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The Modulation of Value-Driven Attentional Capture by Exploration for Reward Information

Jangkyu Ju and Yang Seok Cho
School of Psychology, Korea University

Previous studies on *value-driven attentional capture* (VDAC) have demonstrated that the uncertainty of reward value modulates attentional allocation via associative learning. However, it is unclear whether such attentional exploration is executed based on the amount of potential reward information available for refining value prediction or the absolute size of reward prediction error. The present study investigated the effects of reward information (information entropy) and prediction error (variance) on attentional bias while controlling for the influence of the strength of reward association. Participants were instructed to search for either a red or green target circle and respond to the line orientation within the target. Each target color was associated with reward contingencies with different levels of uncertainty. In Experiment 1, one color was paired with a single reward value (zero entropy and variance) and the other with multiple reward values (high entropy and variance). In Experiment 2, one color had a high-entropy, low-variance reward contingency and the other had the inverse. Attentional interference for distractors with high entropy was consistently greater than low or zero entropy distractors. In addition, in Experiment 3, when distractors with an identical level of variance were given, information entropy was observed to modulate the attentional bias toward distractors. Lastly, Experiment 4 revealed that distractors associated with contrasting levels of variance, while information entropy was kept identical, failed to modulate VDAC. These results indicate that value-based attention is primarily allocated to cues that provide maximal information about the reward outcomes and that information entropy is one of the key predictors mediating attentional exploration and associative learning.

Keywords: attention capture, uncertainty, visual search, entropy, variance

The world we inhabit is filled with a massive amount of information, some of which is necessary for our survival, while the rest tends to be meaningless or even cause distractions from essential day-to-day operations. Hence, selective attention is one of the most essential functions of human cognitive processing, as it enables us to prioritize and comprehend valuable or relevant information at the expense of distracting or irrelevant information. The specific mechanism through which selective attention operates has been the topic of intense examination for a long time (for review, see Anderson, 2013). Two core mechanisms of selective attention are widely accepted: goal-driven (or top–down) and stimulus-driven (or bottom–up) attentional mechanisms (Connor et al., 2004). In other words, the human attentional system can proceed in accordance with the prioritization of stimuli that possess either goal-related information or strong physical salience, to promote the successful selection of necessary information (Folk et al., 1992; Jonides & Yantis, 1988; Theeuwes, 1992).

Lately, a growing body of research has established that the history of attentional deployment (or selection history) guides selective attention as well (Awh et al., 2012; Failing & Theeuwes, 2018). In particular, the history of reward provision serves as a potent drive that promotes attentional selection. Stimulus features that are associated with reward values modulate the deployment of visual attention, a phenomenon termed *value-driven attentional capture* (VDAC; Anderson et al., 2011; Chelazzi et al., 2013).

In their experiment, Anderson et al. (2011) had participants perform different visual search tasks in two distinct phases. In the initial Training Phase, either a red or green circle was presented as a target among an array of six heterogeneously colored circles. Participants were instructed to respond to the orientation of a line segment inside the target. One of the two target colors was associated with a high probability (80%) of a large monetary reward (5 cents), while the other was associated with a high probability of a small monetary reward (1 cent). Hence, the amount of reward provided on a given trial was probabilistically associated with the color of the target circle, rather than the function of participants' responses in earning the reward. Critically, participants were able to formulate stimulus-reward associations through extensive training (1,008 trials in Experiment 1) in the Training Phase. In the subsequent Test Phase, participants searched for a shape-singleton target (a diamond among five circles) while a distractor among

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Yang Seok Cho https://orcid.org/0000-0002-8481-3740

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Correspondence concerning this article should be addressed to Yang Seok Cho, School of Psychology, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Korea. Email: yscho_psych@korea.ac.kr

nontarget circles was rendered in the reward-associated color (either red or green) on half of the trials. The results revealed significant attentional interference during trials where the distractor formerly associated with high reward was presented in comparison with distractor-absent trials, indicating that learned reward associations trigger involuntary attentional prioritization counter to the task goal. The finding that VDAC was induced by a nonsalient, task-irrelevant stimulus provides a critical implication that the modulation of attentional allocation by value relies heavily on Pavlovian conditioning (i.e., learning about the extent to which a stimulus predicts reward) rather than instrumental learning (Bucker & Theeuwes, 2017; Le Pelley et al., 2015). Furthermore, Le Pelley et al. (2019) found that participants failed to suppress involuntary attentional and oculomotor captures by the distractors that predicted high-value reward, even when orienting toward them resulted in the omission of reward. These findings collectively demonstrate that the critical determinant of VDAC is the Pavlovian signal that predicts the presence and magnitude of reward.

Two competing models link associative learning with attentional allocation, presenting fundamental principles that seem intuitively plausible: predictiveness-based (attentional exploitation) and uncertainty-based (attentional exploration) attentional principles (Easdale et al., 2019; Griffiths et al., 2011; Le Pelley et al., 2016). According to the predictiveness principle proposed by Mackintosh (1975), attention prioritizes cues that reliably predict subsequent events to exploit known stimulus-outcome relationships (Easdale et al., 2019). A wealth of human and nonhuman animal studies have demonstrated that observers are likely to deploy their attention more toward a stimulus feature that allows accurate forecasting of the occurrence of expected outcomes (Le Pelley et al., 2013; for reviews, see Le Pelley, 2004). However, it is important to note that such biased attentional allocation to predictive cues has not been thoroughly examined in the context of value-driven attentional capture. This is not a trivial question, as the effects of learned predictiveness and learned value in guiding attention are, in fact, orthogonal (Le Pelley et al., 2013). Specifically, the predictiveness, or the extent to which a cue signals the presence of "reward," was kept identical in most experiments examining VDAC (Anderson & Halpern, 2017; Anderson & Yantis, 2012, 2013; Anderson et al., 2011, 2014; Mine & Saiki, 2015). Here, regardless of its size, a reward was provided on all trials with correct responses and the predictiveness of the target stimuli was always 100%. In addition, the eye-gaze data from Experiment 2 of Le Pelley et al.'s (2019) study revealed that participants' gaze and first saccade were more likely to be directed toward nonpredictive than predictive distractors, which is inconsistent with the prediction from Mackintosh's (1975) attentional model.

On the other hand, the uncertainty-based attentional theory proposed by Pearce and Hall (1980) suggests that attention is preferentially allocated to cues for which the outcome is currently uncertain. Such attentional bias then promotes the exploration of cues to "hopefully" reduce uncertainty and refine stimulus-outcome associations (Easdale et al., 2019; Le Pelley et al., 2019). Consequently, the uncertainty principle establishes an adaptive allocation mechanism of limited cognitive resources toward objects that we do not fully understand, rather than wasting them on processing cues for which meanings are highly predictable (Luque et al., 2017; Russo et al., 2019). Recent studies have shown that distractors associated with uncertain reward elicited larger attentional capture than distractors associated with certain reward. For example, Cho and Cho (2021) found a larger VDAC for distractors associated with uncertain reward than those associated with certain, fixed reward. Notably, although the size of reward is a fundamental factor for modulating VDAC (Anderson & Halpern, 2017), the effect of value (i.e., the size of reward) cannot account for the findings described in Cho and Cho's study, as the distractors signaled an identical level of expected value. Hence, the attentional bias shown in the study suggests that participants deployed their attention to the uncertain distractors to learn the stochastic relationship between the stimulus and reward delivery or magnitude. Similarly, the results from Le Pelley et al.'s (2019) study are interpreted as the presence of an overt attentional bias toward distractors associated with uncertain reward. Specifically, the nonpredictive distractor is characterized as an "uncertain" distractor that is paired with a 50% chance of providing both 100 points and 0 points. In addition, Koenig et al. (2017) showed that the duration of gaze fixation for both the targets in the learning trials and the distractors in the search trials were closely linked to reward uncertainty. Hence, there is strong evidence that uncertainty in associative learning modulates the value-based attentional bias.

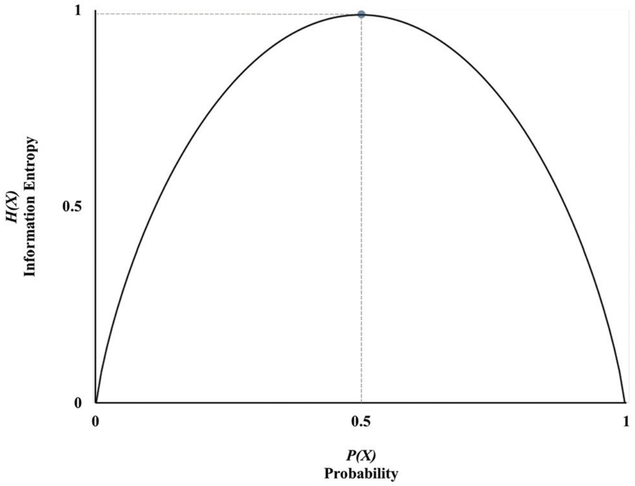
Uncertainty regarding value-based decision-making takes a number of forms: ambiguity refers to occasions in which the probabilities associated with the reward distribution are unknown, while risk denotes uncertainty when the probabilities are known (Burke & Tobler, 2011). Risk can be divided into multiple parameters including variance, standard deviation, entropy, and skewness, which are highly correlated with each other but can still be separated into distinct concepts. There is a lack of consensus, however, as to which representation of uncertainty in terms of reward provision can best explain the attentional modulation shown in the context of VDAC. In particular, studies that investigated the relationship between prediction error and associative learning often identified uncertainty as the variance of the reward magnitudes (Fiorillo et al., 2003; Rushworth & Behrens, 2008; Tobler et al., 2007). Variance represents the degree of dispersion of values in a variable from the central point (the average value). Thus, variance is closely related to the absolute amount of reward prediction error (RPE) used in many associative learning models, as prediction error denotes the discrepancy between the size of reward received and the prediction formed through association (Schultz, 2006). Essentially, the Rescorla-Wagner model assumes that learning (Pavlovian conditioning) depends on the degree of surprisingness of the unconditioned stimulus (US): a more surprising US signals a bigger violation (prediction error) of the existing associative strength between the stimulus and the outcome, which in turn leads to a bigger update (i.e., learning) of the associative strength (Rescorla & Wagner, 1972). In addition, Pearce and Hall's (1980) uncertainty model of learning also posits that attention is enhanced for cues that are accompanied by surprise; that is, those that induce unexpected changes in the stimulus-reinforcement association (Rouhani & Niv, 2021). Rouhani and Niv found that high-variance reward outcomes improve memory for associated events more than low-variance ones. This shows the influence of variance and its association with prediction error in the context of learning and memory formation. Hence, variance is one of the reliable parameters in representing uncertainty in the context of attention and associative learning.

