Motivation sharpens exogenous spatial attention

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ABSTRACT

Although both attention and motivation affect behavior, how these two systems interact is currently unknown. To address this question, two experiments were conducted in which participants performed a spatially-cued forced-choice localization task under varying levels of motivation. Participants were asked to indicate the location of a peripherally cued target while ignoring a distracter. Motivation was manipulated by varying magnitude and valence (reward and punishment) of an incentive linked to task performance. Attention was manipulated via a peripheral cue, which correctly predicted the presence of a target stimulus on 70% of the trials. Taken together, our findings revealed that the signal detection measure d', reflecting perceptual sensitivity, increased as a function of incentive value during both *valid* and *invalid* trials. In addition, trend analyses revealed a linear increase in detection sensitivity as a function of incentive magnitude for both reward and punishment conditions. Our results suggest that elevated motivation leads to improved efficiency in orienting and reorienting of *exogenous* spatial attention and that one mechanism by which attention and motivation interact involves the *sharpening* of attention during motivationally salient conditions.

Keywords: visual attention, motivation, monetary reward, orienting, reorienting

Two systems are critical for successful performance during goal-directed behavior: (a) visual attention, which allocates limited processing resources to stimuli that are central to current behavioral goals (Corbetta & Shulman, 2002; Kastner & Ungerleider, 2000), and (b) the reward system, which is responsible for defining goals, encoding incentive value, and motivating goal-directed behavior (Robbins & Everitt, 1996; Schultz, 2000). While these two systems have been characterized in much detail, the interaction between them has received relatively little attention.

Evidence for such interaction is suggested by studies demonstrating that stimuli carrying motivational significance preferentially engage attention, including stimuli with positive emotional valence such as pictures of food items (LaBar et al., 2001; Mogg, Bradley, Hyare, & Lee, 1998; Mogg, Bradley, Field, & De Houwer, 2003) and stimuli with negative emotional valence such as threatening pictures (Armony & Dolan, 2002; Mogg & Bradley, 1999). Furthermore, findings from recent electrophysiological studies suggest that structures typically thought to be involved in attention, such as the monkey lateral intraparietal area (LIP), also process information related to reward contingencies (Platt & Glimcher, 1999; Sugrue, Corrado, & Newsome, 2004) and may be involved in the integration of attention and motivation (Bendiksby & Platt, 2006). Finally, a recent neuroimaging study demonstrated that monetary incentives enhanced responses in areas associated with visuospatial expectancy as well as areas associated with the disengagement of attention (Small et al., 2005).

Although previous studies indicate that attention and motivation interact, the nature of such interaction remains unclear. In the present study, we tested the hypothesis that motivation interacts with *exogenous* attention by enhancing perceptual sensitivity. In two related experiments, we employed a spatially-cued localization task, in which a peripheral cue predicted target location on 70% of the trials (Fig. 1A). Spatial cues provide a performance benefit when they validly predict target location during *orienting* and produce a performance cost during invalid trials, which require *reorienting* (Posner, Snyder & Davidson, 1980). Thus, by utilizing both *valid* and *invalid* spatial cues, we probed the effects of monetary incentives on both the *orienting* and *reorienting* attentional systems, respectively (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Kincade, Abrams, Astafiev, Shulman, & Corbetta, 2005; Posner, Walker, Friedrich, & Rafal, 1984). Motivation was manipulated by varying the magnitude and the valence of a monetary incentive expected by participants for performing well on the task. We hypothesized that the reward system informs the exogenous attentional system about the incentive magnitude associated with the detection of task-relevant stimuli in the environment. Evidence for this hypothesis would be provided by an increase in *detection sensitivity* (d') as a function of incentive magnitude. We investigated both the effects of reward (i.e., cash reward) and punishment (i.e., losing money) on task performance.

Experiment 1

Methods

Participants

Thirty-five Brown University students participated in Experiment 1 (15 females, age-range: 19 to 34 years). All participants had normal/corrected vision and gave written informed consent. Data of two participants were excluded from analysis (equipment malfunction in one case; exclusion criteria were not met in another case).

Materials

The image database consisted of 880 gray-level face and house images (width = 4^o; height = 5.5^o). The target stimulus was a faint red dot that was superimposed on task-irrelevant face or house images, which provided “background noise” to increase task difficulty (Fig. 1a). The red-dot target was semi-transparent, with opacity set to a level that produced 85% correct overall performance in pilot studies. Face-house pairs were presented to the left and right of fixation (4^o eccentricity). Target type (face/house) and location were varied randomly and counterbalanced and all images were repeated an equal number of times in each location and experimental condition. The cue was a white asterisk (width = 1.5^o, height = 1.8^o) that was presented at 4^o from the central fixation cross (Fig.1A). All stimuli were presented via Presentation software (Neurobehavioral Systems, Albany, CA).

Procedure

Participants were instructed that the goal of the task was to win as much money as possible. Participants completed 10 training blocks (110 trials) followed by the actual experiment (100 test blocks: 1100 trials, consisting of 700 *valid* trials, 300 *invalid* trials and 100 catch trials). During training, reaction time (RT) and accuracy feedback was provided; no feedback was provided during the experiment.

The behavioral task is depicted in Figure 1A. At the beginning of each block, participants were informed about reward/punishment contingencies via pie charts that reflected reward probability, magnitude, and valence (Figs. 1B and 1C). Participants were told that they had a 50% chance of winning (reward condition, green background, Fig. 1B), or avoiding to lose (punishment condition, red background, Fig. 1C) an incentive (value indicated in the pie chart) if they maintained adequate levels of accuracy and RT. Winning thus depended on a combination of chance and average performance (at least 7/11 correct trials and mean RT below 605 ms for each block; the latter reflected the mean RT plus 2 standard deviations as obtained in pilot studies). Participants could win either $1 or $4 and avoid losing either $0.5 or $2. This asymmetry between incentive values was employed because, in the context of gambles, losses are valued higher than gains by a factor of about 2 (e.g., Tversky & Kahneman, 1992). Zero-dollar blocks (no cash won/lost), were used as the neutral condition. At the end of each block, participants were informed about the reward/punishment outcome via an animated pie chart presented together with the updated account total.

