Neurally reconstructing expected utility

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Abstract

While the concept of "expected utility" informs many theories of decision making, little is known about whether and how the human brain might compute this quantity. This article reviews a series of functional magnetic resonance imaging (FMRI) experiments designed to localize brain regions that respond in anticipation of increasing amounts of monetary incentives. These studies collectively suggest that anticipation of increasing monetary gains activates a subcortical region of the ventral striatum in a magnitude-proportional manner. This ventral striatal activation is not seen during anticipation of losses. Actual gain outcomes instead activate a region of the mesial prefrontal cortex. During anticipation of gain, ventral striatal activation is accompanied by feelings characterized by increasing arousal and positive valence. The results affirm the role of emotion in the anticipation of incentives, and may provide an initial step towards a neural reconstruction of expected utility.

Background

Psychology has historically taken a descriptive stance by describing *actual* behavior. Economics, on the other hand, has typically adopted a prescriptive (or normative) stance by prescribing *ideal* behavior (with the exception of recent hybrid offshoots such as "behavioral decision making"). However, a judicious combination of both descriptive and prescriptive approaches may be necessary in order to specify how people can move from nonoptimal but actual behavior to more optimal or ideal behavior.

Our laboratory has taken a descriptive approach in attempting to isolate and understand the neural underpinnings of desire. Decades of psychometric research indicate that much of the variance in peoples' ongoing affective states (including emotions, moods, attitudes, and preferences) can be described in terms of two independent dimensions termed valence (going from bad to good) and arousal (going from low to high)(Thayer, 1989; Watson & Tellegen, 1985). Using this framework, we define the affective component of desire as involving increases in arousal and valence (see Figure 1). Thus, such a desirous state could also be called a "positive activated" (PA) state. In accordance with the traditional ethological distinction between appetitive and consummatory phases of incentive processing (Craig, 1918), we further predict that individuals are especially likely to experience PA states in anticipation of acquiring and consuming a reward (Knutson, Adams, Fong, & Hommer, 2001a). Here, a reward is defined simply as anything that an organism will work to acquire.

To evoke PA states in the laboratory, we have utilized a variety of incentive delay tasks. In these tasks, individuals are exposed to a cue that predicts a potential reward, wait a delay interval, make a response to obtain the reward, and then receive feedback regarding the outcome of their action. Incentive delay paradigms can be traced back to Pavlov's classic studies of gastric secretions in dogs (Pavlov, 1927). Although Pavlov primarily focused on the ability of reward cues to elicit salivation, dogs undoubtedly show other behavioral reactions to the presentation of reward-predicting cues including increased locomotor activity, seeking behavior, and even vocalizations. These coordinated behaviors can also be evoked by presentation of other types of reward cues, for instance, presentation of a leash before going on a walk. From an affective neuroscience perspective, we postulate that if the covariant occurrence of these behaviors indexes an affective state, then specific neural events must generate that state (Panksepp, 1998). If the PA state occurs during reward delay intervals, then its neural correlate should also show activity during reward delay intervals.

Recently, electrophysiologists have identified neurons that fire during cued reward delay intervals in the brains of monkeys. For instance, Schultz and colleagues have identified neurons in striatal regions that begin firing upon the presentation of reward cues and cease firing when monkeys respond to obtain juice rewards (Schultz, Tremblay, & Hollerman, 2000). These subcortical regions receive modulatory input from ascending midbrain dopamine (DA) neurons. In addition to innvervating these subcortical regions, midbrain DA neurons also innervate cortical regions including the orbital, mesial, and

lateral prefrontal cortices. Critically, experimental stimulation of some but not all of these DA-modulated sites can unconditionally elicit appetitive behavior (Olds & Fobes, 1981). Specifically, rats will work vigorously to self-administer either electrical stimulation or DA-like compounds into subcortical regions including the lateral hypothalamus and ventral striatum (VS), as well as cortical regions such as the mesial prefrontal cortex (MPFC; see Figure 2). Thus, dopamine projection areas associated with appetitive behavior might provide reasonable places to begin the search for reward delay activity in humans.

