Isolating Neural Reward-Related Responses via Pupillometry

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ABSTRACT

Recent research has shown that reward-related stimuli capture attention in an automatic and involuntary manner, or reward-salience (Le Pelley, Pearson, Griffiths, & Beesley, 2015). Although patterns of oculomotor behavior have been previously examined in recent experiments, questions surrounding a potential neural signal of reward remain. Consequently, this study used pupillometry to investigate how reward-related stimuli affect pupil size and attention. Across three experiments, response time, accuracy, and pupil were measured as participants searched for targets among distractors. Participants were informed that singleton distractors indicated the magnitude of a potential gain/loss available in a trial. Two visual search conditions were included to manipulate ongoing cognitive demands and isolate reward-related pupillary responses. Although the optimal strategy was to perform quickly and accurately, participants were slower and less accurate in high magnitude trials. The data suggest that attention is automatically captured by potential loss, even when it is counterintuitive to current task goals. Regarding a pupillary response, patterns of pupil size were inconsistent with our predictions across the visual search conditions. We hypothesized that if pupil dilation reflected a reward-related reaction, pupil size would vary as a function of both the presence of a reward and its magnitude. More so, we predicted that this pattern would be more apparent in the easier search condition (i.e., cooperation visual search), because the signal of available reward was still present, but the ongoing attentional demands were significantly reduced in comparison to the more difficult search condition (i.e., conflict visual search). In contrast to our predictions, pupil size was more closely related to ongoing cognitive demands, as opposed to affective factors, in cooperation visual search.

Surprisingly, pupil size in response to signals of available reward was better explained by affective, motivational and emotional influences than ongoing cognitive demands in conflict visual search. The current research suggests that similar to recent findings involving LC-NE activity (Aston-Jones & Cohen, 2005; Bouret & Richmond, 2009), the measure of pupillometry may be used to assess more specific areas of cognition, such as motivation and perception of reward. However, additional research is needed to better understand this unexpected pattern of pupil size.

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At any given time, humans are confronted with more information than their attentional systems can adequately process. Items in different areas of the visual field compete for attention and visual selection (Theeuwes, 2010). In the attention capture literature, visual selection is theoretically divided between top-down (goal-oriented) and bottom-up (stimulus-driven) control. Attentional shifts toward salient stimuli (bottom-up) are often swift and involuntary (Theeuwes, 2010). In contrast, top-down controlled tasks, such as reading, usually require the programming of voluntary attentional control. However, this dichotomy between goal-oriented and stimulus-driven attentional control fails to account for recent studies involving reward-related stimuli (Awh, Belopolsky, & Theeuwes, 2012).

Recent studies (e.g., Le Pelley, Pearson, Griffiths, & Beesley, 2015) have shown that attention is affected by the reward values of different stimuli, information that is not necessarily task-relevant (top-down) or physically salient (bottom-up). Instead, attention is biased toward reward-related stimuli, shaped by previous selection history and feedback. In visual search, for example, reward-related distractors are assigned attentional priority via associative learning, becoming Pavlovian signals of reward (Le Pelley et al., 2015). Moreover, this reward salience is malleable and extends to irrelevant stimuli, even when it is counterproductive toward current task goals. Taken together, recent findings present an exciting opportunity to further understand the effects of reward on attention. Although reward-related studies of attention typically analyze eye movements during visual search, such investigations have rarely examined ongoing changes in pupil size, or pupillometry. In the present research, pupillometry was used to

investigate the effects of reward-related attentional capture and reward processing in continuous neural activity via pupil size in a visual search task.

Pupillometry is a classic approach to measuring cognitive effort in various tasks. Although seemingly related only to the perception of light, pupillary changes reflect deep-brain activity and provide a time-sensitive index of ongoing neural activity, such as cognitive load, memory processes, and emotion (Laeng, Sirois, & Gredebäck, 2012). The best-known cognitive interpretation of pupil dilation is that it reflects a time-sensitive increase in effort, or mental workload during a task (Beatty, 1982; Hess & Polt, 1964). These task-evoked pupillary reflexes (TEPRs) signal the increased demand for cognitive and neural resources (i.e., attention) during event-related, phasic activity (Beatty, 1982). Although it has been less widely documented, recent findings show that the same neural processes that evoke TEPRs are also involved in memory creation and retrieval processes (Kafkas & Montaldi, 2011; Otero, Weekes, & Hutton, 2011; Papesh & Goldinger, 2012; Võ et al., 2008).

Although TEPRs are involved in both attention and memory processes, paradoxical findings come from pupil dilation during the creation and retrieval of accurate, confident memories. A recent study on subsequent memory found that pupils are surprisingly larger during encoding when people hear words that eventually lead to strong, accurate memories (Papesh, Goldinger, & Hout, 2012). That is, pupil size was the largest on trials in which memory encoding is apparently easy and accurate. Moreover, Papesh and Goldinger (2015) posited that the pupillary response at encoding is closely linked to self-regulatory processes that are connected to feelings of future recollection, or

meta-memory. The data suggest that two opposing processes yield the same, pupil-dilation response: cognitive effort and cognitive ease. Furthermore, it is well known that tonic pupil changes occur independently of phasic activity in response to emotional arousal and stress, such as fear and surprise (Darwin, 1872). If the pupillary response at encoding reflects an awareness of ongoing cognitive performance, might it indicate an emotional, reward activity response in the brain?

Relevant to the current study, changes in pupil sizes serve as a proxy for locus coeruleus norepinephrine (LC-NE) activity (Gabay, Pertzov, & Henik, 2011; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Hayes & Petrov, 2016) as well as general arousal (Kahneman, 1973). The LC-NE system is an important neuromodulator of NE on target LC neurons and activated by stress and responds by increasing NE secretion. Although a classic view of LC-NE activity is that it is related to general arousal, recent research in non-human primates and rats suggests that it may be closely related to more specific information processes and cognition (Aston-Jones & Cohen, 2005; Bouret & Sara, 2004; Bouret & Richmond, 2009). Furthermore, recent research has shown that the LC processes emotion stimuli even when a subject is actively unaware due to overlapping attentional demands (Tamietto & de Gelder, 2010). Consequently, a growing body of research has begun identifying the role of emotion in reward processing and cortical activity.

Recent research has found a novel relationship between the timing of LC discharge and emotional and goal-directed events. Bouret and Richmond (2009) investigated LC activation in monkeys during operant and Pavlovian conditioning tasks.

In contrast to typical findings of arousal, LC activation did not reflect a simple correlate of attention. Instead, LC phasic activation followed the presentation of task cues and occurred in close temporal proximity to Pavlovian behavior (i.e., appetitive behavioral reflex, lipping). Further, the intensity of conditioned lipping behavior appeared to influence the strength of LC responses, independent of attention or motivation. As a result, Bouret and Richmond (2009) posited that the observed LC activation was more closely related to sympathetic activation or emotion processes. Taken together, recent evidence suggests that the LC-NE system is critical to navigating task demands across various areas of cognition. These findings further indicate that like LC-NE activity, pupil dilation reflects more specific cognitive processes, in addition to general arousal. In the proposed study, we have one fundamental question: Can a neural reward-related response be isolated through pupillometry?

Because pupil dilation may occur for different reasons, we need experimental designs capable of dissociating dilation responses stemming from various psychological processes. The challenge arises from different neural processes feeding into the same autonomous pathway: In particular, pupils dilate when people exert mental effort, when they are emotional, and when they are aroused (e.g., in response to rewards). Consequently, the current research focused on the challenge of dissociating the overlap between theoretically separate cognitive processes that elicit the same, pupil dilation response.

To accomplish this, we used a variant of the additional singleton visual search paradigm (Theeuwes, 1991a, 1992) similar to Le Pelley et al. (2015). In this procedure,

participants were asked to find a simple visual target (e.g., an object with a unique shape) while another object was visually salient (e.g., an object with a unique color). The additional singleton competed for visual selection and made search less efficient. Critically, the competing singletons were associated with different levels of reward. For example, in trials when the reward-related singleton was red, correct answers may be worth 1 cent. But when the reward-related singleton is green, accurate answers are worth 10 cents. Reward-related colors were randomly assigned to a high-value, medium-value, or low-value reward conditions across participants. Moreover, participants were explicitly informed of these reward-color pairing during the instruction period. Finally, participants earned hypothetical money for each quick and accurate response and lost the amount they would have gained for every slow (>750 ms) and inaccurate response. Top-earning participants received a gift card.