Another key parameter for uncertainty is information entropy (Shannon entropy). Although information entropy and variance seem to go hand in hand, the two indices represent distinct, independent concepts. In his paper, Shannon (1948) stated that information entropy represents the amount of choice involved in the selection of events, or the degree of uncertainty of the outcomes associated with events. Simply put, information entropy measures the average level of information, choice, surprise, or uncertainty associated with the possible outcomes of an event (see Figure 1). For instance, an ordinary coin toss that has a 50% chance of showing heads or tails leads to 1 bit of information entropy. By contrast, tossing a biased coin with a 90% chance of heads and a 10% chance of tails, or vice versa, results in .47 bits of entropy. By the same token, rolling a dice holds bigger information entropy (2.58 bits) than a coin toss (1 bit). In other words, the information entropy associated with a given event increases when the probability distribution of outcomes resembles a uniform distribution and when the number of outcomes within the event increases (Hirsh et al., 2012). The information entropy of reward outcomes associated with a target stimulus, in the context of associative learning, is closely related to the violation of the expected cue-reward contingency. Critically, the more uncertain the reward outcomes, the more information is available for refining the stimulus-reward association, which in turn helps reduce the uncertainty.

It is yet unclear, however, whether attentional exploration is executed based on the amount of potential reward information (i.e., information entropy) available for refining the value prediction, or the absolute size of reward prediction error (i.e., variance). Thus, the present study attempted to adjudicate between the two possible explanations by directly comparing the effects of information entropy and variance in modulating the value-related attentional bias. Throughout the experiments, the level of uncertainty was defined in terms of information entropy and variance and quantified following the formulas given below. When an event has n possible outcomes (x_1 through x_n) each of which occurs with a probability P ($P(x_1)$ through $P(x_n)$), the information entropy of the event can be formally defined as:

Figure 1

The Level of Information Entropy as a Function of Probability of an Event With Two-Class Variables



$$H(X) = -\sum_{i=1}^{n} P(x_i)\log_2 P(x_i) \quad (1)$$

Information entropy (H(X)) of an event is given by the negative sum of the log probabilities of each possible outcome of that event (Hirsh et al., 2012). In the formula, the base of the logarithm varies between different applications. Base 2 gives the unit of bits (i.e., shannons), while base *e* gives the unit of nats (i.e., natural units), and base 10 gives a unit termed “dits,” “bans,” or “hartleys.” Given that the original study used the unit of bits when introducing the theorem, the current study also uses the formula with base 2 to calculate the information entropy of the reward contingencies (Applebaum, 1996; Shannon, 1948).

On the other hand, variance can be formally defined as:

$$Var(X) = \sum_{i=1}^{n} (x_i - m)^2 P(x_i) \quad (2)$$

Unlike the formula for information entropy, the mean value of reward outcomes takes part in this formula, which is denoted as *m*. It is important to note that as variance is an indication of the degree of dispersion from the central point, the mean value plays an integral role in calculating variance. Information entropy and variance of the reward contingencies associated with the target colors can be quantified using the given formulas.

It is important to note that the amount of VDAC is strongly related to the strength of stimulus-reward association. Specifically, the strength of reward association has been represented as the EV or the absolute associative value of the reward contingencies in previous studies (Anderson et al., 2011, 2014; Le Pelley et al., 2019). Hence, the reward contingencies associated with the target colors in the present study were assigned an identical EV, so as to control for the influence of the strength of reward association in biasing VDAC.

The purpose of the present study was to investigate which of the two proxies of uncertainty—information entropy and variance—modulates value-related attentional bias. Experiment 1 was conducted to confirm whether the modulation of VDAC by reward uncertainty observed in Experiment 2 of Cho and Cho’s (2021) study is replicable, with a different sample size to increase statistical power. Here, the two measures were associated with the target colors in a compatible manner. In the following series of experiments, uncertainty was manipulated by modifying both the information entropy and variance of reward magnitude. In Experiment 2, we aimed to test whether VDAC prioritizes information entropy over variance—or vice-versa—by coding the two measures in a complementary manner. In addition, Experiment 3 was conducted to explore whether information entropy alone is sufficient to induce VDAC even when the involvement of variance is controlled. Lastly, in Experiment 4, we investigated whether variance of reward modulates attentional priority when the contribution of information entropy is equated.

Experiment 1

Cho and Cho (2021) found that the distractors associated with uncertain reward elicited a greater attentional capture than those associated with a certain magnitude of reward. Here, the purpose of Experiment 1 was to revisit the findings of Cho and Cho's Experiment 2 and replicate the modulation of attentional allocation by reward uncertainty with two slight modifications: a larger sample size ($n = 48$) and a different reward contingency for the uncertainty target.

In the Training Phase, participants were instructed to respond to the orientation of a bar inside a red or green circle among six heterogeneously colored circles. One of the two target colors was associated with uncertain reward scores (20, 40, 60, and 80 points), referred to as the "uncertainty target." Note that the proportions of variable reward scores were equiprobable across the scores (i.e., 25% of the total trials). The other target color was associated with a constant reward score of 50 points with 100% probability, referred to as the "certainty target." The expected values, defined as the product of reward magnitude and probability, were identical for both target colors (50 points), whereas they varied in terms of the number and the magnitude of reward outcomes. The two formulas previously mentioned yields the amount of information entropy and variance of the reward contingencies for each target type; reward contingency for the uncertainty target renders 2 bits of information entropy and the variance of 500, while the certainty target renders 0 bits of entropy and 0 variance (see Table 1).

In the Test Phase, the target was defined as a bar stimulus in a diamond shape among heterogeneously colored circles, with the color of the target diamond randomly selected from a set of colors excluding red and green. Half the trials included a distractor that was either red or green, and the other half displayed a target diamond and five nontarget circles. Here, heterogeneous color nontargets were used to avoid a confounding capture effect by the color-singleton features (e.g., red and green) of the distractors (Anderson et al., 2011; Cho & Cho, 2021; Theeuwes, 1992). Attentional interference effects were measured to examine whether reward-associated distractors with contrasting levels of uncertainty but an identical EV, involuntarily captured attention.

Method

Participants

We conducted a power analysis using G-Power 3.1 software (Faul et al., 2007) to determine a proper sample size for examining the difference in interference effects of the distractors. Based on the reported effect size (η_p^2) in previous studies, which ranged from .14 to .16 (Anderson et al., 2013; Cho & Cho, 2021; Koenig, Uengoer, & Lachnit, 2017), a power of .95, an alpha level of .05, and a minimum sample size (n) of 22 was necessary for a within-subjects analysis of variance (ANOVA). Considering the need to counterbalance conditions (see Design section below) and to increase power in the analyses, we decided to double the sample size, which led to 48 participants ($M_{\text{age}} = 22.5$, 14 males) from Korea University being recruited. All participants had self-reported normal or corrected-to-normal visual acuity and color vision. The participants provided informed consent and received a monetary compensation of KRW 8,000 (approximately US$7) for their participation. All experiments were approved by the Institutional Review Board at Korea University (KU-IRB-2021-0424-01).

Apparatus

All experiments were programmed and displayed using MATLAB software Version R2019a (www.mathworks.com) with Psychophysics Toolbox (Psychtoolbox) Version 3 extensions. Stimuli were presented on a 17-in. CRT monitor of a personal computer at a viewing distance of approximately 60 cm in a dimly lit, sound-attenuated room. Responses were collected using a standard computer keyboard.

