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Brain Activation Covaries with Reported Criminal Behaviors When Making Risky Choices: A Fuzzy-Trace Theory Approach

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Abstract

Criminal behavior has been associated with abnormal neural activity when people experience risks and rewards or exercise inhibition. However, neural substrates of mental representations that underlie criminal and noncriminal risk-taking in adulthood have received scant attention. We take a new approach, applying fuzzy-trace theory, to examine neural substrates of risk preferences and criminality. We extend ideas about gist (simple meaning) and verbatim (precise risk-reward tradeoffs) representations used to explain adolescent risk-taking to uncover neural correlates of developmentally inappropriate adult risk-taking. We tested predictions using a risky-choice framing task completed in the MRI scanner, and examined neural covariation with self-reported criminal and noncriminal risk-taking. As predicted, risk-taking was correlated with a behavioral pattern of risk preferences called "reverse framing" (preferring sure losses over a risky option and a risky option over sure gains, the opposite of typical framing biases) that has been linked to risky behavior in adolescents and is rarely observed in nondisordered adults. Experimental manipulations confirmed processing interpretations of typical framing (gist-based) and reverse-framing (verbatim-based) risk preferences. In the brain, covariation with criminal and noncriminal risk-taking was observed predominantly when subjects made reverse-framing choices. Noncriminal risk-taking behavior was associated with emotional reactivity (amygdala) and reward motivation (striatal) areas, whereas criminal behavior was associated with greater activation in temporal and parietal cortices, their junction, and insula. When subjects made more developmentally typical framing choices, reflecting non-preferred gist processing, activation in dorsolateral prefrontal cortex covaried with criminal risk-taking, which may reflect cognitive effort to process gist while inhibiting preferred verbatim processing.

Keywords: risky decision-making; risk-taking; psychopathy; mental representation; parietal cortex

Brain Activation Covaries with Reported Criminal Behaviors When Making Risky Choices: A Fuzzy-Trace Theory Approach

Criminal behavior is one manifestation of heightened risk-taking, which peaks in adolescence for most individuals, but continues through adulthood for others (Cohen & Casey, 2014; Moffitt, 1993). Crime has been analyzed as a reasoned choice balancing risks (e.g., of getting caught) against rewards (e.g., of money or drugs; Matsueda, 2013) and as an impulsive or reactive choice in which emotions and desires overwhelm self-control (Casey, Galvan, & Somerville, 2016), among other approaches (see Sweeten, Piquero, & Steinberg, 2013). In this study, we take a new and theoretically based approach to examining the neural substrates of risk preferences and criminality grounded in fuzzy-trace theory (FTT; Reyna, 2012). In particular, we extend ideas about mental representation that have been used to explain adolescent risk-taking to uncover the neural correlates of developmentally inappropriate adult risk-taking that crosses the line into criminal behavior.

Prior research on neural substrates has related criminal behavior to differential processing of rewards and incentives (Buckholtz et al., 2010; Cohn et al., 2015; Pujara, Motzkin, Newman, Kiehl, & Koenigs, 2013), reduced attention and inhibition (Aharoni et al., 2013; Banich et al., 2007; Freeman et al., 2015; Larson et al., 2013; Pujol et al., 2012), and abnormal processing of emotional and moral stimuli (Birbaumer et al., 2005; Carre, Hyde, Neumann, Viding, & Hariri, 2013; Marsh & Cardinale, 2012). Broadly consistent with this work, FTT incorporates influences of reward sensitivity, emotion, and inhibition on risky decision-making (Reyna & Casillas, 2009; Reyna, Wilhelms, McCormick, & Weldon, 2015). However, FTT adds a cognitive distinction between verbatim (literal and precise) and gist (bottom-line meaning)

mental representations that are relied on in decision-making (Kwak, Payne, Cohen, & Huettel, 2015; Mills, Reyna, & Estrada, 2008; Reyna et al., 2015; White, Gummerum, & Hanoch, 2015).

Specifically, reliance on verbatim and gist representations varies developmentally and across individuals in ways that affect risk preferences (for a review, see Reyna & Brainerd, 2011). We apply these tenets of FTT to make predictions about criminal risky decisions, which we characterize as developmentally less advanced compared to decisions of non-disordered adults (see Shannon et al., 2011, for an analogous developmental argument).

Background: Mental Representations and Risk Taking

To understand FTT's predictions, consider that any decision can be described in terms of probabilities and outcomes (e.g., rewards) associated with each option (Tversky & Kahneman, 1986). Traditionally, theories have assumed that decision makers trade off risk and reward: Given a choice between receiving $10 for sure versus a 1/3 chance to receive $30 and a 2/3 chance to receive nothing, a larger reward ($30 vs. $10) can compensate for a smaller probability of receiving that reward (1/3 vs. 1.0). FTT assumes that, for any decision, most adults mentally represent both the literal details (exact words or numbers) and multiple levels of gist of their options, but they rely more on the simplest gist. In our example, the simplest gist is the categorical contrast between some money and no money, and so this decision boils down to receiving some money for sure versus taking a chance on receiving either some money or none. Thus, the categorical gist of this decision about "gains" or positive outcomes favors the sure option because some money is better than none (Reyna, 2012). (This is only the first step in our argument; below, we explain why gist is *necessary* to predict choices.) Note that, when this decision is represented in terms of categorical gist, the magnitude of reward does not offset the magnitude of risk (i.e., the decision is not a tradeoff).

The verbatim representation of this same gains decision contains representations of numbers, which support precise thinking. Experiments have shown that children make decisions such as these by relying on verbatim representations of numbers, roughly "multiplying" probabilities and outcomes (i.e., 1.0 X $10 = $10 and 1/3 X $30 = $10), that is, by trading off risk and reward (Reyna & Brainerd, 1994; Schlottmann, 2001). (Children are less able to process numbers accurately than adults although they rely on such literal details more; see below.) As predicted by FTT, the tendency to rely on verbatim representations rather than gist declines with development from childhood to adulthood, producing increasing risk avoidance for decisions like these in which the simple gist favors the safe option. Processing measures such as eye movements (e.g., Kwak et al., 2015) and meta-analyses of risky choice (e.g., Defoe, Dubas, Figner, & van Aken, 2015) confirm FTT's prediction that development proceeds from a lesser to greater reliance on gist that supports risk avoidance for gains.

Many decisions relevant to law and public health also have this structure, namely, a choice between a less rewarding but safe option and a tempting, more rewarding option with a small probability of an unsatisfying or negative outcome (Reyna & Farley, 2006). FTT predicts that the more that decision makers rely on precise representations, trading off risk and reward, rather than categorical gist, the more likely they are to take such risks, which has been confirmed (e.g., Mills et al., 2008; Reyna, Estrada, DeMarinis, Myers, Stanisz, & Mills, 2011; Reyna & Farley, 2006; White et al., 2015). This developmental trend for risk preference is distinct from the ability to choose mathematically advantageous options or to monitor cognition, both of which improve during the same period (Levin, Bossard, Gaeth, & Yan, 2014; Reyna & Brainerd, 1994; Weller, Levin, & Denburg, 2011).