The study of incentive processing in humans thus requires a method that allows investigators to visualize rapid subcortical changes in brain activity in humans. Functional magnetic resonance imaging (FMRI), developed in the early 1990's (Bandettini, Wong, Hinks, Tikofsky, & Hyde, 1992; Kwong et al., 1992), provides a method that promises to meet these spatial and temporal demands. FMRI enables investigators to localize and track changes in blood oxygenation (a proxy for neural activity) during ongoing cognitive tasks. At present, researchers typically acquire an entire image of a brain at 4 mm cubic spatial resolution every 2 seconds. This provides adequate spatiotemporal resolution to visualize changes in brain activity in striatal regions during short delay intervals. Thus, our laboratory has adopted FMRI as a tool for investigating incentive delay activity in the human brain.

Along with technical issues, the study of human incentive processing also raises significant conceptual challenges. Individuals show an astonishing amount of variability

in their affective reactions to the same stimuli. For instance, while some people like steak, others prefer tofu. In light of this variability, three features make money an attractive experimental incentive. First, money is a compelling incentive, in that most people will work for it. Second, money is a scalable incentive, in that the amount at stake can be increased or decreased. Third, money is a reversible incentive, since it can be given or taken away, and thereby acquire either a positive or negative value. The reversibility of money is an especially important feature in human research, since it allows investigators to compare positive and negative incentives within the same stimulus modality — a comparison that is less straightforward in nonhuman species (i.e., how do presence of juice squirts translate to an absence of electrical shocks?). To avail ourselves of the flexibility of financial incentives, we have developed a monetary incentive delay (MID) task for use with FMRI (Knutson, Westdorp, Kaiser, & Hommer, 2000).

The MID task was designed to enable investigators to determine whether different brain regions are activated by anticipation of incentives and incentive outcomes. The task proceeds at a rapid pace, with each trial taking a total of 6 seconds and no pauses between trials, in order to maximize engagement and minimize distraction (Taylor, Phan, Decker, & Liberzon, 2003). Trials share a consistent format. First, a cue (250 msec) is initially presented indicating whether subjects can respond to gain money, avoid losing money, or simply respond for no monetary outcome. Second, subjects wait a delay period while fixating on a point in the center of the screen (2000-2500 msec). Third, subjects see a rapidly presented target (180-280 msec) to which they must respond with a button press. If subjects respond while the target is on the screen, the trial is coded as a "hit,"

otherwise, the trial is coded as a "miss." Fourth, depending on which cue was presented, and whether the trial was coded as a hit or miss, subjects receive feedback indicating how much they won or lost on that trial as well as their running total (see Figure 3).

To minimize learning effects, subjects receive training on the task and take a test indicating that they are explicitly aware of the incentive contingencies prior to entering the scanner. During training, reaction time is also measured to provide a metric for adjusting task difficulty to equate performance across subjects. Finally, the experimenter also shows subjects the cash they can win and informs them that they will leave the experiment with the amount they accumulate while playing in the magnet.

In conjunction with FMRI, the MID task provides a tool that might enable investigators to address questions in humans that have not yet been resolved in the comparative literature. For instance, do specific brain regions activate during anticipation of gain? Do they activate in a manner that scales with the magnitude of anticipated gain? Can they be distinguished from areas activated by anticipation of loss? Are areas recruited by anticipation of gain also active during actual gain outcomes? Is activity in these areas associated with changes in affect? We turn now to describe a series of studies that attempt to provide initial empirical answers to these basic questions.

Findings

In a first study, we reported on the feasibility of using the MID task in the FMRI environment with 12 healthy subjects (Knutson et al., 2000). In this initial experiment, subjects were cued to respond in order to gain money (+$1.00), cued to respond in order to avoid losing money (-$1.00), or cued to respond for no monetary outcome ($0.00). Although other investigators had done so in conjunction with PET (Thut et al., 1997), this was the first published study to utilize real monetary incentives in the context of FMRI, and was rapidly followed by others (Delgado, Nystrom, Fissell, Noll, & Fiez, 2000; Elliott, Friston, & Dolan, 2000). While subjects showed predicted activations in dorsal striatal and mesial prefrontal cortical regions in incentive versus nonincentive comparisons, we did not observe obvious differences in brain activation to positive versus negative incentives. Later studies bore out the speculation that this non-finding was due to limitations in data analysis. Specifically, each trial was modeled as a whole instead of divided into distinct components (e.g., anticipation versus outcome). In later studies, separate modeling of different trial components revealed not only dissociations between anticipation of gain and loss, but also dissociations between gain and loss outcomes.