Training Phase

Stimuli. The sequence of displays and time course for the Training Phase are shown in Figure 2A. All stimuli were presented on a black background. Each trial consisted of three displays: a fixation display, a search display, and a feedback display. A white fixation cross (.9° × .9° visual angle; Red, Green, Blue [RGB]: 255, 255, 255; Commision Internationale d'Elairage [CIE]: $x = .270$, $y = .297$) was presented at the center of the fixation display and remained throughout the trial. The search display consisted of a fixation cross surrounded by six colored circles (each 1.9° × 1.9°), which were spaced at equal intervals along an imaginary circle with a 4.2° radius centered at the fixation. Targets were either a red (RGB: 255, 0, 0; CIE: $x = .581$, $y = .347$) or green (RGB: 0, 255, 0; CIE: $x = .285$, $y = .599$) circle, one of which was presented on each trial. The color of nontarget circles was randomly selected from a set of blue (RGB: 0, 0, 255; CIE: $x = .152$, $y = .080$), yellow (RGB: 255, 255, 0; CIE: $x = .388$, $y = .513$), cyan (RGB: 0, 255, 255; CIE: $x = .205$, $y = .286$), magenta (RGB: 255, 0, 255; CIE: $x = .262$, $y = .148$), orange (RGB: 255, 127, 0; CIE: $x = .498$, $y = .418$), and brown (RGB: 170, 100, 50; CIE: $x = .443$, $y = .401$) colors

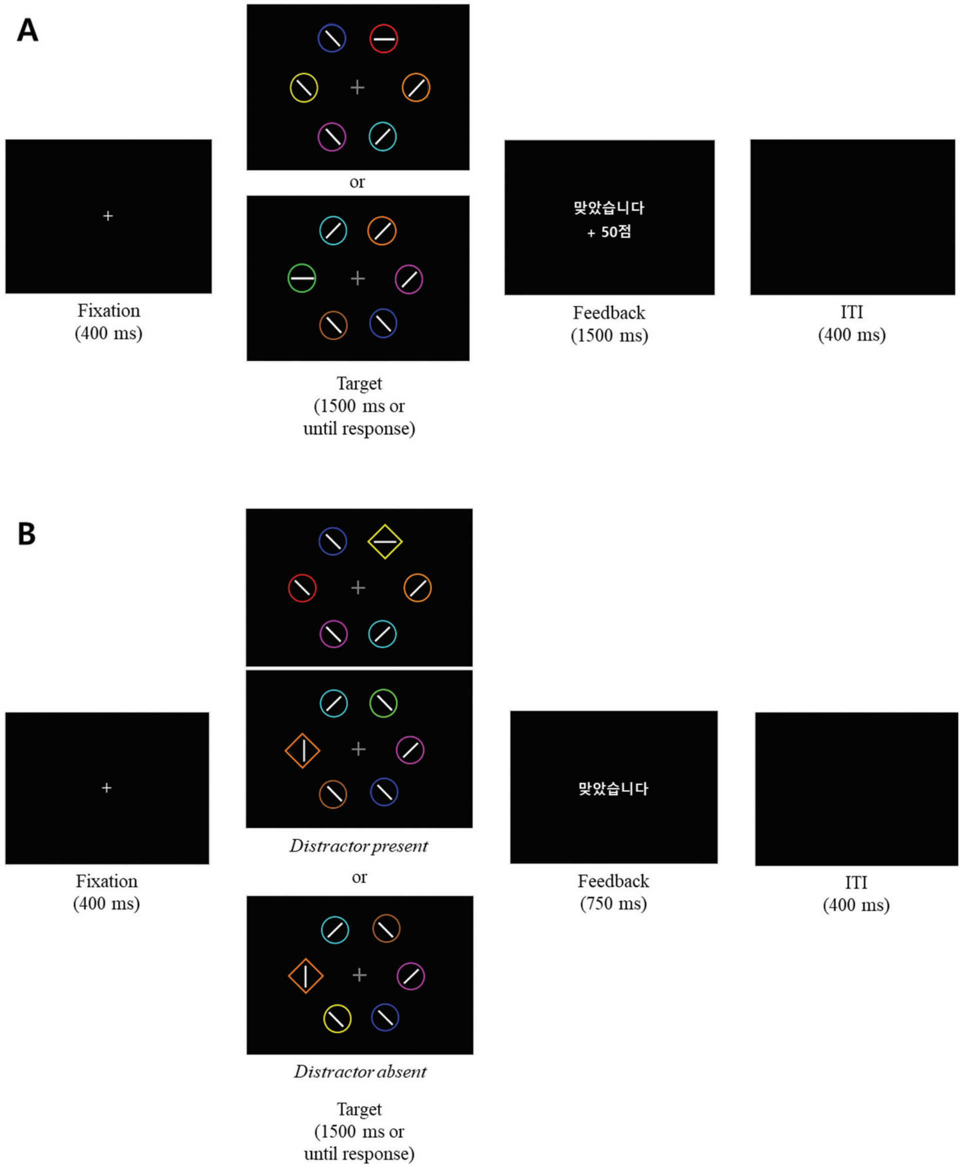
Table 1

The Levels of Reward Magnitude, Probability, Expected Value, Information Entropy, and Variance of Reward-Associated Targets (Distractors) as a Function of Target (Distractor) Type in Experiments 1, 2, 3, and 4

Experiment	Target type	Reward magnitude	Reward probability	Expected value	Information entropy	Variance
Experiment 1	Uncertainty target	20, 40, 60, 80	.25 for each reward	50	2	500
	Certainty target	50	1	50	0	0
Experiment 2	High entropy target	10, 30, 50, 70, 90	.2 for each reward	50	2.32	800
	High variance target	10, 90	.5 for each reward	50	1	1,600
Experiment 3	High entropy target	60, 70, 100, 130, 140	.2 for each reward	100	2.32	1,000
	Low entropy target	50, 100, 150	.6 for 100 points,.2 for 50 and 150 points	100	1.37	1,000
Experiment 4	High variance target	30, 50, 70	.4 for 50 points,.3 for 30 and 70 points	50	1.57	240
	Low variance target	40, 50, 60	.4 for 50 points,.3 for 40 and 60 points	50	1.57	60

Figure 2

Examples of a Trial Sequence in the Training (A) and Test (B) Phases in Experiments 1, 2, 3, and 4



Note. See the online article for the color version of this figure.

without replacement. Inside the target circle, there was a white line segment (.9° visual angle), oriented either horizontally or vertically. Inside each of the nontarget circles there was a line segment tilted 45° either clockwise or counterclockwise (assigned at random). On correct trials, the feedback display provided written feedback—“맞았습니다” (“Correct” in Korean)—and, underneath, the amount of reward points earned in the trial. For an incorrect response, a 1,000-Hz tone sounded for 500 ms while the written feedback “틀렸습니다” (“Incorrect” in Korean) was shown and no reward points were given.

Procedure. In the Training Phase, each participant performed 24 practice trials followed by two blocks of 240 main-task trials each. Each trial started with the fixation display for an interval of 400 ms. The search display was then presented for 1,500 ms or until a response was made, which was followed by the feedback display that lasted 1,500 ms. The intertrial interval (ITI) was 400 ms.

Participants were instructed to respond to the orientation of the line segment in the target circle (red or green) among heterogeneously colored nontarget circles. Using a standard computer keyboard, participants were to press the “Z” key with their left index finger when the target line was horizontal and the “M” key with their right index finger when the target line was vertical. When a correct response was made, participants were rewarded with points (20, 40, 50, 60, or 80 points) at the end of the trial. Participants were instructed to earn as many points as possible to exceed an unspecified score limit, to maximize their monetary compensation for participation. Regardless of the actual points earned by each participant, however, the compensation was provided in full when the overall response accuracy exceeded 80%. The reward was given depending on the target type: one of the two target colors was associated with variable reward magnitude scores, which delivered 20, 40, 60, or 80 points with 25% probability for each reward outcome and was defined as the uncertainty target or prediction error-present target. The other color was associated with a constant reward magnitude score (50 points) with 100% probability and was defined as a certainty target or prediction error-absent target. Thus, the two target colors were associated with an identical EV (50 points) but differed in terms of uncertainty in reward provision (Fiorillo et al., 2003; Preuschoff et al., 2006; Schultz et al., 2008). The target circle was shown equally often in each of the six possible locations on an imaginary circle with a 4.2° radius. The color and the reward uncertainty type of the target were randomized and counterbalanced across participants. The debriefing included information about the relationship between performance and reward and was given upon the completion of the experiment.

Design. The target location, target bar orientation, and target color were fully crossed and counterbalanced. Trials were presented randomly and the target color, target location, and line orientation varied unpredictably.

Test Phase

Stimuli. The sequence of displays and time course for the Test Phase are shown in Figure 2B. All stimuli were presented on a black background. Each trial consisted of three displays: a fixation display, a search display, and a feedback display. The fixation display was arranged in the same manner as in the Training Phase. The search display consisted of a fixation cross surrounded by six colored shapes, including the target, which was defined as a diamond shape (2.1° × 2.1°), and five nontarget circles. The color of the diamond was randomly selected from a set of blue, yellow, cyan, magenta, orange, and brown, but never red or green, which were the colors of the targets in the Training Phase. The feedback display only informed participants of whether their response was correct or not by presenting written feedback identical to that of the Training Phase.

Procedure. In the Test Phase, each participant performed twelve practice trials followed by two blocks of 144 main-task trials each. Each trial began with the fixation display for an interval of 400 ms. After the fixation display, the search array was presented for 1,500 ms or until a response was made. The feedback display was presented for 750 ms. The ITI was 400 ms. The procedure was identical to that of the Training Phase, except the target was a diamond among circles and no reward points were given. Participants were instructed to ignore the color of the shapes and respond according to the orientation of the line inside the diamond. Critically, a red or green circle, which had been associated with reward in the Training Phase, was presented as a distractor in 50% of the trials. Based on the target type in the Training Phase, one of the two colored circles (red or green) was defined as the uncertainty distractor (prediction error-present distractor) while the other was defined as the certainty distractor (prediction error-absent distractor). The remaining 50% of trials did not contain any reward-associated distractor. Participants were not explicitly informed that the target would never be rendered in red or green, and that reward would no longer be provided in the Test Phase.

Design. The target location, target bar orientation, target color, distractor presence, and distractor type were fully crossed and counterbalanced. Trials were presented randomly so that the distractor type and target identity varied unpredictably. The target line orientation-response mapping was identical to that of the Training Phase.

