants. Therefore, the response expected did not depend on colour but instead on the orientation of the line. All other items contained an oblique-oriented line. To avoid the oblique effect (cf. Appelle, 1972), one or two of the other items also contained a cardinal line, albeit in the opposite direction. To our knowledge, during the training phase in Anderson et al. (2011) the oblique effect was not accounted for, as the line in the target was the only cardinal line.

Anderson et al. (2011) used a reward scheme that led to a reward if participants answered correctly. Depending on the target colour they received a higher or lower reward with different probabilities. In our design participants were rewarded 100 points with a probability of 80% and 0 points with 20 a % probability of a correct answer. When answered correctly in trials with the value-associated target, visual feedback of the accumulated points was displayed. Unlike Anderson et al. (2011) this reward scheme followed a partial reinforcement schedule as there was a 20% chance of not receiving a reward despite providing a correct answer. The resulting operant conditioning leads to conditioned responses that resist extinction more persistently in comparison to continuous reinforcement (Mackintosh, 1975). Partial reinforcement schedules have already been used to study value-driven attention (e.g. Preciado et al., 2017). Four participants went through the experiment with a changed reward scheme to make the awareness of the reward scheme easier to identify. They received 100 points with a probability of 80% and 10 points with a probability of 20%. Also, a difference from Anderson et al. (2011), we used a point system instead of a monetary reward. The comparability of the effect of points-based reward systems and the effect of monetary rewards has already been demonstrated (cf. Rusz et al., 2020). Trials with wrong answers were repeated at the end. Participants were not informed about the repetition. The repetition should lead to a comparability of the influence of *selection history* and the influence on the reward of attentional capture.

Following the training block, different to Anderson et al. (2011), participants were also asked whether they were aware of the reward association by entering text into a dialogue box. There is empirical evidence that the awareness of reward association is crucial for an attention guidance effect of reward-associated stimuli (Mine et al., 2021). To investigate the potential impact of reward contingency awareness on value-driven attentional capture, we compared measurements from participants who correctly reported the reward association with those who did not, alongside the general reaction time analysis. This part of the study is not preregistered and has an explorative purpose.

Singleton Search Task

The singleton search task started with the same fixation display as in the training phase. Then the target display was presented for 1200 ms, with six items aligned in a circle as well. The same upper limit for the allowed duration of the reaction time in the search task was used in experiment 3 by Anderson et al. (2011). There was one item of different shape in this task. The target with the different shape was the singleton search target. Participants had to report the orientation of the line within this shape as a singleton among non-singletons, a circle among squares, or a square among circles. The target was as often a circle as a square. The possible line orientation to report and the key-response mapping per participant were the same as in the training phase. The line orientation was also the same as in the training phase. Each item had a distinct colour, but the colour of the items was not relevant to the task. In one condition an item had the same colour as the rewarded target colour in the training block, this was the reward-associated distractor condition. In the second condition, an item had the same colour as the not-rewarded target colour, the no-reward-associated distractor condition, and in the third condition all items were regular non-target items, this was the absent distractor condition. The target never had any of the colours used to identify the target in the training phase. In total, there were 576 trials, 192 per distractor condition. Unlike Anderson et al., who used a study design in which only 25% of all trials included reward-associated conditions, our study employed an equal distribution of conditions to prevent an imbalanced design. Each target display was followed by a feedback display as in the training block indicating whether the participant's response was correct. If participants gave an incorrect answer, they received the feedback "*Falsch*!" ["Wrong!"] for one second. Since no reward was given during the singleton search task no reward feedback was given. Before the real run, there were at least 20 trials, as in training, where the participants could familiarise themselves with the task until they reached at least 80% accuracy.

Feature Search Task

The feature search task was set up in the same way as the singleton search task. A fixation display was followed by a target display and a feedback display. Participants again had to report the orientation of a line inside a target item. The target item was either an equilateral triangle pointing upwards or pointing right, allocated to each participant at random. The other items had a unique shape (circle, diamond, square, pentagon, 18° rotated pentagon, the nontarget equilateral triangle [pointing upwards or right, depending on the random assignment to participants]) and a unique colour. All items had the same size, and the possible line orientation was the same as in the training phase. Colour was irrelevant to solving the task. In this task, participants could not find the target by using a singleton search. Like in the singleton search task, there was a reward-associated distractor condition, a no-reward-associated distractor condition and an absent distractor condition. Participants did not receive a reward and therefore the feedback display only indicated whether the answer was correct.

The reaction time was measured throughout the experiment. The position of the stimuli was random in each trial. Yet, each target was presented at each position equally often, therefore a real randomization was not utilised. The orientation of the line that was inside the target stimulus was equally often horizontal as vertical. The target position and the response were uncorrelated. Again, before the real run there were at least 20 trials where the participants could familiarise themselves with the task until they reached at least 80% accuracy.

Stimuli

The items had the following parameters: The lines whose orientation had to be reported were 0,84° long and 0,196° wide. The triangle in the upright position and the triangle rotated by 90° had a side length of 2,59°. The square had a side length of 1,93°. The pentagon in the upright position and the pentagon rotated by 90° had a side length of 1,55°. The circle was 2.5° in diameter. The items were positioned evenly in an imaginary circle of 13° diameter. Overall, all shapes had the same circumference (approx. 7,.8°).

The following objective colour val”es, ’easured with colorimeter, according to CIELAB colour space, were used for the items: Red: [70 99 90], Green: [70 -70 67], Blue: [70 25 -110], Yellow: [70 0 73], Cyan: [70 -41 -20], Magenta: [70 105 -81], Violet: [70 88 -112], Gray: [70 0 0], White: [140 0 0]. The colour of the line inside the items was Black: [2 0 -5]. The colour of the background was Dark Gray: [35 0 0].

Apparatus

The experiment was conducted on monitors with a resolution of 1920 x 1080 pixels (aspect ratio of 16:9) and 100 Hz global refresh rate and a monitor size of 543,74 mm x 304,6 mm (weight x height). Each participant's head was stabilized with a chin rest 57 cm in front of the monitor to maintain a constant distance between the monitor and the head.

Answers were given on a standard keyboard. The experiment was run on MATLAB: 9.4.0.929293 (R2018a) Update 5 and the Psychtoolbox version 3.0.15.