The difficulty of locating a visual search target was manipulated across two key conditions: cooperation and conflict visual search. These were designed to help separate reward processing from mental effort. In the conflict search condition, people had to avoid looking at the reward-related singletons (requiring mental effort) to locate the target in time and receive a reward (Figure 1A). Therefore, observed pupil dilation may reflect either effort or reward, or both. In contrast, in the cooperation search condition, the reward-related singleton was no longer distracting, as it perfectly corresponded to the target location, but its color still signaled different reward values (Figure 1B). The aim of the conflict search condition was to examine pupil dilation in response to overlapping cognitive processes of effort (i.e., attention) and reward. In contrast, the aim of the cooperation search condition was to examine a pupillary response associated

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with reward, isolated from overlapping cognitive processes.

Below we describe three experiments investigating the effects of reward-related stimuli on attentional capture and neural activity via pupillometry. Experiments 1 and 2 focused on reward-related attentional capture via behavioral measures of response time and accuracy. Pupillometry was used in Experiment 3 to further investigate changes in pupil size in response to reward-related stimuli, cognitive effort, or both. Although all three experiments focused on the investigation of reward and attention, the experiments varied somewhat in their methodology.

In Experiment 1, we investigated how loss aversion affects attention by making the cost of a loss much greater than that of a partnering gain in a visual search task. The purpose of this was to observe a more significant effect of reward-related attentional capture across reward values (e.g., high-value and low-value) than our earlier findings. Previously, we conducted an experiment using a Pavlovian signal of reward and associative learning. Although our results followed the general trend that we predicted (e.g., high-value items yielded the largest attentional capture followed by low-value and control trials) differences between reward values were not statistically significant. Consequently, it was difficult to decipher whether participants' search times were slowed because the distractor was associated with reward (i.e., reward-related attentional capture) or because the distractor's color created a pop-out search effect (Geyer & Müller, 2009). Because the differences in RTs between reward values are relatively small (~10 ms) in the literature (e.g., Anderson, Laurent, & Yantis, 2011; Le Pelley et al., 2015), we investigated whether the heightened threat of a potential loss may yield a larger effect of

attentional capture via RTs. We based our predictions on prospect theory, which posits that potential losses are weighed more heavily than potential gains (Kahneman & Tversky, 1979).

In Experiment 2, we examined how different information about the upcoming trial (i.e., cues) influenced RTs and accuracy. The purpose of Experiment 2 was to implement procedures that would be desirable for pupillometry, in Experiment 3. Although the overall design of Experiment 2 was similar to Experiment 1, we made several changes. First, we presented one of four different cues for 1000 ms before the visual search task. The cues either contained: 1) information about the upcoming visual search condition (task cue) 2) reward condition (reward cue) 3) both visual search and reward condition (combination) or 4) no information (no cue). Second, we changed the cost of missing a trial to that of its partnering gain because our research question focused on pupil size and perceived reward (as opposed to loss) in Experiment 3. Finally, we removed the medium-level reward because it was mostly indistinguishable from the low-value and high-value reward conditions in Experiment 1. Therefore, Experiments 2 and 3 contained only three levels of reward condition: high-value, low-value, and control trials. Finally, the visual search condition was manipulated within-subjects, as opposed to between-subjects like in Experiment 1. This way, all participants were exposed to both levels of the visual search task in Experiments 2 and 3. Experiment 3 was similar Experiment 2, but with the addition of eye tracking. Overall, the goal of Experiment 3 was to examine whether we could observe a unique pattern of pupil dilation in response to perceived reward.

Across all experiments, we predicted that RTs would vary as a function of a stimulus's

reward magnitude on a given trial, thus reflecting reward-related attentional capture, similar to previous research (Le Pelley et al., 2015). We predicted that in the conflict condition, high-value trials would yield the longest RTs, reflecting attention capture, followed by low-value and control trials. In contrast, we predicted that RTs would be significantly shorter in the cooperation condition, indicating both the ease of the task (relative to the conflict condition) and the facilitation of overlapping reward-related colors and the target.

In experiment 3, pupillometry allowed us to disentangle pupillary responses associated with cognitive effort from those associated with reward. In the cooperation search condition (in which the target and the reward-signaling colors were integrated into the same object), we anticipated observing a distinct pattern of pupillary dilation in response to reward-related targets, in comparison to trials in which the targets do not signal a specific reward (i.e., control trials). If pupil dilation reflects a reward-related response, changes in pupil size will vary as a function of both the presence of a reward and its magnitude. For example, a high magnitude reward-stimulus should exhibit more substantial pupil dilation, relative to low reward magnitude and reward-related stimulus absent (control) trials.

METHODS

Experiment 1

The purpose of Experiment 1 was to observe a reliable measure of reward-related attentional capture and to investigate how loss aversion affects attention by making the cost of a loss much (3x) larger than that of a partnering gain.

Participants. 36 students from Arizona State University were recruited from the Psychology 101 subject pool and received course credit for their participation. All subjects were at least 18 years old, English or native-English speakers, and had normal or corrected-to-normal vision by self-report. Nine subjects were excluded from analysis for having mean accuracies or response times that were 2.5 standard deviations above or below their group means.

Apparatus. Behavioral data was collected using up to 9 computers simultaneously (all have identical hardware and software). Dividing walls separated each viewing station, and experimental sessions were monitored at all times by one or more research assistants. The PCs were Dell (Round Rock, TX) Optiplex 380 systems (3.06 GHz, 3.21 GB RAM) operating at 1,366 X 768 resolution on Dell E1912H 16-in. monitors (operated at a 60 Hz refresh rate). Displays were be controlled by an Intel (Santa Clara, CA) G41 Express chipset, and the operating system was Windows XP (Microsoft, Redmond, WA). E-Prime Version 2.0 software (Psychology Software Tools, Inc., Sharpsburg, PA; Schneider, Eschman, & Zuccolotto, 2002) was used to control the experiment.

Stimuli and design. Each trial contained the following: (1) instruction screen (2) fixation display (3) visual search display (4) feedback display (see experimental procedure in Figure 2). All stimuli were presented on a black background. The fixation display contained a centrally located gray cross. The search display contained one diamond target and five distractor circles.

There were two between-subjects visual search conditions (cooperation and

conflict) and four within-participants reward conditions (high-value, medium-value, low-value, and control), randomly selected across trials. In the conflict search condition, reward-related trials contained a color singleton distractor that randomly replaced one of the five gray distractor circles (Figure 1A). In contrast, reward-related trials in the cooperation search condition did not have a color singleton distractor but instead contained a reward-indicative colored target replaced a gray target (Figure 1B). Each item in the visual search array contained a vertical line that was tilted either 45° to the left of right. Line orientation was randomized throughout the experiment. The feedback display contained two pieces of information: (1) how much participants earned (or lost) in the current trial and (2) their running total.

The stimuli were created using Microsoft Paint and all shapes were approximately 100x100 pixels. In total, we had one unique target shape (diamond) in four possible colors (red, green, blue, and gray) and one unique distractor shape available in the same four colors. Across both visual search conditions, the experiment contained eight blocks with a total of 384 trials. Each block contained 48 trials: 12 high-value (+10/-30 cents), 12 medium-value (+5/-15 cents), 12 low-value reward trials (+1/-3 cent), and 12 control trials (equal likelihood of high-value, medium-value, or low-value). High-value, medium-value, and low-value reward conditions were randomly assigned to either red, green, blue singleton distractors (or targets for the cooperation search condition) across participants.

Procedure. Before the experiment, instructions informed participants to find the target diamond as quickly and accurately as possible. During the instructions, participants saw a screen that displayed how much they could gain or lose when a particular colored

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distractor (or target in the cooperation visual search condition) was present. Participants were also notified of the following reward contingencies: (1) only fast (< 750 ms) and accurate responses will earn "money" and (2) if participants answer incorrectly or if they take too long to respond, the trial will time out and they will lose 3X the amount of "money" they could have earned. Participants were instructed that they were not competing for real money, but that participants with the highest amount of hypothetical money would win a prize (i.e., 1 of 5 $20 gift cards).

Each trial began with an instruction screen to remind participants what key corresponded to the left or right target line orientation (e.g., 'f' = left). The trial began when participants pressed the space bar to indicate that they were ready to continue. A fixation display then appeared for 500 ms, after which the visual search array would appear for a maximum duration of 750 ms, or until the participant responded. During this period, participants made a forced-choice target line identification by pressing either "f" or "j" depending on whether the line was tilted to the left or right. After the trial, participants saw a feedback screen for 500 ms that displayed how much they had gained or lost in the previous title, as well as their running total. A short break occurred after the fourth block.