Taken by itself, the evidence for gains might be interpreted as indicating that adults generally avoid risks. However, research on gain-loss framing effects shows that this is not the case. Suppose that a decision maker were given $30 but were asked to then choose between giving up $20 for sure versus a 2/3 chance to give up $30 and 1/3 chance to give up nothing. Here, most adults prefer the risky option for losses, the opposite of their preference for gains. This framing effect is a cognitive bias because the net outcomes are the same for gains and losses ($30 -$20 = a net gain of $10 for sure and $30 – 2/3 X $30 = a net gain of $10). The framing effect shows that most adults are not risk avoiding in the sense that they always dislike uncertainty or variance. According to FTT, adults are risk seeking for losses because simple categorical gist translates the loss decision into a choice between losing some money for sure versus taking a chance on either losing some money or losing none. Losing no money is better than losing some money, and so adults prefer the risky option. In fact, differences between risk preferences for gains and losses generally increase developmentally, as predicted by FTT (Reyna, Chick, Corbin, & Hsia, 2014; Reyna & Ellis, 1994; Reyna et al., 2011). The tendency to show framing effects has been used as an index of gist thinking that predicts behavior in different tasks (e.g., gist-based false memories), and is used here for that purpose (Corbin, Reyna, Weldon, & Brainerd, 2015).

Manipulating Mental Representations: Why Gist is Necessary

The cognitive representational explanation of gain-loss framing in terms of gist has been tested by deleting parts of the risky option to emphasize either quantitative tradeoffs (e.g., $10 vs. 1/3 chance to receive $30) or qualitative categorical distinctions (e.g., $10 vs. 2/3 chance to receive $0): Focusing on tradeoffs eliminates gain-loss framing effects, despite the fact that the deleted portion of the gamble is equal to zero (2/3 X $0 = $0) and should therefore make no

difference according to traditional theories (Kühberger & Tanner, 2010; Reyna et al., 2014). This deletion of "nothing" makes older subjects look like younger ones under standard conditions (without any deletion; i.e., under conditions when both parts of the risky option are present).

In contrast, focusing on the qualitative distinction between something for sure and a probability of nothing augments framing effects, as predicted by FTT. The latter deletion makes younger subjects look like older subjects under standard conditions. In these experiments, full information about deleted parts of the risky option is provided prior to choice, so there is little to no ambiguity; those who pass ambiguity tests nevertheless exhibit the effects of deletion (Chick, Reyna, & Corbin, 2015). Thus, these deletion manipulations can produce variation in the degree to which decision makers rely on gist versus verbatim processing, as evidenced by their pattern of choices.

For example, it is not the case that gist is necessary to explain choosing a sure $10 rather than a 1/3 chance of $30. In fact, FTT predicts that people do not prefer the sure $10 rather than a 1/3 chance of $30 when the zero complement is missing (i.e., when 2/3 chance of $0 is deleted). This critical test was introduced to test predictions of FTT versus prospect theory (Kühberger & Tanner, 2010; for a review, see Reyna, 2012). Prospect theory (and other theories of framing effects) predict that people choose the sure gain of $10 and choose the risky option for corresponding losses. Prospect theory has two ways to predict such gain-loss framing effects: the value function and the probability function (Tversky & Kahneman, 1986). Both functions are fully represented in the zero-complement-truncated condition (i.e., the Verbatim condition in Figure 1). Yet, according to FTT, the predicted preference for the sure gain should not be observed when the zero complement is truncated (deleted). Similarly, according to FTT, there should be no preference for the risky option in the loss frame when the zero complement is

truncated (deleted). Thus, people are predicted to be indifferent between a sure loss and a risky option in the Verbatim condition. (These examples assume that options are equal in expected value.) In other words, although all of the factors that prospect theory predicts should matter are present, FTT suggests that the framing effect should not be observed, ruling out prospect theory.

We have discussed only two results (one result for gains and one result for losses) out of six effects illustrated in Figure 1. FTT predicts all six effects. According to FTT, the Verbatim condition emphasizes trading off outcome and probability, which is contrasted with emphasizing categorical distinctions in the Gist condition (when the non-zero complement of the gamble is deleted). Both verbatim and gist processing should contribute to choices in the traditional mixed condition (i.e., both gamble complements are present), which is then predicted to be intermediate in its framing effect. Thus, gist is hypothesized to be necessary to explain framing effects because when that simple categorical distinction is not there, the framing effect should not be there either.

Reversing Framing Effects

Although adults typically choose risky losses and sure gains under standard conditions, a pattern of choices that is observed in children and adolescents, but rarely observed in adults, is called "reverse framing" or framing-inconsistent choice: choosing the sure loss and the risky gain (Levin, Gaeth, Schreiber, & Lauriola, 2002; Reyna & Ellis, 1994; Reyna et al., 2011). Framing-inconsistent choices are more evident when differences between outcomes are large, which makes sense theoretically because such decision makers rely on representations that emphasize precise differences rather than categorical gist that glosses over precise differences (emphasizing instead some-or-none qualitative distinctions). Focusing on differences in outcomes (e.g., in magnitudes of rewards) should elicit reward-related approach to risky options

(Galvan, Hare, Voss, Glover, & Casey, 2007; Shulman et al., 2016). However, cognitive representation has a unique effect on risk-taking controlling for reward sensitivity. Hence, the effects of both reward sensitivity and cognitive representation seem to be synergistic in promoting risk-taking (Levin & Hart, 2003; Reyna et al., 2011).

As predicted, the degree to which risky decisions in framing problems deviate from standard adult biases—toward framing-inconsistent choices—the higher the extent of self-reported risk-taking in adolescents (e.g., Reyna et al., 2011). Conversely, inducing categorical some-none thinking about the gist of risks (e.g., of HIV or pregnancy from unprotected sex) was found to reduce adolescents' self-reported risk-taking in a randomized experiment with a one-year follow-up (Reyna & Mills, 2014). We present framing decisions in the deletion and standard conditions in the current study, which should produce a variety of choices for behavioral and brain analyses. Extending developmental predictions of FTT, some of these patterns of choices are compatible with immature response tendencies of risk takers (sure choices for losses and risky choices for gains) and others are incompatible (sure choices for gains and risky choices for losses). Thus, behavioral risk-taking is expected to correlate with framing-inconsistent choices (i.e., reverse framing) and overriding these response tendencies to make framing-consistent choices may require cognitive effort.