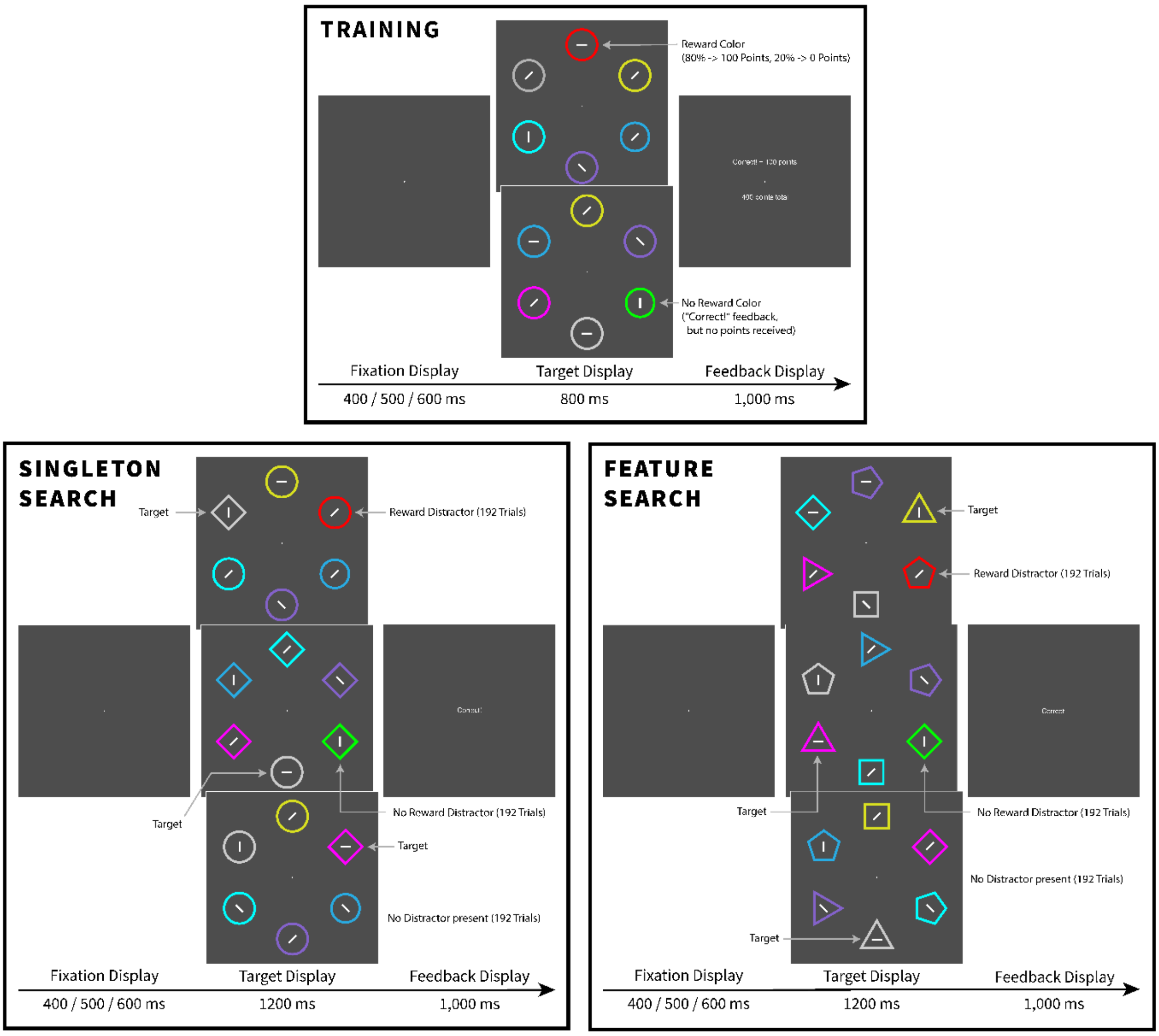

Figure 1. Experiment 1 Procedure. The training block (top), singleton search task (bottom left), and feature search task (bottom right) are illustrated. The stimuli are drawn to scale, excluding the grey background which does not depict the screen size.

Results

Data Analysis

We used R [Version 4.1.1; R Core Team (2021)] and the R-packages data.table [Version 1.14.2; Dowle and Srinivasan (2021)], *emmeans* [Version 1.7.2; Lenth (2022)], ggplot2 [Version 3.3.5; Wickham (2016)], lme4 [Version 1.1.27.1; Bates et al. (2015)], MBESS [Version 4.8.1; Kelley (2021)], and psychometric [Version 2.2; Fletcher (2010)] for our analyses.

The variables reaction time, accuracy rate and then distractor effect are assessed to derive the effect of rewarded stimuli on participants' attentional allocation. Excluded were all trials with reaction times below or above three standard deviations (SD) from the mean of each person per condition. Accuracy is defined as the proportion of correctly responded trials after the aforementioned exclusions.

Reward awareness

The behavioural data from the training block were adjusted for 18.34% of the trials that contained incorrect answers and for 0.32% of the correct answers.

After the training block, the participants were asked whether they had noticed any reward contingency and if so, what the reward contingency was. To elaborate on the potential effect of reward awareness on value-driven attentional capture (VDAC) we separated the participants who reported that they had noticed the reward contingency and correctly reported the contingency from those who failed to report the correct reward contingency, even if they had reported to having noticed any reward contingency. The group that affirmed to have noticed the reward contingency and correctly reported it will be further called the **"**reward-aware group". The other group is the **"**reward-unaware group**".** Because the study focuses on the effect of "reward awareness," participants who affirmed the reward contingency but could not correctly report it were excluded from the "reward-aware group," and their data was not analysed. However, it would be interesting to investigate whether there is a discernible impact of the supposed reward awareness on this subgroup of participants. Also, it should be noted that the probability of answering the question about the precise reward contingency accurately is fifty percent. Therefore, it is possible that participants who did not notice the correct reward contingency still replied correctly. Twenty-one participants were able to report the correct correlation between the colour of the target stimulus and the reward. The remaining twenty-four participants gave either an unclear or an incorrect answer. Three participants were assigned to the unaware group because they answered the question about the relationship between target colour and reward incorrectly or ambiguously.

In addition, we analysed the data without separating the two groups. This was essential since we wanted to reproduce the results of Anderson et al. (2011) who did not take a closer look at the reward awareness of the participants in their study.

Reward-aware group A two-tailed one-sample t-test conducted against a null hypothesis of zero demonstrated that, during the training phase, participants reacted on trials featuring a reward colour significantly faster compared to absent trials (Δ 17 ms, 95%-CI [8, 26], $t(20) = 3.96$, $p = .001$). This effect is characterised by a standardised effect size of $d_{unb} = 0.83$ (with a confidence interval of [0.35, 1.36]), with d_{unb} ($_{unb}$ stands for unbiased) representing the standard deviation adjusted through Hedges' (1981) correction factor. In cases where the sample size is fewer than 50 an adjustment becomes necessary due to the inherent bias in d, which tends to overestimate the population effect size according to Cumming (2013). Given its superior performance as a confidence interval estimator, the 95% confidence interval is computed around the biased d (c.f. Cumming, 2013). Furthermore, the participants of the reward-aware group answered more accurately in trials with the reward colour present in comparison to unrewarded colour trials, although not significantly (Δ 2.24%, 95%-CI [-0.26, 4.74], $t(20) = 1.87$, $p = .077$, $d_{unb} = 0.39$, [-0.04, 0.85]). This result suggests that participants successfully learned the reward association and that their behaviour was measurably influenced by it. A strategically wiser approach would have been to give the response less quickly to maximise gain and to take extra care. Since both accuracy and speed were higher in runs with rewarded stimuli than in runs without rewarded stimuli, it can be assumed that this is a real effect of the reward.