Experiment 2

The goal of Experiment 2 was to examine how information about the upcoming trial affected performance on a visual search task. This allowed us to better understand potential pupillary changes in Experiment 3.

Participants. 38 new students from Arizona State University were recruited

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from the Psychology 101 subject pool and received course credit for their participation. All subjects were at least 18 years old, English or native-English speakers, and had normal or corrected-to-normal vision. Four subjects were excluded from analysis for having mean accuracies or response times that were 2.5 SD above or below their group means.

Apparatus. Materials used were identical to those used in Experiment1.

Stimuli, design, and procedure. The design and procedure of Experiment 2 was similar to that of Experiment 1, with a few key differences: 1) a cue screen appeared before the visual search task 2) the visual search task was manipulated within-subjects, as opposed to between-subjects 3) the medium-level reward condition level was removed and 4) the experiment consisted of 4 blocks of 96 trials, as opposed to 8 blocks of 32 trials as in Experiment1.

Each trial contained the following: (1) instruction screen (2) fixation display (3) cue screen (4) visual search display (5) feedback display (see procedure in Figure 3). There were two within-subjects visual search conditions (cooperation and conflict), three within-subjects reward conditions (high-value, low-value, and control), and four within-subjects cue conditions (no cue, reward, task, and combination).

The cues appeared on the screen for 1,000 ms and contained different information about the upcoming trial. For a reward cue, the words "high" low" or "control" appeared, depending on the reward-value in the upcoming trial. Similarly, the words "easy" or "hard" appeared in a visual search cue, depending on whether the upcoming trial was a cooperation (i.e., "easy") or conflict (i.e., "hard") search task. In the combination

cue, both reward and search condition information appeared on the screen. The absent cue (i.e., no cue) simply served as a control for the cue condition. Consequently, a black screen appeared for 1,000 ms during the absent cue. All cue information appeared in gray courier new size 36 font that was centrally located against a black screen.

The remaining stimuli were identical to those used in Experiment1, with the exception of the medium-level reward color. Consequently, the remaining reward-related colors were red, green, or gray for distractors (conflict search condition) or targets (cooperation search condition). The experiment consisted of 4 blocks of 96 trials, with a total of 384 trials. Each block contained 32 high-value trials (+/- 10 cents), 32 low-value trials (+/- 1 cent), and 32 control (equal likelihood of high or low-value) trials. Each block contained 48 cooperation and 48 conflict visual search tasks. Cue condition was randomly selected per block.

Experiment 3

The purpose of Experiment 3 was to apply pupillometry to the paradigm used in Experiment 2. This allowed us to better understand the influence of reward-related attention capture on pupil size.

Participants. 20 new students from Arizona State University were recruited from the Psychology 101 subject pool and received course credit for their participation. All subjects were at least 18 years old, English or native-English speakers, and had normal or corrected-to-normal vision. Two subjects were excluded from analysis for having mean accuracies or response times that were 2.5 SD above or below their group means.

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Apparatus. Participants completed the experiment one at a time on a Dell Optiplex 755 PC (2.66 GHz, 3.25 GB RAM). Pupil size was binocular and recorded by an EyeLink 1000 eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada). A chinrest was used to stabilize participants' head and eye movements during the experiment Again, E-Prime Version 2.0 software (Psychology Software Tools, Inc., Sharpsburg, PA; Schneider, Eschman, & Zuccolotto, 2002) was used to administer the experiment.

Stimuli, design, and procedure. Experiment 3 three was identical to Experiment 2, with two differences: 1) we added the measure of pupillometry and 2) decreased the amount of trials. Due to time constraints (e.g., calibration time) the amount of experimental trials were divided in half to keep the experiment length 1 hour. In addition, a gaze contingent gray box was added to the procedure and appeared on the screen for 2,000–5,000 ms before the fixation display appeared (see experimental procedure in Figure 4). This was included to make sure participants were properly calibrated throughout the experiment. Participants had to look at the gray box for a minimum of 2,000 ms to begin the trial. This screen appeared for a maximum of 5,000 ms. If participant's gaze did not trigger the experiment to start within ~2,000 ms, participants calibration was assessed and they were re-calibrated as necessary. There was a short break halfway through the experiment.

The experiment consisted of 4 blocks that contained 48 trials each. Within each block, there were 16 high-value (+/-10 cents), 16 low-value (+/-1 cent), and 16 control (equal likelihood high or low-value) trials. Furthermore, each block contained 26

cooperation search trials, and 26 conflict search trials. Finally, every block contained 12 trials per cue condition. Reward and visual search conditions were randomly selected within a block. Again, cue condition was randomly selected per block.

RESULTS

Experiment 1

We performed separate 2x4 repeated-measures analyses of variance (ANOVAs) for accuracy and reaction times, with visual search condition (cooperation and conflict) as a between-subjects factor and reward condition (high-value, medium-value, low-value, and control) as a within-subjects factor. Post hoc comparisons used the Bonferroni correction. Only correct answers were analyzed for RT data. See Figures 5 and 6 for accuracy and RT means, respectively.

Accuracy. Overall, participants performed well and accuracy was high ($M = $ 86%) across both visual search conditions. As predicted, participants were significantly more accurate in the cooperation search condition ($M = 88\%$) than in the conflict search condition ($M = 83\%$), $t(33) = 9.49$, $p < .001$. In addition, there was a significant two-way interaction between reward and visual search condition, $F(3, 96) = 3.18$, $p = .03$, η2p =.09. We followed up the interaction by performing simple effects tests that compared reward condition accuracy separately within the two search conditions: cooperation and conflict. These analyses indicated that, within the cooperation search condition, there was a significant effect of reward condition on search accuracy, $F(1.9, 32.34) = 3.98$, $p = .03$, η2p = .19. In contrast, no such difference existed for the conflict search condition, $F(3, 45) = .78$, $p = .51$, η2p = .05. Further, post hoc comparisons within the cooperation search

condition indicated that there were no significant differences in mean accuracy among reward values.

RTs. Overall, participants were quite fast to correctly locate the target ($M = 532$ ms). Further, participants were significantly faster in the cooperation search condition ($M = 522$ ms) than in the conflict search condition ($M = 544$ ms), $t(32), = -4.35, p < .001$. Again, there was a significant interaction between reward and visual search condition on RTs, $F(3, 96) = 10.73, p < .001, \eta2p = .25$. We followed up the interaction by performing simple effects tests that compared reward condition RTs separately within the two search conditions: cooperation and conflict. These analyses indicated there was a significant effect of reward condition on RTs in both the cooperation search condition, $F(3, 51) = 11.44, p < .001, \eta2p = .40$, and in the conflict search condition, $F(3, 45) = 3.04, p = .04$. Post hoc comparisons indicated that in the cooperation search condition, mean RTs for the control trials ($M = 527$ ms) were significantly slower than high-value ($M = 516$ ms), medium-value ($M = 520$ ms), and low-value trials ($M = 521$ ms). There were no significant differences in mean RTs among the remaining reward value compairisons. Finally, there were no significant differences in mean RTs in the conflict condition, as a function of reward values.

Experiment 2

We performed a 2x3x4 repeated measures analyses of variance (ANOVAs) with visual search condition (cooperation and conflict), reward condition (high-value, low-value, and control), and cue condition (no cue, reward, task, and combination) as within-subjects factors for accuracy and reaction times. Post hoc comparisons used the

Bonferroni correction. Only correct answers were analyzed for RT data. See Figures 5 and 6 for accuracy and RT means, respectively.

Accuracy. Again, participants performed well and the overall accuracy was high ($M = 86\%$). There was a significant three-way interaction between reward, cue, and search conditions, $F(6, 198) = 16.98$, $p < .001$, η2p = .34. Following the significant three-way interaction, we performed simple interaction contrasts that examined the two-way interaction of reward by cue condition separately for the cooperation and conflict visual search tasks. A repeated measures ANOVA with a Greenhouse-Geisser correction revealed that the two-way interaction was not significant for either the cooperation search condition, $F(4.36, 143.95) = .93$, $p = .46$, η2p = .03, or the conflict search condition, $F(4.48, 147.98) = 1.56$, $p = .16$, η2p = .05. However, there was an effect of search condition on accuracy, $F(1, 33) = 4.52$, $p = .041$, η2p = .120. Again, post hoc pairwise comparisons indicated that participants were significantly more accurate in the cooperation search condition ($M = 90\%$) than in the conflict search condition ($M = 83\%$). Finally, there were null effects of both reward condition, $F(2, 66) = 2.62$, $p = .08$, η2p = .07, and cue condition on accuracy, $F(3, 99) = 1.23$, $p = .30$, η2p = .04.