Neural Substrates of Risk Taking and Crime

Prior research identifies several brain circuits that would be expected to covary with criminal and noncriminal risk-taking. Neurodevelopmental theories of risk-taking implicate subcortical circuitry, especially amygdala and striatum, in either valence-specific processes (amygdala as negative, striatum as positive; Ernst et al., 2005) or as promoting cue-triggered motivated behavior regardless of positive or negative valence (Casey et al., 2016).

Developmental differences in engagement of these emotional and motivational systems may underlie the peak in risk-taking in adolescence and young adulthood (e.g., Galvan et al., 2007). Our developmental immaturity approach to adult risk-taking suggests that similar systems may be activated in criminal decision-making. Consistent with this approach, studies have identified differences in the size and functioning of the amygdala among those engaged in criminal behavior (compared to those not engaged), along with lower sensitivity to fear, and, thus, presumably to negative consequences associated with crime (see Glenn & Raine, 2014). Similarly, resting-state connectivity analyses have shown greater connectivity between the amygdala (as a seed region) and the right middle frontal gyrus, left cingulate gyrus, left precuneus and right inferior parietal lobule in risk-taking adolescents than in non-risk-taking adolescents (Dewitt, Aslan, & Filbey, 2014).

In opposition to such emotional and motivational systems, cortical circuits, especially medial and lateral prefrontal cortex (mPFC and lPFC) and the anterior cingulate cortex (ACC), have been associated with emotional regulation and self-control, and would be expected to be less engaged in criminal risk takers. Consistent with this view, in one study, prisoners with lower ACC activity during an inhibitory-control task were twice as likely to reoffend four years after they left prison, as compared with prisoners with higher ACC activity (Aharoni et al., 2013).

Also, an area that is not central to neurodevelopmental or dual/triadic models of risk-taking, the parietal cortex (including precuneus), has long been associated with decision-making and shown to predict risk preferences (Clithero & Rangel, 2013; Gilaie-Dotan et al., 2014; Huettel, Stowe, Gordon, Warner, & Platt, 2006; Louie & Glimcher, 2010; Platt & Glimcher, 1999; Sugrue, Corrado, & Newsome, 2004). Another such area, the insula, is predominantly

active in the presence of potential losses (Mohr, Biele, & Heerkeren, 2010) and when decision makers try to minimize losses in risky decisions (Venkatraman, Rosati, Taren, & Huettel, 2009). Thus, decision neuroscience research suggests that, in addition to the interplay of hot risk-promoting and cold risk-inhibiting circuits, activation of parietal cortex (and for losses, insula) may reflect mental representations of risk used in decision-making.

In drawing on neurodevelopmental theory and other prior research on risk-taking, it is important to distinguish psychological states, such as sensation-seeking, and the neural processes believed to underlie these states (e.g., striatal and orbitofrontal systems of reward sensitivity; Abler, Walter, Erk, Kammerer, & Spitzer, 2006; Leyton et al., 2002; Shulman et al., 2016). Neurobiological phenomena are expected to have psychological manifestations, some of which can be measured via self-reports and behavioral assessments. Thus, as in prior work, we use self-reports of sensation-seeking as an overarching label for the inclination to pursue "varied, novel, complex, and intense sensations and experiences and the willingness to take physical, social, legal, and financial risks for the sake of such experiences" (Zuckerman, 1994, p. 26). We also include measures of cognitive processes that have been predicted to inhibit unwarranted risk-taking and framing biases, such as objective numeracy (the ability to understand and use numbers) and cognitive reflection (the ability to reflect on and inhibit cognitive biases), both of which correlate with general intelligence (Frederick, 2005; Liberali, Reyna, Furlan, Stein, & Pardo, 2012; Peters et al., 2006).

Summary

In sum, reviews of real-world risk taking and of laboratory studies indicate that some risk takers trade off risks and rewards, applying thinking that is characteristic of younger people. That is, they make finer distinctions among magnitudes of risk and reward, and are more willing

to take risks when they offer the potential for larger gains. In contrast, adults who are typically risk-avoidant for gains tend to make simpler gist distinctions, for example, between gaining something versus nothing. These verbatim-versus-gist thinking tendencies can be assessed using risky-choice tasks, which predict real-world risk-taking and produce robust effects in incentive-compatible study designs (when real money is at stake; e.g., Galvan et al., 2007; Lejuez, Aklin, Zvolensky, & Pedulla, 2003; Reyna & Ellis, 1994). Therefore, in the current study, we expect that self-reported risk-taking in adults should be related to immature risk preferences called "reverse framing" that reflect cognitive representations of risky decisions. Moreover, we distinguish between criminal and noncriminal risk-taking to test neurodevelopmental hypotheses about reactive mechanisms in subcortical circuits involving the amygdala and striatum as well as cognitive representational mechanisms in prefrontal and parietal cortices.

Specifically, we investigate the following hypotheses:

1. Self-reported risky behavior should be associated with sensation seeking and, thus, with neural substrates of "hot" cognition, such as emotional reactivity and reward sensitivity;
2. Self-reported risky behavior should also reflect "cold" cognition and, thus, the neural substrates of risk preferences arrived at through a greater emphasis on verbatim rather than gist processing. Consequently, neural activation should covary with criminal behavior when subjects make framing-inconsistent choices because such choices are associated with verbatim processing, and therefore more unhealthy risk-taking regarding crime;
3. When activation is greater for those with greater levels of criminal behavior in traditional framing-consistent contrasts, this activation may be in areas of the brain involved in cognitive control and inhibition. This is because individuals with a tendency to rely on verbatim processing need to exert cognitive control to go against their natural tendency and

choose options consistent with bottom-line gist-based processing (i.e., framing-consistent decisions).

Materials and Methods

Subjects

Subjects were thirty-two healthy, right-handed adults recruited from the Columbia University campus and surrounding region (New York, NY). Subjects ranged in age from 18-35 (M = 22.88, SD = 4.74) and 56.3% were female. Subjects self-identified as Caucasian (46.9%), African American (12.5%) and Hispanic (12.5%). Subjects were screened to exclude left handedness, psychiatric disorder, current use of psychoactive medications, head trauma with loss of consciousness, learning disability, current serious medical problems, premature birth, current pregnancy, or serious physical handicap preventing completion of study tasks. Safety exclusions included history of surgery involving metal implants, possible metal fragments in the eyes, braces, pacemaker, pregnancy, a history of claustrophobia, or weight over 220 lbs. Age was restricted to between 12 and 45 years; the upper age limit guarded against cognitive decline (Brainerd, Reyna, & Howe, 2009). The study was conducted with the approval of the Institutional Review Boards at both Cornell and Columbia universities. All subjects provided informed consent and were compensated with a fixed payment. One subject did not complete behavioral survey questions (e.g., on criminal behaviors).