In a second study, we focused exclusively on anticipation of gain and loss in eight healthy subjects (Knutson et al., 2001a). This study utilized a parametric design in which subjects were cued to respond in order to gain various amounts of money (+0.20, +1.00, +5.00), cued to respond to avoid losing various amounts of money (-0.20, -1.00, -5.00), or cued to respond for no monetary outcome (+0.00, -0.00). The parametric design allowed us to conduct a conjunction analysis that highlighted regions with increasing

activity proportional to the magnitude of anticipated gain or loss. Three regions, all subcortical, showed magnitude-proportional activation during anticipation of gain. These included the thalamus, medial caudate (a region of the dorsal striatum), and nucleus accumbens (NAcc; a region of the ventral striatum). However, the thalamus and medial caudate also showed increasing activation when subjects anticipated increasing losses. Only the NAcc preferentially showed increasing activation for increasing anticipated gains but not losses. Interestingly, subjects' self-reported PA in response to seeing the high reward (+$5.00) cue correlated with the NAcc activation in response to presentation of that cue. Based on these findings, we concluded: "…reward anticipation may carry a distinctive 'signature' characterized not only by increased positive affect but also by activation of the nucleus accumbens."

Although these were the first human findings to implicate the NAcc as a candidate neural substrate for anticipation of gain, they did not clarify whether NAcc activation also occurred in response to gain outcomes. Thus, in a third study with a simpler design, we examined anticipation of gain as well as gain outcomes in nine healthy subjects (Knutson, Fong, Adams, Varner, & Hommer, 2001b). In this study, subjects were cued to respond in order to gain money (+$1.00), to respond for no monetary outcome (+$0.00), or not to respond at all. In addition to examining areas recruited by anticipation of gain versus non-gain, we also controlled for gain anticipation and compared gain versus non-gain outcomes. The findings of the previous parametric study were replicated — subjects showed increased NAcc activation when anticipating gain versus non-gain. However, analyses also indicated that this activation ceased by the time that subjects actually made

money. Thus, the NAcc did not appear to discriminate between gain and non-gain outcomes. Instead, a cortical region along the medial wall of the prefrontal cortex (MPFC) appeared to discriminate between gain and non-gain outcomes, and it did so by deactivating when people failed to get the money that they anticipated.

While the results of the third study suggested that the MPFC, and not the NAcc, discriminated between gain and non-gain outcome, they raised yet another question. Was the MPFC activation due to discrimination of gain versus non-gain outcomes, or simply to some more general phenomenon such as a violation of expectation? To rule out this latter possibility, we conducted a fourth study, once again utilizing the parametric version of the MID task with both gain and loss contingencies in twelve healthy subjects (Knutson, Fong, Bennett, Adams, & Hommer, 2003a). The findings of this study indicated that while the MPFC discriminated between gain and non-gain outcomes, it did not distinguish between loss and nonloss outcomes.

Because the second and fourth studies shared identical parametric designs, we have aggregated their findings across all twenty subjects and summarized the combined results here. Both group activation maps and individual timecourse analyses suggest two recurring patterns. First, a region of the ventral striatum (including the NAcc) is most potently activated by anticipation of monetary gains. This activation scales with magnitude of anticipated gain and may be related to subjects' feelings of positive activation as they anticipate making money. However, the NAcc is not similarly activated by anticipation of monetary loss, gain outcomes, or simple motor preparation (see Figure

4). Second, a region of the prefrontal cortex (the MPFC) is most potently activated by monetary gain outcomes and is deactivated by non-gain outcomes. The MPFC is not similarly recruited by anticipation of monetary gain, anticipation of loss, or loss outcomes (see Figure 5).

Implications

In a series of FMRI studies using the MID task, we identified two brain regions implicated in reward processing. The NAcc, a subcortical region of the ventral striatum, preferentially activates during anticipation of monetary gains. Additionally, the MPFC, a cortical region of the frontal lobe, preferentially activates in response to gain outcomes. These findings raise the surprising possibility that a prefrontal cortex is not necessary for anticipation of previously-learned rewards, but instead provides critical feedback when reward contingencies change. By way of analogy, while the NAcc may provide a "gas pedal" that fuels appetitive behavior, the MPFC may provide a "steering wheel" that flexibly directs appetitive behavior towards appropriate goal objects (Knutson et al., 2003a).