Results

Trials with response times (RTs) shorter than 150 ms or greater than three standard deviations from the participant's mean RT for each condition were excluded from the analyses (2.04% of the trials in the Training Phase and 2.30% of the trials in the Test Phase). Mean correct RT and percent errors (PEs) were calculated for each participant as a function of block (first or second) and target type (reward uncertainty or certainty target) in the Training Phase, and block (first or second) and distractor type (uncertainty distractor, certainty distractor, or distractor absent) in the Test Phase. Repeated-measures ANOVAs were conducted on the mean correct RT and PE data, with those variables as within-subject factors for each phase (see Table 2). The data sets of all experiments are available at the Open Science Framework: https://osf.io/wnx9j/ (Ju & Cho, 2022).

Training Phase

The overall mean RT was 589 ms. A significant main effect of block was found, $F(1, 47) = 54.65$, $p < .001$, $MSE = 1{,}164$, $\eta_p^2 = .54$. The mean RT was greater in the first block ($M = 607$ ms) than the second block ($M = 571$ ms). The main effect of target type was also significant, $F(1, 47) = 7.55$, $p = .008$, $MSE = 1{,}110$, $\eta_p^2 = .14$, with a greater mean RT on the certainty target trials ($M = 595$ ms) than the uncertainty target trials ($M = 582$ ms). Lastly, the interaction between block and target type was significant, $F(1, 47) = 4.58$, $p = .038$, $MSE = 188$, $\eta_p^2 = .09$. Separate analyses on each

Table 2

Mean Response Times (RTs; in Milliseconds, With Standard Deviation in Parentheses) and Percent Errors (PEs) in Experiment 1 as a Function of Target Type in the Training Phase and Distractor Type in the Test Phase

	Training Phase		Test Phase		
Dependent variables	Uncertainty target	Certainty target	Uncertainty distractor	Certainty distractor	Distractor absent
RT	582 (72)	595 (64)	611 (67)	597 (60)	600 (66)
PE	2.24 (1.73)	2.00 (1.44)	2.38 (2.14)	2.82 (2.42)	2.85 (2.19)

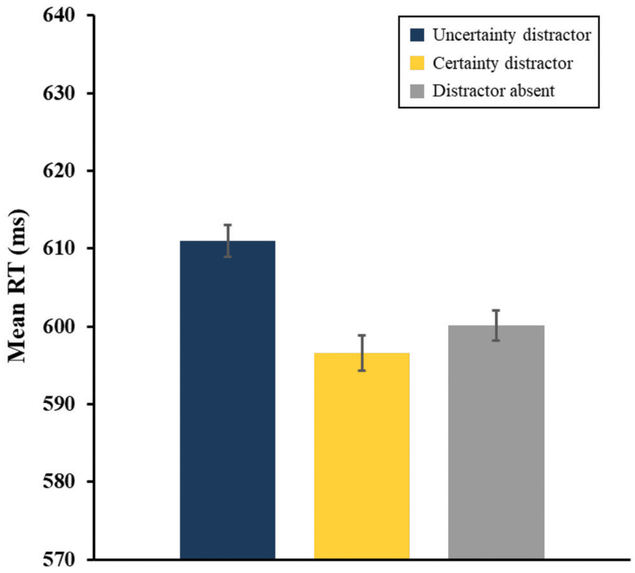
block demonstrated that the main effect of target type was not significant in the first block, $F(1, 47) = 2.85$, $p = .098$, $MSE = 680$, even though the mean RT for the uncertainty target trials ($M = 603$ ms) was numerically shorter than that for the certainty target trials ($M = 612$ ms). However, it was significant in the second block, $F(1, 47) = 11.82$, $p = .001$, $MSE = 619$, $\eta_p^2 = .201$. The mean RT for the uncertainty target trials ($M = 562$ ms) was shorter than that for the certainty target trials ($M = 579$ ms). The overall PE was 2.1%. The main effect of block was significant, $F(1, 47) = 6.41$, $p = .015$, $MSE = 2.4$, $\eta_p^2 = .12$. PE was higher in the first block (2.4%) than the second block (1.8%). Neither the main effect of target type, $F(1, 47) = 1.68$, $p = .202$, $MSE = 1.58$, nor the interaction between the block and target type, $F(1, 47) = 1.22$, $p = .275$, $MSE = 2.31$, was significant.

Test Phase

The overall mean RT was 603 ms. The main effect of block was not significant, $F(1, 47) < 1$. The main effect of distractor type was significant, $F(2, 94) = 8.62$, $p < .001$, $MSE = 628$, $\eta_p^2 = .155$ (see Figure 3). Subsequent pairwise comparisons showed that the mean RT was significantly greater when the uncertainty distractor was presented ($M = 611$ ms) than when either the certainty distractor ($M = 597$ ms), $t(47) = 3.73$, $p = .001$ (Cohen's $d = .538$) or no distractor was presented ($M = 600$ ms), $t(47) = 3.28$, $p = .002$ (Cohen's $d = .474$). However, the mean RT did not differ significantly between trials with a certainty distractor and distractor absent trials, $t(47) = .98$, $p = .331$. The interaction between block and distractor type was not significant, $F(2, 94) = 2.08$, $p = .131$, $MSE = 469$. The overall PE was 2.7%. No main effect or interaction was significant for the PE data.

Figure 3

Mean Response Times (RTs; in Milliseconds) as a Function of Distractor Type in the Test Phase of Experiment 1



Note. Error bars show within-subjects standard error of the mean (Cousineau, 2005). See the online article for the color version of this figure.

Discussion

The results from the Training Phase indicated that participants became acquainted with the task of searching for red or green target circles as the phase progressed, leading to shorter response latencies and higher accuracy in the second block than the first block. There was a significant effect of reward uncertainty on response latency, such that the mean RT was shorter for uncertainty than certainty target trials especially in the second block. This result indicates that enhanced attentional orienting for the uncertainty targets sped up the visual search for the target circle, leading to facilitation of responses. Such differential effects of attentional capture between the two target types can be attributed to the different levels of uncertainty, as the expected value for the two target types was kept identical.

Such findings may be at odds with the results from the Training Phase in Experiment 2 of Cho and Cho (2021), where the effect of target type (certainty vs. uncertainty) on behavioral performances was not observed. Nevertheless, previous studies using the classical value-driven attentional capture paradigm (Anderson et al., 2011) showed mixed results as to whether performances in the Training Phase differed based on the reward contingency of the target. Specifically, some studies have reported that participants generally identified high-reward targets faster than low-reward targets (Anderson & Yantis, 2012; Anderson et al., 2017; Anderson, Laurent, & Yantis, 2013; Sha & Jiang, 2016). Considering that stimulus features associated with reward uncertainty acquire priority signals (Anselme, 2010; Gottlieb, 2012) similar to those associated with high reward value, enhanced attentional orienting for the uncertainty targets is expected to facilitate behavioral responses. In contrast, other studies showed a lack of difference in behavioral performances by target reward contingency (Anderson & Halpern, 2017; Kim & Beck, 2020; Miranda & Palmer, 2014; Roper & Vecera, 2016). These mixed results suggest that, while reward feedback allowed participants to adequately form the stimulus-reward associations top–down attentional control modulated the visual search for the two target colors by assigning equal priority (Anderson, Laurent, & Yantis, 2013), as the reward itself is irrelevant for the task goal of identifying the line orientation within the target circles.

Critically, the effect of the reward contingency on behavioral performances in the Test Phase is of primary interest for studies using the classical value-driven attentional capture paradigm (Anderson et al., 2013). Here, the results from the Test Phase showed that the distractors associated with uncertain reward elicited a larger value-driven attentional capture (11 ms) than those associated with a certain magnitude of reward (−3 ms). This directly replicates the results from the Test Phase of Experiment 2 in Cho and Cho (2021). As the EV was kept equal across distractors, the difference in attentional interference between the distractors can only be attributed to the level of uncertainty—with higher levels of uncertainty leading to larger attentional interference. These findings are interpreted as strong evidence that uncertainty in reward provision biases attention, which is in line with the uncertainty principle suggested by Pearce and Hall (1980).

As noted earlier, however, such evident influence of uncertainty in modulating attentional capture can be explained as the effect of both information entropy and variance. Specifically, the uncertainty distractor was associated with high levels of both information entropy (2 bits) and variance (500), while the certainty distractor had 0 bits of information entropy and zero variance. Therefore, to thoroughly investigate which measure is more dominant in representing uncertainty in the context of VDAC, there exists a critical necessity to disentangle the two measures. Information entropy and variance must be manipulated orthogonally to compare the extent of attentional capture by distractors that are associated with contrasting levels (high vs. low) of each measure.

Experiment 2

Although Experiment 1 provided evidence for the idea that the uncertainty of reward provision involuntarily biases attention, the interpretation of uncertainty is yet equivocal. Under the reward scheme of Experiment 1, it is impossible to separate the effects of information entropy and variance; one would suspect that the higher level of information entropy associated with the uncertainty distractor elicited VDAC (2 bits compared with 0 bits), while the other would emphasize the role of variance (500 compared with 0). Therefore, to identify which representation of uncertainty is more dominant in guiding VDAC, a new set of reward contingencies were devised and associated with each of the two target (and distractor) types in Experiment 2.