RTs. Similar to Experiment 1, participants' overall responses were quite fast ($M = 536$ ms). Unlike the previous accuracy data, the three-way interaction between reward, cue, and search condition was not significant, $F(6, 198) = .16$, $p = .99$, η2p = .005. However, there was a significant two-way interaction between the reward and search condition, $F(2, 66) = 55.66$, $p < .001$, η2p = 0.63. We followed up the two-way interaction by performing simple effects tests that compared reward condition RTs

separately within the two search conditions: cooperation and conflict. These analyses indicated that there was a significant effect of reward condition on search RT in both the cooperation search condition, $F(2, 66) = 15.16$, $p < .001$, η2p $= .32$, and the conflict search condition, $F(2, 66) = 77.70$, $p < .001$, η2p $= .70$. Further, post hoc pairwise comparisons in the cooperation condition revealed that RTs in high-value ($M = 519$ ms) and low-value trials ($M = 524$ ms) were significantly faster than control trials ($M = 532$ ms). In contrast, post hoc pairwise comparisons in the conflict condition revealed that high-value ($M = 556$ ms) and low-value trials ($M = 553$ ms) RTs were significantly slower than in the control trials ($M = 532$ ms). There were no significant differences in mean RTs among the remaining reward value comparisons in the conflict and cooperation conditions.

In addition, there was a null two-way interaction between both the reward by cue condition, $F(6, 198) = .31$, $p = .93$, η2p $= .01$, and the visual search by cue condition, $F(2.39, 78.71) = 1.62$, $p = .199$, η2p $= .05$. However, there was an effect of search condition on RTs, $F(1,33) = 98.26$, $p < .001$, η2p $= .75$. Post hoc pairwise comparisons revealed that, again, participants were significantly faster to locate the target in cooperation search condition ($M = 525$ ms), than in the conflict search condition ($M = 546$ ms). Finally, there was no effect of cue condition on RTs, $F(3, 99) = 1.72$, $p = .17$, η2p $= .05$.

Experiment 3

Behavioral Results. The behavioral results were analyzed in the same manner as in Experiment 2. We performed 2x3x4 repeated measures ANOVAs on search

accuracy and RTs, with visual search condition (cooperation and conflict), reward condition (high-value, low-value, and control), and cue condition (no cue, reward, task, and combination) as within-subjects factors. Only correct answers were analyzed for RT data.

Accuracy. Overall, accuracy was slightly lower than previous experiments (M = 83%) across both conditions. Unlike Experiment2, the three-way interaction between reward, cue, and search condition was non-significant for accuracy, $F(3.94, 51.15)$ = 2.01, p = .109, η2p = .13. Again, there was a significant two-way interaction between reward and search condition, $F(2, 26)$ = 9.36, $p < .001$, η2p = .42. We followed up the significant interaction by performing simple effects tests that compared level of reward condition accuracy separately within the two search conditions: cooperation and conflict. These analyses indicated that, within the cooperation search condition, there was no effect of reward condition on accuracy, $F(1.40, 18.18)$ = 1.15, p = .32, η2p = .08. However, there was a significant effect of reward condition on accuracy in the conflict search condition, $F(2, 26)$ = 10.26, $p < .001$, η2p = .44. Post hoc pairwise comparisons revealed that participants were significantly more accurate in control trials (M = 87%) than in high-value (M = 74%) and low-value trials (M = 72%). There were no significant mean differences in accuracy among the remaining reward value comparisons.

There was a significant two-way interaction between search and cue condition, $F(3, 39)$ = 3.61, p = .021, η2p = .22. We followed up the two-way interaction by performing simple effects tests that compared cue condition accuracy separately within the two search conditions: cooperation and conflict. These analyses indicated no effects

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of cue condition on accuracy within either the cooperation search condition, $F(3, 39) =$ .58, $p = .63$, η2p = .04, or the conflict search condition, $F(3, 39) = 1.96$, $p = .14$, η2p = .13. Finally, there was a non-significant two-way interaction between reward and cue condition, $F(6, 78) = .907$, $p =. 49$, η2p = .07. However, there was an effect of search condition on accuracy, $F(1, 13) = 33.87$, $p < .001$, η2p = .72. Similar to previous experiments, post hoc comparisons revealed that participants were significantly more accurate in the cooperation search condition ($M = 90\%$) than in the conflict search condition ($M = 78\%$).

RTs. Like previous experiments, participants were generally quick to locate targets ($M = 561$ ms). The three-way interaction between reward, cue, and search condition was not significant, $F(6, 78) = .62$, $p = .71$, η2p = .05. Similar to previous experiments, there was a significant two-way interaction between reward and search condition on RTs, $F(2, 26) = 10.82$, $p < .001$, η2p = .45. We followed up the two-way interaction by performing simple effects tests that compared reward condition RTs separately within the two search conditions: cooperation and conflict. These analyses indicated that, within the cooperation search condition, there was no effect of reward condition on RTs, $F(2, 26) = 1.95$, $p = .16$, η2p = .13. In contrast, there was an effect of reward condition on RTs in the conflict search condition, $F(2, 26) = 14.88$, $p < .001$, η2p = .53. Post hoc comparisons revealed that participants' mean RTs were significantly faster in the control trials ($M = 554$ ms), than in the low-value ($M = 586$ ms) and high-value trials ($M = 585$ ms). Finally, there was a non-significant two-way interaction for both the reward by cue condition, $F(6, 78) = 1.77$, $p = .12$, η2p = .12, and the cue by search condition, $F(3, 39) = 2.52$, $p = .07$, η2p = .16. However, there was an effect of

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search condition on RTs, $F(1, 13) = 39.25$, $p < .001$, η2p $= .75$. Post hoc analyses revealed that, again, participants were significantly faster to locate the target in cooperation search condition ($M = 547$ ms) than in the conflict search condition ($M = 573$ ms).

Pupil Dilation.

Similar analyses used for the earlier behavioral data were used again for the pupil data. We performed a 2x3x4 repeated-measures analysis of variance (ANOVA) with visual search condition (cooperation and conflict), reward condition (high-value, low-value, and control), and cue condition (no cue, reward, task, and combination) as within-subjects factors for pupil size. Only accurate answers were analyzed. See Figures 7, 8, and 9 for mean pupil size. Although there was a null three-way interaction between reward, cue, and visual search condition, $F(6, 78) = .77$, $p = .60$, η2p $= .46$, there was a significant two-way interaction between cue and visual search condition, $F(3, 39) = 5.98$, $p = .002$, η2p $= .315$ (see Figure 8). We followed up the interaction by performing simple effects tests, comparing pupil size in the cue condition separately within the two search conditions: cooperation and conflict. These analyses indicated that the effect of cue condition on pupil size approached significance within the cooperation search, $F(3, 39) = 2.45$, $p = .077$, η2p $= .159$. In contrast, no such difference existed for the conflict search condition, $F(3, 39) = 1.21$, $p = . 32$, η2p $= .09$. Further, post hoc comparisons within the cooperation search condition indicated that there were no significant differences in mean pupil size among cue conditions.

DISCUSSION

Previous research on pupillary response at encoding suggests that pupil size may indicate an emotional, reward activity response in the brain (Papesh et al., 2012). We tested this hypothesis by measuring the effect of reward-related stimuli on pupil size as an indirect measure of LC-NE activity. In a series of three experiments, participants searched for a target across two versions of a visual search task. We aimed to disentangle pupil dilation in response to emotional arousal via reward from those associated with cognitive effort. Across all experiments, RTs served as a measure of reward-related attentional capture. In the conflict search condition, we predicted that changes in pupil size would reflect ongoing cognitive demands, reward, or both. In contrast, the cooperation search condition presented the opportunity to examine pupil dilation in response to reward with reduced attentional demands. We predicted that, in comparison to the conflict condition, pupil size in the cooperation condition would vary as a function of reward-related stimuli's presence and magnitude.

Regarding reward-related attentional capture on RTs, we found that search times were slowest in trials that contained a high-value distractor in the conflict condition, even when it was counterproductive to do so (Figure 6). In contrast, the presence of high-value items yielded that fastest RTs and accuracy in the cooperation condition, thus demonstrating the motivational effect of reward on visual search. This finding is similar to those observed in reward-related attentional capture (Le Pelley et al., 2015). Furthermore, this pattern occurred in Experiments 1, 2, and 3; which suggests the increased saliency of potential loss in Experiment 1 captures attention much like a

potential reward. That is, increased magnitude of potential loss did not affect search times differently than potential reward.