Localization of brain regions associated with reward processing has implications for economics. For instance, the concept of "expected utility" has guided much of economic theory. The magnitude of anticipated gains represents the first of two terms in D. Bernoulli's initial formula for computing expected utility (Bernoulli, 1738, 1954). Specifically, expected utility (EU) can be expressed as $EU(x) = m(x) * p(x)$, where $m(x)$

represents the magnitude and p(x) represents the probability of rewarding outcome (x). The finding that a brain region activates in proportion to the magnitude of anticipated monetary gains suggests a candidate physiological mechanism for the computation of this term. The anticipated probability of gains represents the second term in Bernoulli's expected utility equation. We are currently conducting experiments that incorporate probability manipulations to determine whether an area of the brain activates in proportion to the anticipated probability of gains. While the NAcc may also code for the anticipated probability of gains, it is also possible that a different region codes for anticipated probability of gains, and that yet another region calculates their interaction so as to derive an estimate of expected utility (Glimcher, 2003; Platt & Glimcher, 1999).

While the NAcc was preferentially activated by anticipation of monetary gains, it was not similarly activated by anticipation of loss. Consistent with both Prospect Theory from the behavioral decision making literature (Kahneman & Tversky, 1984) and affective neuroscience models (Panksepp, 1998), these results suggest that people may utilize different algorithms as well as different neural mechanisms when anticipating gains versus losses. The findings lead to the prediction that stimulation of the ventral striatum should elicit appetitive but not aversive behavior. In fact, when the ventral striatum is experimentally stimulated (electrically or chemically) in comparative studies, rats show marked potentiation of appetitive behavior (such as locomotion, bar pressing, and 50 kHz ultrasonic vocalizations) but not aversive behavior (Burgdorf, Knutson, Panksepp, & Ikemoto, 2001). The relative silence of regions that might preferentially code for anticipated losses in the FMRI studies reviewed above is somewhat puzzling and worthy

of further investigation. Part of this asymmetry may be due to technical issues involving task parameters (e.g., speed of trials), or inadequate modeling of neural responses to aversive incentives (which might last longer than appetitive responses).

While the NAcc activated during anticipation of gains, the MPFC activated in response to gain outcomes. These findings are consistent with a proposed distinction between "expected" and "experienced" utility in the behavioral decision making literature (Kahneman, 2000). They are also consistent with findings from comparative neuroscience studies prominently implicating dopaminergic modulation of the ventral striatum in "wanting" (indexed by appetitive behavior), but not "liking" (indexed by consummatory behavior) (Berridge & Robinson, 1998). Recently, other FMRI investigators have also observed similar dissociations between anticipation and outcome in humans exposed to pleasant tastes and smells (Gottfried, O'Doherty, & Dolan, 2003; O'Doherty, Deichmann, Critchley, & Dolan, 2002). However, not all FMRI investigators have reported clear functional dissociations between incentive anticipation and outcomes (Breiter, Aharon, Kahneman, Dale, & Shizgal, 2001), suggesting that task parameters such as the length of the anticipatory delay may critically determine the degree of separation between distinguishable neural responses.

The FMRI studies surveyed here suggest that expected utility may not only involve the prediction of future hedonic states but may also concurrently carry its own hedonic state (Loewenstein, Loewenstein, Weber, & Welch, 2001; Slovic, Finucane, Peters, & MacGregor, 2002). In the realm of gains, we have proposed that such an appetitive state

should be characterized both by increasing valence and arousal, while consummatory states should be more prominently associated with increased valence but not necessarily arousal (Panksepp, Knutson, & Burgdorf, 2002). These hypotheses lead to the straightforward prediction that people should feel increased PA (or "excitement") when they anticipate increasing gains, a hypothesis that has been borne out in recently collected data (Knutson, Nielsen, Larkin, & Carstensen, 2003b). These hypotheses also lead to the less obvious prediction that individual differences in NAcc activity during gain anticipation may be associated with self-reported PA in response to the presentation of gain cues, and this prediction has also received some empirical support (Knutson et al., 2001a). Finally, these hypotheses are consistent with data collected with another brain imaging modality, positron emission tomography (PET), which allows researchers to make inferences not only about neural oxygenation but also about the release of specific neurotransmitters such as dopamine. A number of investigators have reported that the amount of dopaminergic release in the ventral striatum correlates with the degree to which individuals report euphoric reactions after amphetamine injection (Drevets et al., 2001; Mawlawi et al., 2001; Volkow, Fowler, & Wang, 2002). Together, these findings imply that in addition to rational considerations, calculation of expected utility in the realm of gains may invoke prominent emotional components.