Specifically, the uncertainty of value during stimulus-reward association was manipulated by assigning variable reward contingencies to both target types. For instance, one of the two target colors was associated with a variable reward contingency that provided 10, 30, 50, 70, and 90 points with equal probabilities (20% each). The other target color also had variable reward scores of either 10 or 90 points, presented with equal probability (50% each). The overall range (from 10 to 90 points) and EV (50 points) of reward scores were kept identical across conditions. Above all, the information entropy and variance of the reward scores were formulated in a diametrically opposing manner within each target type (see Table 1). The first reward contingency had 2.32 bits of information entropy (high entropy) and a variance of 800 (low variance)—referred to from now on as the high entropy target. On the other hand, the second had 1 bit of entropy (low entropy) and variance of 1,600 (high variance)—from now on, the high variance target. In doing so, we were able to rigorously examine which of the two measures is more dominant in biasing attentional allocation. If information entropy (i.e., informational value) is the crucial determinant of uncertainty in biasing attention, the high entropy distractor will elicit significantly larger VDAC than the high variance distractor. On the other hand, if variance (i.e., the absolute size of reward prediction error) is the critical component in biasing attention, VDAC would be larger with the high variance distractor than the high entropy distractor.

Method

Participants

A new group of 48 participants ($M_{\text{age}} = 22.4$ years, 29 females) from the same pool as in Experiment 1 took part in Experiment 2. The participants provided informed consent and were given the same monetary compensation as in the previous experiment (KRW 8,000). All participants had self-reported normal or corrected-to-normal visual acuity and color vision.

Apparatus

The apparatus of Experiment 2 was identical to that of the previous experiment.

Stimuli, Procedure, and Design

The stimuli, procedure, and design of the Training Phase in Experiment 2 were identical to those of the previous experiment with two critical exceptions: the number of reward outcomes and their magnitude. Unlike the previous experiment where one of the two target colors was associated with a constant reward magnitude (50 points), both target colors were associated with variable reward magnitude scores in Experiment 2. Here, reward magnitude scores were manipulated in a way that could decouple the confounding effects of information entropy and variance in determining uncertainty. Specifically, the levels of information entropy and variance within each reward contingency were diametrically opposed. One of the two target colors was associated with high-entropy, and at the same time, low-variance reward magnitude scores. Specifically, the possible outcomes were 10, 30, 50, 70, or 90 points with a 20% probability for each. The other color was associated with high-variance, low-entropy reward magnitude scores, which were either 10 or 90 points with a 50% probability for each. As in Experiment 1, the two target colors were associated with an identical EV (50 points) but differed in terms of uncertainty in reward provision. The procedure in the Test Phase of Experiment 2 was identical to that of the previous experiment.

Results

The criteria applied to trim the RT and PE data in Experiment 1 were also used in Experiment 2, which resulted in the exclusion of 1.98% of trials in the Training Phase and 2.11% of trials in the Test Phase from the analyses. Mean correct RT and PEs were calculated for each participant as a function of block (first or second) and target type (high entropy target or high variance target) in the Training Phase, and block (first or second) and distractor type (high entropy distractor, high variance distractor, or distractor absent) in the Test Phase. Repeated-measures ANOVAs were conducted on the mean correct RT and PE data, with those variables as within-subject factors for each phase (see Table 3).

Training Phase

The overall mean RT was 573 ms. The mean RT was significantly greater in the first block ($M = 586$ ms) than the second block ($M = 561$ ms), $F(1, 47) = 32.56$, $p < .001$, $MSE = 925$, $\eta_p^2 = .409$. Neither the main effect of target type, $F(1, 47) < 1$, nor the interaction between block and target type, $F(1, 47) = 1.04$, $p = .312$, $MSE = 163$, was significant. The overall PE was 2.3%. The main effect of block was significant. The PE was higher in the first block (2.7%) than the second block (1.9%), $F(1, 47) = 10.6$, $p = .002$, $MSE = 2.9$, $\eta_p^2 = .184$. Neither the main effect of target type, $F(1, 47) = 2.98$, $p = .091$, $MSE = 2.98$, nor the interaction between the block and target type, $F(1, 47) < 1$, was significant.

Test Phase

The overall mean RT was 610 ms. The main effect of block was significant, $F(1, 47) = 5.25$, $p = .026$, $MSE = 1{,}507$, $\eta_p^2 = .101$, with a greater mean RT in the second block ($M = 615$ ms) than the

Table 3

Mean Response Times (RTs; in Milliseconds, With Standard Deviation in Parentheses) and Percent Errors (PEs) in Experiment 2 as a Function of Target Type in the Training Phase and Distractor Type in the Test Phase

	Training Phase		Test Phase		
Dependent variables	High entropy target	High variance target	High entropy distractor	High variance distractor	Distractor absent
RT	574 (57)	572 (60)	617 (79)	607 (72)	605 (73)
PE	2.06 (1.54)	2.49 (2.15)	2.89 (3.48)	2.71 (2.89)	3.30 (2.99)

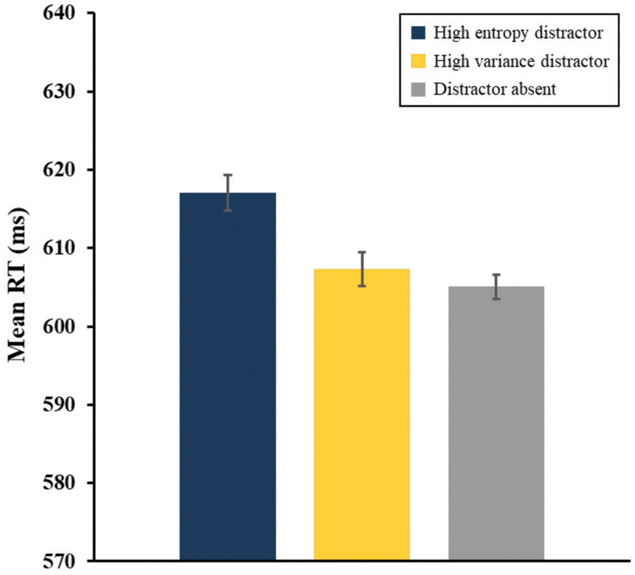
first block (*M* = 605 ms). More important, the main effect of distractor type was significant, *F*(2, 94) = 6.44, *p* = .004, *MSE* = 699, $\eta_p^2 = .12$ (see Figure 4). Subsequent pairwise comparisons showed that the mean RT was significantly greater when the high entropy distractor was presented (*M* = 617 ms) than when either the high variance distractor (*M* = 607 ms), *t*(47) = 2.338, *p* = .024 (Cohen's *d* = .337) or no distractor was presented (*M* = 605 ms), *t*(47) = 3.63, *p* = .001 (Cohen's *d* = .524). However, the mean RT did not differ significantly between trials with a high variance distractor and distractor absent trials, *t*(47) = .777, *p* = .441. The interaction between block and distractor type was not significant, *F*(2, 94) < 1. The overall PE was 3.1%. No main effect or interaction was significant for the PE data.

Discussion

The results from the Training Phase indicated that, as in Experiment 1, participants became acquainted with the task of searching for target circles as the phase progressed, which was demonstrated by shorter response latencies and higher accuracy in the second block than the first block. However, the differential effects of attentional capture between the target types (certainty vs. uncertainty) shown in Experiment 1 were not observed in the present experiment.

Figure 4

Mean Response Times (RTs; in Milliseconds) as a Function of Distractor Type in the Test Phase of Experiment 2



Note. Error bars show within-subjects standard error of the mean (Cousineau, 2005). See the online article for the color version of this figure.

More important, the results from the Test Phase revealed that the distractors associated with high entropy (and low variance) reward magnitude elicited a larger value-driven attentional capture (12 ms) than the distractors associated with high variance (and low entropy) reward magnitude (2 ms). Critically, the uncertainty of value magnitude during stimulus-reward association in Experiment 2 was manipulated in a way that enabled the dissociation of information entropy and variance in conveying uncertainty. In doing so, it became evident that when variance and information entropy of reward values compete against each other in communicating the level of uncertainty, information entropy overshadows variance. Taken together, the results of Experiments 1 and 2 consistently indicate that information entropy is a crucial determinant for inducing VDAC, while the relationship between variance and VDAC is perhaps less clear.

Experiment 3

In the previous experiments, we found a larger attentional interference elicited by uncertainty distractors compared with certainty distractors (Experiment 1) and high entropy (low variance) distractors compared with high variance (low entropy) distractors (Experiment 2). These effects were mainly driven by the influence of information entropy. It is unclear, however, whether the amount of associative information (i.e., information entropy) a stimulus possesses with regards to the reward outcomes is sufficient to induce uncertainty, resulting in VDAC. To thoroughly validate the dominant influence of information entropy on VDAC, there is a critical need to investigate whether information entropy alone can induce a value-driven attentional bias, even when the influence of variance in modulating VDAC is minimized across the distractor types. To test this assumption, a new set of reward contingencies was devised and associated with each of the two target (and distractor) types in Experiment 3. In particular, Experiment 3 compares the extent of attentional capture by distractors that are associated with contrasting levels (high vs. low) of information entropy, while the variance and expected value for both distractor types are kept identical.

Following the pattern of Experiment 2, the uncertainty of value during stimulus-reward association was manipulated by assigning variable reward contingencies to both target types. Critically, reward contingencies were formulated in a way that could contrast the level of information entropy, while keeping reward variance identical across target types. One of the two target colors was associated with reward scores of 60, 70, 100, 130, and 140 points, presented with equal probabilities (20% each). The other target color was associated with scores of 50, 100, and 150 points, which were presented with the probabilities of 20%, 60%, and 20%, respectively. Such formulation allows for a successful distinction of the information entropy, while variance (1,000) and EV (100 points) are kept constant. Here, the former reward contingency is referred to as the "high entropy target," with 2.32 bits of information entropy. In contrast, the latter is referred to as the "low entropy target, with 1.37 bits of entropy (see Table 1). If information entropy (informational value) is sufficient for eliciting uncertainty, a larger VDAC would be observed toward high entropy than low entropy distractors in the Test Phase.