Reward-unaware group. It is particularly noteworthy that for the participants of the reward-unaware group, the reaction times between the two target colours did not differ significantly (Δ 1 ms, 95%-CI [-6, 8], $t(23) = 0.35$, $p = .73$, $d_{unb} = 0.07$, [-0.33, 0.47]. In the reward-unaware group the accuracy in trials with the reward colour present was the same as in trials with the unrewarded colour present (Δ -0.18%, 95%-CI [-2.37, 2.02], $t(23) = -0.17$, $p = .87$, $d_{unb} = -0.03$, [-0.43, 0.37]). This observation demonstrates that reward-unaware participants did not exhibit any measurable effect of the reward on their immediate performance during the training.

Figure 2 displays the reaction times and accuracy. The error bars in this figure depict the 95% comparison interval. Error bars which do not overlap indicate a significant difference.

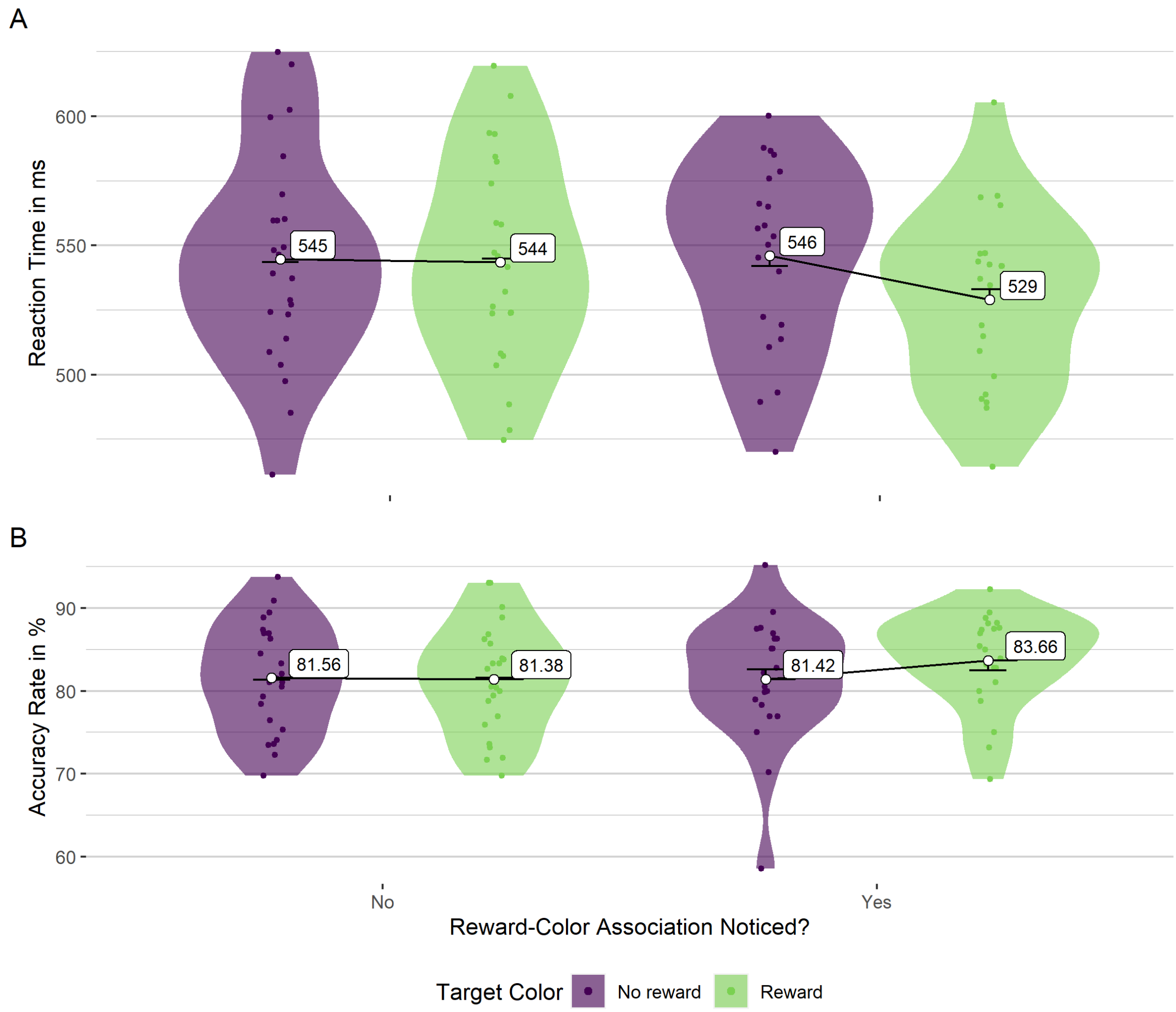

Figure 2. Reaction times (A) and accuracy rates (B) during the Training phase are shown in the graph. The error bars indicate a 95% comparison interval obtained from the R package *emmeans* and signify a statistically significant difference between conditions, adjusted for multiple comparisons, if they do not overlap.

Reaction Times

For the singleton search task, 19.07% of the runs were omitted because an incorrect answer had been given. Of the rest of the correct runs, 0.60% were omitted. Furthermore, we omitted 21.05% of the incorrect trials and trimmed 0.25% of the remaining correct trials in the feature search task.

Linear mixed-effect models were used to analyse the correct trimmed reaction times with the following fixed effects: distractor condition (absent vs. reward vs. no reward) and task (singleton search task vs. feature search task). Reward awareness (reward noticed vs. not noticed) was also added as a fixed effect because an effect of awareness was observed in the training block. The random effect was the random per-participant intercept. The analysis is analogous to a repeated measures ANOVA.

In the singleton search task, reaction times for the three distractor conditions were analysed without distinguishing whether the subjects had noticed the reward contingency or not. This corresponds to Anderson et al.'s (2011) second experiment. The distractor condition model showed a significantly better fit to the data than the null model (which models reaction times as randomly distributed over all conditions), $\chi^2(2) = 14.15$, $p = .001$. Thus, there is a difference in reaction time between the distinct distractor conditions.