While motivation was manipulated on each block, covert exogenous attention was manipulated on a trial-by-trial basis. Participants were presented with a peripheral spatial cue for 50 ms, which correctly predicted target location on 70% of the trials (Fig. 1A). After a 75-ms delay, a face-house stimulus pair was shown for 200 ms. As stated, the target was a faint red dot presented in the center of one of the task-irrelevant stimuli (shown for 200 ms). During catch trials (see below), a stimulus pair was presented, but no red-dot target. After stimulus offset, participants were given 1500 ms to respond. Participants were asked to report the target location as quickly and accurately as possible by pressing the left button when the target was on the left and the right button when the target was on the right. Buttons were not counterbalanced to avoid spatial conflict (Fan, McCandliss, Sommer, Raz, & Posner, 2002). Catch trials were employed to discourage guessing and alternative behavioral strategies and occurred at a rate of 1 per block (9.1% of all trials). Participants indicated the presence of a catch trial by pressing the spacebar. After reinforcement, participants were asked to rate “happiness” on a scale from 1 to 7 (see Supplemental Material).

Behavioral Performance

The sensitivity measure d' (Green & Swets, 1966) was used in statistical analyses. In our spatial task, hits and false alarms were defined in terms of targets appearing on the *left side* of the display: hit rate was defined as the conditional probability that the subject responded “left” given that the target was on the left [P_{HIT} = P(“Target Left” | <T Left>); T: target] and false alarm rate as the conditional probability that the subject responded “left” given that the target was on the right [P_{FA} = P(“Target Left” | <T Right>)] (Green & Swets, 1966; Macmillan & Creelman, 2005). Dprime scores were obtained by entering hits and false alarms into the following equation:

$$d' = \frac{1}{\sqrt{2}}[z(H) - z(F)].$$

Given the spatial symmetry of our design, hits and false alarms naturally could have been defined in terms of targets appearing on the *right side* of the display (Macmillan & Creelman, 2005): hit rate would be defined as the conditional probability that the subject responded “right” given that the target was on the right [P_{HIT} = P(“Target Right” | <T Right>)] and false alarm rate as the conditional probability that the subject responded “right” when the target was on the left [P(“Target Right”|<T Left>]. Results from analyses repeated with these alternative definitions supported those reported below and will not be reported.

In all analyses, Huynh-Feldt corrected *p* values are reported where appropriate (decimal degrees of freedom indicate that a correction was employed). To mitigate the multiple-comparisons problem, post-hoc *t* tests involving the neutral condition and all other reward/punishment conditions were Bonferroni corrected, such that the α level for statistical significance was 0.0125 (4 comparisons). Likewise, for linear trend analyses considering reward and punishment separately, the α level for statistical significance was 0.025 (2 comparisons). We used the abbreviation “nsbc” to indicate *p* values that did not survive Bonferroni correction. Exact *p* values are provided when values do not reach significance levels; *p* values less than 0.1 (or less than 0.05 when Bonferroni correction is involved) are referred to as “near significant”.

Exclusion Criteria

To screen for participants who may have ignored task instructions and followed the simple strategy of reporting cue rather than target location, we examined those participants who reliably failed the task during the *invalid* condition. We excluded participants with significant, negative d' values (higher false alarm rates than hit rates) as indicated by a significant *Z* test performed on d' values for invalid trials pooled across conditions (Macmillan and Creelman, 2005).

Results

Detection Sensitivity

Dprime values were entered into a three-way repeated-measures ANOVA, with INCENTIVE ($0.0, $0.5, $1.0, $2.0, $4.0; only the absolute incentive value was employed in this analysis), VALIDITY (valid, invalid) and TARGET TYPE (house, face) as within-subjects factors. A significant main effect of INCENTIVE was obtained [$F(2.9, 92.5) = 9.20$, $p < 0.001$], with d' increasing linearly as a function of absolute incentive value as indicated by a significant linear trend [$F(1,32) = 16.20$, $p < 0.001$] (Fig. 2A). There was a significant main effect of VALIDITY [$F(1,32) = 65.60$, $p < 0.001$], with larger d' values in the *valid* condition (d' = 2.63) than in the *invalid* condition (d' = 1.68); average performance for *valid* trials was 92% correct and 73% correct for *invalid* trials. A main effect of TARGET TYPE was also observed [$F(1,32) = 22.05$, $p < 0.01$], with larger d' values during house targets (d' = 2.27) compared to face targets (d' = 2.04). No significant interactions were obtained, although a near-significant interaction between VALIDITY and INCENTIVE [$F(4,128) = 2.19$, $p = 0.07$] was observed. Tests of simple main effects showed that INCENTIVE significantly affected d' values during both *valid* [$F(2.8, 88.2) = 3.70$, $p < 0.05$] and *invalid* [$F(3.7, 117.4) = 8.48$, $p < 0.001$] trials. To further explore simple main effects, post-hoc pairwise *t* tests comparing d' values during the neutral condition and the reward/punishment conditions were employed (other pairwise differences were not explicitly tested). These comparisons indicated that, for *valid* trials, there were no significant differences between neutral and reward conditions or between neutral and punishment conditions [\$0.0 vs. \$-2.0: $p = 0.03$, nsbc; \$0.0 vs. \$-0.5: $p = 0.57$; \$0.0 vs. \$1.0: $p = 0.09$; \$0.0 vs. \$4.0: $p = 0.03$, nsbc], while for *invalid* trials, d' values for the neutral condition differed significantly from those of all reward and punishment conditions [\$0.0 vs. \$-2.0: $p < 0.001$; \$0.0 vs. \$-0.5: $p < 0.001$; \$0.0 vs. \$1.0: $p < 0.001$; \$0.0 vs. \$4.0: $p < 0.001$] (Fig. 2B).

The above omnibus ANOVA revealed main effects of INCENTIVE, VALIDITY, and TARGET TYPE. In particular, this analysis allowed us to test the effect of reward/punishment on detection performance during *validly* and *invalidly* cued trials. To further investigate differential effects of VALENCE (positive vs. negative), the data were split into reward and punishment conditions. The same neutral \$0 condition was included in separate reward and punishment ANOVAs. In addition, the data were collapsed across the factor TARGET TYPE for two reasons: (a) no significant *interaction* between TARGET TYPE and other factors was obtained in the omnibus ANOVA; (b) we had no *a priori* hypothesis about TARGET TYPE. Thus, below, d' values were entered into two two-way repeated-measures ANOVAs, with INCENTIVE and VALIDITY as within-subjects factors.

