Cognitive, Affective, & Behavioral Neuroscience (2018) 18:925–931
https://doi.org/10.3758/s13415-018-0613-5

The effects of expected reward on creative problem solving

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Published online: 12 June 2018
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Abstract

Creative problem solving involves search processes, and it is known to be hard to motivate. Reward cues have been found to enhance performance across a range of tasks, even when cues are presented subliminally, without being consciously detected. It is uncertain whether motivational processes, such as reward, can influence problem solving. We tested the effect of supraliminal and subliminal reward on participant performance on problem solving that can be solved by deliberate *analysis* or by *insight*. Forty-one participants attempted to solve 100 compound remote associate problems. At the beginning of each problem, a potential reward cue (1 or 25 cents) was displayed, either subliminally (17 ms) or supraliminally (100 ms). Participants earned the displayed reward if they solved the problem correctly. Results showed that the higher subliminal reward increased the percentage of problems solved correctly overall. Second, we explored if subliminal rewards preferentially influenced solutions that were achieved via a sudden insight (mostly processed below awareness) or via a deliberate analysis. Participants solved more problems via insight following high subliminal reward when compared with low subliminal reward, and compared with high supraliminal reward, with no corresponding effect on analytic solving. Striatal dopamine (DA) is thought to influence motivation, reinforce behavior, and facilitate cognition. We speculate that subliminal rewards activate the striatal DA system, enhancing the kinds of automatic integrative processes that lead to more creative strategies for problem solving, without increasing the selectivity of attention, which could impede insight.

Keywords Subliminal · Monetary rewards · Insight · Problem solving

Creative problem solving is essential for advances in human knowledge, but it is also one of the most challenging cognitive processes to motivate. Reward provides a powerful leverage to motivate human behavior: it facilitates learning, modulates attention and other cognitive-control processes, and reinforces cognitive flexibility (Amabile, Hennessey, & Grossman, 1986; D'Ardenne, McClure, Nystrom, & Cohen, 2008; Krebs, Boehler, Roberts, Song, & Woldorff, 2012; Wittmann et al., 2005). Attempts to facilitate creative problem solving via supraliminal (i.e., conscious perception of) external rewards have so far been unsuccessful and controversial. In fact, some studies have demonstrated that supraliminal external rewards are detrimental, and others have indicated that these explicit rewards increase creativity (*e.g.,* Amabile et al., 1986; Csikszentmihalyi, 1984). However, a few studies have demonstrated that subliminal (i.e., below the level of awareness) information influences problem solving. For example, Maier (1931) observed that a hint surreptitiously given to people can help them solve the two-string (pendulum) problem (Maier, 1931). Schunn and Dunbar (1996) also showed that experience with one problem facilitates performance on another problem without subjects being aware that one problem has helped them solve the other problem (Schunn & Dunbar, 1996).

Generally, subliminal rewards enhance cognitive processes (Capa, Bouquet, Dreher, & Dufour, 2013; Pessiglione et al., 2008; Pessiglione et al., 2007). These studies demonstrated similar effects when a reward is presented subliminally or supraliminally (Kouider & Dehaene, 2007; Morris, Ohman, & Dolan, 1998; Pessiglione et al., 2007). For example,

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Pessiglione and collaborators demonstrated that subliminal monetary rewards increased participants' motivation in a similar fashion to supraliminal rewards in a task where participants had to squeeze a power grip (Pessiglione et al., 2007). Subliminal rewards have been linked to striatal learning mechanisms that are not consciously accessible but nonetheless influence decision-making and have a direct impact on cognitive performance (Pessiglione et al., 2008). In addition, monetary reward presented supraliminally or subliminally can improve cognitive processes such as working memory (Bijleveld, Custers, & Aarts, 2010; Bustin, Quoidbach, Hansenne, & Capa, 2012; Capa et al., 2013). The idea is that awareness of a reward enables people to explicitly modulate the strategies they employ to obtain that reward. Speed–accuracy trade-offs tend to be affected only when individuals are aware of the reward (Bijleveld et al., 2010). These premises led to the idea that the size and/or awareness of reward cues could modulate problem solving. Specifically, we hypothesized that subliminal reward cues (indicating a potential reward for solving the problem that follows).