Procedure

After providing informed consent, subjects received disambiguation instructions and examples to ensure that they did not make assumptions that might alter the numerical value of truncated risky options (see Chick, Reyna, & Corbin, 2015). Additional instructions and examples were provided if subjects misunderstood instructions. A questionnaire ensured

comprehension of these disambiguation instructions. Subjects then completed a set of 60 risky-choice framing problems in an fMRI scanner, and then answered survey questions and other behavioral assessments outside of the scanner (e.g., on sensation seeking and risk-taking). A second ambiguity check followed the framing task.

Materials

Risky-choice framing problems. Risky-choice framing problems were modeled after the Asian Disease Problem: "Imagine the U.S. is preparing for the outbreak of an unusual Asian disease, which is expected to kill 600 people. Indicate the option you prefer: a) 200 people saved for sure, or b) 1/3 probability 600 saved, 1/3 probability none saved." (Tversky & Kahneman, 1986). The framing problems followed a 2x2x3x5 within-subjects design with frame (gain, loss), content (lives and other valued outcomes or money), truncation (verbatim such that thezero part of the risky option was deleted; standard such that both parts of the risky option are present; and gist such that thenonzero part of the risky option was deleted) and replication (five different problems all with the same structure) as factors. For each choice problem, subjects were presented with a preamble in which such outcomes as lives or money were at stake, and asked to make a decision between a sure and risky choice of equal expected value.

Truncation. Keeping the sure option constant, the risky option was manipulated to present only the zero complement in the gist-emphasis condition (e.g. 1/3 probability none saved), only the nonzero complement in the verbatim-emphasis condition (e.g., 1/3 probability 600 saved), or both complements in the mixed condition (e.g., 1/3 probability 600 saved, 1/3 probability none saved) in which both gist and verbatim processes are emphasized. The zero complement is the outcome in which no one is saved or nothing is won (in the gain frame) or no one dies or nothing is lost (in the loss frame).

Problem sets. A total of 120 framing problems were divided into two sets of 60 problem. The gain and loss framed versions of each problem appeared in different stimulus sets, so that no subject received both the gain and loss versions of the same problem. Problems were presented in a pseudorandom order, such that the same problem could not appear twice in a row. Problems were presented in two pseudorandomized and counterbalanced runs of 11 minutes and 20 seconds each.

Trial sequence. The timing of scenarios and decision screens was based on repeated piloting and feedback from subjects to ensure that subjects were able to read the scenarios and respond within the allotted time. During imaging, all problems were presented in an event-related design. Each trial included presentation of a fixation cross (4.5 s), followed by the problem preamble (7 s), the presentation of the sure and the gamble option (up to 8 s, during which subjects entered their selection via button press), and a confidence rating for their choice ("How confident are you in your decision?" with response from 1 [not at all] to 5 [completely], up to 3 s). The decision phase (sure vs. gamble option) lasted only until a response was entered, at which point the next screen (confidence rating) appeared. This usually took less than the allotted 8 s. Similarly, the confidence phase lasted only until the subject entered a rating, at which point the next trial began. The other phases (fixation cross and problem preamble) did not vary in duration. Stimuli were delivered using the Presentation software (Neurobehavioral Systems Inc., Albany, CA, 2010; www.neurobs.com). Subjects viewed the stimuli via a projector and a mirror attached to their head coil, and they indicated their responses using a five-button MRI-compatible keypad operated with their right hand.

Image acquisition. Imaging was conducted using a 1.5 Tesla General Electric Signa MRI scanner (GE Healthcare, Waukesha, Wisconsin) equipped with an 8-channel head coil

(High-Resolution Head Coil, Rev. 4; Invivo, Gainesville, FL). Whole-brain blood oxygen-dependent (BOLD) functional images were acquired using a T2*-weighted, bottom-up, interleaved sequence. The parameters were as follows: repetition time (TR) = 2000 ms; echo time (TE) = 35 ms; flip angle = 84 degrees; field of view (FOV) = 22.4 cm; matrix size = 64 x 64. There were 340 volumes acquired during each of our two runs, each volume contained 27 slices and had a slice thickness of 4 mm (gap=0 mm) and an in-plane resolution of 3.5 × 3.5 mm. Structural images were acquired with a T1-weighted spoiled gradient recalled (SPGR) sequence (TR = 19 ms, TE = 5 ms, flip angle = 20, FOV = 25.6 cm) recording 180 slices with a slice thickness of 1 mm and an in-plane resolution of 1x1 mm.

Questions about engagement in risk taking. After imaging, subjects answered questions from a risk questionnaire used with adolescents and adults, including questions about their engagement in criminal and noncriminal behaviors (Berns, Moore, & Capra, 2009; Gullone, Moore, Moss, & Boyd, 2000). Subjects were asked how often they had engaged in the following behaviors: smoking, roller blading, parachuting, speeding, tae kwon do fighting, staying out late, talking to strangers, flying in a plane, cheating, getting drunk, sniffing gas or glue, having unprotected sex, leaving school, teasing and picking on people (relational aggression), snow skiing, overeating, and entering a competition (all noncriminal), and drinking and driving, stealing cars and going for joy rides, underage drinking, driving without a license, and taking drugs (all criminal). Subjects answered on a four-point scale from “never done” to “done very often.” This resulted in an overall scale from 0 to 88, with 0 representing never having engaged in any of the behaviors, and 88 representing having engaged in all of the behaviors very often (α = .572), a criminal risk-taking scale with scores from 0 to 20 (α = .393), and a noncriminal risk-taking scale with scores from 0 to 68 (α = .439).

Hence, noncriminal risky behavior included substance use that is not criminal (e.g., getting drunk, sniffing gas or glue), relational aggression, and other risky but not criminal behaviors (e.g., unprotected sex). Criminal risky behavior included substance use that crossed the line into criminal behavior (e.g., drinking and driving, taking illegal drugs), aggression against others (e.g., theft), and other risky criminal behaviors. Therefore, there was some overlap in categories across noncriminal versus criminal behavior, such as substance use; items of both types ranged in severity although, naturally, the criminal behaviors were more extreme. One author is a licensed attorney who verified the noncriminal versus criminal status of each behavior.

Subjects also answered other questions (some to be published elsewhere), including those to assess objective numeracy (the Lipkus Peters Objective Numeracy Scale; Peters, Dieckmann, Dixon, Hibbard, & Mertz, 2007), sensation seeking (the Sensation Seeking Scale; Zuckerman, 1994), reflection (the Cognitive Reflection Test [CRT]; Frederick, 2005), and alcohol use (the World Health Organization Alcohol Use Disorders Identification Test [AUDIT]).