In Experiment 3, the addition of pupillometry to our paradigm allowed us a greater understanding of how reward affects ongoing neural processes via changes in pupil size. Overall, our findings across the two visual search conditions were inconsistent and did not reflect our original predictions that pupil size would vary according to the presence and magnitude of a signal of available reward. Surprisingly, pupil size in the cooperation condition was largest in control trials, when a signal of available reward was absent from visual search. One possible explanation is that control trials were more cognitively demanding than reward trials since they lacked a colored singleton to facilitate visual search. This interpretation suggests that ongoing cognitive demand, as opposed to affective factors, better explain pupil size in the cooperation condition.

Conversely, high-value trials were associated with larger pupil size than control and low-value trials in the conflict condition (Figure 8). More so, pupil size was largest when participants viewed feedback after correctly locating the target in high-value trials. Because high-value and low-value trials were equally demanding of attentional resources, this finding supports our hypothesis and suggests that affective factors, such as motivation or emotional arousal, influenced pupil size in the conflict condition. This result is somewhat similar to patterns of pupil size observed by Papesh et al. (2012), in which pupil size was the largest on trials where memory encoding is apparently easy and accurate. Taken together, the pupillary response in high-value trials in the conflict condition may indicate an emotional, reward activity response in the brain. However,

because our results were inconsistent with our predictions, more research is needed to better understand this unexpected pattern of pupil size.

An additional unexpected finding comes from pupil size in control trials during visual search and feedback (Figure 8). In contrast to our predictions, pupil size was slightly larger in control trials without a signal of available reward than low-value reward trials. One possible interpretation of this finding is that although control trials lacked a reward-related stimulus, subjects were informed that control trials could result in either high-value or low-value earnings. That is, subjects may have been more motivated by the opportunity to earn either high-value or low-value rewards in control trials, than a certain low-value reward in the low-value trials. More so, participants were slightly more accurate in control trials than low-value trials in the conflict condition (Figure 5). This finding is consistent with recent evidence from Chiew and Braver (2013), who found that larger pupil size was associated with increased reward incentive and accuracy. Again, this suggests that motivation was an influence on pupil size.

Another interesting finding comes from changes in pupil size in response to the cues presented before visual search. Unique to the current study, we manipulated the type of information presented in a cue before the visual search task to better disentangle the causes of pupil dilation. Cues signaled upcoming available reward value, the difficulty of the visual search task, or both (i.e. a combination cue). In addition, we included trials that contained no cue information. Both visual search conditions yielded similar pupil size in response to cues, with the exception of the combination cue (Figure 7). In contrast to the cooperation condition, the combination cue elicited the second largest pupil size in the

conflict condition, after cues without a trial (i.e., No Cue). It is somewhat difficult to interpret this finding in the conflict condition because two different amounts of information elicited the same response, large pupil size. On the one hand, trials without a cue offered no information about the upcoming trial, while the combination cue provided the most information. Large pupil size in the combination cue may reflect the recruitment of cognitive resources as a function of motivation from having the most information about the upcoming trial. Consequently, larger pupil size in the combination cue was associated with lower levels of accuracy and longer RTs in the conflict condition (Figure 5). This finding suggests that pupil size was better explained by affective factors, such as emotion in response to perceived reward, because increased pupil size was not associated with higher accuracy. Future research should include trials in which no reward is awarded to better explain this finding and further tease out the influence of motivation from cognitive effort.

Our findings of pupil size in response to reward-related stimuli partially support recent evidence that suggests pupil dilation reflects more specific cognitive processes, such as perception of available reward, in addition to general arousal (Bradley et al., 2008; Chiew & Braver, 2014). Similar to previous studies, larger pupil size was associated with increased reward-value during the trial procedure in the conflict condition (Chiew & Braver, 2013). More so, increased pupil size in the conflict condition was not associated with increased accuracy (Figure 5). That is, pupil size was largest in response to high-value items, even though these trials yielded worse performance and slower search times in comparison to control trials. Similarly, Chiew and Braver (2013) noted that pupil size was larger when participants were slow to respond during reward

incentive trials, as opposed to trials where participants were fast to answer but no reward incentive was present. Consequently, Chiew and Braver (2013) to suggest that observed pupil dilation was influenced by more factors, such as motivation and emotional arousal, as opposed to an exact measure of task performance. Altogether, the current evidence partially supports recent findings in which emotional arousal, in addition to task performance, influences pupil dilation.

An additional interpretation of the current results is that changes in pupil size may reflect increased preparatory processing as a function of reward incentive. This interpretation is similar to that posited by Chiew & Braver (2013), who found that incentive was associated with increased task performance. In contrast to our predictions, largest pupil dilation occurred in response to high-value items in the conflict condition, when visual search was relatively difficult, and the reward-related feature of color competed with the target. Perhaps participants were more motivated by high-value items and changes in pupil size reflected the recruitment of neural resources as a function of incentive value, as opposed to emotional arousal.

The current exploratory investigation was intended to examine whether we could observe an isolated neural, reward-related response via pupillometry. Although our results were somewhat inconsistent, the measure of pupillometry in the current investigation adds to our understanding of the impact of reward-related stimuli on attention. This knowledge has significant implications such as better understanding individual differences in reward-seeking behavior, for example as visible in addiction, attention deficit disorder (ADHD), schizophrenia (Carter et al., 2010), and depression

(Beevers, Clasen, Enock, & Schnyer, 2015). The current results also highlight the apparent difficulty of isolating overlapping causes of pupil dilation from one another. Future research might include additional measures, such as reward sensitivity and attentional deficits, to capture individual differences in response to these factors. Therefore, we will gain a greater understanding how neural reward systems affect cognitive processes such as memory, attention, and learning.

Although the present results add to the current literature, the present investigation does have some limitations. First, the small sample size used in Experiment 3 (n = 20) may have impacted our ability to detect significant differences in pupil sizes. Second, previous experiments tended to observe larger differences in mean RT across reward values ~ 10 ms (e.g., Anderson, Laurent, & Yantis, 2011; Le Pelley et al., 2015) than in the current investigation. Instead, we observed an average difference of ~ 5 ms between reward values. One difference between the current investigations and these previous studies is that they used performance contingent monetary compensation as a form of reward. In contrast, top-performing subjects in our experiments received a gift card for $20. Therefore, our method of compensation may have impacted motivation in the current research, thus resulting in smaller differences between RTs. Finally, we modeled our control trials similar to those seen in Le Pelley et al. (2015). That is, there was an equal likelihood of receiving a high-value or low-value reward in control trials that may have resulted in the surprising finding that pupils tended to be larger in control trials than low-value trials. Future experiments should include a number of trials where no reward is available to compare reward trials to reward absent trials to better understand the

influences of cognitive effort and reward on pupil size.

Additional questions surrounding the influence of reward-related stimuli and emotional processes on pupil size remain. Perhaps an increase in pupil size reflected a shift in proactive control as a function of incentive, as opposed to an emotional, affective response. Further, how do we dissociate the influences of motivation from emotion in pupillometry? The current research has significant implications for those interested in understanding of the LC-NE system and reward processing. Further, isolating neural reward-related responses is of critical importance. If we gain a greater understanding of pupillary responses to reward-related stimuli, we will also gain a greater understanding how neural reward systems affect cognitive processes such as memory, attention, and learning. The current investigation used a novel method to examine pupil size in response to reward-related stimuli by including different informational cues and manipulating attentional demands across two versions of a visual search task. Although pupil size in the cooperation condition was inconsistent with our hypothesis, pupil size in the conflict condition was better explained by affective, motivational and emotional influences than ongoing cognitive demands. In conclusion, the current research suggests that similar to recent findings involving LC-NE activity (Aston-Jones & Cohen, 2005; Bouret & Richmond, 2009), the measure of pupillometry may be used to assess more specific areas of cognition, such as motivation and perception of reward.