Some creative problem solving is deliberate and analytic, but other times people solves problems with a sudden insight, also known as a "Eureka!" or "Aha!" moment. Insight solutions are often perceived as an epiphany, suddenly emerging from the recesses of our mind. People are unable to predict when the idea will arrive, or explain the reasoning that led to the emergence of it. Sudden insights are generally considered to reflect an instance of creative thinking, although it is also possible for people to achieve a solution deemed creative through analytic processing, such as using a conscious strategy, methodical step-by-step progress, or through trial and error (Bowden & Jung-Beeman, 2003a; Jung-Beeman et al., 2004). Solving problems via insight relies on a unique pattern of neural activity when compared with problems solved by deliberate analysis (Jung-Beeman et al., 2004; Kounios & Beeman, 2014), leads to more accurate solutions, and it is impaired under stress (e.g., when running out of time; Salvi, Bricolo, Kounios, Bowden, & Beeman, 2016). The solutions via insight and via analysis also differ in their patterns of attention deployment. Our previous studies demonstrated that, as compared with analysis, insight problem solving is associated with turning attention inward and away from external inputs (e.g., Jung-Beeman et al., 2004; Salvi, Bricolo, Franconeri, Kounios, & Beeman, 2015), and with making attention less focused or selective (Rowe, Hirsh, & Anderson, 2007; Wegbreit, Suzuki, Grabowecky, Kounios, & Beeman, 2012). Internal states of attention are particularly conducive to insight problem solving, whereas external states of attention are more conducive to analytic problem solving (Kounios et al., 2006; Salvi et al., 2015).

Although much progress has been made toward identifying the cognitive and neural subcomponents of problem solving, few studies have succeeded in its enhancement (Rowe et al., 2007; Wegbreit et al., 2012). For example, in a recent study, Hattori and collaborators demonstrated that subliminal hints facilitate the solution of "classic insight" problems (Hattori, Sloman, & Orita, 2013). The authors suggested that subliminal cues could specifically affect solutions solved by insight, and they underlined the importance of studying these processes using subliminal priming techniques rather than verbal self-reports that involve conscious processes.

Therefore, in a second step, we hypothesized that subliminal reward might enhance insight problem solving more than analytical problem solving, and we examined the intersecting roles of awareness and reward cues in motivating or improving it.

In sum, we explore whether the size and/or awareness of reward cues could modulate creative problem solving. We hypothesized that subliminal reward cues (indicating a potential reward for solving the problem that follows) would facilitate creative problem solving, and specifically those solutions achieved via insight. We did not expect the same effect for supraliminal rewards, since supraliminal reward could interfere with problem solving by shifting and focusing participants' attention to external information and strong associations, to the detriment of insight. Alternatively, supraliminal reward cues could induce greater anxiety/stress that could interfere with insight problem solving via increased focus and selectivity.

Method

Participants

Forty-one Northwestern University students (32 women, average age 20.2 ± 1.4 years) were recruited for this study. This sample size has the power to detect small to medium size effects.

The study was approved by the Northwestern University Institutional Review Board. All participants gave written informed consent and received the money they earned in the experiment, based on the sum of rewards associated with correctly solved problems.

Stimuli

Participants attempted solving 100 compound remote associate (CRA) problems (Bowden & Jung-Beeman, 2003a). These hybrid-type problems can be solved through insight or through analytic processes, with participants on each successful trial required to report which of the two most contributed to problem solving. Self-reports differentiating between insight and analytic problem solving are reliable, and behavioral and neuroimaging markers have consistently demonstrated that the reports reflect distinct cognitive processes and neural substrates (Bowden & Jung-Beeman, 2003a; Jung-Beeman et al., 2004; Kounios et al., 2008).

Each problem consisted of the simultaneous presention of three words, each of which could form a compound word or phrase with the solution word (e.g., for way/board/sleep the solution word is WALK. For the full list of the problems and solution rates, see Bowden & Jung-Beeman, 2003a). The three CRA words were presented in black font on a white background in normal horizontal orientation above, at, and below the center of the monitor (see Fig. 1). The experimental procedure was presented using E-Prime 2.10 (Schneider, Eschman, & Zuccolotto, 2002) on a 22-in. LCD screen at a viewing distance of 60 cm. We utilized a 2 (reward presentation duration: 100 ms vs, 17 ms) × 2 (reward cue: 1 cent vs. 25 cents) × 2 (insight vs. analysis) within-participants trial design.

