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Humans Integrate Monetary and Liquid Incentives to Motivate Cognitive Task Performance

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by

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ABSTRACT OF THE THESIS

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It is unequivocal that a wide variety of incentives can motivate behavior. However, few studies have explicitly examined whether and how different incentives are integrated in terms of their motivational influence. The current study examines the combined effects of monetary and liquid incentives on cognitive processing, and whether appetitive and aversive incentives have distinct influences. We introduce a novel task paradigm, in which participants perform cued task-switching for monetary rewards that vary parametrically across trials, with liquid incentives serving as post-trial performance feedback. Critically, the symbolic meaning of the liquid was held constant (indicating successful reward attainment), while liquid valence was blocked. In the first experiment, monetary rewards combined additively with appetitive liquid feedback to improve subject task performance. Aversive liquid feedback counteracted monetary reward effects in low monetary reward trials, particularly in a subset of participants who tended to avoid responding under these conditions. Self-report motivation ratings predicted behavioral performance above and beyond experimental effects. A follow-up experiment replicated the predictive power of motivation ratings even when only appetitive liquids were use, suggesting that ratings reflect idiosyncratic subjective values of, rather than categorical differences between, the liquid incentives. Together, the findings indicate an integrative relationship between primary

and secondary incentives and potentially dissociable influences in modulating motivational value, while informing hypotheses regarding candidate neural mechanisms

Introduction

On a daily basis, humans are faced with the formidable feat of integrating multiple diverse incentives to pursue behavioral goals. However, while most extant studies of reward support the indubitable role of motivational incentives in driving cognitive processing and behavior (Atkinson, 1964; Bolles, 1975; McClelland, 1987; Weiner, 1989), they rarely account for (and often ignore) how different categories of incentives motivate behavior. This is particularly true in human cognitive experiments that examine incentive effects on task performance. These studies traditionally use monetary incentives, and 'motivation' is often defined as the behavioral differences between high and low monetary reward conditions (e.g., a participant who responds faster and more accurately during conditions with greater monetary rewards is assumed to be more 'motivated'). As such, the well-controlled laboratory studies of monetary incentives and task performance tend to have a more limited view of motivation, and do not capture variation from the wide array of motivational influences that regularly drive human behavior. This is problematic as these studies may fail to capture the complexity of motivational processing that occurs in real world decision-making.

Studies that solely use monetary incentives (a secondary reward) to measure the impact of motivational incentives on task behavior neglect the role of primary incentives (e.g., food and sex) that may be more "hard-wired" in their influence on human behavior (Krug & Braver, 2014). More importantly, humans appear to seamlessly incorporate different categories of incentives (e.g., ravenously devouring a delicious apple pie during an eating contest in order to both win a $100 monetary prize AND consume an appetitive food incentive), but whether they similarly process qualitatively different motivational incentives during decision-making remains unknown. A particular challenge is how to precisely quantify how multiple diverse incentives contribute to the same behavior. In our pie-eating example, the contestant clearly incorporates both the food (primary) and the money (secondary) in their decision to participate in the eating contest, but estimating the specific contribution of each incentive to that decision is not as simple.

To further complicate things, incentives can either provide a symbolic or a motivational effect in goal-directed behavior (McClelland, 1987). A purely symbolic incentive will indicate the relative importance of a particular trial and/or condition, which can help modulate cognitive processing during a task. In this scenario, "good" and "bad" incentives are equally informative, as both provide clear signals of task performance. Conversely, a purely motivational incentive will both signal the importance of and influence the subjective value of the task goal, which will modulate behavioral task performance via incorporating the subjective value of the incentive. Specifically, a participant's task performance will be contingent on whether a "good" or "bad" incentive is used, and moreover, how strongly they subjectively value that incentive. Monetary reward is a well-known motivational incentive, as individuals expend more effort and utilize more cognitive resources to perform better on tasks with monetary reward (Engelmann et al., 2009; Hübner & Schlösser, 2010; Knutson et al., 2000; Small et al., 2005). However, it remains highly disputed whether non-monetary incentives have similar motivational effects on cognitive task performance (Krug & Braver, 2014).

Researchers have yet to reach a consensus about how primary and secondary incentives combine to modulate cognitive processing and behavior. Some findings suggest that primary and secondary rewards produce similar behavioral changes in a working memory task, albeit through distinct neural mechanisms of reinforcement (Beck et al., 2010). Moreover, a meta-analysis of human functional neuroimaging studies by Sescousse et al. (2013) revealed that different categories of incentives were represented more strongly in distinct brain structures within the reward network (e.g., money elicits greater orbitofrontal cortex activity, while foods elicit greater anterior insula activity). Conversely, some researchers argue that the subjective values of primary and secondary rewards are combined into a "common currency" which is used to bias subsequent decisions (Levy & Glimcher, 2012; McNamara & Houston, 1986). This view has been bolstered by fMRI studies that illustrate that ventromedial prefrontal cortex (vmPFC) and orbitofrontal cortex (OFC) are activated during economic choices about different categories of rewards (Chib, Rangel, Shimojo, & O'Doherty, 2009; O'Doherty, 2007). A more recent study has found that vmPFC also represents the anticipation of both juice and monetary rewards, which also suggests that individuals may process expected rewards without regard to category of incentive (Kim et al., 2011).

A related question is how humans combine appetitive and aversive incentives to modulate behavior. Studies have shown that individuals integrate monetary reward and painful shock stimulations to influence behavioral choices in decision tasks (Park, Kahnt, Rieskamp, & Heekeren, 2011; Talmi, Dayan, Kiebel, Frith, & Dolan, 2009). Notably, when humans integrate monetary reward and physical pain, they produce an attenuated predictive reward signal in anterior cingulate cortex (ACC) and ventral striatum (VS), brain regions believed to be involved with integrating action costs and benefits of a decision (Botvinick et al. 2004; Croxson et al. 2009; Fujiwara et al. 2009; Shenhav et al. 2013). These studies provide strong evidence that motivational conflict not restricted to incentives of the same type. However, while these studies provide evidence that humans may encode the values of diverse incentives in similar brain regions, it remains ambiguous as to how combined primary and secondary incentives translate into measureable changes in cognition and behavior.

To investigate these questions, we have developed a novel experimental paradigm that examines the effects of monetary and liquid incentives on goal-directed behavior, via a classic task of cognitive control: the cued task-switching paradigm. In this paradigm, each trial begins with a cue that indicates which task to perform on that trial, either a letter judgment (vowel vs. consonant classification) or a number judgment (odd vs. even classification). The cued task varies randomly from trial to trial, and the target stimulus is always ambiguous (a letter-number pair), so cognitive control is required to appropriately update the relevant task goal for that trial. The participant's main objective is to earn a monetary reward, which also varies on a trial-by-trial basis, as indicated by the number of dollar sign symbols presented with the task cue (low, medium high). The participant receives the monetary reward for fast and accurate performance on that trial.

The key novel component is that when participants successfully earn the monetary reward in a trial, this successful reward attainment is signaled via a drop of either appetitive, aversive, or neutral liquid (which is manipulated across task blocks) delivered directly to their mouth. Critically, since the liquid feedback only serves as an informational signal about performance success in each trial, the sole utility of the liquid is symbolic. Therefore, we might predict that individuals would perform similarly across all task blocks regardless of the type of liquid they receive as feedback. Alternatively, if the valence of liquid feedback (positive, neutral, negative) modulates task performance, it would demonstrate that individuals incidentally integrate the motivational value of the liquid with monetary incentive to affect behavior. The latter result would have important theoretical implications for how individuals combine multiple categories of incentives to influence the cognitive processing of behavioral goals.

In the current study, we addressed two scientific questions. First, we explore whether and how primary and secondary rewards are integrated to modulate motivational and cognitive processes. If humans do differentially process primary and secondary rewards, the type of liquid given as feedback (which serves as a symbolic incentive) should not influence task performance. Alternatively, individuals may incorporate the subjective value of the liquid feedback with monetary reward to influence task performance, by combining appetitive liquid and monetary reward additively to enhance cognitive processing and task performance. While the latter result may be surprising, given the symbolic role of the liquid incentives, it would suggest that humans automatically integrate the monetary and liquid rewards into a common subjective utility that biases goal-directed behavior.