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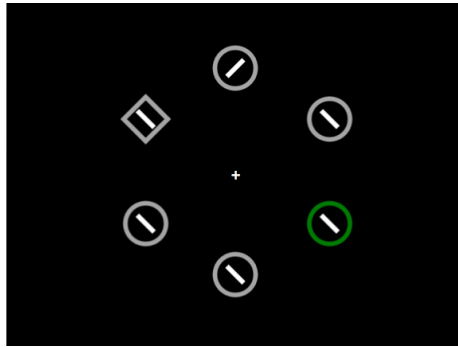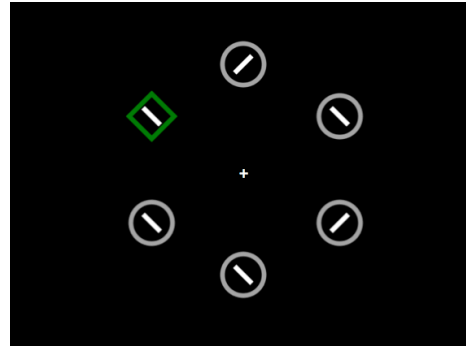
Figure 1. Example of visual search displays: **A**. In the conflict search condition, reward-related singleton distractors competed against diamond-shaped targets for attention. **B.** In the cooperation search condition, reward-related colors overlapped with the target thereby reducing attentional demands and isolating reward from overlapping cognitive processes.
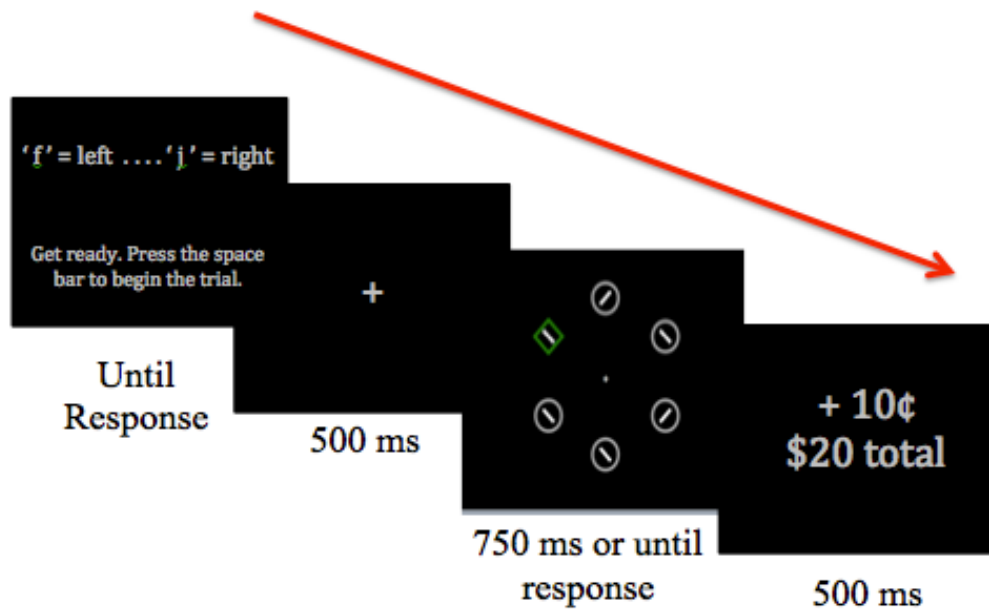
Figure 2. Experimental procedure for Experiment 1. Phases in the procedure from left to right: trial instruction, fixation, visual search, and feedback.
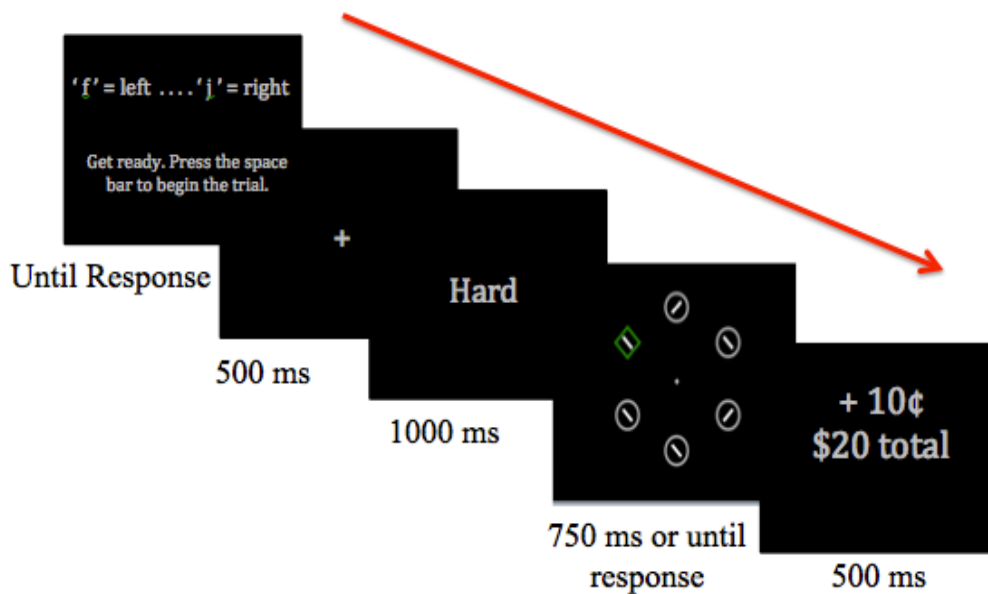
Figure 3. Experimental procedure for Experiment 2. Phases in the procedure from left to right: trial instruction, fixation, cue, visual search, feedback. In the current example, a search condition cue was presented. A reward cue simply contained the word. The main difference between experiments 1 and 2 is the addition of a cue slide before visual search.
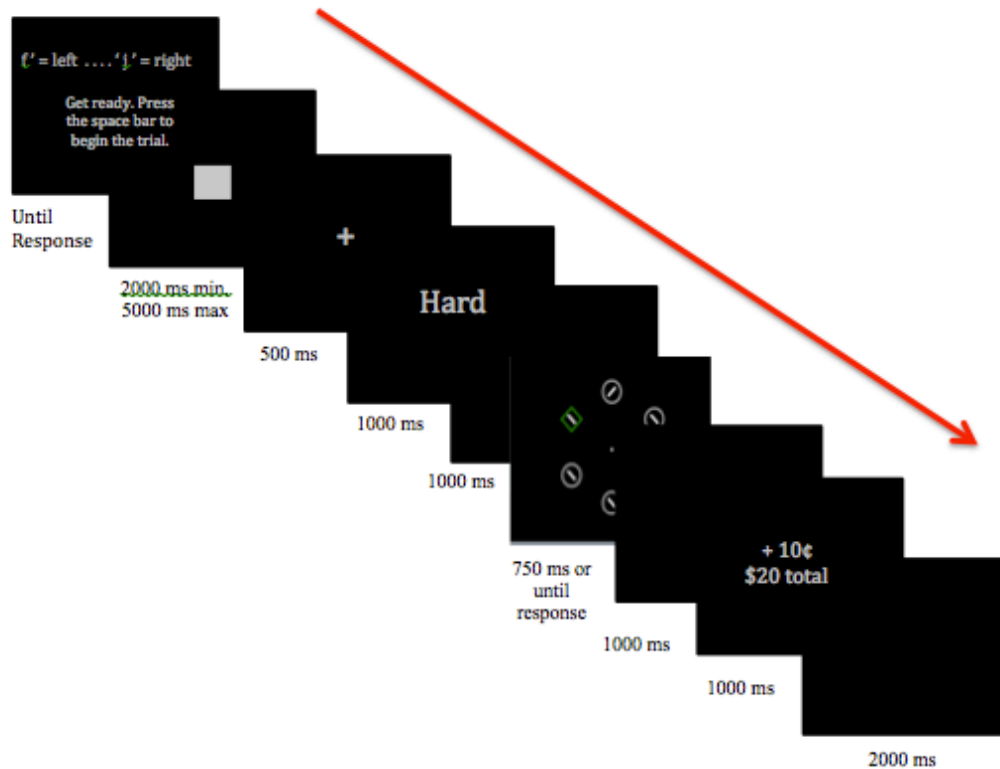