Reward ANOVA

A significant main effect of INCENTIVE was obtained [$F(1.7, 55.0) = 12.17$, $p < 0.001$], with d' increasing linearly as a function of incentive value (\$0.0: 2.01, \$1.0: 2.18,

\$4.0: 2.25), as indicated by a significant linear trend [F(1,32) = 16.47, p < 0.001]. There was also a significant main effect of VALIDITY [F(1, 32) = 63.50, p < 0.001]. A near-significant interaction between INCENTIVE and VALIDITY was observed [F(2, 64) = 2.58, p = 0.08]. To further investigate this near-significant interaction, separate post-hoc trend analyses were conducted for *valid* and *invalid* conditions. A significant linear trend was obtained in the *invalid* reward condition [F(1,32) = 18.95, p < 0.001], but only a near-significant linear trend was obtained in the *valid* reward condition [F(1,32) = 5.1, p = 0.03, nsbc].

Punishment ANOVA

There was a significant main effect of INCENTIVE [F(1.7, 54.5) = 10.02, p < 0.001], with d' increasing linearly as a function of punishment value (\$0: 2.01, -\$0.5: 2.14, -\$2: 2.20), as indicated by a significant linear trend [F(1,32) = 13.58, p < 0.001]. There was also a significant main effect of VALIDITY [F(1, 32) = 69.08, p < 0.001]. Finally, a significant interaction between INCENTIVE and VALIDITY was found [F(2, 64) = 4.23, p < 0.05]. Trend analyses were conducted as specified above. A significant linear trend was obtained in the *invalid* punishment condition [F(1,32) = 15.41, p < 0.001], but only a near-significant linear trend was obtained in the *valid* punishment condition [F(1,32) = 5.19, p = 0.03, nsbc].

Experiment 2

In Experiment 1, the most robust effects of monetary incentives on perceptual sensitivity were observed during *invalid* trials, suggesting that motivation and attention interact during exogenous *reorienting* processes. However, it is possible that the *valid* condition was not taxing enough to reveal an effect of monetary incentives during such trials. To probe the role of motivation during exogenous *orienting* processes, we increased the difficulty of *valid* trials by adjusting each participants' red-dot target appearance via a staircase procedure.

Methods

Participants

Thirty-four Brown University students participated in Experiment 2 (18 females, 19 to 49 years old). All participants had normal/corrected vision and gave written informed consent. Data of two participants were excluded from analysis (equipment malfunction in one case; exclusion criteria [see Experiment 1] were not met in another case).

Materials

All aspects were the same as Experiment 1, except that only face images were used (440 stimuli) in Experiment 2; thus, stimuli appeared as face-face pairs. The opacity level of the red-dot target was determined by a staircase procedure. Location was varied randomly and counterbalanced and all images were repeated an equal number of times in each location and experimental condition, except for the first 5 subjects, for which the right:left ratio was 1.2:1 for invalid trials only, due to a programming error.

Procedure

All aspects were the same as in Experiment 1, except that participants completed a training session in Experiment 2 that included a threshold estimation procedure. In Experiment 2 only face targets were presented.

Threshold Estimation Procedure

During *training*, an adaptive “one-up-three-down” staircase procedure was used to approximately track the 79% correct level for *valid* and, separately, *invalid* trials for each participant. Opacity levels of the red-dot target were decreased (easier) for each incorrect response and increased (harder) for every three consecutive correct responses. To avoid subject expectancies, 2 staircase algorithms were employed per condition (i.e., 2 for *valid* and 2 for *invalid* trials), one starting at the highest opacity level and one starting at the lowest opacity level. The training session was terminated after all 4 staircases completed 12 reversals, or after 100 blocks were completed (the length of Exp. 1). The opacity values of the 2 same-condition staircases were then averaged. These final opacity values were used during *testing*, and remained fixed.

Results

Accuracy

Accuracy values were entered into a three-way mixed ANOVA with experimental GROUP (Experiment 1, Experiment 2) as between-subjects factor and INCENTIVE and VALIDITY as within-subjects factors (the factor TARGET TYPE from Experiment 1 was “collapsed”). A significant effect of GROUP indicated that Experiment 2 (mean accuracy: 75%) was significantly more difficult than Experiment 1 (mean accuracy: 82%) [F(1,63) = 10.53, $p < 0.01$]. A significant interaction between VALIDITY and GROUP [F(1,63) = 7.88, $p < 0.01$] was also observed. Tests of simple main effects showed that the staircase procedure significantly decreased average accuracy during *valid* trials compared to Experiment 1 (Exp. 1: 92%, Exp. 2: 78%) [F(1, 63) = 30.80, $p < 0.001$] but not during *invalid* trials (Exp. 1: 73%, Exp. 2: 72%) [F(1,63) = 0.06, p = 0.81]. Similar results were obtained for d’ values in a combined analysis of Experiments 1 and 2 (see Supplemental Material).

Detection Sensitivity

Dprime values were entered into a two-way repeated-measures ANOVA, with INCENTIVE ($0.0, $0.5, $1.0 $2.0, $4.0) and VALIDITY (valid, invalid) as within-subjects factors. Consistent with Experiment 1, significant main effects of INCENTIVE and VALIDITY [F(1,31) = 12.20, $p < 0.001$] were obtained [F(3.90,120.83) = 3.85, $p < 0.01$]. Accordingly, d' increased linearly as a function of absolute incentive value, as indicated by a significant linear trend [F(1,31) = 14.77, $p < 0.001$] (Fig. 2C) and larger d' values were obtained in the *valid* condition (d' = 1.99) compared to the *invalid* condition (d' = 1.40). No significant interaction between INCENTIVE and VALIDITY was obtained [F(4, 124) = 0.49, p = 0.74]. However, to compare the effects of monetary incentives on *valid* and *invalid* trials, tests of simple main effects were conducted. These showed that INCENTIVE significantly affected d' values during *invalid* trials [F(4, 124) = 2.54, $p < 0.05$], while only a near-significant result was obtained during *valid* trials [F(3.8, 117.2)

= 2.19, $p = 0.078$]. Post-hoc pairwise *t* tests comparing d' values for the neutral condition to the reward/punishment conditions were employed to further explore simple main effects. These comparisons indicated that, for *both valid* and *invalid* trials, there was a significant difference between the neutral and the $4.0 reward condition only [VALID: $0.0 vs. $-2.0: $p = 0.09$; $0.0 vs. $-0.5: $p = 0.6$; $0.0 vs. $1.0: $p = 0.52$; $0.0 vs. $4.0: $p < 0.01$; INVALID: $0.0 vs. $-2.0: $p = 0.03$, nsbc; $0.0 vs. $-0.5: $p = 0.04$, nsbc; $0.0 vs. $1.0: $p = 0.12$; $0.0 vs. $4.0: $p < 0.01$] (Fig. 2D).