Second, we tested whether appetitive and aversive motivational incentives have distinct impacts on cognitive processing. If appetitive and aversive liquids were processed via the same cognitive mechanism, we should observe additive effects of liquid on task performance. Alternatively, different liquid valences may have distinct motivational effects on task performance (Kahneman & Tversky, 1979). In this scenario, we would still predict an additive effect of two appetitive incentives (e.g., juice and money) on task performance. However, if aversive incentives combine with appetitive incentives via a separate mechanism (i.e., one that is responsible for integrating benefits with costs), this integration could result in either a net positive or negative motivational value. In such a case, we might expect an interactive effect of the two incentive types (e.g., saltwater and money), in which the aversive liquid has a particularly strong deleterious impact on performance in trials with low monetary reward, signifying when motivational value becomes negative. In other words, the presence of an interactive, rather than sub-additive, effect of saltwater on task performance would provide evidence for separate mechanisms responsible for aversive versus appetitive motivational integration.

We also conducted a second experiment using the same task paradigm, which included only monetary and different appetitive liquid rewards (e.g., three distinct juices). By eliminating categorical differences across the liquids, we directly tested whether task performance reflected the subjective motivational value of the liquid incentives (as measured by self-report motivational ratings), rather than their categorical or symbolic properties.

1 Experiment 1: How do Appetitive and Aversive Liquid Incentives Influence Motivation to Attain Monetary Incentives?

1.1 Materials and Methods

1.1.1 Participants

Forty-two adults (27 females; ages 18-32; M=20.3; SD=2.4) were recruited from the Washington University Psychology Department Experimetrix Subject Pool. All gave written consent and were given a nominal payment for their participation ($20 for a two-hour session), with additional earnings based on performance up to seven dollars (M=$4.80, SD=$0.93), following procedures approved by the Washington University institutional review board. Three participants were excluded from analyses due to experimental and/or technical error.

Study data were collected and managed using Research Electronic Data Capture (REDCap) electronic data capture tools hosted at Washington University. REDCap is a secure web-based application designed to support data collection for research studies, provide an intuitive interface for validated data entry, audit trails for tracking data manipulation and export procedures, and automatically export procedures for common statistical packages and other external sources (Harris et al., 2009).

1.1.2 Task

Subjects performed a computerized letter-digit task-switching paradigm programmed in E-Prime Version 2.0.10.242 (Psychology Software Tools, Pittsburgh PA; www.pstnet.com). Each trial began with a fixation cross for 200 ms, followed by brief fixation flicker. Next, a cue was presented for 500 ms to indicate which task to perform on that trial. If the cue text was "Attend Letter," the task would be to classify a letter as a vowel or a consonant, whereas if it was "Attend Number," the task would be to classify a number as odd or even. The number of dollar signs displayed above and below the written text cue indicated the reward value of the trial, when applicable. Following a cue-to-target interval of 1850 ms, the target stimulus was presented for up to 2000 ms, which consisted of a letter and a digit displayed in the center of the screen. Since the target stimulus was ambiguous, cognitive control is recruited to appropriately update the relevant task goal for that trial. Subject responses were recorded using an E-prime SR box, and response mappings were counterbalanced between participants. After the target was removed from the screen, a fixation cross appeared on the screen for 1000 ms, followed by feedback. During practice sessions, participants received written verbal feedback on the screen indicating whether the trial was correct, incorrect or too slow. In baseline and incentive conditions, participants no longer received visual feedback on their performance, but simply saw the text "Next Trial Coming Up" after each completed trial. In the incentive condition, participants received a squirt of liquid as feedback if they were accurate and were faster than the reward criterion that was calculated after mixed baseline session (37.5^{th} percentile of correct RTs). Following the feedback, a fixation cross was presented until the start of the next trial. Reference Figure 1.

1.1.3 Procedure

Participants performed three practice runs of the letter-digit task-switching paradigm. First, they practiced the letter task or digit task (order was counterbalanced), followed by a mixed task that combined both letter and digit tasks. In single task runs (letter only or digit only), the entire run consisted of the same written task cue. In the mixed task, both "Attend Letter" and "Attend Number" written verbal cues were intermixed during the run. During practice runs, participants received performance feedback after each trial. The experimenter was available to answer questions and ensure that the participant understood the task.

Following the practice runs, participants performed three longer baseline runs. During baseline runs, participants performed the same letter-digit task but received no performance feedback. First, they performed two single task baseline runs (letter only or digit only) consisting of 48 trials, followed by a mixed task baseline run consisting of 96 trials. Subjects were instructed to respond as quickly and accurately as possible. Participants performed with an average response time of 806 ms (SD=190 ms) and with 90% accuracy (SD=0.12), suggesting that they performed this challenging task with a high-level of proficiency in the baseline conditions. Although dollar signs symbols were presented with the task cue, participants were told that they did not hold any significance during the baseline condition.

Next, the participant performed three runs of the mixed letter-digit task in the incentive condition. Participants were informed that if they would only earn the monetary reward in that trial if they performed accurately and faster than a reward criterion. The reward criterion was calculated for each participant, based on the 37.5^{th} percentile of correct reaction times (RT) during the mixed task baseline run. This reward criterion was set to make the incentive blocks challenging, such that the participants would have to substantially improve their performance relative to baseline (i.e., maintaining accuracy while increasing speed), in order to earn rewards on a majority of the trials during these runs.

If the participant was both accurate and faster than their reward criterion, they received a squirt of liquid as feedback to indicate that they had earned the monetary reward for that trial. Conversely, if they did not earn the monetary reward, they would receive no liquid feedback, indicating that they had not the performance level necessary to receive the monetary reward. The number of dollar signs presented with the cue indicated how much money the participant could earn per trial ("$"=low, "$$"=medium, "$$$$"=high). While participants were not told the exact dollar amount per trial, they understood that the dollar signs indicated the relative worth of each trial type. They could earn up to seven dollars in addition to their hourly payment, which they would receive at the end of the experiment. Reward cues and letter-digit presentation order were randomized and counterbalanced between subjects.

The incentive condition consisted of six task blocks of 48 trials, with three different feedback liquids (apple juice, an isotonic like neural solution, and saltwater). Two blocks of each liquid were performed consecutively, and the liquid order was counterbalanced between subjects. Liquid was delivered via a digital infusion pump (model SP210iw, World Precision Instruments, Inc.) and Tygon tubing directly to the participant's mouth. The liquid pump was triggered by an output signal from the E-Prime script that delivered 2 mL of liquid as feedback if participants earned the monetary reward (i.e., both accurate and faster than the reward criterion).

Participants filled out various questionnaires upon completing the letter-digit task-switching paradigm. They rated how much they liked the three liquids, as well as how intense they were, on a 7-point Likert Scale. They also rated their motivation, performance, and how much they liked performing the low reward, medium reward, and high reward trials in each of the three liquid conditions on a 7-point scale. Following completion of the questionnaires, participants were informed of their additional earnings, paid, and debriefed.

1.2 Results

1.2.1 Monetary Incentives Modulate Reward Rate

First, we examined the effect of monetary incentives on task performance. Critically, participants knew if they had earned a monetary reward for that trial only if they received a drop of liquid at the end of that trial. We utilized reward rate, the percentage of rewarded trials in the experiment, as a measure of subject task performance. Reward rate was determined by accuracy and speed below a reward criterion that was calculated based on each individual's performance from the mixed baseline run. To examine the "pure" effects of monetary reward, we first examined data from the neutral liquid condition only. A 3x1 repeated measures ANOVA tested the effect of monetary reward on reward rate. We observed a monotonic effect of monetary reward, in which increased reward rates attained with increasing amounts of monetary reward [$F(2,76)=7.547$, $p=.001$]. See Table 1 for reference.