Participants in the reward-associated distractor condition responded significantly slower than in the absent distractor condition, i.e. reaction times were longer when the distractor had a colour that was previously targeted and rewarded than when no distractor with a previously relevant colour was present (Δ 9 ms, 95%-CI [3, 14], $t(44) = 3.17$, $p = .008$, $d_{unb} = 0.46$, [0.16, 0.78]). This was revealed in the subsequent post-hoc analysis. In comparison to absent distractor trials the participants have been slower when the no-reward distractor was present (Δ 7 ms, 95%-CI [1, 13], $t(44) = 2.31$, $p = .038$, $d_{unb} = 0.34$, [0.04, 0.64]). Therefore, we replicated the key finding of Anderson et al. (2011). That longer reaction times were measured in the reward-associated distractor condition compared to the absent distractor condition. Interestingly, a significant attentional capture effect is observed for no-reward distractors, which points to a selection driven attentional capture effect. The null model better fitted the reaction time measurement during the feature search task. This means that no significant difference of the reaction time was measurable during the feature search task. This is in line with our hypothesis, namely that since the singleton detection mode is not applicable, reward associated colours do not induce an attentional capture effect.

In conclusion, the data set was divided into two groups, the participants who reported the correct reward contingency and the participants who either did not notice any reward contingency or reported the wrong relationship between colour and reward. For the unaware group the main effect model was significantly worse than the interaction model, $\chi^2(2) = 7.43$, $p = .024$. The composition of this interaction is that reaction times are significantly longer in trials with a reward distractor than in trials with no distractor in the singleton search task (Δ 13 ms, 95%-CI [4, 22], $t(23) = 3.01$, $p = .019$, $d_{unb} = 0.59$, [0.17, 1.05]). No significant difference was found between trials with no reward distractors and absent distractor trials (Δ 5 ms, 95%-CI [-3, 13], $t(23) = 1.36$, $p = .28$, $d_{unb} = 0.27$, [-0.13, 0.68]). For the aware group the main effect model was not significantly worse than the interaction model, and not better than the task model (including only the factor task), $\chi^2(2) = 4.46$, $p = .11$. Still, the null model was a worse fit than the task model, $\chi^2(1) = 388.59$, $p = < .001$. Significantly longer reaction times have been measured during the feature search task than during the singleton search task. To illustrate the results, please refer to Figure 3 below.

Figure 4 displays the reaction times for each task, categorised by levels of reward awareness. The error bars presented show the 95% comparison intervals and provide a statistical measure of significance. When these intervals do not overlap, a significant difference can be presumed. These intervals have been adjusted for multiple comparisons across three search tasks and different levels of reward awareness using Tukey's honest significance test. Only a single error bar is depicted for the most extreme values due to the lack of a comparable extreme value. It should be noted that an error bar terminates at the intended value of comparison, as displaying an error bar spanning a value would already indicate maximum overlap.

The rates of accuracy reflect the results of reaction time, which can be found in Figure 5 of the Appendix.

To summarise, we replicated the main finding of Anderson et al. (2011). Please note VDAC was especially prominent for reward contingency unaware participants during the singleton search task. VDAC was not measurable during the feature search task, confirming our main hypothesis.

Distractor Effects

As another post-hoc test for the reaction time analysis distractor effect as the primary indicator of attentional capture was calculated by subtraction of the mean reaction time per participant in the trials with no distractor (absent distractor condition) from the mean reaction time of trials with a reward distractor (reward-associated distractor condition) or trials with no reward distractor (no-reward-associated-distractor-condition). It was calculated for each participant. A slowing down of the reaction time in the reward-associated distractor condition compared to the absent distractor condition is evident in a positive distractor effect and indicates an attentional capture.

In the singleton search task a significant distractor effect was found in the rewarded distractor condition for those participants who were unaware of the reward association, according to a one-sample *t* test of the distractor effect separated by task and reward awareness (M = 13 ms, $t(23) = 3.01$, $p = .019$). No comparable effect was observed in the feature search task.

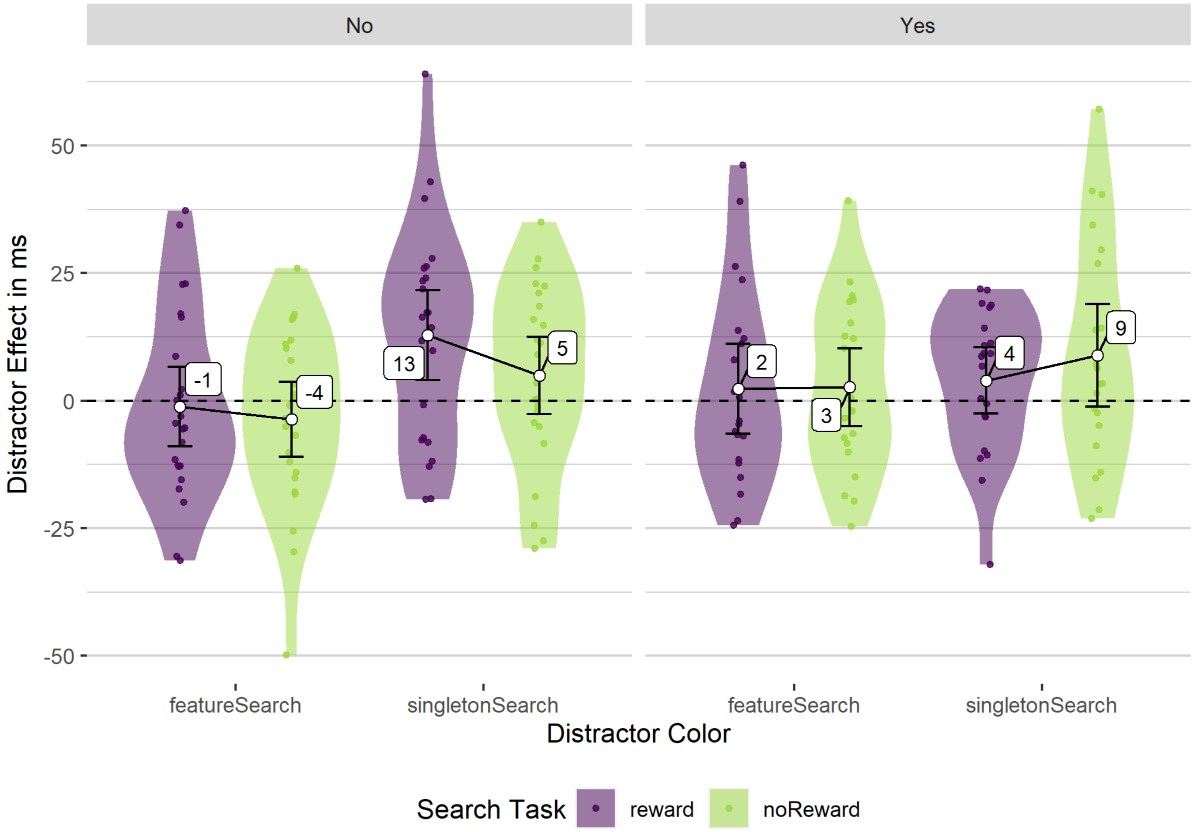

Figure 3. This figure shows the distraction effects, separated by task and reward awareness. Error bars represent 95% CIs from a two-tailed one-sample t test against zero.