Reward ANOVA

In agreement with Experiment 1, significant main effects of INCENTIVE [$F(2, 62) = 7.23$, $p < 0.01$] and VALIDITY were observed [$F(1, 31) = 12.17$, $p < 0.001$]. Dprime increased linearly as a function of incentive value ($0: 1.60, $1: 1.68, $4: 1.79), as indicated by a significant linear trend [$F(1,31) = 12.50$, $p < 0.001$]. There was no significant interaction between INCENTIVE and VALIDITY, indicating that INCENTIVE influenced orienting and reorienting in a similar manner [$F(1.95, 60.34) = 0.29$, $p = 0.74$]. For comparison with Experiment 1, trend analyses were conducted for *valid* and *invalid* conditions. Significant linear trends were obtained in both the *valid* [$F(1,31) = 8.30$, $p < 0.01$] and *invalid* condition [$F(1,31) = 7.83$, $p < 0.01$].

Punishment ANOVA

There was a near-significant main effect of INCENTIVE [$F(1.84, 57.10) = 2.77$, $p = 0.08$], with d' increasing linearly as a function of punishment value ($0: 1.60, -$0.5: 1.70, -$2: 1.72); the test for the linear trend actually reached significance [$F(1,31) = 7.09$, $p <$

0.05]. Consistent with Experiment 1, a significant main effect of VALIDITY was obtained [F(1, 31) = 12.34, $p < 0.001$]. No significant interaction between INCENTIVE and VALIDITY was obtained, suggesting that incentive influenced orienting and reorienting in a similar manner [F(2, 62) = 1.37, p = 0.26]. A significant linear trend was observed in the *invalid* punishment condition [F(1,31) = 5.53, p = 0.025], but only a near-significant linear trend in the *valid* punishment condition [F(1,31) = 3.12, p = 0.09].

Discussion

In two related experiments, we employed a spatially-cued detection task involving monetary reward and punishment to investigate potential interactions between attention and motivation. We showed that d' scores increased linearly as a function of absolute monetary incentive value, revealing that monetary incentives enhanced detection sensitivity.

By utilizing both *valid* and *invalid* trials, we probed the effects of monetary incentives on *orienting* and *reorienting* exogenous attentional mechanisms, respectively. In Experiment 1, an improvement of detection sensitivity was observed in all reward and punishment conditions compared to the neutral condition during *invalid* trials. Similar trends were observed during *valid* trials, although the effect was not statistically significant. Because *valid* trials in Experiment 1 were not sufficiently demanding, in Experiment 2 we employed a more challenging version of the task to explore potential differences between *valid* and *invalid* trials. Results from Experiment 2 confirmed and extended those obtained in Experiment 1. Trend analyses from Experiment 2 and a combined analysis of Experiments 1 and 2 (Supplemental Material) confirmed the effect of reward and punishment on detection sensitivity during *invalidly* cued trials. While rewards and punishments had a smaller effect on detection sensitivity during *validly* cued trials, sensitivity improvements during *both valid* and *invalid* trials in the largest *reward* condition ($4) were revealed in Experiment 2. The enhancement of sensitivity by reward during *valid* trials was confirmed by trend analyses. We suggest that the observed differences in performance enhancement during *valid* and *invalid* conditions may be due to differences in how reward information is relayed to attentional *orienting* and *reorienting* systems, respectively. Alternatively, it could be simply more difficult to further strengthen an already present benefit during *validly* cued trials compared to counteracting the cost of *invalid* cueing. Note that, in both experiments, observed changes in sensitivity were not due to speed/accuracy trade-offs (Supplemental Material).

A distinction between two attentional systems has been made by previous research, with one system *orienting* attention to a cued location, while the other disengages attention to enable *reorienting* to behaviorally relevant stimuli (Corbetta & Shulman, 2002; Posner et al., 1984). Some neuroimaging studies have supported this distinction by revealing that orienting and reorienting are processed by distinct functional networks (Corbetta, Kincade, Lewis, Snyder, & Sapir, 2005; Kincade et al., 2005; Thiel, Zilles, & Fink, 2004). On the one hand, *valid* task-relevant cues are known to guide attention to a specific location (Posner, Snyder, & Davidson, 1980) and have been suggested to be processed by the orienting network (Corbetta et al., 2000; Thiel et al., 2004). Results from the current experiments indicating that monetary rewards and punishments increase detection sensitivity during orienting of exogenous attention support and extend previous findings of motivational effects on attentional orienting (Derryberry, 1989). On the other hand, the detection of an *invalidly* cued target stimulus involves multiple processes including disengagement of attention and shifting of attention to a novel location (Posner, Choate, Rafal & Vaughn, 1985), which are thought to be mediated by the reorienting network (Corbetta et al., 2000; Kincade et al., 2005). Activation of the reorienting network is influenced by behavioral relevance (Downar, Crawley, Mikulis, & Davis, 2001), as well as novelty and frequency of occurrence of a given stimulus (Downar, Crawley, Mikulis, & Davis, 2002). Our findings suggest that a further factor can enhance the efficacy of the reorienting system, namely, the incentive magnitude associated with target detection.

Our findings are consistent with a recent neuroimaging paper, which demonstrated a neural interaction between endogenous attention and motivation using a reaction time task of low difficulty. Findings from Small et al. (2005) revealed that monetary incentives increased activations in the posterior cingulate cortex during orienting of attention, and in the inferior parietal lobule during reorienting of attention. Their findings suggest that incentives differentially enhanced neural processing within the attentional system during orienting and reorienting and may provide a neural basis for our findings.

The present results demonstrate that monetary rewards and punishments improve detection sensitivity. Consistent with our hypothesis, the improvement in performance involved *enhanced detection sensitivity* during both *orienting* and *reorienting* of exogenous visuospatial attention, suggesting that one mechanism by which attention and motivation interact involves the *sharpening* of attention during motivationally salient conditions. Overall, the present findings add to a growing literature that reveals that attention and motivation closely interact in the generation of complex behavior.

Figures

Figure 1.