1.2.2 Liquid Feedback Also Modulates Reward Rate

Next, we examined whether the type of liquid used as feedback provided additional motivational effects on reward rate beyond monetary incentive effects. We compared reward rates between juice (appetitive) and neutral solution conditions, as well as between saltwater (aversive) and neutral solution conditions. The reward rates across all monetary and liquid conditions are illustrated in Figure 2.

1.2.2.1 Juice vs. Neutral

Participants performed better with juice than with neutral solution as liquid feedback. A 3x2 repeated measures ANOVA showed a main effect of liquid type [$F(1,38)=9.660$, $p=.004$], with an average reward rate of 75% in the juice blocks, compared to 70% in the neutral blocks. The ANOVA also confirmed that the main effect of monetary reward was still present when combining both liquid types [$F(2,76)=11.288$, $p<.001$]. Importantly, there was no significant interaction [$F(2,76)=0.463$, $p=0.631$], indicating that the two effects were additive.

1.2.2.2 Saltwater vs. Neutral

Participants performed significantly worse with saltwater than with neutral solution as liquid feedback. A 3x2 repeated measures ANOVA demonstrated a main effect of liquid type [$F(1,38)=15.271$, $p<.001$], with an average reward rate of 60% in the saltwater blocks, compared to the 70% in the neutral blocks. The main effect of monetary reward was still present, with higher reward rates for greater monetary reward [$F(2,76)=25.222$, $p<.001$]. Notably, there was a significant interaction between the monetary reward and liquid factors [$F(2,76)=4.864$, $p=.010$]. Post hoc analyses revealed that the saltwater most strongly impacted reward rate in trials with low monetary reward. Subjects performed worse with saltwater feedback on trials with low and medium monetary reward [$t(38)=3.570$, $p<.001$; $t(38)=3.830$, $p<.001$], but not during trials with maximum monetary reward [$t(38)=1.383$, $p=.175$].

When we further examined the individual subject patterns in the data, we discovered that a subset of the subjects actually withheld some of their responses during low reward trials in the saltwater condition. We performed a more focused analysis to determine whether these intentional 'no responses' contributed to the observed interactive pattern between saltwater and neutral solution liquid feedback.

1.2.3 No Response Subgroup

While most of the 39 participants responded on every task trial, a subset of 9 participants withheld responses from at least 3 trials during the low reward trials of saltwater condition, with a range from 7 to 62 'no responses.' We categorized these nine participants as our 'No Response' (NR) subgroup. We ran a 3x2x2 ANOVA on reward rate with monetary reward, liquid type, and group as factors. We observed significant effects of monetary reward and liquid type [$F(2,74)=31.825$, $p<.001$; $F(1,37)=28.252$, $p<.001$], and a trend-level effect of response subgroup [$F(1,37)=2.964$, $p=.093$]. More imporantly, there were significant two-way interactions between subgroup and liquid type [($F(2,74)=33.302$, $p<.001$], and between subgroup and monetary reward [$F(1,38)= 10.949$, $p<.001$]. Most critically, we observed a significant three-way interaction between subgroup, liquid feedback, and monetary reward [$F(2,74)=7.686$, $p<.001$].

Based on these findings, we analyzed each subgroup separately to test whether the NR subgroup was driving the two-way interaction observed in the full dataset. In the Regular Response Group (i.e., when NR subjects were omitted), we observed a significant effect of monetary reward [$F(2,58)=16.530$, $p<.001$] and a marginally significant effect of liquid feedback [$F(1,29)=3.658$, $p=.066$]. Critically, the interaction between monetary reward and liquid feedback in this trimmed dataset was no longer significant [$F(2,58)=1.052$, $p=0.356$]. These results reveal that interactive pattern between saltwater and neutral solution feedback is heavily driven by the NR subgroup. Since the effect of saltwater was weaker in the trimmed dataset (i.e., excluding NR participants), we suspect that individuals in this NR subgroup may be more sensitive to aversive liquid incentives than those in the regular response group. The reward rates divided by group are illustrated in Figure 2.

Post-hoc analyses of the saltwater condition in the trimmed dataset revealed that participants performed better on high monetary reward trials (M=.720, SD=0.085) compared to low and medium monetary reward trials (M=.617, SD=.095; M=.618, SD=.024). Interestingly, saltwater had the weakest motivational impact during trials in which participants could earn the highest monetary reward. One possible explanation is that although these subjects did not exhibit an extreme response, they may have been motivated enough by the prospect of earning a greater monetary reward to overcome the aversive taste of the saltwater feedback during these trials. If this were true, these data give evidence that individuals integrate both primary and secondary incentives to subsequently modulate their behavioral goals.

1.2.4 Response Times

To better understand the motivational effects of the liquid feedback on reward rate, we analyzed participant response times (RT) on correctly responded trials. We first compared RTs between juice (appetitive) and neutral solution conditions, and then between saltwater (aversive) and neutral solution conditions. The RTs are listed in Table 1.

1.2.4.1 Juice vs. Neutral

Both the juice and monetary rewards provided positive motivational effects on participant RT. We ran a 3x2 repeated measures ANOVA to examine the effects of monetary reward and juice on RT. Participants were faster when receiving juice as liquid feedback, with an average RT of 562 ms, compared to 585 ms with neutral solution [$F(1,38)=6.297$, $p=.016$]. Participants were also faster on trials where they could earn more money [$F(2,76)=22.789$, $p<.001$]. There was no significant interaction [$F(2,76)=0.600$, $p=.552$].

1.2.4.2 Saltwater vs. Neutral

The saltwater provided a negative motivational effect on participant RT. We ran a 3x2 repeated measures ANOVA to examine the effects of monetary reward and aversive liquid (saltwater) on RT. Participants responded slower when receiving saltwater as liquid feedback, with an average RT of 639 ms, compared to 585 ms with neutral solution [$F(1,38)=8.309$, $p=.006$]. However, participants were still faster on trials where they could earn more money [$F(2,76)=16.910$, $p<.001$]. There was no significant interaction [$F(2,76)=0.839$, $p=.436$].

1.2.5 Error Rates

Error rates were defined strictly in terms of commission errors (i.e., excluding no response trials from the analysis). We first compared error rates between juice (appetitive) and neutral solution conditions, and second between saltwater (aversive) and neutral solution conditions. The error rates are listed in Table 1.

1.2.5.1 Juice vs. Neutral

Participants did not differ significantly in error rates between juice and neutral solution liquid feedback conditions. A 3x2 repeated measures ANOVA on error rate with monetary reward and liquid feedback as factors, indicating similar error rates across the two liquid conditions [$F(1,38)=0.703$, $p=.401$], as well as across different amounts of monetary reward [$F(2,76)=0.500$, $p=.609$]. There was no significant interaction [$F(2,76)=0.204$, $p=.816$].

1.2.5.2 Saltwater vs. Neutral

Conversely, the saltwater incentive was found to modulate error rates. We ran a 3x2 repeated measures ANOVA to examine the effects of monetary reward and liquid feedback on participant error rate. Participants committed more errors on trials in which they could earn less monetary reward [$F(2,76)=3.644$, $p=.031$]. Additionally, there was a marginally significantly liquid effect, with an average error rate of 18% on saltwater blocks, compared to 15% with neutral solution blocks [$F(1,38)=3.322$, $p=.076$]. There was no significant interaction [$F(2,76)=2.365$, $p=.101$]

1.2.6 Switch Costs

Since switch costs are a hallmark of cognitive control, we examined RT switch costs (i.e., between-task subtracting within-task performance) as a specific measure of monetary and liquid effects on cognitive processing. We observed a small, but significant, switch cost when we collapsed all task conditions within each subject (M=25 ms, $t(38)=5.685$, $p<.001$). The small magnitude of the switch cost, while significant, is not too surprising since participants were given a long cue-to-target interval to prepare for the task. This long interval has been shown in prior work to significantly reduce switch costs (Meiran, 1996; Rubin & Meiran, 2005), and thus decrease the sensitivity of this index as an indicator of cognitive control demand.