CRA trials were randomly distributed in the task, removing any unexpected association between CRA difficulty and subliminal/supraliminal presentation. In addition, CRA difficulty was balanced across conditions according to normative data previously published (Bowden & Jung-Beeman, 2003b).

Experimental procedure

Participants first read the task instructions and also received verbal instructions before starting the experimental procedure. We explained the difference between insight versus analytic problem solving, and we made sure that subjects understood the difference between the two different problem-solving strategies before beginning the experiment and again afterward when completing the debriefing questionnaire. Participants were additionally familiarized with the masks and stimuli in a practice task (trials $N = 10$).

CRA task

Each trial started with a 100-ms mask followed by the presentation of the coin (at 17 or at 100 ms) followed by a second 100 ms mask. Participants were told that the coin would sometimes be difficult to perceive. In accordance with Pessiglione et al. (2007), half of the trials displayed the coin supraliminally (i.e., 100 ms) and the other half presented the coin subliminally (i.e., 17 ms). Afterwards, the three CRAs problem words were presented simultaneously on the screen. Participants had 15 seconds to solve the problem, and they were instructed to press the space bar as soon as they attained the solution. Following their verbally reported solution, or the end of the time limit (15 s), the problem words were erased and, if solved, participants had to report how they solved the problem: via insight or via analysis. Participants were instructed that there was no optimal problem-solving style or right or wrong answers in reporting the way they used to solve each problem. Further explanation of the task was given if necessary. If the solution provided was correct, a screen appeared, saying, “Congratulations—you won 1 cent (or 25 cents)!”; coins were physically given to participants at the end of each trial. No feedback was given if the participant ran out of time or provided the wrong solution. At the end of the experiment, participants were paid the amount of money gained during the task, plus a fixed amount of $10. Participants earned an average of $ 16.50 ± 1.61.

Following the set of 100 CRA problems, participants performed a forced-choice task of 70 trials of reward cues detection, in which they had to report which coin they saw on the the screen. The coins were the same as those presented before each CRA (1 or 25 cents) at two different durations (17 and 100 ms). Each trial consisted of masks and reward cues stimuli, followed by the two choices presented simultaneously (1 or 25 cents). Participants pressed the 1 key if they saw “1 cent,” 2 if they saw “25 cents.” The participants were told that accuracy, not speed, was important. The choices remained on the screen until a response was made (see Fig. 1). The experiment was precceded by 10 practice trials. In total, the experiment took approximately 1 hour. After the CRA task, participants performed a forced-choice task, to ensure