Figure 4. Experimental procedure for the pupillometry portion of Experiment 3. Phases in the procedure from left to right: trial instruction, gray calibration box, fixation, cue, visual search, feedback. In the current example, a search condition cue was presented. A reward cue simply contained the word. The main difference from Experiment1 and 2 is the addition of a cue slide before the trials.
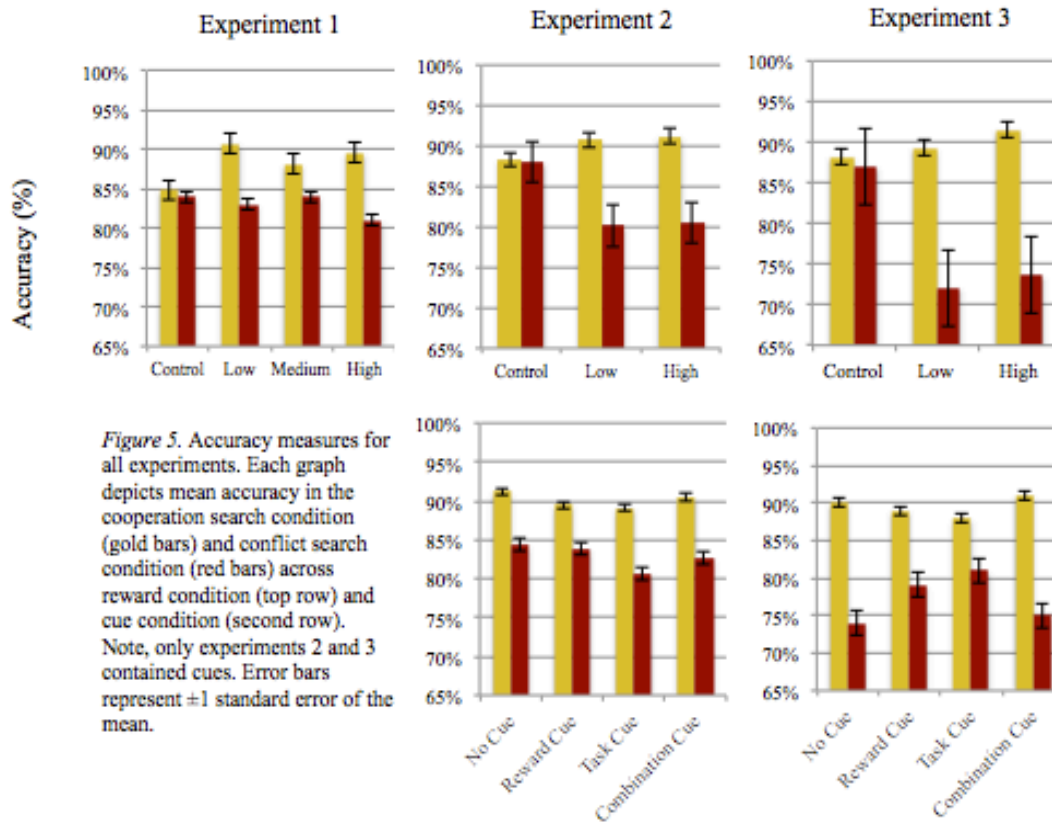
Figure 5. Accuracy measures for all experiments. Each graph depicts mean accuracy in the cooperation search condition (gold bars) and conflict search condition (red bars) across reward condition (top row) and cue condition (second row). Note, only experiments 2 and 3 contained cues. Error bars represent ±1 standard error of the mean.
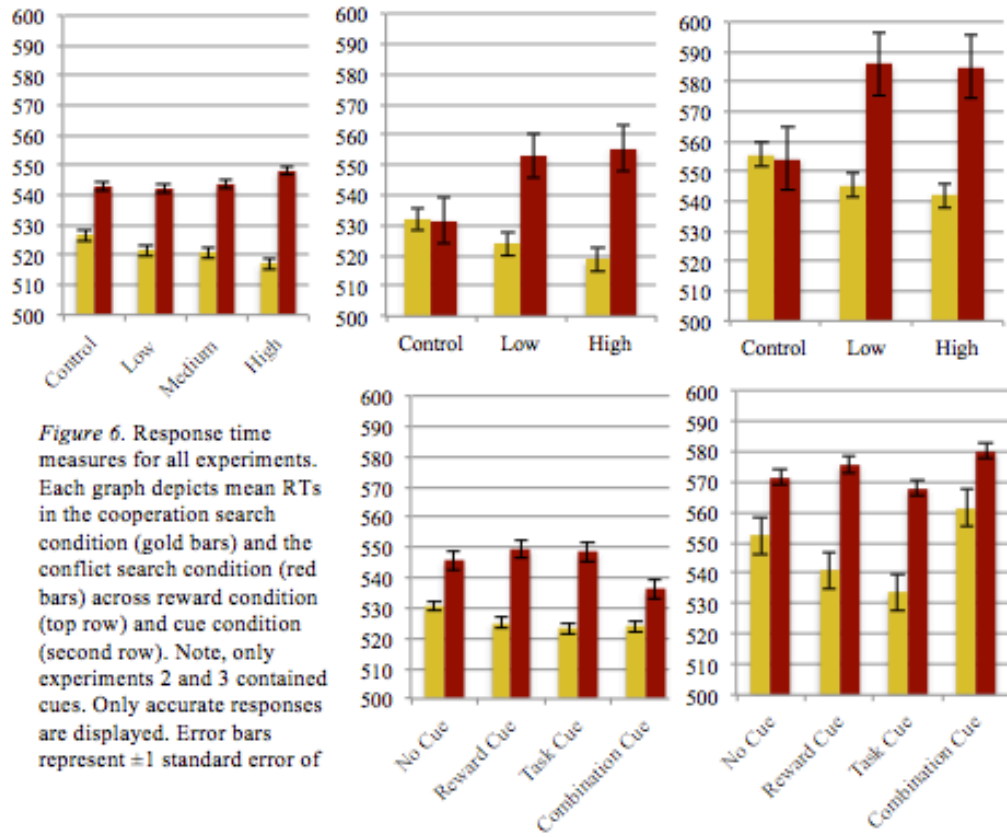
Figure 6. Response time measures for all experiments. Each graph depicts mean RTs in the cooperation search condition (gold bars) and the conflict search condition (red bars) across reward condition (top row) and cue condition (second row). Note, only experiments 2 and 3 contained cues. Only accurate responses are displayed. Error bars represent ±1 standard error of
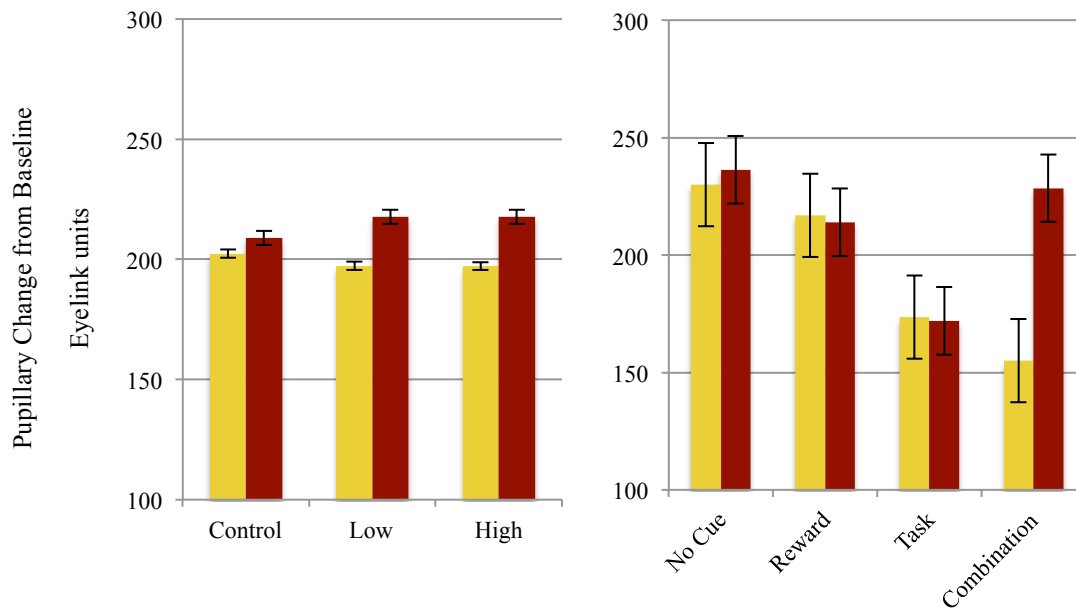
Experiment 3