These findings represent a step towards a neural reconstruction of expected utility. They suggest both that FMRI provides a useful tool in this endeavor, and that a region of the ventral striatum appears to code for the expected magnitude of gains in humans. Neural correlates of the expected probability of gains are under active investigation and would

add a second piece to the puzzle. Nonetheless, the findings raise more questions than they answer. For instance, do the same or different neural mechanisms drive anticipation of losses? How is affect implicated in these anticipatory activations? How might these anticipatory activations and associated affective reactions modulate subsequent economic and social behavior (Dickhaut et al., 2003; McCabe, Houser, Ryan, Smith, & Trouard, 2001; Rilling et al., 2002)? While future findings may echo Bernoulli's initial formulation, they may also take on quite a different form (Kahneman & Tversky, 1984). This should not necessarily surprise us. As prescriptive approaches inform descriptive approaches, so can description inform prescription. As theory informs observation, observation informs theory. The dance of science continues.

Bibliography

Bandettini, P. A., Wong, E. C., Hinks, R. S., Tikofsky, R. S., & Hyde, J. S. (1992). Time course EPI of human brain function during task activation. Magnetic Resonance in Medicine, 25, 390-397.

Bernoulli, D. (1738, 1954). Exposition of a new theory on the measurement of risk. Econometrica, 22, 23-36.

Berridge, K. C., & Robinson, T. E. (1998). What is the role of dopamine in reward: Hedonic impact, reward learning, or incentive salience? Brain Research Reviews, 28, 309-369.

Breiter, H. C., Aharon, I., Kahneman, D., Dale, A., & Shizgal, P. (2001). Functional imaging of neural responses to expectancy and experience of monetary gains and losses. Neuron, 30, 619-639.

Burgdorf, J., Knutson, B., Panksepp, J., & Ikemoto, S. (2001). Nucleus accumbens amphetamine microinjections unconditionally elicit 50-kHz ultrasonic vocalizations in rats. Behavioral Neuroscience, 115, 940-944.

Craig, W. (1918). Appetites and aversions as constituents of instincts. Biological Bulletin, 34, 91-107.

Delgado, M. R., Nystrom, L. E., Fissell, C., Noll, D. C., & Fiez, J. A. (2000). Tracking the hemodynamic response to reward and punishment in the striatum. Journal of Neurophysiology, 84, 3072-3077.

Dickhaut, J., McCabe, K., Nagode, J. C., Russtichini, A., Smith, K., & Pardo, J. V. (2003). The impact of the certainty context on the process of choice. Proceedings of the National Academy of Science, 100, 3536-3541.

Drevets, W. C., Gautier, C., Price, J. C., Kupfer, D. J., Kinahan, P. E., Grace, A. A., Price, J. L., & Mathis, C. A. (2001). Amphetamine-induced dopamine release in human ventral striatum correlates with euphoria. Biological Psychiatry, 49, 81-96.

Elliott, R., Friston, K. J., & Dolan, R. J. (2000). Dissociable neural responses in human reward systems. Journal of Neuroscience, 20, 6159-6165.

Glimcher, P. (2003). Decisions, uncertainty, and the brain: The science of neuroeconomics. Cambridge, MA: MIT Press.

Gottfried, J. A., O'Doherty, J., & Dolan, R. J. (2003). Appetitive and aversive olfactory learning in humans studied using event-related functional magnetic resonance imaging. Journal of Neuroscience, 22, 10829-10837.

Kahneman, D. (2000). Experienced utility and objective happiness: A moment-based approach. In D. Kahneman & A. Tversky (Eds.), Choices, values, and frames (pp. 673-692). Cambridge, U. K.: Cambridge University Press.

Kahneman, D., & Tversky, A. (1984). Choices, values, and frames. American Psychologist, 39, 341-350.

Knutson, B., Adams, C. M., Fong, G. W., & Hommer, D. (2001a). Anticipation of increasing monetary reward selectively recruits nucleus accumbens. Journal of Neuroscience, 21, RC159.

Knutson, B., Fong, G. W., Adams, C. M., Varner, J. L., & Hommer, D. (2001b). Dissociation of reward anticipation and outcome with event-related FMRI. NeuroReport, 12, 3683-3687.