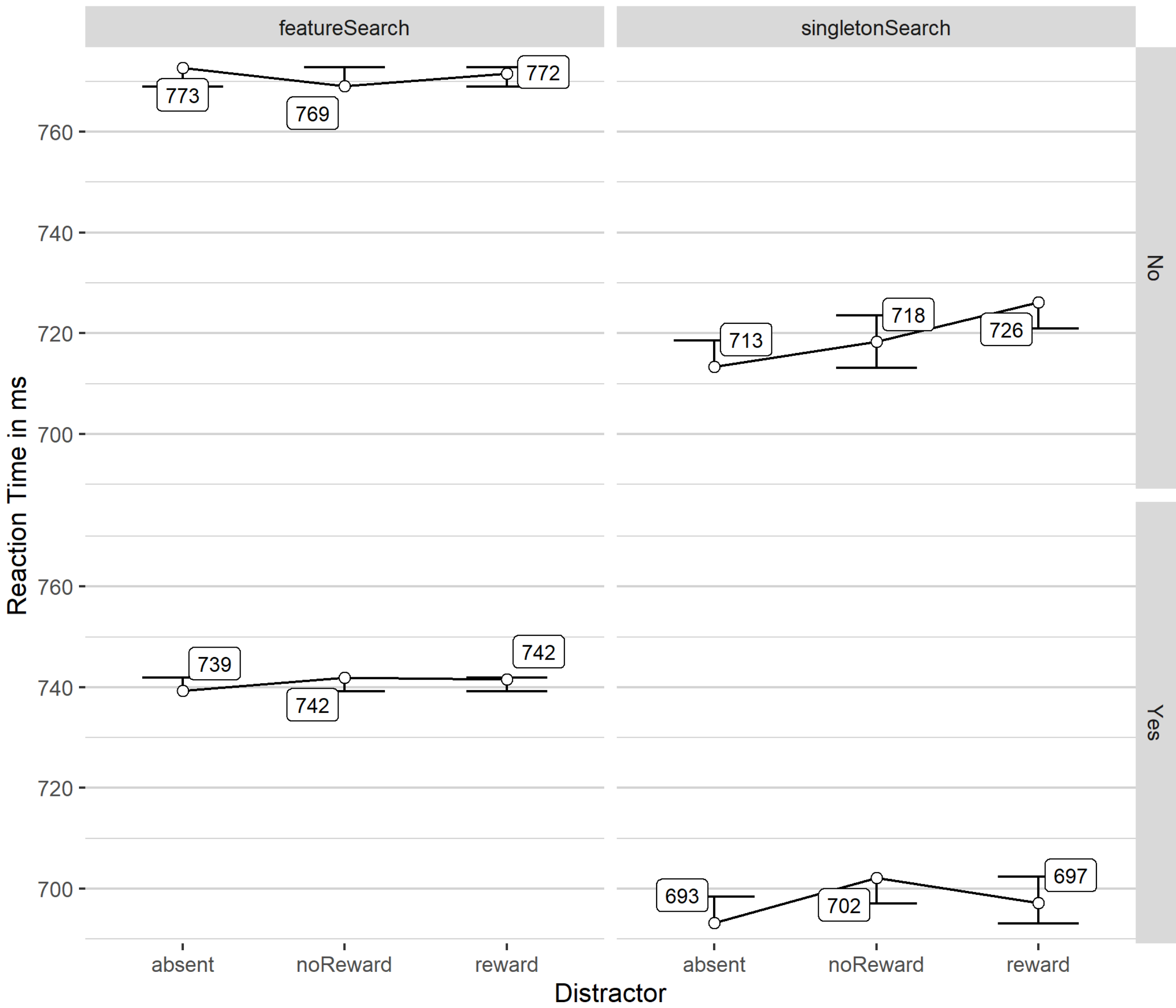

Figure 4. This figure shows the reaction times in Experiment 1, separated by tasks and reward awareness. The error bars represent 95% comparison intervals that indicate a significant difference if they do not overlap, corrected for multiple comparison using Tukey’s honest significance test.

Table 1

Search task	Distractor	*M* (SD)	95% CI	*t*(df)	p^a	d_{unb}	95% CI
Reward not noticed							
Singleton	Reward	13 (21)	[4, 22]	3.01(23)	.019	0.59	[0.17, 1.05]
Feature	Reward	-1 (18)	[-9, 7]	-0.31(23)	1.00	-0.06	[-0.46, 0.34]
Singleton	No reward	5 (18)	[-3, 13]	1.36(23)	.28	0.27	[-0.13, 0.68]
Feature	No reward	-4 (17)	[-11, 4]	-1.02(23)	.95	-0.2	[-0.61, 0.2]
Reward noticed							
Singleton	Reward	4 (14)	[-2, 10]	1.28(20)	.32	0.27	[-0.16, 0.71]
Feature	Reward	2 (19)	[-6, 11]	0.56(20)	.88	0.12	[-0.31, 0.55]
Singleton	No reward	9 (22)	[-1, 19]	1.86(20)	.23	0.39	[-0.04, 0.85]
Feature	No reward	3 (17)	[-5, 10]	0.72(20)	.88	0.15	[-0.28, 0.59]

Note: Mean and standard deviation in milliseconds. The indicator of whether participants noticed the association between reward and target colour in the Training block is marked as 'Reward noticed or not noticed'.

[a]The results were corrected for the two comparisons per search task and reward noticed using the method of Benjamini and Yekutieli (2001).

[b]The effect size was standardised using the group standard deviation, which was corrected using Hedges' correction factor.

Discussion

We investigated the effect of previously task-relevant, reward-associated distractors on the reaction time in two different attention tasks, starting with training, followed by a feature search and a singleton search task. During the training, participants reported the orientation of a line inside a target that was defined by colour. Of the two target colours one was rewarded with points that participants received upon answering correctly according to a partial reinforcement schedule. The participants have not been explicitly informed about the reward contingency. In the subsequent task that followed, either first singleton search or feature search task, participants have not been reinforced for a correct answer. Instead, the target colours from the training were present as distractor colours in three different conditions (reward-associated distractor condition, no-reward-distractor condition, or absent distractor condition). Again, participants reported the orientation of a line inside the targets, defined by either the singleton status of the item in the singleton search task or by the specific shape in the feature search task. Participants who noticed the reward association performed better in the training (significantly faster reaction times and higher accuracy than the unaware participants). In line with our main hypothesis, no difference in reaction time between the conditions was found in the feature search task. In addition, we have replicated the main finding of Anderson et al. (2011). Namely, reward-associated stimuli significantly distracted the participants during the singleton search task. Furthermore, when dividing the participants according to whether they had noticed the correct reward contingency, the participants who had not been aware were significantly slower in the reward-associated distractor condition in comparison to the absent distractor condition during the singleton search task.