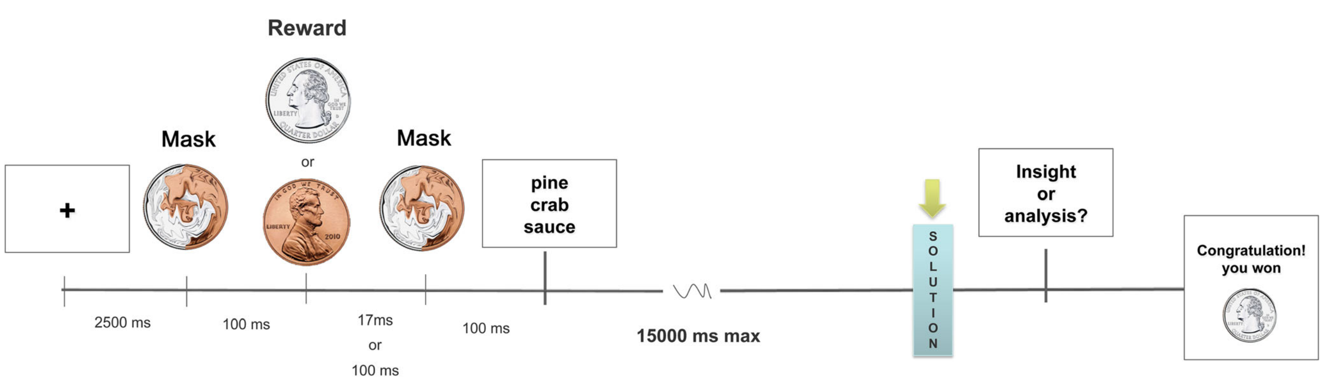

Fig. 1 Incentive CRA task. Successive screens displayed in one trial are shown from left to right. Coin images, either one 25 cents or 1 cent, indicate the monetary value that participants could earn if they responded correctly to a CRA. The last screen indicates the cumulative total of the money won so far. Participants were informed if they responded correctly with a feedback screen at the end of the trial. Solving a problem via insight or analysis did not affect the earnings

that the participants had not perceived the displayed coin in the subliminal condition.

Statistical analysis

Behavioral data analysis was performed using SPSS 22.0 (www.spss.com) and the significance level was set to $p < .05$. Data were tested for Gaussian distribution (Kolmogorov–Smirnov test) and homogeneity of variance (Levene's test). Data were normally distributed, and assumptions for analysis of variance were not violated. Only problems correctly solved were used for the analyses.

Results

Forced-choice task

We first examined whether participants might have perceived the displayed coin in the subliminal condition. We debriefed participants before the forced-choice task, and not one reported being able to detect whether 1 cent or 25 cent coins were presented subliminally. We next examined whether participants might have perceived the displayed coin in the subliminal and supraliminal conditions.

A total of six participants performed more that 2.5 standard deviations (corresponding to 80.13%) above average in the subliminal reward condition or performed 2.5 standard deviations (corresponding to 69.11%) below average in the supraliminal reward condition. They were excluded from the analysis. Then we also calculated a *d'* measure (i.e., the difference between normalized rates of hits; correct "different" response) and false alarms (incorrect responses), and this measure was not significantly different from zero at the group level, $t(1, 34) = -0.778$, $p > .05$. Therefore, we analyzed the means of correct responses, defined as the participant having seen or guessed the coins. In the subliminal condition, the mean percentage of correct responses was 55.81 ($SD = 19.78$) for 1 cent, which did not differ significantly from chance level $t(34) = 1.73$, $p > .05$, and 57.68 ($SD = 24.27$) for 25 cents, which did not differ significantly from chance level $t(34) = 1.87$, $p > .05$.

CRA task

Participants responded correctly to 35.11% of problems ($SD = 9\%$); the rest of the problems were discarded from the analysis. Ignoring cue awareness, problems with low reward cues were solved correctly at 38.14% ($SD = 10.82\%$); problems with high reward cues were solved correctly at 43.69% ($SD = 11.78\%$). Problems associated with subliminal reward cues were solved correctly at 44.49% ($SD = 12.38\%$); whereas problems associated with supraliminal reward cues were solved at 38.34% ($SD = 11.78\%$).

In a logistic regression, awareness, $b = 0.274$, $p < .01$, Exp(b) = 1.315, and reward, $b = 2.41$, $p < .01$, Exp(b) = 0.786, were found to be significant predictors of problem-solving accuracy. Subliminal rewards were 1.315 times more likely to produce correct solutions, compared with supraliminal reward, and lower rewards were 0.786 times less likely to produce correct solutions, compared with higher rewards. The logistic regression model was statistically significant, $\chi^2(2) = 28.126$, $p < .0001$.

We also computed a 2 × 2 ANOVA with reward cues (1 cent vs. 25 cents) and awareness (subliminal vs. supraliminal) as factors on the percentage of problems solved correctly. This analysis revealed that participants solved significantly more problems following high-reward than low-reward cues, $F(1, 34) = 12.17$, $p < .001$, $\eta_p^2 = 0.264$. They also solved more problems following subliminal than supraliminal reward cues; main effect $F(1, 34) = 9.09$, $p < .01$, $\eta_p^2 = 0.211$, with a significant interaction between awareness and size of reward cues, $F(1, 34) = 4.2$, $p < .05$, $\eta_p^2 = 0.112$ (see Fig. 2).

Effect of reward and solution type on problem solving

Of the correctly solved problems, participants solved 50.89% ($SD = 23.85\%$) of them via insight, and 49.11% ($SD = 23.85\%$) via analysis.