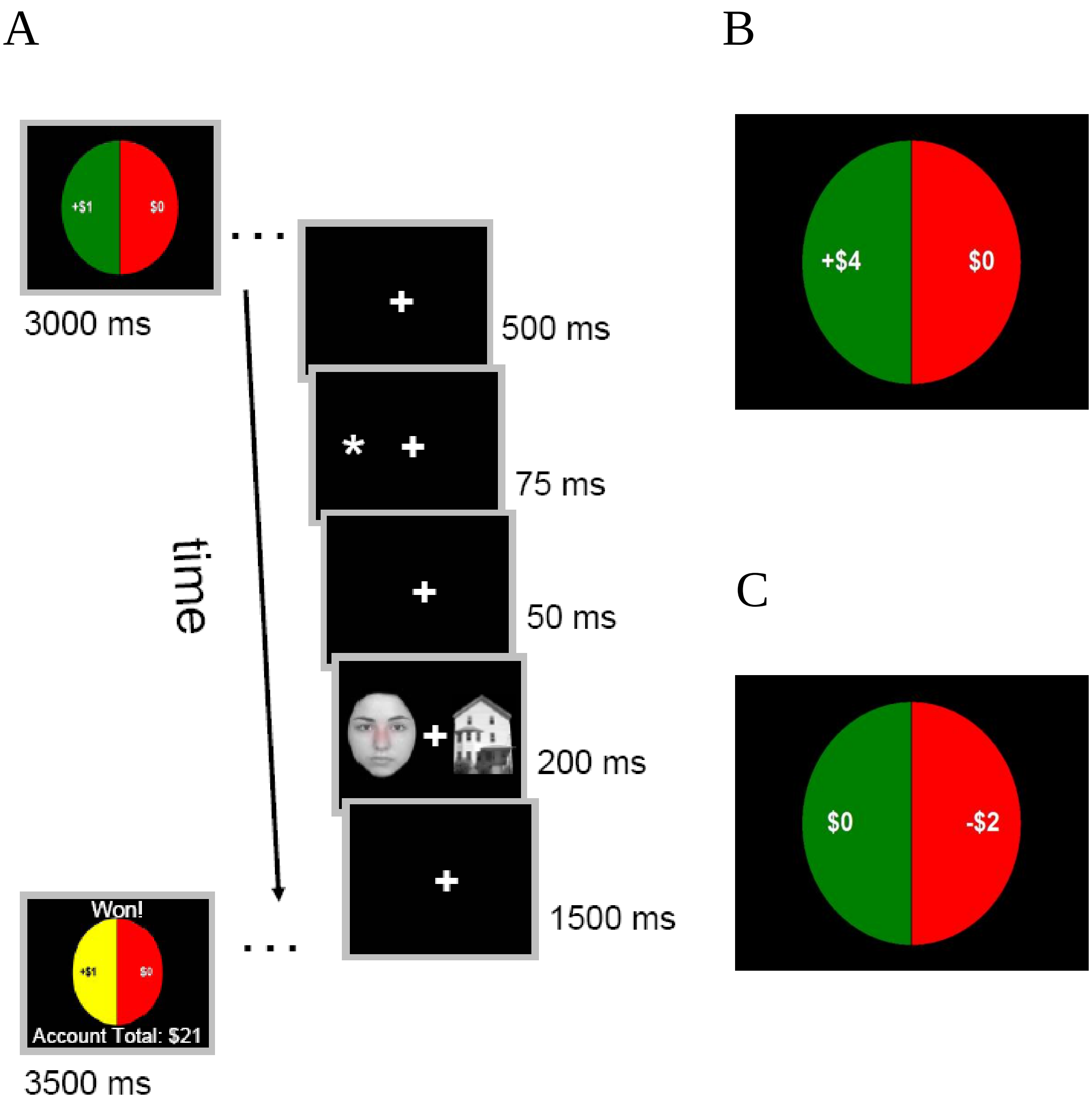
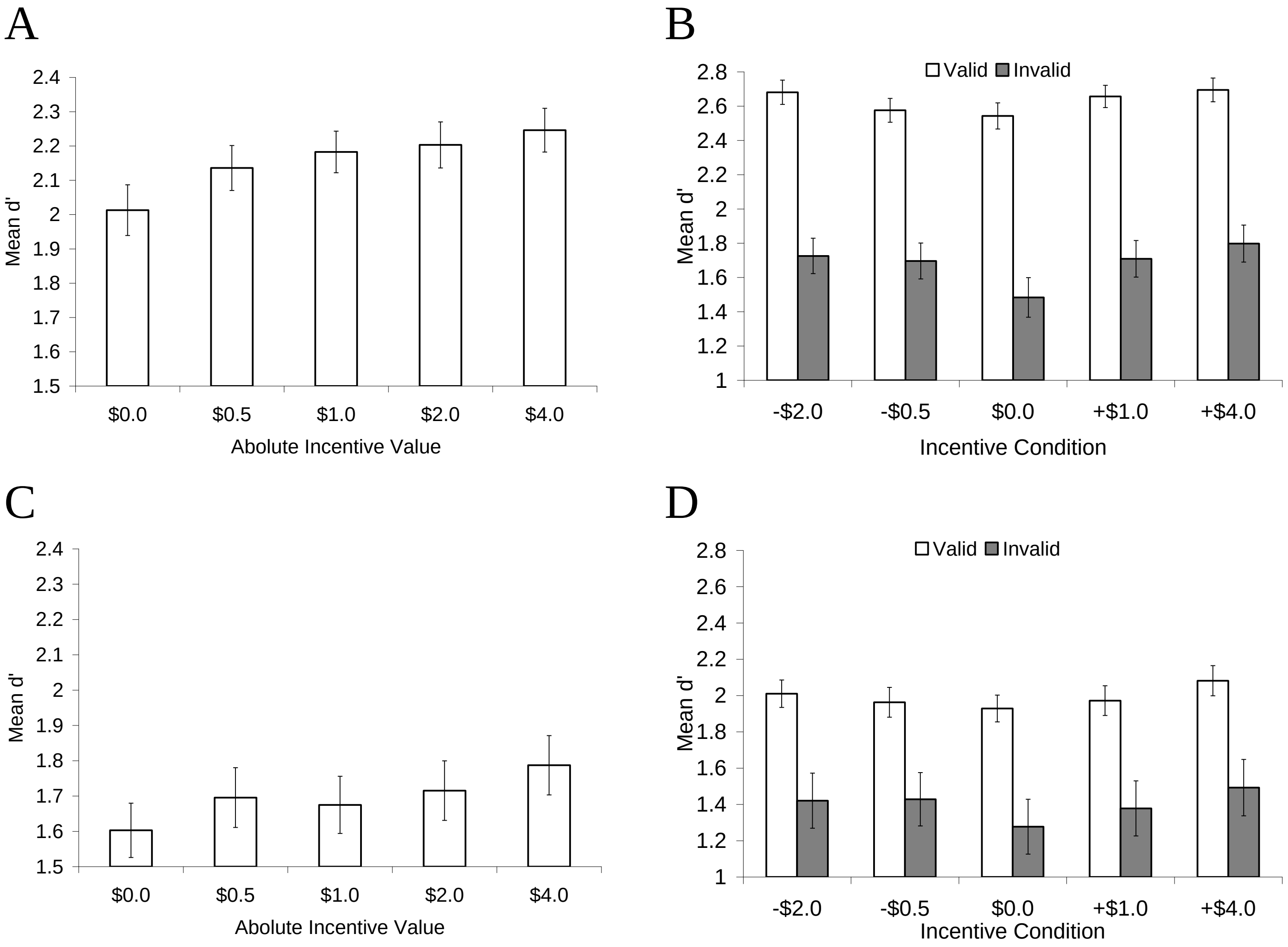