In a seminal experiment, Anderson et al. (2011) demonstrated that associating features with a reward can induce attentional capture by the reward-associated stimulus. They arrive at this conclusion because they found that reward-associated stimulus features are distracting, even though they are neither useful for locating a target nor physically salient per se. The effect is known under the term value-driven attentional capture (VDAC) and was connected to a series of other attentional guidance effects under the umbrella term selection history effects. Like priming, where neither a clear bottom-up involuntary nor a top-down voluntary attentional allocation can be distinguished, this group of effects describes learning or rather experience-related impacts on attentional guidance (cf. Anderson et al., 2021; Awh et al., 2012; Failing & Theeuwes, 2018).

In Anderson et al. (2011) participants first learned the reward-stimulus association and, in a separate singleton search task, were instructed to search for the item with singleton status, i.e., an item that has a unique feature relative to the respective other items in the search array. We hypothesise that VDAC is induced because the value makes the reward-associated item a singleton. There is existing research supporting the assumption that singleton search can be a top-down mechanism (cf. Bacon & Egeth, 1994; Eimer & Kiss, 2010; Ogawa & Komatsu, 2004). Duncan and Humphreys (1989) proposed a theory that revolves around the similarity of the target to the non-target. As the similarity increases, more time is required to discriminate between the target and the distractor. When there is no similarity, the search is maximally efficient. However, if a specific target template is not available, because the target varies from trial to trial, participants must update their search template on each trial and therefore scan the array to infer from context what the target might be. This is also the case in Anderson et al.'s (2011) singleton search task. The target is either a circle among squares or a square among circles, and participants do not know in advance what the exact target will look like. They first must search the array for the singleton. In this case, the similarity lies in the common feature of being a singleton. We therefore argue that singleton detection mode induced by the instruction to search for a singleton is necessary to induce VDAC. Without the instruction to search for a singleton among non-singletons the reward-associated feature would not match any top-down search criteria and would therefore be ignored. Therefore, VDAC is only observed when the reward-associated feature matches the top-down search criterion.

Thus, to test our hypothesis, i.e., that under a condition in which the target is not a singleton, the VDAC will not be observable, we test whether task-irrelevant stimuli associated with a reward still capture attention during a feature search task. In a feature search task, only specific features are targets, in our case a distinct shape. Since the target-defining feature is unambiguous, not dependent on the surrounding items´ features and not detectable using a broader search template like in singleton detection mode, we argue that reward-associated distractors won´t capture the attention of the participants. We argue that if the singleton status of the reward-associated distractor is not necessary for the VDAC to appear, we would observe slower reaction times during the feature search task in trials where the reward-associated distractor is present in comparison to absent trials as well. If we don´t observe any difference of the reaction times between the conditions this points to the necessity of the singleton status of the target and therefore the application of the singleton detection mode.

Additionally, although not pre-registered, we have also included reward-contingency awareness as an additional variable to explore whether implicit and/or explicit learning leads to VDAC. We asked the participants after the training block whether they had noticed the reward contingency that was present during the training block. We then compared the participants that had noticed the correct reward contingency with those who did not report the correct reward contingency to explore whether there is a difference in the mean reaction times of these two groups.

Because during the feature search task, no difference between the conditions was measured we conclude that no VDAC was evoked. Neither the reward-aware nor the naïve participants were significantly influenced by reward-associated stimuli. The task required to focus on a specific shape of the stimuli. The reward-associated colour does not align with any top-down search criteria and therefore no distractor effect is observed. According to this result it is sensible to assume that the singleton search is required for VDAC, confirming our initial hypothesis.

Thereby, we question the assumption of Anderson et al. (2011), namely that VDAC is independent of top-down attentional allocation since the singleton detection mode is considered a top-down effect and appears to be a crucial condition to evoke VDAC. Milner et al. (2023) also question the assumptions made by Anderson et al. (2011). In their study, which consists of five experiments, Milner et al. (2023) vary different parameters to examine their influence on VDAC and the extinction of VDAC, in a learning and a test phase, just as Anderson et al. (2011). They found that either task-relevance of the rewarded feature or salience of the target feature plus a reduction in the frequency of exposure to the rewarded feature is necessary to observe VDAC. Our experimental design also entails absent trials that reduce the frequency of exposure to the rewarded-feature and we use the same singleton search paradigm.

Salience is a property of a stimulus that can arise from different contrasts like the colour of an item in relation to its´ surroundings. Bachman et al. (2020) studied physical salience and value-driven salience separately. In their EEG study equally short reaction times have been measured for high-physical-salient targets and high-value targets, but notably, the N2pc-amplitude of the high-value targets was larger but emerged with a higher latency than the high-physical-salient targets. The authors concluded that both forms of salience have a similar behavioural result but are based on separate neuronal processes. However, the distinction between physical and value-driven salience is not perceived so clearly by all.

Anderson & Kim (2019) argue that due to the comparable effect on attentional control the sharpness of the separation between these two forms of salience is debatable since they observed that individuals that are more prone to distraction are equally influenced by physical and value-driven salience. Physical salience is highly dependent on the environment, as it leads to a pop-out effect of the feature against the background (Itti & Koch, 2001; Theeuwes, 1994). On the other hand, incentive salience is the process by which reward-associated stimuli become attractive and therefore salient (Hickey et al., 2010; Hickey & Peelen, 2015; Robinson & Berridge, 2008). The latter is mostly studied in the context of addiction (Robinson & Berridge, 1993). Looking closer at the fashion in which Milner et al. (2023) define ‘physical salience’ it is noteworthy that they use the term 'salient' to describe a stimulus that is considered a singleton in the search array and can therefore be detected by focusing on the most salient stimulus, thus applying a *singleton detection mode*. In their study the reward-associated stimuli are not physically salient since regarding their physical properties they are not specifically distinct in comparison to their surrounding items.

It Is also worth mentioning that Goodhew et al. (2014) examined semantic salience, which is another phenomenon that could be related to the effects we observe when value makes a stimulus more distinct and therefore salient. During their visual search task, participants were instructed to locate a word and use a cue that embodied its meaning–- for instance, finding the word ‘red’ written in black among other black words. When a red cue was presented prior to the task, participant'' reaction time was quicker compared to when cues did not correspond with the meaning of the target word. Transferred to the singleton search task, the fact that the stimulus is no longer neutral but loaded with the meaning of a reward association and thus has semantic salience could influence behaviour.

Milner et al. (2023) and us observe that this attentional capture is only induced when participants are instructed to search for a singleton. Recall that no distracting effect of reward-associated stimuli was observed in the feature search task. Although there is currently no undisputable definition for the various types of salience, the impact of salience can still be measured. Whether it is enhanced by the value associated with the stimulus or by the semantic enrichment of the otherwise neutral stimulus, salience interacts with the intention to find a singleton and is observable as VDAC. In other words, the intention to search for a singleton leads to distraction by salient reward-associated stimuli that are not particularly task relevant and would have been otherwise ignored, as it is the case in the feature search task.