Behavioral Data Analysis

Choice. Subjects selected between two options (sure or risky) on each decision problem. Initial analyses focused on choices that subjects made (sure or risky for each problem) as they varied across truncation (verbatim, mixed, gist) and frame (gain, loss); lives versus money and replications did not differ significantly across truncation or frame and responses were summed across these factors.

Framing index. A framing index was calculated as the average number of risky choices in the loss frame minus the average number of risky choices in the gain frame. The index ranged from all framing-consistent choices to all framing-inconsistent choices. Thus, a positive framing

index indicates a standard framing effect and a negative framing index indicates a reverse framing effect.

fMRI Data Analysis

Preprocessing. Each subject's anatomical images were skull stripped in AFNI using 3DSkullStrip (Cox, 1996), and functional images were masked using 3DAutomask. Subsequent preprocessing was completed using SPM8 (Wellcome Department of Imaging Neuroscience, London, UK, 2009; www.fil.ion.ucl.ac.uk/spm) implemented in MATLAB R2012b (MathWorks, Natick, Massachusetts, USA: Ged Ridgway, http://www.cs.ucl.ac.uk/staff/g.ridgway/vbm/get_totals.m). The first four acquisitions were discarded to allow for T1-equilibration effects. Preprocessing in SPM8 began with slice-timing correction to adjust for differences in timing of the interleaved slice acquisition. Images were then realigned to correct for head movement. Four subjects were eliminated for excessive motion in any direction; thus, no subject exceeded 2.5mm head motion. Realigned images were then coregistered and normalized to the EPI Montreal Neurological Institute (MNI) template. Smoothing was applied to the normalized images with an 8mm full-width half-maximum (FWHM) Gaussian kernel. Images were also individually screened for scan stability (< 2.5mm head movement) and imaging artifacts to ensure data quality.

Covariate analysis. Voxelwise whole-brain covariate analyses were conducted with our previously defined set of *a priori* contrasts in order to test modulation of BOLD signal by differences in self-reported criminal and noncriminal risky behavior. The framing contrast (Framing>Reverse Framing) was defined as (collapsing across the three truncation manipulations) activation when choosing the sure option in the gain frame plus activation when choosing the risky option in the loss frame minus activation when making the opposite choices:

(GainSure + LossRisky) - (LossSure + GainRisky). The opposite framing-inconsistent contrast (Reverse Framing>Framing) was also examined, again collapsing across the three truncation manipulations. We also analyzed the three truncation conditions separately and combined each of the two truncation conditions with the mixed (nothing deleted) condition, for example, (GistGainSure + Mixed GainSure + GistLossRisky + MixedLossRisky) – (GistLossSure + MixedLossSure + GistGainRisky + MixedGainRisky). Finally, we analyzed gain and loss choices separately that were either framing-consistent (e.g., LossRisky - LossSure, and GainSure - GainRisky) or framing-inconsistent (e.g., LossSure – LossRisky, and GainRisky – GainSure).

Cluster detection threshold was set at $p < .001$. Cluster-level results were examined at a Family Wise Error (FWE)-corrected threshold of $p < .05$ to account for multiple comparisons. Results significant for both peaks and clusters are designated by bolding in the tables. All coordinates are reported in MNI space.

Results

Behavioral Results

ANOVA. We first conducted a repeated-measures ANOVA to examine the effects of each of our manipulations (frame and truncation) on decisions in the risky-choice framing task. This analysis yielded a main effect of frame, $F(1,31) = 52.7$, $p < .001$, $\eta_p^2 = .629$, such that subjects picked the risky option more in the loss frame and the sure option more in the gain frame (choosing the risky option 32% of the time in the gain frame, and 61% of the time in the loss frame). The analysis also revealed an interaction between frame and truncation, $F(2,30) = 18.4$, $p < .001$, $\eta_p^2 = .550$ (Figure 1). Pairwise comparisons show a significant framing effect in the gist condition ($p < .001$, $d = 2.28$) and mixed condition ($p < .001$, $d = .996$), but no significant

framing effect in the verbatim condition (p = .408, d = .192). The largest framing effect was in the gist condition.

Subjects were generally confident about their choices, averaging 3.76 on a 1-5 scale, and were slightly more confident in the gist (nonzero-deleted) than verbatim (zero-deleted) conditions; mixed was in the middle. Signed confidence ANOVAs and correlations were also conducted in which confidence ratings were multiplied by 1 if a subject chose the risky option, but by -1 if they chose the sure option. Similar factors were significant in the signed-confidence and choice analyses, indicating that choices did not reflect mere guessing (a confidence rating of 1). Because results are similar for choice and signed confidence, only choice results are reported in detail below.

Criminal and noncriminal risky behavior. Total observed scores on the self-reported risky behavior scale ranged from 37 to 64, M = 49.74, SD = 6.22. The criminal risky behavior scale ranged from 5 to 14, M = 9.03, SD = 2.30. The noncriminal risky behavior scale ranged from 32 to 50, M = 40.71, SD = 4.87. The sensation seeking scale ranged from 4 to 19, M = 10.48, SD = 3.73. The objective numeracy scale ranged from 0 to 9 correct, M = 7.97, SD = 1.82. The CRT ranged from 0 to 3 correct, M = 1.45, SD = 1.09. The AUDIT ranged from 0 to 14, M = 6.65, SD = 3.78.

To test hypotheses about adult risk-taking, we correlated the number of gain and loss risky choices as well as the overall framing index with total self-reported risk-taking. Although the correlation of total risk-taking with risky choices for gains was positive and for losses was negative, only the framing index (losses – gains) was significant (r = -.376, p = .044). That is, the greater the extent of reverse framing, the more frequently subjects engaged in risky behaviors overall.

The pattern of correlations with gain, loss, and framing scores was similar for the AUDIT scale but did not reach significance (e.g., framing index, r = -.296, p = .106). Like risky behaviors, sensation seeking correlated negatively with the framing index (r = -.488, p=.005), but it also correlated significantly with risky choices for gains (r = .417, p =.019). Sensation seeking, total risky behavior, and AUDIT all correlated significantly with one another: sensation seeking-AUDIT was .384 (p = .033), sensation seeking-total risky behavior was .411 (p = .022), and total risky behavior-AUDIT was .673 (p <.001). Thus, risky choices in the framing decisions correlated as predicted with self-reported real-world risk-taking.

When we scored criminal and noncriminal risk-taking separately, noncriminal risk-taking missed significance for the framing index (r = -.333, p = .068) but was significant for the signed confidence framing index (r = -.377, p = .037) and it also correlated positively with sensation seeking (r = .423, p = .018) and with AUDIT (r = .560, p = .001). Criminal risk-taking also correlated positively with AUDIT (r = .502, p =.004). Criminal risk-taking did not correlate significantly with framing indexes or sensation seeking.