Knutson, B., Fong, G. W., Bennett, S. M., Adams, C. M., & Hommer, D. (2003a). A region of mesial prefrontal cortex tracks monetarily rewarding outcomes: Characterization with rapid event-related FMRI. NeuroImage, 18, 263-272.

Knutson, B., Nielsen, L., Larkin, G., & Carstensen, L. L. (2003b). Affect dynamics: Psychometric and physiological validation. Stanford.

Knutson, B., Westdorp, A., Kaiser, E., & Hommer, D. (2000). FMRI visualization of brain activity during a monetary incentive delay task. NeuroImage, 12, 20-27.

Kwong, K. K., Belliveau, J. W., Chesler, D. A., Goldberg, I. E., Weisskoff, R. M., Poncelet, B. P., Kennedy, D. N., Hoppel, B. E., Cohen, M. S., Turner, R. A., Cheng, H.-M., Brady, T. J., & Rosen, B. R. (1992). Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation. Proceedings of the National Academy of Science, 89, 5675-5679.

Loewenstein, C. K., Loewenstein, G. F., Weber, E. U., & Welch, N. (2001). Risk as feelings. Psychological Bulletin, 2, 267-286.

Mawlawi, O., Martinez, D., Slifstein, M., Broft, A., Chatterjee, R., Hwang, D., Huang, Y., Simpson, N., Ngo, K., Van Heertum, R., & Laruelle, M. (2001). Imaging human mesolimbic dopamine transmission with positron emission tomography: I. Accuracy and precision of D2 receptor parametr measurements in ventral striatum. Journal of Cerebral Blood Flow and Metabolism, 21, 1034-1057.

McCabe, K., Houser, D., Ryan, L., Smith, V., & Trouard, T. (2001). A functional imaging study of cooperation in two-person reciprocal exchange. Proceedings of the National Academy of Science, 98, 11832-11835.

O'Doherty, J. P., Deichmann, R., Critchley, H. D., & Dolan, R. J. (2002). Neural responses during anticipation of a primary taste reward. Neuron, 33, 815-826.

Olds, M. E., & Fobes, J. L. (1981). The central basis of motivation: Intracranial self-stimulation studies. Annual Review of Psychology, 32, 523-574.

Panksepp, J. (1998). Affective neuroscience: The foundations of human and animal emotions. New York: Oxford University Press.

Panksepp, J., Knutson, B., & Burgdorf, J. (2002). The role of emotional brain systems in addictions: A neuro-evolutionary perspective. Addiction, 97, 459-469.

Pavlov, I. P. (1927). Conditioned reflexes: An investigation of the physiological activity of the cerebral cortex. Oxford, England: Oxford University Press.

Platt, M. L., & Glimcher, P. W. (1999). Neural correlates of decision variables in the parietal cortex. Nature, 400, 233-238.

Rilling, J. K., Gutman, D. A., Zeh, T. R., Pagnoni, G., Berns, G. S., & Kilts, C. D. (2002). A neural basis for social cooperation. Neuron, 35, 395-405.

Schultz, W., Tremblay, L., & Hollerman, J. R. (2000). Reward processing in primate orbitofrontal cortex and basal ganglia. Cerebral Cortex, 10, 272-283.

Slovic, P., Finucane, M., Peters, E., & MacGregor, D. (2002). The affect heuristic. In T. Gilovich, D. Griffin, & D. Kahneman (Eds.), Heuristics and biases: The psychology of intuitive judgment (pp. 397-420). New York: Cambridge University Press.

Taylor, S. F., Phan, K. L., Decker, L. R., & Liberzon, I. (2003). Subjective rating of emotionally salient stimuli modulates neural activity. NeuroImage, 18, 650-659.

Thayer, R. E. (1989). The Biopsychology of Mood and Arousal. New York: Oxford University Press.

Thut, G., Schultz, W., Roelcke, U., Nienhusmeier, M., Missimer, J., Maguire, R. P., & Leenders, K. L. (1997). Activation of the human brain by monetary reward. Neuroreport, 8(5), 1225-1228.

Volkow, N. D., Fowler, J. S., & Wang, G. J. (2002). Role of dopamine in drug reinforcement and addiction in humans: results from imaging studies. Behavioral Pharmacology, 13, 355-366.

Watson, D., & Tellegen, A. (1985). Toward a consensual structure of mood. Psychological Bulletin, 98, 219-235.