It is noteworthy that a perspective exists suggesting that bottom-up attentional allocation precedes top-down attentional guidance (e.g. Theeuwes, 2010). In the context of our study, this viewpoint suggests that attentional capture is driven by salience before any top-down influence becomes relevant. Nevertheless, given the absence of evidence indicating distraction caused by reward-associated and therefore possibly salient stimuli in the context of our feature search, we must refrain from making such an assumption.

We have replicated the main findings of Anderson et al. (2011) meaning that during the singleton search task we have found a significant difference in reaction times between the different conditions (reward-associated distractor condition, no-reward-associated distractor condition, absent distractor condition). When dividing the data between the reward-aware and reward-unaware participant groups this difference became more evident. Participants who were aware of the reward-association reacted faster during the training than the naïve participants which points to a successful learning effect. And in the singleton search task only the naïve participants had a significant distractor effect in the presence of reward-associated distractors, meaning they responded slower in trials with the reward-associated distractor condition. The replication of the original study by Anderson et al. (2011) shows that our experimental setup is generally sufficient to induce value-driven attentional capture although we used a point-based reward scheme in combination with a partial reinforcement schedule instead of a monetary reward with a fixed reinforcement schedule.

Looking closer at the unaware participants group we observe the typical effect VDAC has on reaction times, namely slower reaction times in trials with reward-associated distractor condition in comparison with the absent distractor condition. How is VDAC in naïve participants and the lack of VDAC in aware participants explainable? The task instruction was to search for the singleton among non-singletons. The learned value of the reward-associated distractors rendered it salient (Hickey et al., 2010; Hickey & Peelen, 2015; Robinson & Berridge, 2008). The increased saliency makes the stimulus a singleton, which in turn fits with the top-down set of attention-control for singletons. Generally, it is imaginable that for naïve participants the absence of reward-related goal-driven attentional guidance during the training made subtle influence of salience as a *selection history* effect like VDAC more likely (c.f. Anderson et al., 2021; Awh et al., 2012; Failing & Theeuwes, 2018). Reward-related goal-driven attentional guidance would have led to special attention for the rewarded features. The reward-aware participants were not noticeably influenced by this *selection history* during the singleton search task. This observation, however, seemingly partially contradicts a study by Mine et al. (2021) who concluded that awareness for the reward association is necessary for a VDAC. Mine et al. (2021) compared unaware participants with participants who spontaneously noticed the location-reward association in a visual search task. The goal was to examine whether an instruction that reveals the reward association, also referred to as goal-driven manipulation, was necessary for the VDAC to occur. According to the authors, VDAC can be elicited without goal-driven manipulation. Although reward-awareness seems to be necessary for a reward-effect, we have not observed any reward-effect during the singleton search task in the reward-aware group. To reconcile our observation one possible explanation is that the awareness of a reward association and the absence of the awareness lead to different reward effects, namely a conscious and an unconscious reward effect. The conscious reward effect leads to a better performance in the rewarded task. The unconscious reward effect leads to subtle *selection history* influence, possibly based on the salience-enhancing effect of the reward association. This observation points to the necessity to investigate different types of reward-learning effects on spatial attention and the influence of different extinction rates that come with those learning types. Furthermore, in the study of Mine et al. (2021) participants had two competing goals at the same time: namely, the explicit goal to respond fast and correct to the searched-for stimulus, but also a potential implicit goal to collect and maximise the reward which the participants set for themselves. In our experiment, reward-conscious participants pursued the explicitly stated goal to report the orientation of the line inside the target and in the test phase of the experiment solely the explicit goal of reporting the line orientation. Also, they pursued a possibly implicitly stated goal during training namely maximising the number of points they make. When the goal changed from training to test phase the reward-association had no relevance, and the previous implicit goal was erased. The lack of the implicit goal during the singleton search task could be the reason why we do not see a reward effect during this part of our experiment.

Although we believe that the point-based reward scheme worked well, a monetary reward scheme, being less abstract than a point-based reward scheme, should be considered in a follow-up experiment. Also, the comparison between high and low rewards would be interesting since this reward scheme was used in the original experiment by Anderson et al. (2011). Furthermore, we reproduce the VDAC observed by Anderson et al. (2011) without the separation of the data of the two awareness groups of participants. However, when separating the participants according to whether they had noticed the reward contingency, only the reward-unaware group had a significant distractor effect. Therefore, it is crucial to do a follow up experiment with a preregistration of the reward-awareness as an additional factor with a larger number of participants so that the number of participants in the two awareness groups is sufficiently high.

The present results suggest that VDAC is dependent on top-down search goals. The reward-induced salience of the stimulus only becomes attentional in the context of goal-directed search. Thus, we uncover another aspect that illustrates the complex interaction between goal-directed and stimulus-driven attention. The extent to which awareness of reward contingency and thus the conscious processing of salience plays a factor in VDAC needs to be uncovered in further research.

Conclusion

Our study shows that value-driven attentional capture (VDAC) does not occur without the existence of a fit to the top-down search template, as it is in the case of the feature search task. The result highlights the need to examine the existing literature on VDAC from the perspective of top-down visual attention control and a possible influence of awareness of reward contexts.

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Appendix

Abstract

Reward-associated stimuli capture attention in singleton search tasks despite being task-irrelevant. We question the common conclusion that this effect, termed *Value-Driven Attention Capture* (VDAC), is not the result of either bottom-up or top-down processes of visual control. In the three-phase experiment, participants learn the association of a colour with a non-monetary reward. The stimuli previously associated with the reward are present as distractors in subsequent visual search tasks, either a feature search task or a singleton search task. The *contingent-capture* hypothesis suggests that only stimuli that match our top-down attentional control will capture our attention. We observed that reward-associated stimuli captured attention in the singleton search task only when they were unaware of the reward association. No VDAC was observed in the feature search task. We argue that in the singleton search task, reward-associated stimuli are top-down congruent with the singleton search template because the reward association makes the stimuli semantically unique and therefore they appear as singletons. Furthermore, reward association is said to increase the salience of a stimulus. In the feature search task, the reward-associated stimuli do not match any top-down search template and therefore do not attract attention. We conclude that without a match to a top-down search template, no VDAC can be observed.