In a logistic regression, awareness, $b = 0 .159$, $p < .05$, Exp(b) = 1.172, and reward, $b = .194$, $p < .05$, Exp(b) = 0.823, were found to be significant predictors of problem-solving style. Subliminal rewards were 1.172 times more likely to produce an insight solution compared with supraliminal reward, and lower rewards were 0.823 times less likely to produce insight solutions compared with higher rewards. The logistic regression model was statistically significant, $\chi^2(2) = 10.692$, $p < .005$.

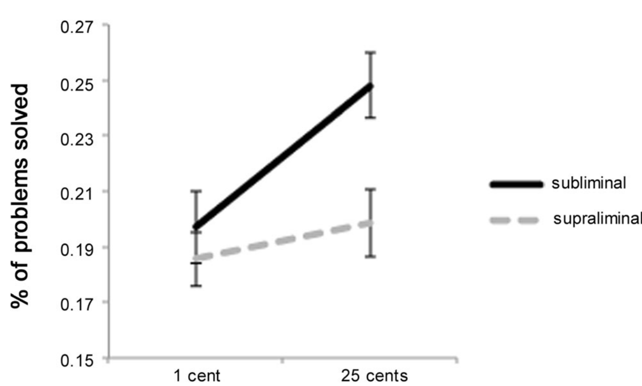

Fig. 2 Percentage of problems solved in subliminal versus supraliminal condition for low and high reward cues (percentages are calculated on total problems given)

Effect of reaction times (RTs) on problem solving

Finally, we also assessed the effect of solution style by analyzing reaction times (RTs) and percentage of correct responses by 2 × 2 (2 durations of reward presentation × 2 reward values) and 2 × 2 × 2 ANOVA (2 durations of reward presentation × 2 reward values × 2 solution types). The only significant main effect was of awareness on overall problem-solving RT, $F(1, 34) = 11.06$, $p > .05$, $\eta_p^2 = 0.246$. No other effect was found (all $ps > .05$).

Discussion

We investigated whether subliminal versus supraliminal reward cues facilitate problem solving. Our results demonstrated that people solved more problems when motivated by monetary reward presented subliminally. The results also indicate that the higher percentage of problems solved in the high reward cue condition was in part driven by insight-based solutions. In contrast to previous reports on the detrimental effects of monetary supraliminal reward on insight problem solving and functional fixedness (for a review, see McGraw, 1978), here we find that insight problem solving benefits from higher reward cues, but primarily due to the subliminal reward condition. There remains a debate regarding the conditions under which subliminal stimuli gain access consciousness of the stimuli. In our study, we referred to subliminal stimuli as stimuli not accessible to awareness. Nevertheless, the subliminal state can be influenced along a continuum depending on masking properties, top-down attention, and task instructions (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006).

Previous studies showed how positive mood both facilitates insight problem solving and enhances dopamine (DA) activity in the anterior cingulate cortex (Subramaniam, Kounios, Parrish, & Jung-Beeman, 2009). We speculate that a potential subliminal reward, by inducing positive affect, benefits insight problem solving and stimulates the DA/reward system—results that are not likely to be obtained if the reward is presented supraliminally. In the latter case, conscious reward could increase "approach motivation," possibly increase anxiety, and in either case increase focus/selectivity—which impairs problem solving (Kounios et al., 2006; Salvi et al., 2015; Salvi et al., 2016).