Correlations with ONS and CRT were near zero for total risk-taking. Correlations of criminal and noncriminal risk-taking separately with ONS and CRT were also each close to zero.

Covariation of Neural Activation with Criminal and Noncriminal Risky Behavior

We examined how activation (BOLD signal) in the brain for different types of decisions varied as a function of noncriminal and criminal risky behavior scores. The complete significant covariate results, including visual and motor areas, can be found in Tables 1S, 2S, and 3.

Non-criminal risky-behavior scores. All significant covariations with noncriminal risky-behavior scores were in framing-inconsistent contrasts (Table 1). One cluster, in the Verbatim + Mixed GainRisky > Verbatim + Mixed GainSure contrast, had a *peak* that also

survived family-wise error correction, meaning activation in both the cluster and peak itself had activation that significantly increased as noncriminal risky behavior increased. This cluster had a peak in the amygdala and also extended into the striatum (putamen) and hippocampus (Figure 2).

Criminal risky-behavior scores.

Framing-inconsistent contrasts. In our framing-inconsistent contrasts, we first looked for activations in our overall contrasts (contrasts that were not specific to the gist, mixed, or verbatim conditions): LossSure>LossRisky, GainRisky>GainSure, and Reverse Framing>Framing. None of these overall contrasts showed activations that increased as criminal behavior increased. We then looked at our more specific contrasts (including activations only in a specific truncation condition or a combination of mixed and each deletion), and found activation that significantly covaried with criminal behavior in multiple clusters across five contrasts (Verbatim Reverse Framing > Gist Framing, Mixed Reverse Framing > Gist Framing, Gist Reverse Framing > Gist Framing, Gist + Mixed LossSure > Gist + Mixed LossRisky, and Gist LossSure > Gist LossRisky) (Table 2). Across four of our five contrasts, activations in parietal areas increased as criminal behavior increased. In Gist LossSure > Gist LossRisky, activation in a cluster including the inferior parietal lobule (IPL), temporal gyri, and the insula increased as criminal behavior increased (Figure 3). This cluster encompassed the anterior temporal parietal junction. Both the cluster itself and the peak of this cluster (in the angular gyrus of the IPL) survived FWE correction.

In the Gist + Mixed LossSure > Gist + Mixed LossRisky contrast, which subsumes the cluster above, activation in a cluster containing the IPL and insula increased as criminal behavior increased. For this contrast, activation in the anterior cingulate cortex also increased as criminal behavior increased. In two of our three Reverse Framing > Framing contrasts (Mixed Reverse

Framing > Gist Framing, and Gist Reverse Framing > Gist Framing), we observed clusters of activation in the right supramarginal gyrus and right angular gyrus of the IPL that increased as criminal behavior increased, extending into the temporal gyri.

Framing-consistent contrasts. Fewer clusters of activation increased as criminal behavior increased in framing-consistent contrasts (Table 3). Again, we first looked for activations in our overall contrasts (LossRisky > LossSure, GainSure > GainSure, and Framing > Reverse Framing). Activation in one of these contrasts covaried with criminal behavior: LossRisky > LossSure (Figure 2S). In this contrast, activation in the pre-supplementary motor area (SMA) increased as criminal behavior increased. In order to check whether this effect was driven by the fact that the contrast involved framing or the fact that the contrast involved choosing the risky option, we examined the corresponding framing-consistent contrast in the gain frame (GainSure > GainRisky) and the corresponding risky contrast in the gain frame (GainRisky > GainSure). Neither of these contrasts showed significant activations that increased with criminal behavior when correcting for FWE. (When not correcting for FWE, activation in a cluster in the left pre-supplementary motor area, 38 voxels of activation with a peak at -4 20 48, increased as criminal behavior increased in the GainSure > GainRisky contrast.) Activation in this area did not increase as criminal behavior increased in the GainRisky > GainSure contrast.

We then examined more specific contrasts (including activations only in a specific truncation) and found covariation with criminal behavior in one of them (Table 3). This was the condition in which we encouraged verbatim thinking: Verbatim LossRisky > Verbatim LossSure. In this contrast, two clusters of activation increased as criminal behavior increased – one cluster in the right dlPFC and one cluster in the left dlPFC (Figure 4). In order to check whether this effect was driven by the fact that the contrast involved framing or the fact that the

contrast involved choosing the risky option in the verbatim frame, we examined the corresponding framing contrast in the gain frame (Verbatim GainSure > Verbatim GainRisky) and the corresponding risky contrast in the gain frame (Verbatim GainRisky > Verbatim GainSure). In the Verbatim GainSure > Verbatim GainRisky contrast, when not correcting for FWE, activation in a cluster in the left dlPFC (79 voxels of activation with a peak at -16 42 30) increased as criminal behavior increased. There was no increase in the risky contrast.

Discussion

Criminal behavior involves inherent risk, notably, the risk of legal sanctions. Typically, those who engage in crime are aware of these sanctions, but pursue rewards, such as "joy" riding (stealing cars) or the highs of substance use despite the potential penalties. Noncriminal behavior--smoking, drunkenness, and unprotected sex—can also incur risks. Two routes to risk-taking have been identified in prior work with adolescents: a "hot" route that involves emotional reactivity and reward sensitivity and a "cold" reasoned route that involves trading off magnitudes of risk and reward (Reyna & Farley, 2006). The current study provides evidence for distinct neural and behavioral substrates for both types of risk-taking in adults.

Noncriminal risk-taking correlated with sensation seeking and substance use (using an established measure of alcohol dependence), and covaried with activation in emotion and reward areas of the brain. Criminal risk-taking correlated to a similar degree with substance use, but covaried with activation in risk preference areas of the brain that also support magnitude comparisons (i.e., the inferior parietal cortex, including the supramarginal and angular gyri; Huettel et al., 2006), as well as with the right temporal parietal junction (rTPJ) that has been associated with moral and social cognition (both anterior and posterior rTPJ were activated as indicated in Table 2; Krall et al., 2015). Noncriminal risk-taking was not entirely hot, even

though it covaried with activation in emotion and reward areas, to the extent that behavioral choices (see below) and activation of superior and inferior parietal cortices can be taken to imply a cognitive evaluation of risk and reward (Table 1; see Reyna et al., 2011). Criminal risk-taking was apparently not entirely cold either; activation of the insula was correlated with criminal behavior when the sure loss was chosen, consistent with experiencing loss aversion (e.g., DeMartino, Harrison, Knafo, Bird, & Dolan, 2008). Thus, higher risk-taking was associated with choosing the sure loss, perhaps despite experiencing some negative affect when doing so (but reverse inferences from brain to behavior should be made with caution; Poldrack, 2006).