Method

Participants

A new group of 36 participants (M_{age} = 23.8 years, 23 females) from the same pool as the previous experiments took part in Experiment 3. The participants provided informed consent and were given the same monetary compensation as in the previous experiments (KRW 8,000). All participants had self-reported normal or corrected-to-normal visual acuity and color vision.

Apparatus

The apparatus of Experiment 3 was identical to that of the previous experiments.

Stimuli, Procedure, and Design

The stimuli, procedure, and design of the Training Phase in Experiment 3 were identical to those of the previous experiments with the following exceptions. Reward scores associated with the target colors were manipulated in a way that could elicit two different values of information entropy (high vs. low), while variance was kept constant. One of the two target colors—the high entropy target—was associated with the following scores: 60, 70, 100, 130, and 140 reward points with 20% probability for each. The low entropy target color was associated with 50, 100, and 150 points with 20%, 60%, and 20% probabilities, respectively. The two target colors were associated with an identical EV size (100 points) and variance (1,000). The procedure of the Test Phase in Experiment 3 was identical to that of the previous experiments.

Results

The criteria from the previous experiments were also applied in Experiment 3 to trim the RT and PE data, resulting in the exclusion of 1.71% of trials in the Training Phase and 1.75% of trials in the Test Phase from the analyses. Mean correct RT and PEs were calculated for each participant as a function of block (first or second) and target type (high or low entropy target) in the Training Phase, and block (first or second) and distractor type (high entropy distractor, low entropy distractor, or distractor absent) in the Test Phase. Repeated-measures ANOVAs were conducted on the mean correct RT and PE data, with those variables as within-subject factors for each phase (see Table 4).

Training Phase

The overall mean RT was 573 ms. The main effect of block was significant, $F(1, 35) = 54.52$, $p < .001$, $MSE = 734$, $\eta_p^2 = .609$. Specifically, the mean RT was greater in the first block (M = 590 ms) than the second block (M = 557 ms). Neither the main effect of target type, $F(1, 35) = 2.19$, $p = .147$, $MSE = 821$, nor the interaction between block and target type, $F(1, 35) = 2.10$, $p = .156$, $MSE = 115$, were significant. The overall PE was 2.3%. The main effect of block was significant, $F(1, 35) = 24.43$, $p < .001$, $MSE = 1.7$, $\eta_p^2 = .411$. PE was higher in the first block (2.8%) than the second block (1.7%). Neither the main effect of target type, $F(1, 35) < 1$, nor the interaction between block and target type, $F(1, 35) < 1$, was significant.

Test Phase

The overall mean RT was 602 ms. The main effect of block was not significant, $F(1, 35) < 1$. More important, the main effect of distractor type was significant, $F(2, 70) = 4.99$, $p = .017$, $MSE = 740$, $\eta_p^2 = .125$ (see Figure 5). Subsequent pairwise comparisons showed that the mean RT was significantly greater when the high entropy distractor was presented (M = 609 ms) than when the low entropy distractor (M = 598 ms), $t(35) = 2.31$, $p = .027$ (Cohen's $d = .385$) or no distractor was presented (M = 599 ms), $t(35) = 2.747$, $p = .009$ (Cohen's $d = .458$). The mean RT did not differ significantly between trials with a low entropy distractor and distractor absent trials, $t(35) = .428$, $p = .671$. The interaction between block and distractor type was not significant, $F(2, 70) < 1$. The overall PE was 2.8%. No main effect or interaction was significant for the PE data.

Discussion

The results of the Training Phase indicated that again, participants became acquainted with the task of searching for target circles as the phase progressed, which was demonstrated by shorter response latencies and higher accuracy in the second block than the first block. Similar to Experiment 2, the differential effects of attentional capture between the target types were not observed.

More important, Experiment 3 was conducted to investigate the sole effect of information entropy in modulating VDAC, while the

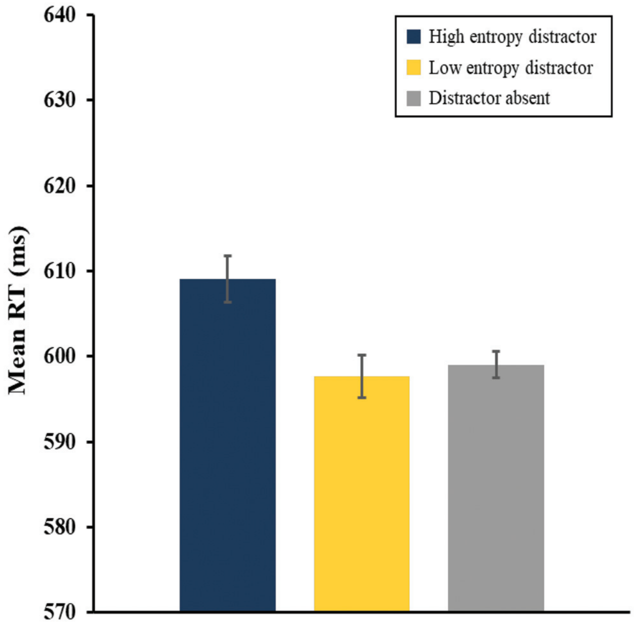
Table 4

Mean Response Times (RTs; in Milliseconds, With Standard Deviation in Parentheses) and Percent Errors (PEs) in Experiment 3 as a Function of Target Type in the Training Phase and Distractor Type in the Test Phase

	Training Phase		Test Phase		
Dependent variables	High entropy target	Low entropy target	High entropy distractor	Low entropy distractor	Distractor absent
RT	577 (72)	570 (74)	609 (88)	598 (78)	599 (81)
PE	2.23 (1.89)	2.28 (1.70)	2.55 (2.62)	3.19 (3.03)	2.70 (2.00)

Figure 5

Mean Response Times (RTs; in Milliseconds) as a Function of Distractor Type in the Test Phase of Experiment 3



Note. Error bars show within-subjects standard error of the mean (Cousineau, 2005). See the online article for the color version of this figure.

influence of variance was equated between the distractors. As expected, the results revealed that the distractors associated with high uncertainty (high entropy) reward magnitude elicited a larger value-driven attentional capture (10 ms) than the distractors associated with low uncertainty (low entropy) reward magnitude (−1 ms). This indicates that information entropy (i.e., informational value) exerts a clear as well as sufficient influence in generating value-related attentional priority. In other words, the results from Experiment 3 corroborate the finding that information entropy is a reliable source of uncertainty in guiding VDAC.

Experiment 4

In Experiment 3, information entropy was found to modulate value-driven attentional capture when the influence of variance was equated for both types of distractors, which provides evidence that information entropy is a reliable and sufficient source of uncertainty in guiding VDAC. Nevertheless, to further verify the necessity of the influence of information entropy on reward uncertainty, it is important to investigate whether variance of reward modulates value-based attentional priority, even when the involvement of information entropy is controlled. Therefore, Experiment 4 compared the extent of attentional capture by distractors that were associated with a new set of reward contingencies with contrasting levels (high vs. low) of variance, while information entropy and EV for both distractor types were kept identical.

In the Training Phase of Experiment 4, one of the two target colors was associated with reward scores of 30, 50, and 70 points with the probabilities of 30%, 40%, and 30%, respectively. Reward scores associated with the other target color were presented with the corresponding probabilities but with different respective scores of 40, 50, and 60 points. Such formulation allows for a distinction of variance while information entropy (1.57) and EV (50 points) are equated between the target types. Here, the former reward contingency is referred to as the “high variance target,” with a variance of 240, while the latter is referred to as the “low variance target,” with a variance of 60 (see Table 1). If variance is a modulatory factor for VDAC, a significantly larger VDAC would be observed for high variance than for low variance distractors. However, if variance is not a major determinant in modulating VDAC, the distractors would yield no significant difference in attentional capture.

Method

Participants

A new group of 48 participants (M_{age} = 23.5 years, 32 females) from the same pool as the previous experiments took part in Experiment 4. The participants provided informed consent and were given the same monetary compensation as in the previous experiments (KRW 8,000). All participants had self-reported normal or corrected-to-normal visual acuity and color vision.

Apparatus

The apparatus used in Experiment 4 was identical to that of the previous experiments.

Stimuli, Procedure, and Design

The stimuli, procedure, and design of the Training Phase in Experiment 4 were identical to those of the previous experiments with the following exceptions. One of the two target colors—the high variance target—was associated with the following scores: 30, 50, and 70 reward points with 30%, 40, and 30% probabilities, respectively, which yielded a variance of 240. The low variance target color was associated with 40, 50, and 60 points with probabilities identical to the high variance target, rendering a variance of 60. Both target colors were associated with an identical EV size (100 points) and information entropy (1.57). The procedure of the Test Phase in Experiment 4 was identical to that of the previous experiments.

Results

The criteria from the previous experiments were also applied in Experiment 4 to trim the RT and PE data, resulting in the exclusion of 1.86% of trials in the Training Phase and 1.93% of trials in the Test Phase from the analyses. Mean correct RT and PEs were calculated for each participant as a function of block (first or second) and target type (high or low variance target) in the Training Phase, and block (first or second) and distractor type (high variance distractor, low variance distractor, or distractor absent) in the Test Phase. Repeated-measures ANOVAs were conducted on the mean correct RT and PE data, with those variables as within-subject factors for each phase (see Table 5).