Next, we tested whether RT switch costs were significantly modulated by monetary reward and liquid incentives. These analyses were conducted using the lmerTest (Kuznetsova et al., 2015) and LME4 (Bates et al., 2015) packages in the R statistical language. We ran a linear mixed-effects model on RT switch costs with subject as a random factor, and liquid type and monetary reward as fixed factors. We dummy coded the liquids (saltwater = -1, neutral solution = 0, juice = 1) and monetary reward ($ = -1, $$ = 0, $$$$ = 1). We used the standard step-up model building approach and selected the linear mixed model with minimum Akaike Information Criterion (AIC) and Bayesian information criterion (BIC) (West, Welch, & Galecki, 2015). We observed a significant main effect of liquid incentive [$F(1,351)=5.987$, $\beta=4.345$, $p=0.015$], but no effect of monetary reward and nor an interaction. Interesting, the switch costs were higher for both juice and saltwater [$M_{juice}=33$ ms, $SD_{juice}=32$ ms; $M_{salt}=25$ ms, $SD_{salt}=27$ ms], compared to neutral solution [$M_{neut}=18$ ms, $SD_{neut}=35$ ms]. Most surprisingly, switch costs were greatest in the juice condition, which is opposite to what we might predict (Aarts et al., 2010).

1.2.7 Self Report Ratings Predict Unique Variance in Reward Rate

We conducted a hierarchical multiple regression to determine whether self-report ratings had additional predictive utility on reward rate beyond the effects of liquid type and money reward. These analyses were conducted using the lmerTest (Kuznetsova et al., 2015) and LME4 (Bates et al., 2015) packages in the R statistical language. Mathematically, this is represented as a linear mixed model with the reward rate predicted by the monetary reward m and the liquid feedback l (Equation 1). The betas represent the weights for money, liquid, and the interaction, from left to right. Dummy coding was used to label the three liquids (juice=1, neutral solution=0, saltwater=-1) and amount of monetary reward ($=-1, $$=0, $$$$=1). A mixed level regression analysis was conducted, with liquid type and monetary reward as fixed effects, while treating subject as a random effect, and included correlated intercepts and slopes for the fixed factors (Barr, Levy, Scheepers, & Tily, 2013; Magezi, 2015). Model selection was determined by step-up model building approach and choosing the model with the lowest AIC and BIC criterion (West et al., 2015). We observed significant effects of monetary and liquid rewards, as well a significant interaction, which confirmed our previous results.

Equation 1: $\text{Reward Rate} = \beta_{\text{m}} m + \beta_{\text{l}} l + \beta_{\text{ml}} ml$

Next, we mean-centered the self-report liking ratings (e.g., How much did you like the $ trial with juice?) and motivation ratings (e.g., How motivated were you on a $ trial with juice?), by each subject. Reward rate performance was independently and significantly predicted by liking ratings [$F(1,38)=38.706$, $p<.001$], as well as motivation ratings [$F(1,38)=55.892$, $p<.001$]. Adding liking ratings to the model (Equation 2) predicted additional variance in the reward rate [$\chi^2(1)=11.846$, $p<.001$]. Furthermore, adding motivation ratings significantly improved the model (Equation 3), but the liking ratings were no longer a significant factor in predicting reward rate variance [$\chi^2(1)=11.986$, $p<.001$]. Interestingly, when we reversed the order and added motivation ratings before the liking ratings, motivation ratings enhanced the model [$\chi^2(1)=23.374$, $p<.001$], but adding liking ratings in addition to motivation ratings did not predict any additional variance [$\chi^2(1)=0.458$, $p=.499$]. These regression patterns suggest that the variance in the reward rates explained by liking is shared with motivation, but that the motivation ratings predict additional unique variance in reward rate (See Table 2).

Equation 2: Reward Rate $= \beta_{\mathrm{m}} m + \beta_{\mathrm{liq}} l + \beta_{\mathrm{m*l}} ml + \beta_{\mathrm{like}}\mathrm{like}$

Equation 3: Reward Rate $= \beta_{\mathrm{m}} m + \beta_{\mathrm{liq}} l + \beta_{\mathrm{m*l}} ml + \beta_{\mathrm{like}}\mathrm{like} + \beta_{\mathrm{mot}}\mathrm{motive}$

Together, these results indicate that self-report ratings of motivation provide unique predictive utility regarding task performance across the experimental conditions, which suggests that knowing the participant's subjective motivational state can explain a significant degree of intra- and inter-individual variation in cognitive control task performance (See Figure 3a). Furthermore, since motivation ratings appeared to account for unique variance over and above the liking ratings, it is possible that motivation and liking may tap into distinct cognitive constructs that contribute to motivational state, such as incentive salience and hedonic value, respectively (Finlayson et al., 2007; Dai et al., 2010).

Moreover, these self-report results suggest that subjective motivational state is induced, but not completely determined, by experimental manipulations. This finding motivated our second experiment, which aimed to elucidate whether this induced motivational state reflects idiosyncratic subjective preferences or categorical differences across the liquid feedback conditions (i.e., intrinsic properties of the liquids themselves).

2 Experiment 2: Do Self-Report Motivation Ratings Reflect the Motivational Impact of Liquid Incentives?

In experiment 1, the categories of liquid feedback were clearly designated (e.g., juice is appetitive, saltwater is aversive). We ran a second experiment with the same task paradigm, except using only appetitive liquids (e.g., three juices) as feedback, in order to decouple categorical from motivational effects across different liquid conditions. The purpose of the second experiment was to determine whether self-report motivation ratings predicted unique variance in task performance above and beyond the experimental reward manipulations, as in the first experiment. If so, it would provide strong evidence that these self-report ratings tap into a latent motivational state that reflects the motivational impact of each liquid (which is idiosyncratic), rather than the intrinsic property of the liquid incentive.

2.1 Materials and Methods

2.1.1 Participants

Thirty-nine adults (18 females; ages 18-25; M=19.92; SD=2.17) were recruited from the Washington University Psychology Department Experimetrix Subject Pool. All gave written consent and were given nominal payment for their participation ($25 for a two separate sessions totaling 2.5 hours), with additional earnings based on performance up to 7 dollars (mean = $4.90, SD = $0.70), following procedures approved by the Washington University institutional review board. One participant was excluded from analyses due to experimental and/or technical error. Similar to experiment 1, study data were collected and managed using Research Electronic Data Capture (REDCap) electronic data capture tools hosted at Washington University (Harris et al., 2009).

2.1.2 Task

The task was identical to the first experiment, except that only appetitive juices were used as liquid feedback (V8 Strawberry Banana vegetable and fruit juice, V8 Tropical Orange vegetable and fruit juice, and Welch's Grape Juice) during the incentive runs.

2.1.3 Procedure

We determined the subjects' preferences for each of the three juices in a separate 15-minute session prior to the task session. First, subjects participated in a preference-ranking procedure, in which the subject was presented with a choice between two of the four liquids in a single trial (three juices and one isotonic neutral solution), and asked to choose which liquid they preferred. Each possible combination of liquids was presented, and preference rankings were derived. Next, subjects tasted each of the four liquids in a random order and asked to evaluate each liquid based on its pleasantness, on a Likert scale ranging from -10 to 10. Subjects also filled out the Behavioral Inhibition/Approach System survey (Carver & White, 1994), the Generalized Reward and Punishment Expectancy Scale (Ball & Zuckerman, 1990), and the Regulatory Focus Questionnaire (Higgins & Friedman, 2001).

During the second session (on a separate day), participants performed the same letter-digit switching paradigm as in experiment 1. They were explicitly asked to not eat or drink anything except water for two hours prior to the start of the experiment. First, they performed three practice runs of the letter-digit task-switching paradigm, where they received performance feedback after each trial. Next, they performed three longer baseline runs, where they no longer received any performance feedback. During the mixed task baseline run of 96 trials, participants performed with an average response time of 834 ms (SD=179 ms) and 92% accuracy (SD=0.07).

As in Experiment 1, the dollar signs were present with the task cue, but they did not hold any significance in the practice or baseline runs.

Next, the participants performed three runs of mixed letter-digit task in the incentive condition. The juice identity was blocked and counterbalanced across subjects. With the exception of the liquids used as feedback, the task procedure was identical to Experiment 1.