For criminal risk-taking, we also observed activation of areas related to anti-social behavior in prior work, such as the superior temporal gyrus, angular gyrus, insula (Table 2) and dlPFC (Table 3; see Glenn & Raine, 2014, for an overview). The amygdala/hippocampus, also previously associated with anti-social behavior, was activated in noncriminal risk-taking that included anti-social behavior, such as relational aggression (i.e., teasing and picking on people). Taken as a whole, our results suggest that the broader category of anti-social behaviors, which encompasses criminal and non-criminal risk-taking, may result from different kinds of developmental delays in emotionally reactive and cognitive representational systems.

For both types of risk-taking, behavior correlated negatively with the framing index, indicating that higher levels of risky behavior were related to risky choices that reflected a reverse-framing pattern rarely observed in non-disordered adults. The predominant and most reliable brain results also were obtained when subjects chose in accordance with reverse framing: choosing risky gains (Table 1) or sure losses (Table 2). Criminal and noncriminal risk-taking did not vary with proxy measures for general intelligence or inhibition in this sample. According to fuzzy-trace theory, reverse-framing choices not only reflect the pull of rewards (in choosing the

risky gains option with larger rewards), but also a way of thinking about risk and reward that makes the sure loss more attractive than the risky loss because it is smaller. This focus on precise, quantitative comparisons between options (modulated by both outcomes and probabilities, as demonstrated in prior work) stands in stark contrast to the simple qualitative comparisons that mature adults make between gaining or losing something versus nothing.

The kind of verbatim processing that emphasizes literal and precise details is eschewed by most mature adults when decisions have potentially life-altering consequences. Developmentally advanced adults typically rely more on gist, such as simple but meaningful categorical contrasts between options, and thereby avoid low-probability but potentially catastrophic consequences. In this sense, gist thinking is thought to have a protective effect in that it reduces unhealthy or negative outcomes. The relative reliance on verbatim versus gist thinking in risky decision-making can be assessed using traditional framing tasks that pit sure options against risky ones because they reveal a cognitive bias to process gist that deviates from rational, objective thinking. For most people, this bias grows from childhood to adulthood, so that their decision processes become progressively more technically irrational but globally adaptive.

Representations of Risk: Behavioral Results

Although many of the results we have discussed are correlational (with the limitations of such designs), it is useful to note that we provided an experimental test of our processing explanations, demonstrating effects in this sample, and these experimental manipulations of frame and truncation (Figure 1) were incorporated in our behavioral and brain analyses. Theoretically motivated manipulations of gist and verbatim processing were successful in making traditional framing effects grow and shrink, respectively, collectively producing a wide

range of variability in risky choices. These results buttress FTT's explanation that risk preferences have to do, in part, with thinking that emphasizes tradeoffs between risk and reward as opposed to simple gist categories, such as gaining something rather than nothing (Kühberger & Tanner, 2010). The manipulations induce ways of thinking that have been shown to be related to real-world risk taking in domains other than criminal risk-taking (Blalock & Reyna, 2016; Broniatowski, Klein, & Reyna, 2015; Fraenkel et al., 2012, 2015; Reyna & Mills, 2014; Reyna et al., 2015; Wolfe et al., 2015).

With respect to criminal risk-taking, reliance on gist representations should have a protective effect in reducing criminal behavior when risks are low and benefits are high, as they often are (e.g., the risk of arrest from a single instance of drunk driving; Matsueda, 2013). Individuals relying on gist tend to engage in categorical thinking, such as it only takes once to get caught. In contrast, verbatim thinking promotes risk-taking because benefits offset risks. Although both verbatim and gist representations of decision options are typically encoded so that gist thinkers process the low risks and high rewards, mature adults nevertheless rely more on the simple bottom line.

Here, we have argued that adult risk-takers, including those whose risk-taking ventures into crimes, exhibit an immature verbatim way of thinking exemplified in laboratory tasks as reverse framing—preferring sure losses and risky gains—because of greater emphasis on surface details, such as quantitative differences in potential outcomes. As predicted, we observed significant correlations between this pattern of behavioral choices in the laboratory and self-reported risky behavior. Also as expected, greater sensation seeking (i.e., reward sensitivity) was related to risking seeking for gains because the risky option offered larger rewards, replicating prior research (Reyna et al., 2011). However, behavioral and brain covariation results cannot be

explained solely by reference to reward sensitivity: Overall risk-taking was not associated with either risk seeking for gains nor risk avoidance for losses by themselves and preferences for sure losses are not explained by reward sensitivity (Ernst et al., 2005).

Neural Activation Covaries with Self-reported Criminal Risk-taking

Our analyses revealed a greater number of significant results when examining the relationship between criminal behavior and neural activation in reverse-framing contrasts (than in framing-consistent contrasts), broadly supporting the prediction that verbatim cognitive processes are related to unhealthy risk-taking, such as crime.

Consistent with the behavioral results, noncriminal risk-taking was most reliably related to choices of the risky option in the gain frame (the option with the larger reward), covarying with areas previously associated with emotional reactivity (e.g., the amygdala) and reward sensitivity (e.g., striatal areas including putamen and caudate). This result is consistent with neurodevelopmental and dual/triadic systems approaches, suggesting that adult risk takers react much like adolescents when making risky choices for rewards (Casey et al., 2016; Shulman et al., 2016). Criminal risk-taking in our sample did not reliably covary with activation in the amygdala and striatum. Because our subjects were community dwelling rather than incarcerated, the latter result could be interpreted as supporting the argument that "successful" (not incarcerated) psychopaths are less likely to be impulsive reactive risk-takers, unlike unsuccessful ones (Gao & Raine, 2010).

As the frequency of self-reported criminal behavior increased, activation increased in areas normally associated with risk preferences, such as the parietal cortex, when subjects chose the sure loss (Gilaie-Dotan et al., 2014; Huettel et al., 2006). However, this activation was not especially posterior. Interestingly, activation extended to areas identified in moral cognition and

psychopathy, including the angular gyrus, superior temporal gyrus, and right temporal-parietal junction (Glenn & Raine, 2014; Harenski, Harenski, Shane, & Kiehl, 2010; Krall et al., 2015). Preferring sure losses may suggest less susceptibility to loss aversion or negative outcomes, consistent with prior research on criminality (again, despite some insula activation; Glenn & Raine, 2014; Pujara et al., 2013).