Training Phase

The overall mean RT was 590 ms. The main effect of block was significant, $F(1, 47) = 19.10$, $p < .001$, $MSE = 1{,}271$, $\eta_p^2 = .289$. Here, the mean RT was greater in the first block (M = 602 ms)

Table 5

Mean Response Times (RTs; in Milliseconds, With Standard Deviation in Parentheses) and Percent Errors (PEs) in Experiment 4 as a Function of Target Type in the Training Phase and Distractor Type in the Test Phase

	Training Phase		Test Phase		
Dependent variables	High variance target	Low variance target	High variance distractor	Low variance distractor	Distractor absent
RT	587 (87)	593 (89)	629 (107)	627 (100)	621 (99)
PE	1.98 (1.83)	1.95 (1.80)	2.55 (3.23)	3.19 (2.82)	2.70 (2.42)

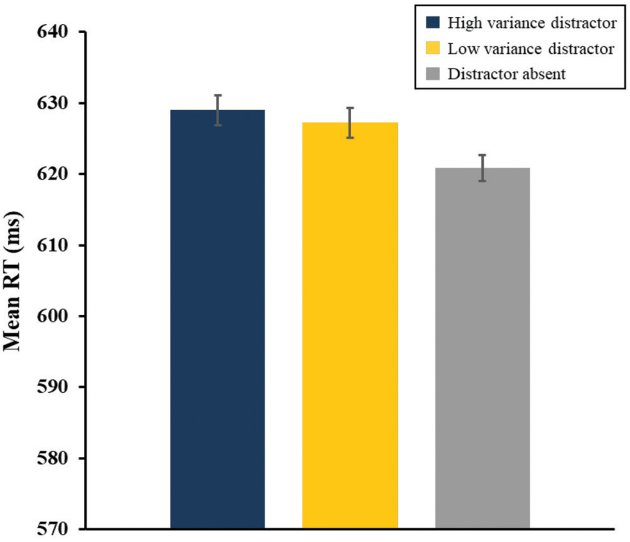
than the second block (M = 579 ms). Neither the main effect of target type, $F(1, 47) = 2.56$, $p = .114$, $MSE = 627$, nor the interaction between block and target type, $F(1, 47) = 1.11$, $p = .297$, $MSE = 193$, was significant. The overall PE was 2.0%. No main effect or interaction was significant for the PE data.

Test Phase

The overall mean RT was 626 ms. The main effect of block was not significant, $F(1, 47) = 2.54$, $p = .118$, $MSE = 2{,}328$. The main effect of distractor type was marginally significant, $F(2, 94) = 3.06$, $p = .052$, $MSE = 571$, $\eta_p^2 = .061$ (see Figure 6). Subsequent pairwise comparisons showed that the mean RT was greater when the high variance distractor was presented (M = 629 ms), $t(47) = 2.50$, $p = .016$ (Cohen's $d = .361$), and marginally greater when the low variance distractor was presented (M = 627 ms), $t(47) = 1.92$, $p = .061$ (Cohen's $d = .277$) compared with when no distractor was presented (M = 621 ms). Critically, the mean RT did not differ significantly between trials with a high variance distractor and a low variance distractor, $t(47) = .473$, $p = .638$. The interaction between block and distractor type was not significant, $F(2, 94) < 1$. The overall PE was 2.7%. No main effect or interaction was significant for the PE data.

Figure 6

Mean Response Times (RTs; in Milliseconds) as a Function of Distractor in the Test Phase of Experiment 4



Note. Error bars show within-subjects standard error of the mean (Cousineau, 2005). See the online article for the color version of this figure.

Discussion

The results indicated that again, participants became accustomed to the task of searching for target circles as the Training Phase progressed, which was demonstrated by shorter response latencies in the second block than the first block. As in Experiments 2 and 3, the differential effects of attentional capture between the target types were not observed.

More important, the results of the Test Phase revealed that the variance associated with the distractors did not modulate VDAC: the attentional interference by the distractors associated with high variance reward contingency (8 ms) and low variance reward contingency (6 ms) did not reveal a significant difference. This indicates that variance did not exert a clear influence in modulating value-related attentional priority when information entropy was kept identical.

Notably, similar amounts of attentional interference were observed for both types of distractors, which is at odds with the previous experiments where significant VDAC was observed only with uncertain- (Experiment 1) or high entropy-related distractors (Experiments 2 and 3). In fact, such mixed results are easily reconciled with the evident influence of information entropy. Specifically, the distractors in Experiment 4 were associated with an equal amount of information entropy (1.57 bits). As information entropy plays a necessary and sufficient role in inducing VDAC, the two types of distractors in Experiment 4 are expected to yield attentional priority signals with comparable strength, leading to a similar amount of VDAC.

General Discussion

The four experiments reported here investigated the effects of information entropy and variance in representing uncertainty in the context of value-driven attentional capture. Reward contingencies associated with the target colors in the Training Phase varied in each experiment on the amount of information entropy and variance. Experiment 1, in which uncertainty was tuned by varying the magnitude of the reward outcomes as in Cho and Cho's (2021) Experiment 2, replicated their findings that distractors previously associated with uncertain reward outcomes led to larger attentional interference than distractors previously associated with certain reward outcomes. These results indicate a significant modulation of VDAC by reward uncertainty when EV was held constant.

The present study extended the discussion of the effect of uncertainty in modulating VDAC by specifying and separating the effects on attentional allocation of two indices of uncertainty: information entropy and variance. In Experiment 2, distractors associated with high entropy (and low variance) reward outcomes led to a larger VDAC than those associated with high variance (and low entropy) reward outcomes. Furthermore, the results from Experiment 3 illustrate the consistent as well as sufficient influence of information entropy in guiding VDAC, where high entropy distractors attracted attention more than low entropy distractors. Lastly, in Experiment 4, the distractors associated with contrasting levels of variance rendered no significant difference in VDAC, which further confirms that the modulation of VDAC observed in Experiments 1, 2, and 3 resulted from the influence of information entropy. Taken together, these findings corroborate the hypothesis that information entropy is one of the major determinants mediating how the uncertainty of reward provision biases attentional capture.

It is important to note that, to the best of our knowledge, no studies in the field of VDAC have yet examined a direct comparison between the effects of information entropy and variance in signaling uncertainty. This is in part due to the lack of consensus among previous studies on reward-attention associations in operationally defining uncertainty. In other words, although measures such as variance, standard deviation, and information entropy have been frequently utilized as useful proxies of uncertainty (Fiorillo et al., 2003; Gottlieb et al., 2013; Rushworth & Behrens, 2008), these measures have not been thoroughly verified in the context of VDAC.

Critically, however, the influence of information entropy in inducing VDAC can be easily observed from previous studies on the relationship between uncertainty in value prediction and attentional capture. In their Experiments 1 and 2, Cho and Cho (2021) observed a larger VDAC for the distractors that were imbued with higher levels of information entropy; uncertainty targets had .81 bits (Experiment 1) and 2 bits of information entropy (Experiment 2), while certainty targets had 0 bits in both experiments. In Le Pelley et al.'s (2019) Experiment 2, gaze was more likely to be detected on nonpredictive distractors, and participants' first saccades were more likely to be directed toward nonpredictive distractors than predictive distractors. Notably, nonpredictive distractors were imbued with a higher level of information entropy (1 bit) than predictive distractors (0 bit), which again confirms the role of information entropy in modulating value-related attentional capture. Collectively, these findings provide converging evidence that cues that possess the maximal amount of information capture attention.

It is important to note that the present study provides a clear distinction between the effects of information entropy and reward value (i.e., EV) in modulating VDAC. Reward value is an integral factor for generating VDAC (Anderson & Halpern, 2017). In fact, most previous studies with the classical VDAC paradigm manipulate reward size while controlling the amount of information entropy. For instance, in Anderson et al.'s (2011) experiment, reward contingencies were composed of an 80% probability of providing one type of reward (e.g., high, 5 cents) and a 20% probability of providing another (e.g., low, 1 cent), which is calculated as having .72 bits of information entropy. Notably, the present study used the same (but reversed) logic, by manipulating information entropy and controlling EV. The presence of significant difference in VDAC between the distractors that hold contrasting amounts of informational value, and an identical EV, corroborates the robustness of the effect of information entropy.

In Experiments 2 and 3, the distractors associated with low-entropy reward contingencies (e.g., alternative conditions) failed to produce significant attentional interference compared with when no distractor was presented, although the distractors were associated with some degree of information entropy (e.g., 1 bit for Experiment 2, 1.57 bits for Experiment 3). In fact, the absence of VDAC for the alternative condition is a common phenomenon in VDAC studies (Anderson & Halpern, 2017; Anderson & Yantis, 2013; Anderson et al., 2011; Cho & Cho, 2021; Mine & Saiki, 2015). More important, VDAC itself is often defined as the presence of a robust attentional bias toward distractors associated with "high" reward (Anderson et al., 2011, 2013, 2017). Such disproportional allocation of attention signifies that VDAC is a selective attentional orienting mechanism toward the features that demand higher priority signal, rather than being a mere stimulus-reward association proportional to the amount of reward. Considering that a stimulus feature associated with reward uncertainty acquires a priority signal (Anselme, 2010; Gottlieb, 2012), high-entropy distractors in the present study would induce significant attentional capture as high-reward distractors do.

In a similar vein, the amount of VDAC elicited by the distractors in Experiment 4 revealed no significant difference. Considering that the distractors were associated with equal amounts of information entropy (i.e., 1.57 bits), participants had no particular reason to ascribe disproportionately larger attentional priority to either one of the target features during associative learning. Thus, a comparable strength of stimulus-reward association between the target features would have occurred in the Training Phase, resulting in a comparable amount of attentional capture at least marginally in the subsequent Test Phase.