Figure 2.



A
Mean d'
2.4
2.3
2.2
2.1
2
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Abolute Incentive Value
B
☐ Valid ■ Invalid
Mean d'
2.8
2.6
2.4
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+$1.0
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Mean d'
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2
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Abolute Incentive Value
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Mean d'
2.8
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2
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1.6
1.4
1.2
1
-$2.0
-$0.5
$0.0
+$1.0
+$4.0
Incentive Condition

Captions

Figure 1. (A) Illustration and timing of an example trial sequence with *valid* cue and face target. The incentive condition and outcome are shown on the left. (B) Reward condition in which subjects had a 50% chance of winning four dollars. (C) Punishment condition in which subjects had a 50% chance of avoiding to lose two dollars.

Figure 2. (A, C) Detection performance (d') as a function of absolute incentive value in Experiment 1 (A) and Experiment 2 (C). Detection sensitivity increased linearly with increasing incentive value. (B, D) Detection performance as a function of incentive value and validity (valid, invalid) in Experiment 1 (B) and Experiment 2 (D). In both experiments, increased perceptual sensitivity was observed as a function of increasing incentive magnitude during *valid* and *invalid* cue conditions (in Experiment 2, the latter was significant only during reward conditions).

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Supplemental Material

Motivation sharpens exogenous spatial attention

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Experiment 1

Happiness Ratings

To evaluate our manipulation of motivation, we probed happiness ratings (Knutson et al., 2001). Increased happiness ratings after obtaining (winning a positive reward) or avoiding (avoiding a punishment) an incentive would provide additional evidence of the effectiveness of our manipulation, indicating that subjects were happier after winning and less happy after losing. Happiness ratings were entered into two linear regression analyses for (a) winning and (b) losing. Happiness ratings increased significantly as a function of absolute incentive value after winning [F(1,163) = 25.05, $p < 0.001$] (mean happiness ratings: \$0.0: 4.24, \$0.5: 4.62, \$1.0: 5.04, \$2.0: 4.96, \$4.0: 5.77) and decreased significantly after losing [F(1,163) = 14.57, $p < 0.001$] (mean happiness ratings: \$0.0: 3.39, \$0.5: 2.95, \$1.0: 2.96, \$2.0: 2.23, \$4.0: 2.48). Thus, winning and losing cash rewards affected motivation as intended.

Reaction Time

Mean reaction times (RTs) were entered into a two-way repeated-measures ANOVA, with INCENTIVE (\$0.0, \$0.5, \$1.0, \$2.0, \$4.0) and VALIDITY (valid, invalid) as within-subjects factors. Consistent with previous research employing predictive spatial cues, a significant main effect of VALIDITY was obtained [F(1,32) = 60.18; $p < 0.001$], with shorter RTs after valid compared to invalid cues (Valid: 414.3 ms; Invalid: 451.9 ms). INCENTIVE had no effect on mean RTs, as indicated by a lack of a significant main effect of INCENTIVE ($p = 0.408$) and no interaction between INCENTIVE and VALIDITY ($p = 0.391$).

Speed/Accuracy Trade-Off

To investigate the possibility of speed/accuracy trade-offs, each subject's d' scores were correlated with his or her reaction times within each INCENTIVE and VALIDITY condition. Negative correlations were obtained in all *valid* and *invalid* cueing conditions, indicating that increased d' values were associated with faster reaction times (Table 1). Significance tests for correlation coefficients were Bonferroni corrected, such that the α level for statistical significance was 0.01 (5 comparisons). Pearson correlation coefficients reached significance only in the largest punishment ($r = -0.449$, $p < 0.01$, two-tailed; Figure 4A) and near-significance in the largest reward condition (Table 1). These results indicate an absence of speed/accuracy trade-offs in all incentive and validity conditions, because the relationship between d' and RT was in the *opposite* direction as the one expected for speed/accuracy trade-offs (Figure 4).

Experiment 2

Happiness Ratings

As in Experiment 1, happiness ratings increased significantly as a function of absolute incentive value after winning [F(1,155) = 27.75, p < 0.001] (mean happiness ratings: $0.0: 4.02, $0.5: 4.34, $1.0: 4.73, $2.0: 4.60, $4.0: 5.37). While happiness ratings decreased after losing (mean happiness ratings: $0.0: 3.07, $0.5: 2.70, $1.0: 2.79, $2.0: 2.45, $4.0: 2.53), results did not reach significance [F(1, 158) = 2.54, p = 0.11] – possibly due to the increased difficulty in Experiment 2 and more frequent losses, some "desensitization" may have occurred.

Reaction Time

Mean RTs were entered into a two-way repeated-measures ANOVA, with INCENTIVE ($0.0, $0.5, $1.0, $2.0, $4.0) and VALIDITY (valid, invalid) as within-subjects factors. In agreement with Experiment 1, a significant main effect of VALIDITY was obtained [F(1,31) = 21.73; p < 0.001] with shorter reaction times in the valid compared to the invalid condition (Valid: 440.3 ms; Invalid: 467.5 ms). INCENTIVE had no effect on mean RTs, as indicated by a lack of a significant main effect of INCENTIVE (p = 0.667) and no interaction between INCENTIVE and VALIDITY (p = 0.101).