Participants filled out various questionnaires upon completion of the task, which included ratings that asked on a 7-point Likert scale how much they liked and how intense they found each of the three juices. They rated their motivation for performing each the low, medium, and high reward trials on each of the three liquid conditions on a 7-point scale. Lastly, they evaluated each liquid based on its pleasantness again on a Likert scale from -10 to 10. Following completion of the questionnaires, participants were informed of their additional earnings, paid and debriefed.

2.2 Results

2.2.1 Juice Preference Patterns

First, we examined juice preference patterns, which were derived from the preference-ranking procedure. Only 22 of the 39 total subjects demonstrated consistent (i.e., transitive) preferences. Within this subset, eight preferred grape juice as their top choice, while ten preferred tropical orange, and one preferred strawberry banana. A 3x1 repeated measures ANOVA revealed that preference rank was not a significant predictor of reward rate [$F(2,42)=1.438$, $p=0.248$]. Since the contrast between the liquids was less stark compared to experiment 1, we suspected that participants tended to like all of the juices relatively equally, and may not have had strong preferences between them. This is clearly reflected in the juice Likert ratings (range 1 to 7), which demonstrate that individuals generally gave the juices similar ratings (M_{grape}=4.45, M_{orange}=4.54, $M_{strawberry}$=3.95). When we more closely examined the rank-preference data, we found that 2 subjects preferred the neutral solution to all the juices, which is surprising since the juices are appetitive incentives. Given the high rate of intransitive and inconsistent ratings, we chose not to include preference rankings in our primary analyses. However, while the rank preferences may not have been fine grained enough to detect juice preferences, we suspected that the self-report motivation ratings may have been more sensitive to the subtle influences of the juices on motivating cognitive task performance.

2.2.2 Monetary Reward Influences Task Performance

Next, we looked at reward rates, separated by monetary reward amount (low, medium, high) and juice identity (e.g., grape, strawberry, or orange). A 3x3 repeated measures ANOVA on reward rate with monetary reward and juice identity as factors revealed a significant effect of monetary reward amount on reward rate [$F(2,74)=27.407$, $p<.001$], indicating the reward rate monotonically increased with amount. Juice identity did not have a significant effect on reward rate [$F(2,74)=1.397$, $p=.254$], and there was no significant interaction [$F(4,148)=0.332$, $p=.865$]. We ran a 3x1 repeated measures ANOVA on liking ratings with juice identity as a factor, and found no significant differences in liking ratings across different juice identities [F(2,74=1.835, p=.167]. This confirmed that the different types of juice (i.e., juice identity) did not impact reward rate performance. Performance profiles across task conditions are summarized in Table 3.

2.2.3 Motivation Ratings Predict Unique Variance for Appetitive Liquids

We conducted a hierarchical multiple regression to test whether self-report motivation ratings had predictive utility on reward rate performance beyond experimental task manipulations (similar to experiment 1). The analyses were conducted using lmerTest (Kuznetsova et al., 2015) and LME4 (Bates et al., 2015) packages in the R statistical language.

We used a linear mixed model with reward rate predicted by monetary reward *m* and juice identity *j*, with beta weights for money, juice identity, and the interaction (Equation 1). Monetary rewarded was dummy coded ($=-1, $$=0, $$$$=1), and the juice identity was effects coded (contrast 1 = orange vs. grape, contrast 2 = strawberry vs. grape). We conducted a mixed level regression with monetary reward and juice identity as fixed effects, subject as a random effect, and correlated intercepts and slopes for the fixed factors. Unsurprisingly, we observed a significant effect of monetary reward on reward rate, but no effect for juice identity.

Equation 1: Reward Rate $= \beta_{\mathrm{m}} m + \beta_{\mathrm{j}} j + \beta_{\mathrm{mj}} mj$

Next, we added motivation ratings (e.g., How motivated were you on the $ trial with Juice 1?) in the mixed model, which were mean-centered by subject. Reward rate performance was significantly predicted by motivation ratings [$F(1,37)=33.277$, $p<.001$]. When we added the motivation ratings to model (Equation 2), we found that the motivation ratings predicted additional variation in reward rate [$\chi^2(1)=20.566$, $p<.001$]. The betas and t values are shown in Table 4.

Equation 2: Reward Rate $= \beta_{\mathrm{m}} m + \beta_{\mathrm{j}} j + \beta_{\mathrm{mj}} mj + \beta_{\mathrm{mot}}\mathrm{motive}$

Similar to experiment 1, the motivation ratings significantly predicted performance above reward effects in the task (see Figure 3b). Critically, since all three liquids were juices (i.e., there was no categorical distinction between the incentives), these ratings likely reflect the subjective utility assigned to the task condition, which is idiosyncratic and unrelated to the intrinsic properties of the liquids themselves. Furthermore, these data provide strong evidence for motivational impact of the liquid incentives on cognition, which informs our understanding of how latent motivational states are explicitly linked to cognitive processing.

2.2.4 Individual Difference Measures and Task Performance

Next, we tested whether individual difference personality measures predicted reward rate. We utilized linear regression statistical models to test whether individual differences between personality measures contributed to additional variance in reward rate. All personality measures were grand mean centered. None of these personality measures significantly predicted task performance.

2.2.5 Satiation Effects on Reward Rate Performance Trial Order Effects

Since participants received appetitive liquid on every trial in the experiment, it is possible that satiation may have been a factor influencing cognitive task performance. If present, satiation would predict reduced benefits of receiving juice as liquid feedback in later trials in the experiment (when satiation should be higher). To test putative satiation effects, we used a mixed effects logistic regression with the LME4 package (Bates et al., 2015) in the R statistical language, since this approach enables greater flexibility in modeling effects of experimental factors on a trial-by-trial basis. Our logistic regression modeled whether the log of the odds of a trial being rewarded (1=yes, 0=no) was predicted by monetary reward and trial order across the entire session (trials 1 to 288). Monetary reward was dummy coded, as in previous linear mixed models. We observed a significant negative effect of trial order [$\beta=-0.0009$, $z=-3.238$, $p=.001$] on the likelihood of reward attainment, such that later trials were significantly less likely to be rewarded. We replicated the same analysis for experiment 1, but found no significant trial order effect. While our interpretation of these trial order effects are only speculative, they are consistent with the hypothesis that increased satiation drove participant to devalue the subjective value of the juice throughout the experiment. Such effects would not be predicted to be as strong in the first experiment, given the strong categorical and valence-related differences between the liquid types. However, since these post-hoc analyses, further study is warranted to more systematically manipulate and test for satiation influences on task performance.

3 Discussion

Understanding how diverse types of incentives impact motivation and behavior is important, as there is much ecological validity of incentive integration in the real world. This question is particularly relevant to understanding daily decision-making or mechanisms underlying eating disorders and affective-motivation disorders (Berridge, 2009; Kringelbach & Radcliffe, 2005; Stice et al., 2009). Our novel experimental paradigm provides experimental leverage, by providing a clear-cut measure of how the motivational impact of primary liquid incentives can modulate monetary effects on cognitive performance. In particular, this paradigm a means of incorporating primary incentives into experimental designs, which has great utility for further investigating the modulatory effects of a wide range of motivational incentives on decision-making and task behaviors.

3.1 Motivation as Response Vigor

These results raise two important questions: what exactly is motivation and what are its impacts on cognitive processing and behavioral task performance? When we parsed reward rate by its subcomponents (RT and error rates) in experiment 1, we found that subjects performed faster when they earned more monetary rewards and received appetitive liquid feedback. In other words, the rewards appeared to systematically modulate RT. Critically, this increased *response vigor* could reflect the impact of motivational influences on behavioral responses (Talmi et al., 2008). According to the pavlovian-instrumental transfer account, appetitive rewards induce an approach-related motivational state, which exerts a concomitant influence on goal-directed action selection. Some evidence has suggested that tonic levels of the neuromodulator dopamine

(DA) have targeted effects on the response vigor of motivated behavior, by facilitating quicker responses in humans in highly motivating incentive contexts (Beeler, Daw, Frazier, & Zhuang, 2010; Beierholm et al., 2013; Niv, Daw, Joel, & Dayan, 2007).