Watson, D., Wiese, D., Vaidya, J., & Tellegen, A. (1999). The two general activation systems of affect: Structural findings, evolutionary considerations, and psychobiological evidence. Journal of Personality and Social Psychology, 76, 820-838.

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Figure Legends

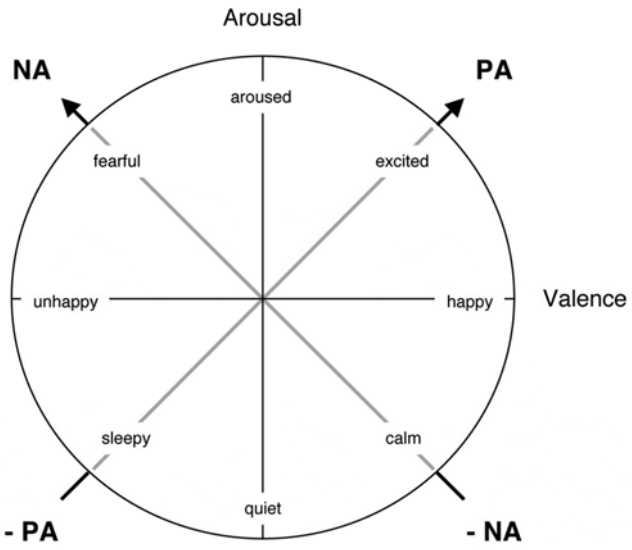
Figure 1: The affective circumplex (Watson, Wiese, Vaidya, & Tellegen, 1999).

Figure 2: Brain regions innervated by ascending dopamine neurons.

Figure 3: Monetary Incentive Delay (MID) task trial structure (Knutson et al., 2003a).

Figure 4: Monetary gain anticipation activates the ventral striatum (n=20) (Knutson et al., 2001a; Knutson et al., 2003a).