Keywords: value-driven attentional capture, contingent capture of attention, singleton search

Zusammenfassung

Belohnungsassoziierte Stimuli ziehen die Aufmerksamkeit bei Einzelsuchaufgaben auf sich, obwohl sie für die Aufgabe irrelevant sind. Wir stellen die verbreitete Schlussfolgerung in Frage, dass dieser Effekt, der als wertorientierte Aufmerksamkeitserfassung (engl. *value-driven attention capture*; *VDAC*) bezeichnet wird, weder das Ergebnis von Bottom-up- noch von Top-down-Prozessen der visuellen Kontrolle ist. In dem dreiphasigen Experiment lernen die Teilnehmer die Assoziation einer Farbe mit einer nicht-monetären Belohnung. Die Reize, die zuvor mit der Belohnung assoziiert wurden, sind als Distraktoren in nachfolgenden visuellen Suchaufgaben vorhanden, entweder in einer Merkmals- oder in einer Einzelsuchaufgabe. Die Zielreizabhängige-Verlagerung-von-Aufmerksamkeit-Hypothese (engl. *contingent-capture hypothesis*) besagt, dass nur Stimuli, die unserer Top-down-Aufmerksamkeitssteuerung entsprechen, unsere Aufmerksamkeit erregen. Wir beobachteten, dass Reize, die mit einer Belohnung assoziiert waren, nur dann unsere Aufmerksamkeit in der Einzelsuchaufgabe auf sich zogen, wenn sie sich der Belohnungsassoziation nicht bewusst waren. In der Aufgabe zur Merkmalssuche wurde keine VDAC beobachtet. Wir argumentieren, dass in der Singletonsuchaufgabe belohnungsassoziierte Reize top-down mit der Singletonsuchschablone kongruent sind, weil die Belohnungsassoziation die Reize semantisch einzigartig macht und sie daher als Singletons erscheinen. Darüber hinaus wird gesagt, dass die Belohnungsassoziation die Salienz eines Stimulus erhöht. In der Aufgabe zur Merkmalssuche entsprechen die belohnungsassoziierten Reize keiner Top-down-Suchschablone und erregen daher keine Aufmerksamkeit. Wir schließen daraus, dass ohne eine Übereinstimmung mit einer Top-down-Suchvorlage keine VDAC beobachtet werden kann.

Schlagwörter: wertorientierte Aufmerksamkeitserfassung, kontingente Aufmerksamkeitserfassung, Singleton Suche

Accuracy Rates in Experiment

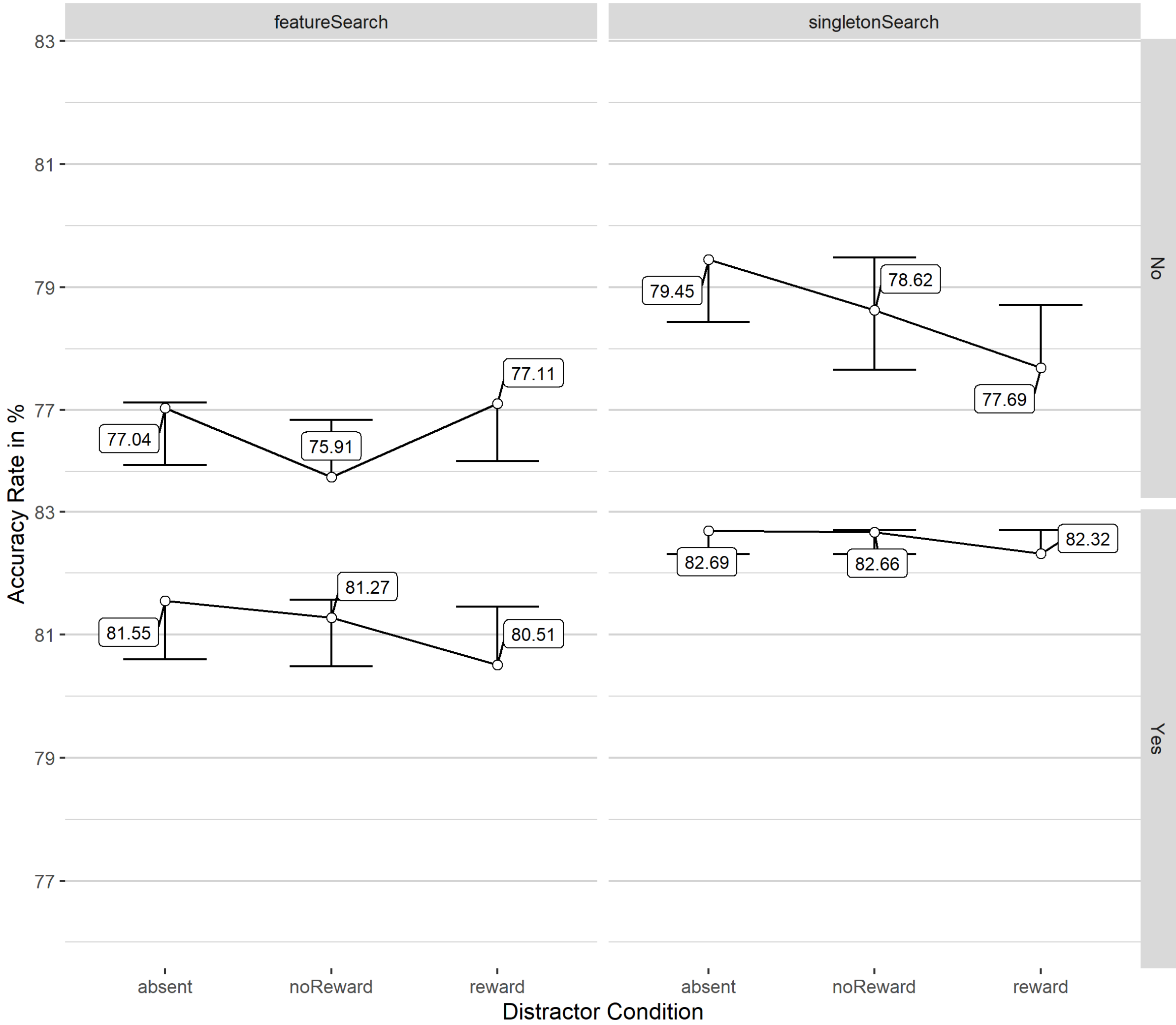

Figure 5. Accuracy.

Awareness Questionnaire

A three-question survey was used to gather participants' opinions regarding the relationship between target stimulus colours and rewards after the training block. Participants were asked to respond to the following questions:

Question 1: In your opinion, was there a connection between the target stimulus colours and the reward?

(Available Answer Options: [ ] Yes [ ] No)

Gab es Ihrer Meinung nach einen Zusammenhang zwischen den Zielreiz-Farben und der Belohnung?

([ ] Ja [ ] Nein)

Question 2: (If question 1 was answered with "Yes") What connection do you suspect? Describe your guess in the text field (at least 5 letters required).

Welchen Zusammenhang vermuten Sie? Beschreiben Sie Ihre Vermutung im Textfeld (mindestens 5 Buchstaben nötig).

Question 3: (This question was included in all surveys) In your opinion, which target stimulus color earned more points?

(Available Answer Options: [ ] Green [ ] Red)

Welche Zielreiz-Farbe brachte Ihrer Meinung nach mehr Punkte?

([ ] Grün [ ] Rot)