Conversely, aversive incentives can negatively impact motivation via decreasing response vigor during a behavioral task. This was this case in experiment 1 data, as the same participants performed significantly slower when receiving saltwater as liquid feedback compared to the neutral solution. Some researchers argue that the neuromodulator serotonin (5-HT) plays an instrumental role in decreasing response vigor in tasks during aversive processing (Cools et al., 2011; Crockett et al., 2012). Moreover, 5-HT has also been implicated in behavioral inhibition, which is when individuals curtail ongoing actions in light of predicting aversive outcomes, by either choosing to not respond or to make intentional errors to avoid an anticipated aversive outcome (Crockett et al., 2009; Dayan & Huys, 2008). This theory is consistent with our data, as participants both responded slower, but also committed significantly more errors with saltwater feedback as feedback compared with neutral solution. Notably, a small subset of subjects (N=9) appeared to be especially reactive to the saltwater, such that the disutility of the saltwater was clearly greater than the utility of low monetary rewards, which drove these individuals to intermittently forgo the opportunity to earn a monetary reward rather than risk receiving saltwater in those trials. A previous study had found that participants with high punishment-sensitivity showed an overall increase in RT in a cognitive control task after receiving punishments (Braem et al. 2013). However, while it is plausible that this extreme impairment of task performance may have been linked to punishment-sensitivity, we were unable to directly test this hypothesis, since we did not administer any surveys that measured reward and punishment sensitivity in experiment 1. Taken together, these results suggest that aversive incentives have a multiplicative impact on cognitive processing, and we hypothesize that the extent of this impact may be correlated with to how reactive individuals are to the aversive incentives.

Appetitive and aversive incentives appear to impact cognitive processing via qualitatively different neural mechanisms (DA vs. 5-HT). Some speculate that these DA and 5-HT play opposing roles in processing rewards and punishments via a single mechanism (Daw et al., 2002). However, 5-HT has been implicated in behavioral persistence and impulse control, which suggests that this neural mechanism could potentially operate independently of the aversive effects of incentives (Fonseca et al., 2015). Recent studies have attempted to reconcile how these two neuromodulators interact to modulate cognitive processing, but the precise interactions between DA and 5-HT are yet to be fully understood or empirically tested in humans (Cools et al., 2010; Guitart-Masip et al., 2014).

3.2 Neural Mechanisms Enabling Integration Primary and Secondary Incentives

These results naturally raise the broader question of how the brain integrates diverse types of incentives (e.g. combining primary and secondary) to motivate cognitive processing and behavior. One hypothesis is that individuals integrate the values of diverse rewards into an internal "common currency," which is used to facilitate comparisons between future potential actions and/or rewards (Levy & Glimcher, 2012). Much of the prior research supports the notion of an "integration hub" in the brain, and some argue that this hub region sends a signal to influence cognitive processing in higher-order brain regions. The ventromedial prefrontal cortex (vmPFC) and orbitofrontal cortex (OFC) are promising candidate hub regions, as they have been found to respond to a wide range of rewards, including primary sensory stimuli and abstract monetary rewards and punishments (Chib et al., 2009; McClure, York, & Montague, 2004;

Montague & Berns, 2002; O'Doherty, 2007; Peters & Büchel, 2010). Additionally, since vmPFC signals correlate with activity in the dorsolateral prefrontal cortex, this pathway may be a putative mechanism by which these signals influence cognitive processing (Hare et al., 2009; Pochon et al., 2001). Similarly, the ventral striatum (VS) is activated in response to both primary and secondary rewards (Knutson et al., 2001; O'Doherty et al., 2002; Oberlin et al., 2013). While the VS activity has typically been found to correlate with violations in expected reward (e.g., the reward prediction error), it also may play a critical role in directly influencing goal-directed actions (Delgado et al., 2000; Delgado et al., 2008; Hare et al., 2008; Lak et al., 2014; Pagnoni et al., 2002).

Concomitantly, an orthogonal fundamental question naturally emerges of how the brain processes conflicting incentives to modulate decision-making. The anterior cingulate cortex (ACC) is thought to monitor neural signals from conflicting sources and output a unified signal that modulates cognitive control (Botvinick et al., 2004; Engelmann et al. 2009). Additionally, some accounts highlight the ACC as playing an important role in integrating rewards and punishments in order to generate a 'motivational' or 'energizing' signal that contributes to cognitive control (Fujiwara et al., 2009). There has been some work to reconcile these two views; as some have claimed that the ACC supports the selection and maintenance of 'options': motivational context-specific sequences of actions that are directed towards particular goals (Holroyd & Yeung, 2012). These 'options' have costs and benefits, which are combined to produce a net expected value of control (Shenhav et al. 2013). Furthermore, others have argued that ACC plays a critical role as a substrate involved in value integration (Park et al. 2011; Plassmann et al. 2010). However, whether the ACC integrates the values of potentially conflicting primary and secondary incentives is unknown, and thus remains to be empirically tested in future work. Our current findings suggest that the present paradigm might be a potentially productive for examining this issue.

3.3 Motivation and Cognitive Control

It is intuitive to imagine that cognitive control and motivation are two distinct but intertwined drives that bias decision-making. Cognitive control refers to the processes involved in regulating cognition and actions based on currently maintained goals, while motivation (as we have operationalized it), is the vigor of response in which one performs that action. From this, one might reasonably conclude that motivational influences ought to impact the regulation of cognition and actions, while an individual is maintaining a single or multiple goal(s). Task performance is generally slower and more error-prone on task-switching blocks relative to single-task blocks (i.e., mixing costs), and on task-switch trials relative to task-repeat trials (i.e., switch costs) (Monsell, 2003). However, individuals are also able to reduce their mixing and switch costs if they are able to adequately prepare for the upcoming task. Motivational incentives, on the other hand, can modulate cognitive control by enhancing context-sensitivity to rewards and increase flexibility in response times (Shen and Chun 2011; Aarts et al. 2011; Braem et al. 2013; Bugg and Braver 2015).

While liquid incentives modulated RT switch costs in experiment 1, the results were fairly subtle and switch costs levels were low. The pattern was not overly surprising, given that high switch costs are thought to reflect suboptimal preparation for the upcoming task, and in the current experiment ample preparation time (1800 msec cue-to-target interval) was provided. For the purposes of our study, we assumed that reward rate improvements were due to enhanced cognitive control, but this may not have been reflected in modulations in switch costs. In short, our task design was not optimized for testing reward effects on cognitive control, as we did not explicitly manipulate switch costs or mixing costs. However, this is a possible future direction in follow up studies, such as by manipulating preparation time or by comparing with incentive effects observed in single task blocks.

3.4 Incentives Modulate Motivational State to Bias Cognitive Task Performance

An exciting aspect of this study was the finding that self-report motivation ratings demonstrated predictive utility above experimental task manipulations. Since our second experiment validated that these ratings reflected subjective idiosyncratic preferences rather than intrinsic properties of the liquids themselves (e.g., categorical knowledge that juice is good, saltwater is bad), we are confident that these ratings are truly motivational in nature. For that reason, we argue that the current results provide strong support that monetary and liquid incentives are influencing cognitive task performance via a direct change in motivational state. In other words, the incentive effects appear cannot be fully explained by a simple shift in task strategy in response to the symbolically-cued importance of each trial (i.e., $ = low importance; $$$$ = high importance), since such an account could neither explain the effects of liquid valence in experiment 1, nor the idiosyncratic patterns of motivation ratings on task performance observed in both experiments. Moreover, participants appear to have explicit access to their own motivational state, and can report this state in a distinct manner from the subjective liking of the liquid or available monetary rewards. These findings suggest the utility of probing self-reported motivation in cognitive experiments, in order to increase explanatory and predictive power regarding associated behavioral performance effects, and likewise to uncover the particular mechanisms that sub serve such effects.