Speed/Accuracy Trade-Off

The possibility of speed/accuracy trade-offs was investigated as described for Experiment 1. Only non-significant correlations were obtained in Experiment 2, indicating an absence of speed/accuracy trade-offs across all incentive and validity conditions (Table 1).

Combined Analysis of Experiments 1 and 2

Detection Sensitivity

To increase statistical power, d’ values from Experiments 1 and 2 were submitted to a combined analysis (N = 65). Dprime values were entered into a three-way mixed ANOVA, with INCENTIVE (\$0.0, \$0.5, \$1.0, \$2.0, \$4.0) and VALIDITY (valid, invalid) as within-subjects factors and experimental GROUP (Experiment 1, Experiment 2) as between-subjects factor. In agreement with the results from Experiments 1 and 2, significant main effects of INCENTIVE [F(3.8, 236.3) = 11.59, p < 0.001] and VALIDITY [F(1,63) = 96.26, p < 0.001] were obtained. Dprime values increased linearly as a function of INCENTIVE as indicated by a significant linear trend [F(1,63) = 30.32, p < 0.001] (Fig. 3A). Larger d' values were obtained in the *valid* condition (d' = 2.31) than in the *invalid* condition (d' = 1.54); average performance for *valid* trials was 85% correct and 73% correct for *invalid* trials. There was a main effect of GROUP [F(1, 63) = 22.46, p < 0.001], with significantly larger d’ scores in Experiment 1 (d’ = 2.16) compared to Experiment 2 (d’ = 1.70). There was furthermore a near-significant interaction between GROUP and VALIDITY [F(1, 63) = 3.02, p = 0.087]. Tests of simple main effects indicated that there was no difference in d’ values as a function of GROUP during *invalid* trials (p = 0.112), while d’ values were significanty lower in Experiment 2 (d’ = 1.99) compared to Experiment 1 (d’ = 2.63) during *valid* trials [F(1, 63) = 45.44 p < 0.001]. No further interactions with the factor GROUP were obtained. These findings replicate our accuracy results (see main text), confirming that the staircase procedure not only affected mean accuracy, but also d’ values in the valid condition, as intended. Consistent with Experiments 1 and 2, no significant interactions were obtained, although a near-significant interaction between VALIDITY and INCENTIVE [F(4,252) = 2.1, p = 0.08] was observed. As in Experiments 1 and 2, this interaction was explored further. Tests of simple main effects showed that INCENTIVE significantly affected d' values during both *valid* [F(3.5, 222.3) = 5.71, $p < 0.005$] and *invalid* [F(4, 252) = 9.28, $p < 0.001$] trials. Post-hoc pairwise *t* tests comparing d' values during the neutral condition and the reward/punishment conditions were conducted next. Comparisons indicated that, for *valid* trials, there were significant differences between the neutral and the largest reward and punishment conditions [$0.0 vs. $-2.0: $p < 0.01$; $0.0 vs. $-0.5: p = 0.44; $0.0 vs. $1.0: p = 0.09; $0.0 vs. $4.0: $p < 0.005$]. For *invalid* trials, d' values for the neutral condition differed significantly from those of all reward and punishment conditions [$0.0 vs. $-2.0: $p < 0.001$; $0.0 vs. $-0.5: $p < 0.001$; $0.0 vs. $1.0: $p < 0.001$; $0.0 vs. $4.0: $p < 0.001$] (Fig. 3B).

As done for Experiments 1 and 2 (see main text), to further investigate differential effects of VALENCE (positive vs. negative), the data were split into reward and punishment conditions. The same neutral $0 condition was included in separate reward and punishment ANOVAs. Thus, below, d' values were entered into two separate three-way repeated-measures ANOVAs, with INCENTIVE and VALIDITY as within-subjects factors, and GROUP as between-subjects factor.

Reward ANOVA

Consistent with Experiments 1 and 2, a significant main effect of INCENTIVE was obtained [F(1.9, 5118.5) = 19.39, $p < 0.001$], with d' increasing linearly as a function of incentive value as indicated by a significant linear trend [F(1,63) = 28.86, $p < 0.001$]. A significant main effect of VALIDITY was also observed [$F(1, 63) = 55.42$, $p < 0.001$]. There was a main effect of GROUP [$F(1, 63) = 22.79$, $p < 0.001$], and a near-significant interaction between GROUP and VALIDITY [$F(1, 63) = 2.82$, $p = 0.098$]. The interaction between INCENTIVE and VALIDITY did not reach significance ($p = 0.133$). However, to compare results from the combined analysis to those of Experiment 1, separate post-hoc trend analyses were conducted for *valid* and *invalid* conditions. Significant linear trends were observed in both *valid* [$F(1,63) = 12.53$, $p < 0.005$] and *invalid* reward conditions [$F(1,63) = 25.24$, $p < 0.001$]. These results indicate that reward expectancy enhanced detection sensitivity in both *valid* and *invalid* cue conditions.

Punishment ANOVA

There was a significant main effect of INCENTIVE [$F(2, 126) = 10.95$, $p < 0.001$], with d' increasing linearly as a function of punishment value as indicated by a significant linear trend [$F(1,63) = 20.45$, $p < 0.001$]. There was also a significant main effect of VALIDITY [$F(1, 63) = 58.50$, $p < 0.001$]. A main effect of GROUP was obtained [$F(1, 63) = 20.03$, $p < 0.001$], as well as a near-significant interaction between GROUP and VALIDITY [$F(1,63) = 3.36$, $p = 0.072$]. Finally, a significant interaction between INCENTIVE and VALIDITY was found [$F(2, 126) = 5.03$, $p < 0.01$]. Trend analyses revealed significant linear trends both in the *invalid* punishment condition [$F(1,63) = 19.74$, $p < 0.001$] and the *valid* punishment condition [$F(1,63) = 8.23$, $p < 0.01$].

While the above trend analyses indicate that punishment expectancy enhanced detection sensitivity during both orienting and reorienting of exogenous attention (valid and invalid trials, respectively), the significant interaction between INCENTIVE and VALIDITY, combined with the results from post-hoc pairwise comparisons (see *Detection Sensitivity* above), indicate that the enhancement of detection sensitivity by punishment expectancy was greater in the *invalid* than the *valid* cueing condition.