Figure 5: Monetary gain outcomes activate the mesial prefrontal cortex (n=20) (Knutson et al., 2001a; Knutson et al., 2003a).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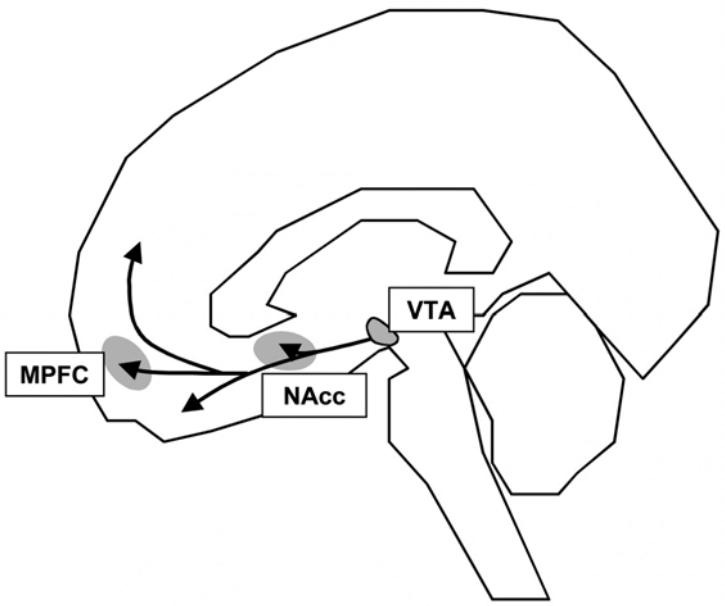
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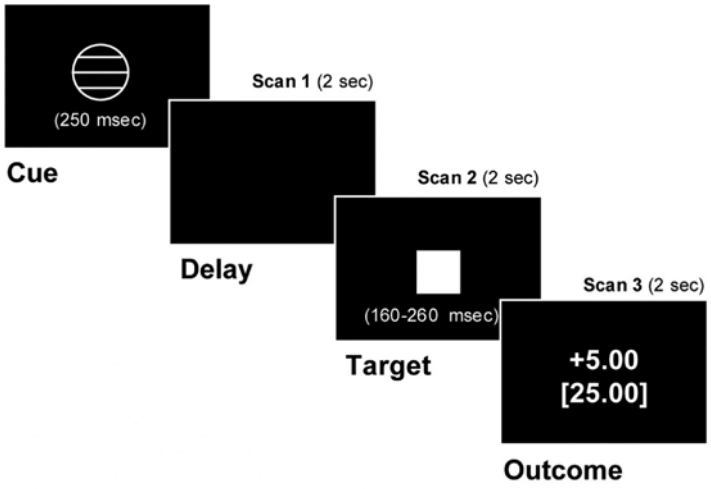
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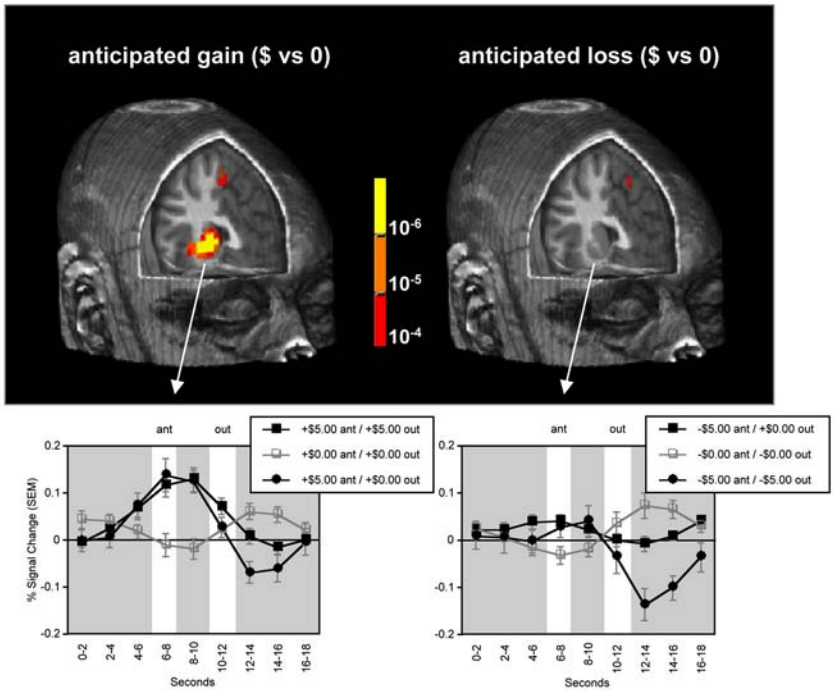
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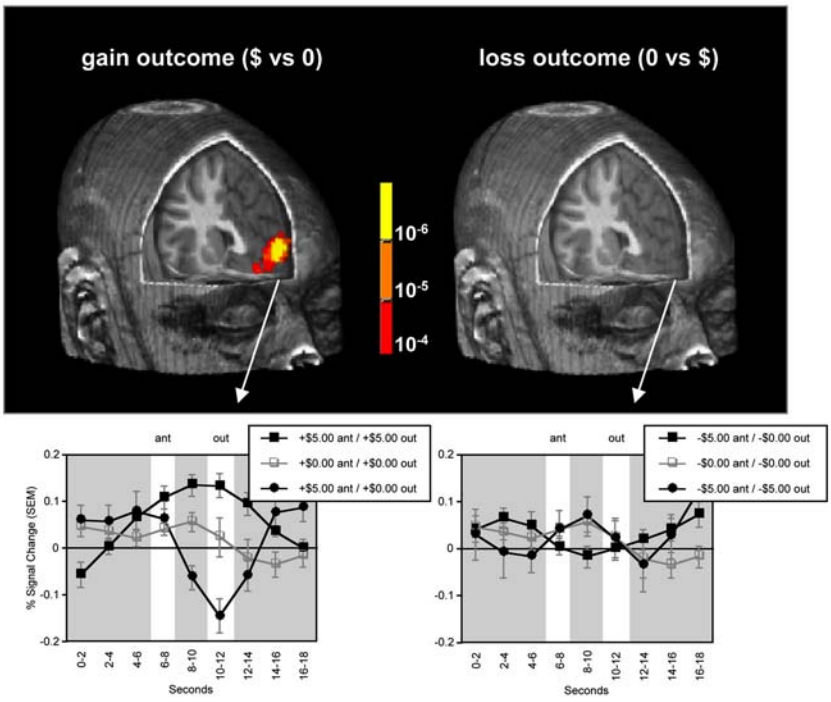
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-0.2
0-2
2-4
4-6
6-8
8-10
10-12
12-14
14-16
16-18
Seconds
ant
out
-$5.00 ant / -$0.00 out
-$0.00 ant / -$0.00 out
-$5.00 ant / -$5.00 out
Seconds