Both an advantage and potential limitation using consummatory incentives is that they have the potential of inducing satiation (a motivational state), which may incidentally cause individuals to devalue the subjective utility of particular actions or trials in a cognitive task. For example, a thirsty individual might perform differently in this study compared to one that had just drank a glass of water. This is particularly relevant to experiment 2, where participants performed significantly worse (i.e., achieved lower reward rates) on later trials of the task. These trial order effects may reflect increased satiation from earning too many juice rewards, which was not a significant factor in experiment 1. Nevertheless, although satiation is a plausible account and potential confound present in experiment 2, more work would be needed to further explore and understand its effects. On the other hand, the possibility of satiation-related influences on motivation and task performance can also be construed as an advantageous feature of the task paradigm. Specifically, the presence of clear outcome devaluation effects (i.e., in response to satiation) has been traditionally used as a diagnostic signature of the degree to which behavior is under goal-directed vs. habitual control (Dickinson & Balleine, 2002; Niv, 2007). Thus, stronger demonstrations of satiation related effects in the current paradigm could provide insight to the specific mechanisms by which liquid and monetary incentives influence motivational states to modulate cognitive processing.

4 Conclusion

Overall, our study provided an important first stage of evidence regarding how humans integrate primary and secondary incentives, while demonstrating that this integrated incentive signal has a strong motivational impact on cognitive task performance. The experimentally-induced motivational state changes are robustly evidenced and indexed by the predictive utility of the self-report motivational ratings, which explain significant variance in the effects of experimental task manipulations in both of our experiments. Taken together, the findings highlight the productive utility of the novel task paradigm we have developed here for investigating mechanisms of motivation-cognition interaction, which can now be further extended in studies utilizing neuroscience-based methods and neural measures (e.g., fMRI and BOLD activation).

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Figure 1: Letter-digit task-switching paradigm.

Each trial began with a fixation cross, followed by a cue that indicated the categorization rule (e.g., “Attend Number” vs. “Attend Letter”) and the reward value of the trial, when relevant (e.g., $, $$, or $$$$). During practice and baseline trials, participants were told that the dollar signs had no importance. The target was presented after 1850 ms, which consisted of a letter and a digit displayed at the center of the screen. Participants would make either a vowel/consonant or odd/even judgment depending on the cue instruction. During practice runs, participants received written feedback to indicate whether they were correct, incorrect, or too slow. During the baseline runs, participants no longer received any performance feedback. The reward criterion (37.5th percentile of correct reaction times) was calculated for each individual subject from mixed task baseline run. During incentive runs, participants received a 2 mL of liquid (juice, neutral, or saltwater) as feedback if they were accurate and faster than their reward criterion. The liquids were blocked across runs and counterbalanced. Following the feedback (if applicable), a fixation cross was presented until the start of the next trial.

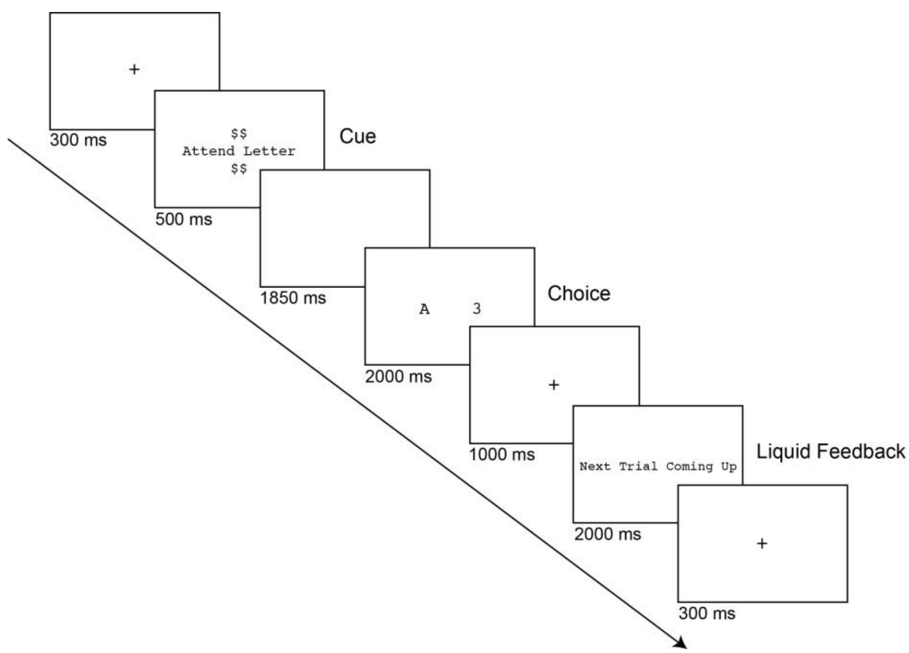

Figure 2: Reward rate bar plot.

This is a bar plot of the reward rate performance by experimental condition (3 levels of monetary reward, and 3 types of liquid feedback). The top figure includes all 39 subjects in the analysis. Notably, participants performed significantly better when given juice as feedback compared to neutral solution [$F(1,38)=9.660$, $p=.004$]. Conversely, the same participants significantly worse when given saltwater compared to neutral solution [$F(1,38)=15.271$, $p<.001$]. Critically, there was also a significant interaction between monetary reward and the liquid in the second analysis [$F(2,76)=4.864$, $p=.010$], which illustrates that individuals are integrating the monetary reward with the disutility of the aversive saltwater. A follow-up analysis revealed that this interaction was heavily driven by a subset of subjects (N=9) who avoided responses in low monetary reward trials, in order to avoid the chance of receiving saltwater as liquid feedback. Importantly, this reveals that certain individuals may be more reactive to saltwater (and more sensitive to punishments in general), which likely modulated their task performance. The reward rate separated by these subgroups is illustrated in the bottom two graphs.

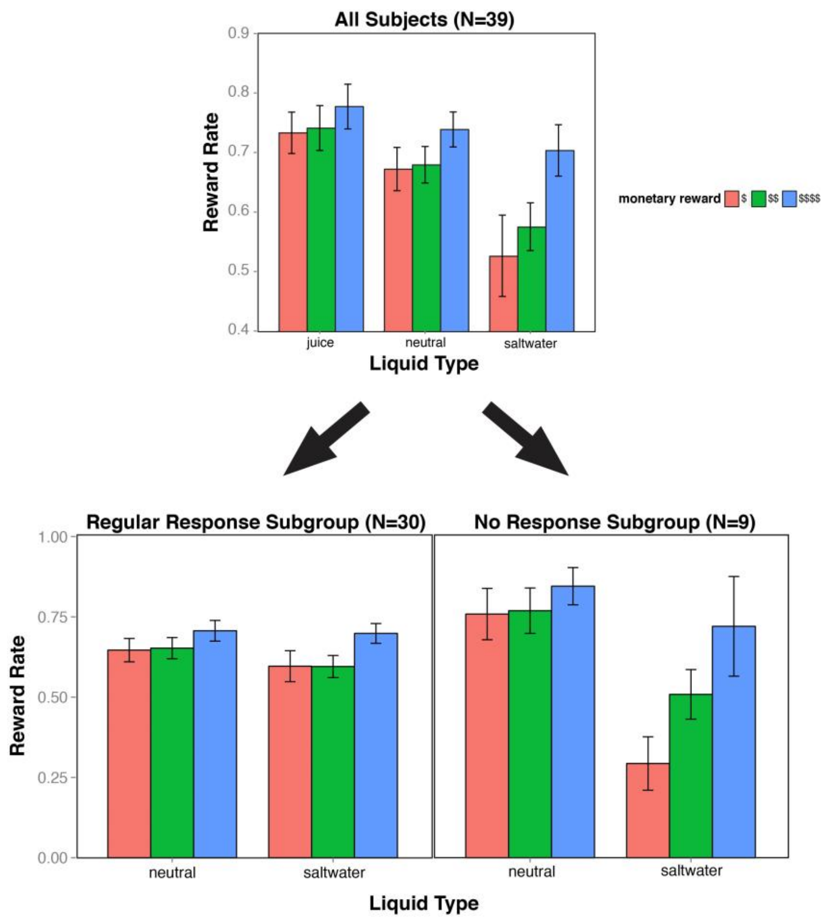

Figure 3: Normalized Residuals of Motivation Ratings and Reward Rate.