Figure 7. Pupillometry measures for experiment 3. Each graph depicts mean pupil size in the cooperation search condition (gold bars) and conflict search condition (red bars) across reward condition (left) and cue condition (right). Only accurate trials are depicted. Error bars represent ±1 standard error of the mean.

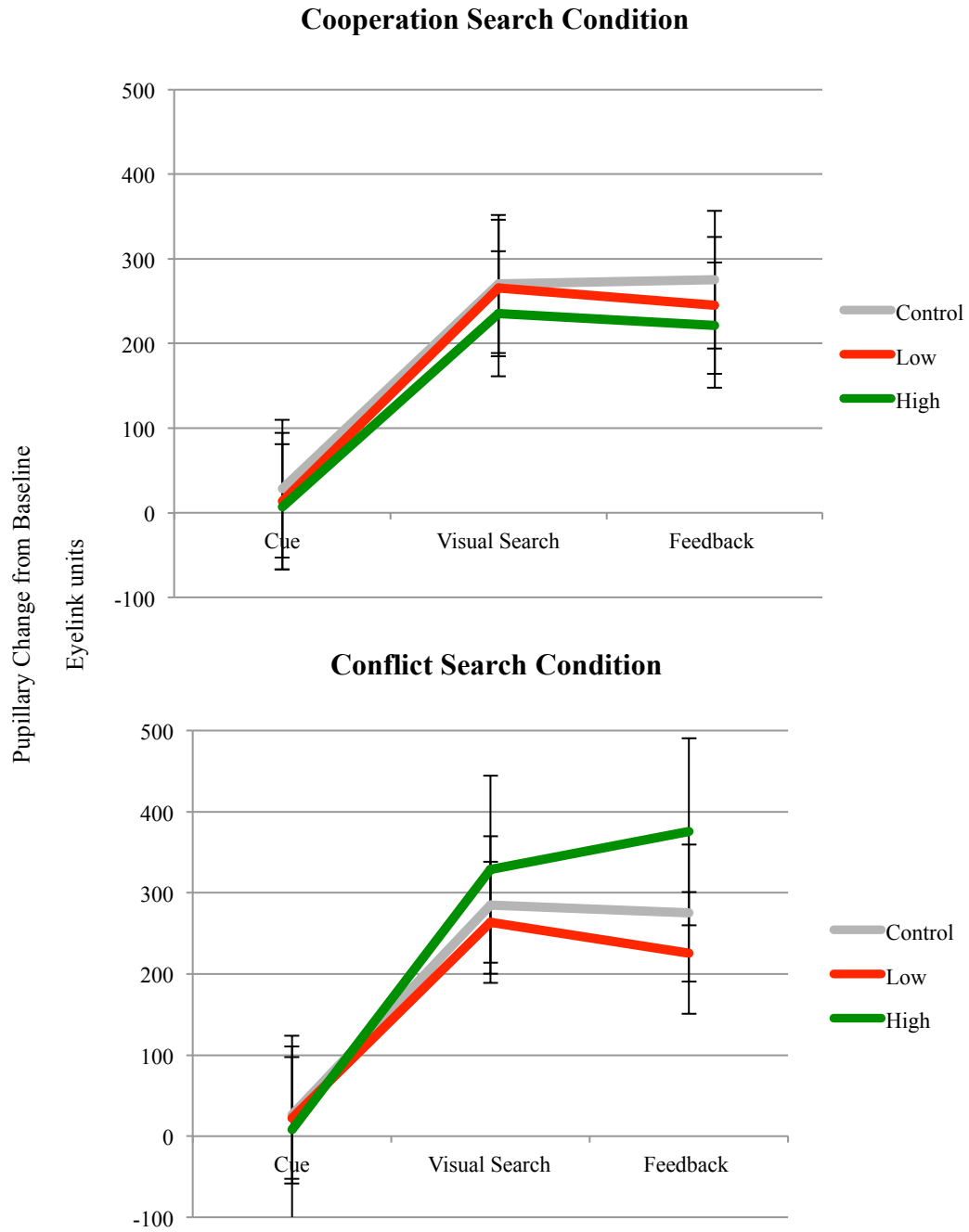Experiment 3: Average Pupil Size as a function of Reward Condition

Cooperation Search Condition

Conflict Search Condition

Figure 8. Average pupil size as a function of reward condition across the trial procedure in the cooperation condition (top) and conflict condition (bottom). Data came from predetermined windows in the trial (e.g., Visual Search). Error bars represent ±1 standard error of the mean.

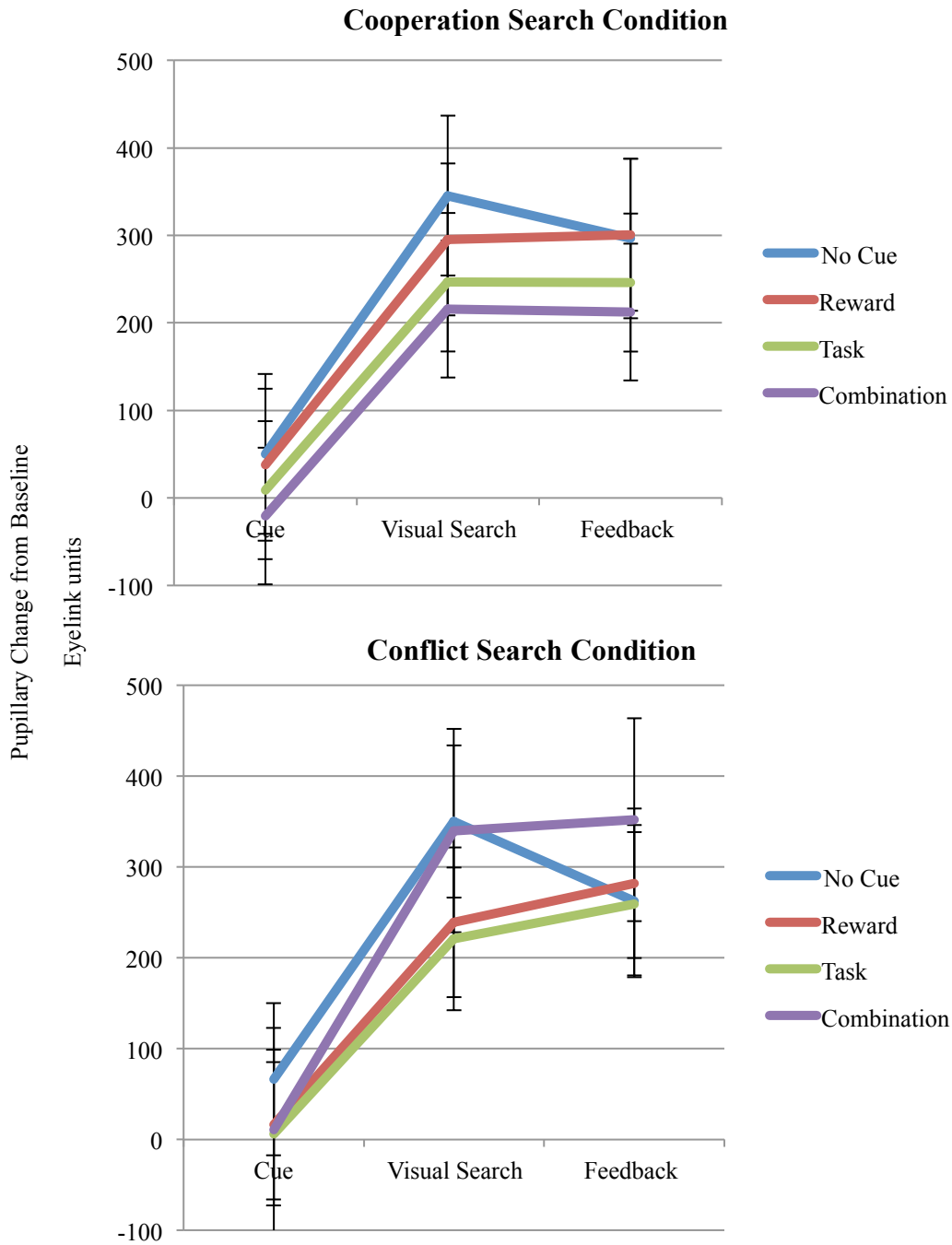Experiment 3: Average Pupil Size as a function of Cue Condition

Figure 9. Average pupil size as a function cue condition across the trial procedure in the cooperation condition (top) and the conflict condition (bottom). Data came from predetermined windows in the trial (e.g., Visual Search). Error bars represent ±1 standard error of the mean.

APPENDIX A

IRB APPROVAL DOCUMENT

EXEMPTION GRANTED

Stephen Goldinger
Psychology
480/965-0127
goldinger@asu.edu

Dear Stephen Goldinger:

On 2/11/2015 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Memory, Language, and Attention
Investigator:	Stephen Goldinger
IRB ID:	STUDY00002143
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Memory_Attention_UPDATEDcoverletter.pdf, Category: Consent Form; • Recruitment_Script.pdf, Category: Recruitment Materials; • updated_TEMPLATE_PROTOCOLSOCIAL_BEHAVIORAL.docx, Category: IRB Protocol; • Memory_and_Perception___Eye_Tracker_Explanation.pdf, Category: Recruitment materials/advertisements/verbal scripts/phone scripts;

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 2/11/2015.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Casey Phifer
        Stephen Goldinger
        Casey Phifer