Note that the trials with incorrect or slow responses, where no reward was provided, were not accounted for in the analyses in the present study. Consequently, it is possible that the absence of reward provision in these trials changed participants' perceived uncertainty about the reward contingencies. However, such differential exposure to reward values is expected to prompt a minimal systematic impact in biasing the calculation of reward contingencies. Specifically, the overall PEs in the Training Phases were 2.1%, 2.3%, 2.3%, and 2.0% for Experiments 1, 2, 3, and 4, respectively, which only yielded approximately 10 trials out of the total 480 trials. More important, the error rates did not differ based on the target types in all four experiments, which indicates that the impact of such unrewarded trials is negligible in disrupting the prearranged asymmetry of information entropy between the reward contingencies.

Uncertainty, Information, and Attention for Learning

From a psychological standpoint, information entropy is interpreted as the average amount of surprise or uncertainty associated with outcomes (Daikoku, 2018; Shannon, 1948). It is important to note that uncertainty represents the amount of "potential" information available to be learned. Consequently, when a random variable assumes a value, the observer is likely to gain information and, in turn, lose uncertainty (Applebaum, 1996). From this point of view, the finding that information entropy modulates VDAC indicates direct as well as potent evidence that potential information available for refining the stimulus-reward association attracts cognitive resources. Likewise, studies in the field of associative learning postulate that "attention for learning" assigns priority based on the variability of a cue's predictions to promote exposure to novel information (Gottlieb, 2012; Pearce & Mackintosh, 2010).

Upon experiencing a prediction error (i.e., uncertainty), people engage in exploratory behavior with the objective of reducing the current state of uncertainty and, in turn, incorporating the true predictive status of the cue into a higher decision-making process (Daikoku, 2018; Luque et al., 2017; Pearce & Hall, 1980). Due to the limited nature of human cognitive resources, attention for learning actively directs an information-seeking mechanism toward cues whose predictive status is currently uncharted, at the expense of those that are fully predictive. Here, the uncertainty-driven attentional exploration likely varies depending on the length of associative learning. Specifically, the exploration of uncertain outcomes initially increases entropy levels in the short term, as the range of perceived outcomes increases. In the long term, however, such exploratory behavior helps minimize the overall entropy levels (Hirsh et al., 2012). Although the specific length of associative learning required to reduce uncertainty is currently unknown, attentional exploration contributes to the establishment of the true predictive status of the cue. Therefore, an information-gathering process acts as an intermediary in achieving the ultimate goal of refining the predictive status, especially in reward-motivated contexts (Gottlieb et al., 2013). In summary, attentional exploration initiated by uncertainty is an essential component of an active process of searching for information to learn, understand, and interact with the environment (Gottlieb et al., 2013; Keller et al., 2020; Kuhlthau, 1993; Luque et al., 2017; Pearce & Hall, 1980). Accordingly, the current findings suggest that information entropy is one of the most reliable predictors mediating attentional exploration and learning, especially in the context of value prediction.

It is worth noting that VDAC observed in the present study is interpreted as an automatic influence of uncertainty in attentional allocation. However, the original uncertainty principle proposed by Pearce and Hall (1980) characterized uncertainty-associated attention as a product of controlled or voluntary processing strategy. From this perspective, there is no particular reason for participants to engage in attentional exploration toward the distractors, as reward is no longer provided in the Test Phase.

However, a wealth of studies have reported the presence of an uncertainty-driven attentional bias that was demonstrated in an automatic manner (Cho & Cho, 2021; Koenig et al., 2017; Le Pelley et al., 2019; Luque et al., 2017). In these studies, the automatic effect of uncertainty was evident even though the stimulus features associated with uncertainty were irrelevant, or even counter to the participants' ongoing task goals. For instance, in the dot probe task of Luque et al.'s (2017) experiment, responses were slower when the probe was cued by an uncertain compound than a certain compound, and such uncertainty effect was observed even at short stimulus onset asynchrony (i.e., 250 ms). Similarly, a longer capture duration for uncertain distractors in the search task was observed in Koenig et al. (2017), which indicates the automatically prolonged retention of attention induced by associative uncertainty.

Critically, Luque et al. (2017) challenged the original characterization of uncertainty-driven attentional exploration as the product of controlled processing. According to Luque et al., the experience of associative prediction error increases the likelihood of the manifestation of automatic orientation toward the stimuli. Consequently, the perception of uncertain stimuli initiates interference with the irrelevant task. In a similar vein, Koenig et al. (2017) argued that associative learning automatically increases the cue's weight following the experience of uncertainty in the learning task. The accumulated weight is then transferred to the subsequent search task and eventually generates an attentional bias toward the uncertain distractors. Such preferential allocation of attention to uncertainty-associated cues can be supported by the increase in sustained dopamine activity in response to reward uncertainty (Fiorillo et al., 2003; Hart et al., 2015) and the rapid encoding of reward uncertainty in the human anterior cingulate cortex (Yu et al., 2011). Collectively, these findings provide converging evidence that the uncertainty-driven attentional processes emerge in an automatic fashion, which is in line with the findings from the present study.

Note that variance has been considered as a fundamental determinant of the amplitude of reward prediction error in conditioning (Rouhani & Niv, 2021). Consequently, the present study postulated that the variance of the reward outcomes directly represented the size of the prediction error associated with cues. As described above, however, the results weighed more heavily on the role of information entropy in generating VDAC, whereas the role of variance seemed relatively inconsistent. Nevertheless, such results do not necessarily underestimate the effect of reward prediction error in modulating VDAC. Instead, information entropy should be considered as a principal component for prediction-error-based learning. It is worth noting that information plays a critical role in calculating reward prediction error, as the arrival of novel or unexpected reward information is a key drive in updating the value of the reward (Iigaya et al., 2020).

Uncertainty as an Integral Factor in Value Formation

So far, most of the previous studies that examined VDAC had specified the concept of value as the absolute magnitude of the reward outcomes associated with the stimuli, which has been manipulated in a dichotomous manner: high or low (for review, see Anderson, 2013). Across these studies, larger attentional interference had been observed for distractors previously associated with a high EV compared with low EV, indicating that VDAC is indeed "value-dependent." In other words, the size of the learned value of reward-associated stimuli modulates attentional selection. The EV of the reward outcomes, which conveys an internal estimate of the expected future reward computed over the sequence of trials, represents the quantified size of the incentive salience of the stimulus (McClure et al., 2003). In other words, the typical attentional bias commonly observed in the previous literature can be explained as the result of the modulatory effect of the incentive salience of reward-related stimuli on attentional allocation.

On the other hand, the results from the present study suggests that the modulation of attentional selection occurs even when the contribution of expected reward value is controlled: the influence of learned value on VDAC was controlled by associating the two target stimuli to equal EVs in the current experiments (50 points in Experiments 1, 2, and 4, 100 points in Experiment 3). Nonetheless, robust VDAC effects were observed, as in previous studies that investigated the effects of uncertainty on value-related attention (Cho & Cho, 2021; Le Pelley et al., 2019). It is worth noting that the effects of learned predictiveness (or uncertainty) and learned value in guiding VDAC are orthogonal (Le Pelley et al., 2013).

Therefore, although VDAC is indeed dependent upon reward value, value itself is not the sole determinant of VDAC. Taken together, VDAC is not a mere representation of the strength of reward association but instead, a much more complex phenomenon that encompasses the uncertainty of reward provision as an important modulatory factor. This leads to the critical question of which aspects of uncertainty deserve the allocation of cognitive resources in the context of value prediction.

As noted above, uncertainty acts as an instrumental drive for information-gathering processes, both from affective, motivational, and cognitive perspectives (Anselme, 2010; Keller et al., 2020). Hence, uncertainty in value prediction is a crucial factor that helps achieve the goal of formulating the value estimate of the reward outcomes by promoting information-seeking during stimulus-reward association (Cho & Cho, 2021). Indeed, this idea is supported by the fact that most previous studies that reported a significant VDAC effect adopted reward contingencies that possessed uncertainty to some extent (e.g., high reward on 80% of trials and low reward on 20% of trials for high reward target), generating prediction error signals during learning. In contrast, a target feature associated with a consistent magnitude of reward in the Training Phase (6 cents for all correct trials; no prediction error) failed to induce VDAC in the subsequent Test Phase (Sali et al., 2014). This does not necessarily imply that reward contingencies should possess some degree of uncertainty for proper associative learning to occur, as there are studies that report significant VDAC with 100% reward delivery (Kim & Anderson, 2019; Munneke et al., 2016; Wentura et al., 2014). Rather, reward uncertainty facilitates a value formation process by promoting associative learning between the target feature and the reward. Specifically, a stimulus imbued with reward uncertainty acquires incentive value, which enhances the priority signal that attracts attentional resources, and in turn triggers exploration as a strategy for obtaining information (Anselme, 2015). In addition, recent studies show that stimuli associated with reward uncertainty captured attention during value learning, providing direct evidence in favor of our findings (Koenig et al., 2017; Le Pelley et al., 2019). Collectively, these findings indicate that uncertainty in stimulus-reward association should be considered as an integral factor for the occurrence of adequate value formation in the context of VDAC.

Conclusion

In the face of uncertainty, attentional exploration is required to alleviate the current state of uncertainty and successfully establish a predictive relationship between a stimulus and its value outcome. The present study consistently demonstrated that attentional allocation depends on the amount of potential information available in the process of value formulation. The human cognitive system values such information and automatically utilizes it as an intermediary in achieving the ultimate goal of refining the predictive status regarding value representation. Therefore, attentional exploration suggests that uncertainty is an essential precursor for an active as well as efficient process of searching for information to learn, understand, and interact with the environment.

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