In Figure 3a, the normalized residuals of the self-report motivation ratings from experiment 1 are divided by liquid feedback type. Here, we observe a wider spread of residuals during the saltwater condition compared to the neutral and juice. Figure 3b illustrates the normalized residuals of the motivation ratings from experiment 2, separated by juice identity. Unlike the residuals in experiment 1, there is not a clear difference in spread across the different liquid conditions.

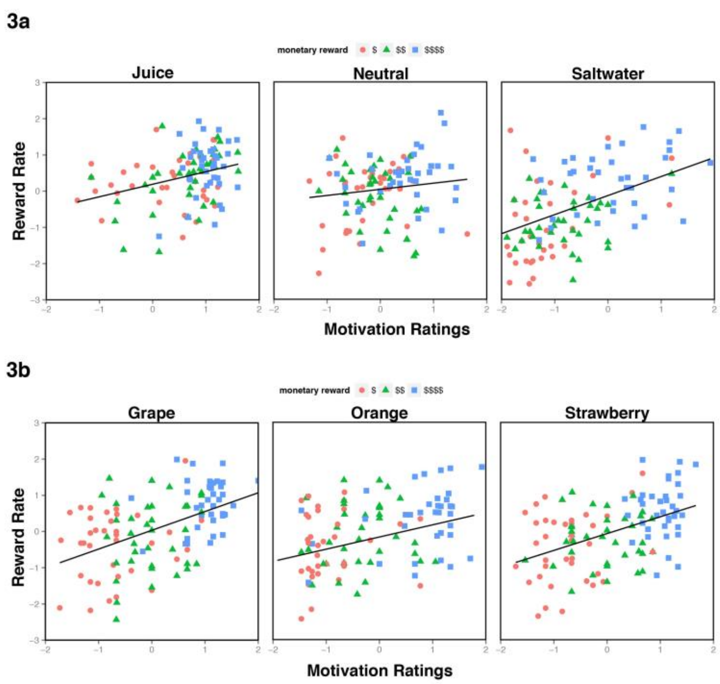

Table 1: Reward Rate, Error Rates, and Response Times (Experiment 1).

Table of reward rates, response times, and error rates by experimental condition (3 levels of monetary reward and 3 types of liquid feedback). The mean score per experimental category is listed, with standard deviation in parentheses. Reward rate is the percentage of incentive trials for which monetary incentive was received. Subjects received a monetary reward during a trial if they were both accurate and faster than a reward criterion, which was established based on performance from the mixed baseline run. Response time includes only correctly responded trials, in milliseconds. Error rate is the percentage of commission errors (i.e., excluding no response trials).

Liquid Feedback			Monetary Reward		
			Low ($)	*Medium ($$)*	*High ($$$$)*
	Juice	*Reward Rate*	.733 (.107)	.741 (.116)	.777 (.116)
		Response Time	574 (60)	570 (57)	543 (52)
		Error Rate	.146 (.076)	.149 (.074)	.135 (.072)
	Neutral	*Reward Rate*	.672 (.112)	.679 (.095)	.739 (.091)
		Response Time	600 (61)	596 (61)	560 (59)
		Error Rate	.158 (.062)	.151 (.079)	.151 (.076)
	Saltwater	*Reward Rate*	.526 (.211)	.575 (.124)	.704 (.133)
		Response Time	670 (12)	660 (97)	599 (92)
		Error Rate	.199 (.099)	.183 (.064)	.148 (.066)

Table 2: Hierarchical linear regression of self-report ratings on reward rate.

We performed a three-step hierarchical regression to determine whether the self-report motivation and liking ratings held predictive utility above and beyond the experimental task conditions. We performed a mixed linear model using the lmerTest and LME4 packages in the R statistical language, with reward rate predicted by monetary reward (money) and liquid feedback (liquid) in step 1. Unsurprisingly, we found significant main effects of money and liquid, as well as a significant interaction. Adding the liking ratings in step 2 predicted additional variance in the reward rate [$\chi^2(1)=11.846$, $p<.001$]. Furthermore, adding the motivation ratings in step 3 enhanced the mixed model, but liking ratings were no longer significant [$\chi^2(1)=23.374$, $p<.001$]. These regression patterns suggest that the variance in the reward rates explained by liking is shared with motivation, but that the motivation ratings predict additional unique variance in reward rate.

Variable	β	*t*	R^2	ΔR^2	AIC	BIC
Step 1			0.782	0.782	-418.8	-360.9
Money	.0479***	5.985				
Liquid	.0744***	5.315				
Money x Liquid	-.033**	-3.170				
Step 2			0.783	0.001	-428.7	-366.9
Money	.0422***	4.930				
Liquid	.0350*	2.127				
Money x Liquid	-.033**	-3.091				
Like	.0218***	3.656				
Step 3			0.785	0.002	-438.7	-373.1
Money	.0291**	3.217				
Liquid	.0332*	2.249				
Money x Liquid	-.0269*	-2.518				
Like	.0050	0.681				
Motivation	.0289***	3.987				

Table 3: Reward Rate, Error Rates, and Response Times (Experiment 2).

Table of reward rates, response times, and error rates by experimental condition (3 levels of monetary reward and 3 types of juice feedback). The mean score per experimental category is listed, with standard deviation in parentheses. Reward rate is the percentage of incentive trials for which monetary incentive was received. Subjects received a monetary reward during a trial if they were both accurate and faster than a reward criterion, which was established based on performance from the mixed baseline run. Response time includes only correctly responded trials, in milliseconds. Error rate is the percentage of commission errors (i.e., excluding no response trials).

			Monetary Reward		
			Low ($)	*Medium ($$)*	*High ($$$$)*
Liquid Feedback	*Orange*	*Reward Rate*	.661 (.131)	.687 (.121)	.750 (.096)
		Response Time	566 (43)	567 (65)	581 (55)
		Error Rate	.169 (.063)	.150 (.066)	.157 (.071)
	Strawberry	*Reward Rate*	.648 (.132)	.678 (.081)	.788 (.096)
		Response Time	589 (82)	568 (50)	551 (48)
		Error Rate	.182 (.081)	.163 (.062)	.146 (.059)
	Grape	*Reward Rate*	.668 (.101)	.711 (.102)	.788 (.093)
		Response Time	588 (66)	562 (51)	558 (69)
		Error Rate	.178 (.081)	.160 (.069)	.121 (.064)

Table 4: Hierarchical linear regression of motivation ratings in experiment 2.

We performed a two-step hierarchical regression to test whether the self-report motivation ratings demonstrated predictive utility above experimental task conditions, when three liquids with the same valence (appetitive) were used. We performed a mixed linear model using the lmerTest and LME4 packages in the R statistical language, with reward rate predicted by monetary reward (dummy coded) and juice identity (contrast coded) in step 1. There was a significant main effect of money, but no main effect of juice identity, as well as no significant interactions. Adding the motivation ratings in step 2 predicted additional variance in reward rate [$\chi^2(1)=20.446$, $p<.001$]. Notably, the effect of monetary reward was weaker, but still significant, while motivation ratings predicted a large portion of the task variance. Importantly, these results demonstrate that the motivation ratings reflect idiosyncratic subjective preferences for the liquids, rather than intrinsic properties of the liquids themselves.

Variable	β	*t*	R^2	ΔR^2	AIC	BIC
Step 1			0.854	0.854	-456.7	-359.1
Money	.0516***	5.291				
Juice Identity						
C1: Orange-Grape	.0186	-1.214				
C2: Strawberry-Grape	.0189	-1.340				
Money x C1	.0173	-.801				
Money x C2	.0137	-.489				
Step 2			0.852	-.002	-471.9	-363.0
Money	.0289*	2.559				
Juice Identity						
C1: Orange-Grape	-.0124	-.733				
C2: Strawberry-Grape	-.0244	-1.335				
Money x C1	-.0148	-.869				
Money x C2	-.0072	-.525				
Motivation	.0324***	5.025				