Accumulating evidence shows that creative acts do not reflect the operation of just one process, brain area, or faculty but rather require the interplay of multiple cognitive processes and neural networks (Eysenck, 1993; Heilman, 2005). One modulating influence might be the neurotransmitter DA that affects various neural networks (Chermahini & Hommel, 2010). Scores on creative tests are negatively related with dopamine (D_2) receptor densities in the thalamus (de Manzano, Cervenka, Karabanov, Farde, & Ullen, 2010). Genetics studies showed that individuals with the DA D_2 receptor gene (locus: DRD2 TAQ IA) had significantly better performance on creativity tasks (Reuter, Roth, Holve, & Hennig, 2006). Higher DA levels are associated with less inhibition of alternative thoughts and greater cognitive flexibility, which is important for generating new ideas (de Manzano et al., 2010; Flaherty, 2005; Takeuchi et al., 2010). Well-established biomarkers of DA activation in the striatum can be detected by eye movements. In particular, spontaneous eye-blink rate has been consistently linked to DA release (Colzato, van den Wildenberg, van Wouwe, Pannebakker, & Hommel, 2009; Colzato, van Wouwe, & Hommel, 2007; Kleven & Koek, 1996) and is often used as an index of striatal DA production (Karson, 1983; Taylor et al., 1999). Recently, several studies demonstrated that spontaneous blinks are involved during internally directed cognition and attentional disengagement from external inputs (Benedek, Stoiser, Walcher, & Korner, 2017; Nakano, 2015; Walcher, Korner, & Benedek, 2017). In the same study, Nakano (2015) found that spontaneous blink-related brain activation in areas that are part of the reward circuit (i.e., the ventral striatum) and brain regions activated by problem-solving tasks, such as the anterior cingulate cortex and the right superior temporal gyrus. An increasing number of studies indicate that higher eye-blink rates and eye-blink duration are associated with idea generation, problem solving (from anagrams to creative sentence generation), and better performance in divergent thinking tasks (Benedek et al., 2017; Chermahini & Hommel, 2010; Ueda, Tominaga, Kajimura, & Nomura, 2015; Walcher et al., 2017). In one of our recent studies, we recorded eye-blink rate when people were solving CRA and found that people have a higher eye-blink rate when solving problems via insight compared with analysis (Salvi et al., 2015).

Given the likely involvement of the DA system in problem solving, it would not be surprising that reinforcement-related DA release could be involved in creativity as well as insight problem solving. DA activity is increased when participants receive monetary rewards (Pas, Custers, Bijleveld, & Vink, 2014), and reward cues also increase the investment of effort in tasks, even when cues are presented subliminally, which makes them harder to be consciously detected (Pessiglione et al., 2007). Subliminal reward cues are assumed to rely on the mesolimbic and striatal DA system (Pas et al., 2014). Two experiments have investigated whether effortful responses vary with individual differences in markers of striatal DA functioning (Pas et al., 2014). The first experiment investigated whether there was an association between physical effort and resting-state eye-blink rate; the second one examined cognitive effort in relation to individually averaged error-related negativity. In both experiments, effort correlated with the markers only for subliminal, but not for supraliminal, monetary reward cues. These findings support the idea that responses to subliminal reward cues are linked to the striatal

DA system, while responses to supraliminal reward cues depend on higher level cortical functions. Bijleveld and colleagues proposed that subliminal stimulus presentations occur outside of conscious awareness and rely on the mesolimbic and striatal DA system (Bijleveld, Custers, & Aarts, 2012). Supraliminal rewards, because they are presented long enough to be processed, become available to and rely upon higher order cortical functions that are linked to conscious deliberation, enabling strategic reward-related decision-making processes while reflecting on the reward that is at stake.

We acknowledge that to better understand at a cognitive/computational level, the phenomenon we observed, further experimentation is necessary, including conducting studies with a larger sample size and adding neurophysiological measures or neuroimaging. This might help clarify the cognitive and neural mechanisms that mediate subliminal effects upon problem solving.

In summary, our results indicated that subliminal reward cues might facilitate problem solving. Insight-based solutions may be particularly susceptible to subliminal cues, and we suspect that this effect may act via subcortical mechanisms that are influenced by the DA system. If substantiated, it would argue that subliminal rewards acting on insight processes could facilitate the processing of distantly or weakly related stimuli. One important implication of this idea is that subliminal reward cues could be used to facilitate desired behaviors without distracting people from ongoing activities—which could, for example, benefit patients participating in therapeutic interventions designed to improve performance in various task domains.

Acknowledgements This work was supported by NIH under Grant No. T32 NS047987 to C.S., by the United States Air Force Research Laboratory FA8650-15-2-5518, and by the Therapeutic Cognitive Neuroscience Fund to J.G.

Author contributions All authors have contributed significantly to the manuscript. I.C., C.S., M.B., and J.G. designed and performed research; I.C. and C.S. analyzed the data; I.C., C.S., M.B., and J.G. interpreted the data and wrote the paper.

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