Reaction Time

Mean RTs were entered into a three-way repeated-measures ANOVA, with INCENTIVE ($0.0, $0.5, $1.0, $2.0, $4.0) and VALIDITY (valid, invalid) as within-subjects factors and GROUP as between-subjects factor. In agreement with Experiments 1 and 2, a significant main effect of VALIDITY was obtained [$F(1,63) = 73.35$; $p < 0.001$] with shorter reaction times in the valid compared to the invalid condition (Valid: 427.31 ms; Invalid: 459.69 ms). INCENTIVE had no effect on mean RTs, as indicated by a lack of a significant main effect of INCENTIVE ($p = 0.366$) and no interaction between INCENTIVE and VALIDITY ($p = 0.145$). Finally, there was no main effect of GROUP ($p = 0.144$), and no significant interaction with the factor GROUP.

Speed/Accuracy Trade-Off

As done for Experiments 1 and 2, the possibility of speed/accuracy trade-offs was investigated. The combined analysis revealed similar trends as in Experiment 1. Negative correlations were obtained in all *valid* and *invalid* cueing conditions, indicating that increased d’ values are associated with faster reaction times (Table 1). Pearson correlation coefficients reached significance in the highest reward condition during *validly* precued trials ($r = -0.354$, $p < 0.005$, two-tailed; Figure 4B), but near-significant correlations were obtained in all other *valid* conditions (Table 1). No significant correlations were obtained during *invalidly* precued trials. Consistent with Experiments 1 and 2, these results indicated an absence of speed/accuracy trade-offs in all incentive and validity conditions.

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Captions

Table 1. Pearson's correlation coefficients (r) and associated p values (two-tailed) across INCENTIVE and VALIDITY conditions in Experiments 1, 2 and the combined analysis. An asterisk denotes significant correlations; nsbc: not significant when Bonferroni corrected.

Figure 3. Results from combined analysis of d' values from Experiments 1 and 2. (A) Detection performance (d') as a function of absolute incentive value. As in Experiments 1 and 2, detection sensitivity increased linearly with increasing incentive value. (B) Detection performance as a function of incentive value and validity (valid, invalid). Increased perceptual sensitivity was observed as a function of increasing incentive magnitude during *valid* and *invalid* cue conditions.

Figure 4. Significant, negative correlations between d' values and Mean RT were obtained in (A) the largest punishment condition (-$2.0) in Experiment 1 and (B) the largest reward condition (+$4.0) in the combined analysis. The direction of the relationship between d' and Mean RT indicates an absence of speed/accuracy trade-offs in all incentive and validity conditions.

Table 1.

Experiment 1	**Valid**		**Invalid**	
	Pearson's r	p value	Pearson's r	p value
-$2.0	-0.449	0.009*	-0.136	0.451
-$0.5	-0.290	0.101	-0.123	0.497
$0.0	-0.297	0.093	-0.079	0.660
+$1.0	-0.300	0.089	-0.242	0.174
+$4.0	-0.422	0.014(nsbc)	-0.132	0.463

Experiment 2	**Valid**		**Invalid**	
	Pearson's r	p value	Pearson's r	p value
-$2.0	0.040	0.829	-0.169	0.354
-$0.5	-0.188	0.303	-0.007	0.970
$0.0	-0.177	0.333	-0.065	0.723
+$1.0	-0.067	0.715	-0.182	0.320
+$4.0	-0.195	0.285	-0.075	0.684

Combined	**Valid**		**Invalid**	
	Pearson's r	p value	Pearson's r	p value
-$2.0	-0.262	0.035 (nsbc)	-0.165	0.189
-$0.5	-0.301	0.015 (nsbc)	-0.078	0.537
$0.0	-0.315	0.011 (nsbc)	-0.085	0.501
+$1.0	-0.271	0.029 (nsbc)	-0.218	0.081
+$4.0	-0.354	0.004*	-0.108	0.391

Figure 3.

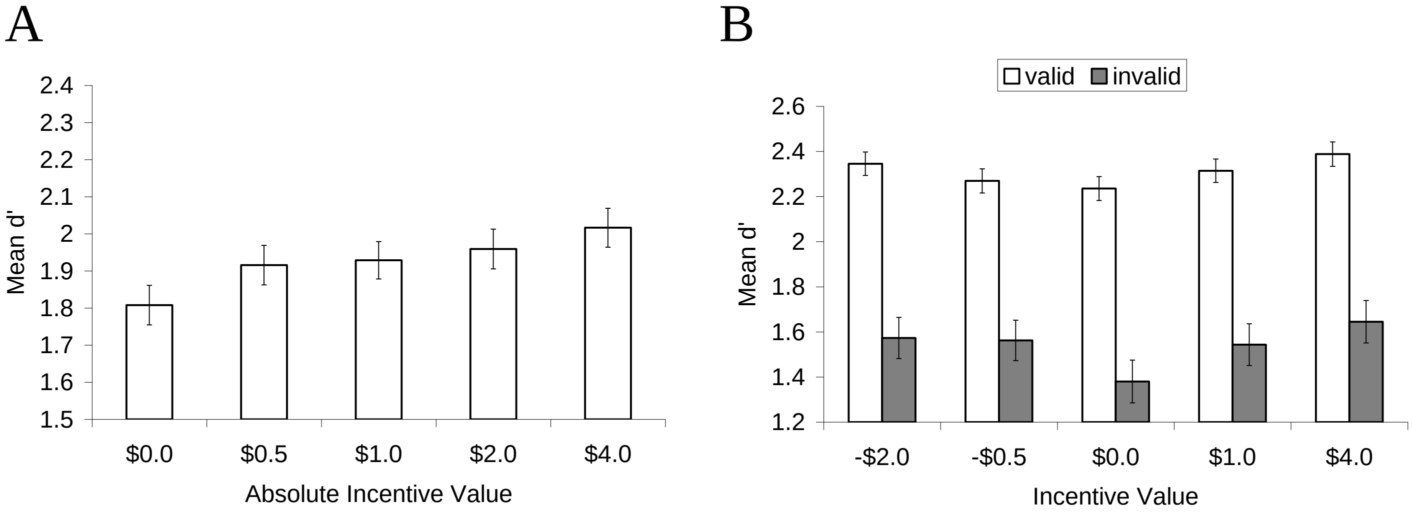

Figure 4.