In sum, significant covariation in the brain was observed with risk-taking when choices were the reverse of traditional framing biases, consistent with cognitive representational as well as motivational mechanisms in brain and behavior. These results are unlikely to be due to differences in numeracy, intelligence, or cognitive reflection because such measures were not related to criminal or noncriminal risk-taking in this sample. However, reverse-framing contrasts were associated with increased activation in parietal areas of the brain (specifically the inferior parietal lobule, the supramarginal gyrus, and the angular gyrus). Previous research has associated parietal areas with number processing and numerical calculation (Dehaene, Piazza, Pinel, & Cohen, 2003; Kaufman, Wood, Rubinsten, & Henik, 2011; Kucian, von Aster, Loenneker, Dietrich, & Martin, 2008) and bilateral parietal activation during magnitude comparison (Chochon, Cohen, Van De Moortele, & Dehaene, 1999; Pinel, Dehaene, Riviere, & LeBihan, 2001; Pinel et al., 1999), which is consistent with verbatim processes of magnitude comparison and trading off of quantities of risk and reward.

Covariation in Framing-Consistent Contrasts

Although less reliable, there was some suggestion that criminal risk-taking was associated with suppressing preferred response tendencies (i.e., reverse framing) when choosing options that were instead consistent with traditional framing effects. That is, when making framing-consistent decisions, higher levels of criminal behavior were associated with increased

bilateral activation in the dlPFC in the Verbatim Loss Risk > Verbatim Loss Sure condition (a condition in which trading off was encouraged), and greater activation in the pre-SMA in the Loss Risk > Loss Sure condition. The dlPFC (Casey et al., 2016; Reyna & Huettel, 2014; Shulman et al., 2016) and the pre-SMA have been associated with inhibition and cognitive control (Barber, Caffo, Pekar, & Mostofsky, 2013; Mayka, Corcos, Leurgans, & Vailliancourt, 2006; Simmonds, Pekar, & Mostofsky, 2008; Swann et al., 2012). For example, dlPFC activity has been correlated with successful self-control (e.g. in go/no-go tasks; Casey et al., 2011; or when choosing between healthy and unhealthy goods; Hare, Camerer, & Rangel, 2009) and research suggests that increasing dlPFC activation reflects increased engagement of self-control (MacDonald, Cohen, Stenger, & Carter, 2000; Schonberg et al., 2012). This dlPFC activation increased with criminal behavior in the verbatim condition, which discourages framing, and where we could expect it to be especially difficult for those with higher levels of criminal behavior to frame. In other words, these are individuals who are not predisposed to frame in addition to being encouraged not to frame based on the verbatim truncation of the risky option. Thus, individuals who have a history of more criminal behavior may require greater cognitive control to engage in framing-consistent decisions associated with a healthy attitude to risk in prior studies.

Policy Implications

Some interventions to reduce crime have aimed at encouraging high-risk individuals to think "slowly" (see Heller et al., 2015). This approach is justified by neurodevelopmental theory, in which crime (especially adolescent crime) reflects an imbalance between "hot" motivational affective systems and "cold" deliberation and inhibition (Somerville & Casey, 2010; Steinberg, 2008). Our research suggests that mental representation (gist or verbatim) could also play an

important role in decisions to commit crime. Thus, while it is important to encourage inhibition, it may also be important to encourage reliance on qualitative gist representations in order to reduce the need for inhibition and, consequently, unwarranted risk-taking. This new approach has previously been applied effectively to reduce other kinds of unhealthy risk taking (e.g., for a review, see Blalock & Reyna, 2016). Cueing and practicing gist processing may help immature adults think about risky choices like neurotypical adults do—as simple decisions about what matters.

Context of Research

Most theories assume that cognitive biases, such as framing, are due to irrational decision processes. Developmental and individual differences are expected to reflect these processes: Younger people and adults who make poor decisions should therefore exhibit more biases. However, FTT predicts the opposite under specific circumstances, and research has borne this out: Children are less biased than adults, adolescents who take unhealthy risks are less biased than those who do not, and novices are less biased than experts in their domain of expertise. We wondered whether adults who make immature risky decisions and engage in criminal behavior would show a similar, developmentally delayed pattern of cognitive biases, which they did. At the level of brain and behavior, we hypothesized that risky behavior springs from cognitive differences in verbatim versus gist thinking about risk (reflected in a reversal of typical framing biases), as well as emotion and motivation. We varied whether thinking was biased by focusing on precise risk-reward tradeoffs (verbatim emphasis) or on simple categorical distinctions between options (e.g., getting something or risking getting nothing, a gist emphasis). In the brain, covariation with criminal and noncriminal risk-taking was observed when thinking veered away from typical adult biases based on gist. Noncriminal risk-taking behavior covaried with

activation in subcortical emotion and motivation areas (amygdala and striatum), whereas criminal behavior was associated with greater activation in temporal and parietal cortices, their junction, and insula, areas associated with risk preferences and psychopathy. Future research will examine whether these cognitive biases vary with psychopathy.

References

Abler, B., Walter, H., Erk, S., Kammerer, H., & Spitzer, M. (2006). Prediction error as a linear function of reward probability is coded in human nucleus accumbens. *NeuroImage, 31*(2), 790-795. doi: 10.1016/j.neuroimage.2006.01.001

Aharoni, E., Vincent, G. M., Harenski, C. L., Calhoun, V. D., Sinnott-Armstrong, W., Gazzaniga, M. S., & Kiehl, K. A. (2013). Neuroprediction of future rearrest. *Proceedings of the National Academy of Sciences, 110*(15), 6223-6228. doi: 10.1073/pnas.1219302110

Banich, M. T., Crowley, T. J., Thompson, L. L., Jacobson, B. L., Liu, X., Raymond, K. M., & Claus, E. D. (2007). Brain activation during the Stroop task in adolescents with severe substance and conduct problems: A pilot study. *Drug and Alcohol Dependence, 90*(2), 175-182. doi: 10.1016/j.drugalcdep.2007.03.009

Barber, A. D., Caffo, B. S., Pekar, J. J., & Mostofsky, S. H. (2013). Effects of working memory demand on neural mechanisms of motor response selection and control. *Journal of Cognitive Neuroscience*, *25*(8), 1235–1248. doi: 10.1162/jocn_a_00394

Berns, G. S., Moore, S., & Capra, C. M. (2009). Adolescent engagement in dangerous behaviors is associated with increased white matter maturity of frontal cortex. *PLoS One,* 4(8), e6773

Birbaumer, N., Veit, R., Lotze, M., Erb, M., Hermann, C., Grodd, W., & Flor, H. (2005). Deficient fear conditioning in psychopathy: a functional magnetic resonance imaging study. *Archives of General Psychiatry, 62*(7), 799-805. doi: 10.1001/archpsyc.62.7.799

Blalock, S. J., & Reyna, V. F. (2016). Using fuzzy-trace theory to understand and improve health judgments, decisions, and behaviors: A literature review. *Health Psychology: Official Journal of the Division of Health Psychology, American Psychological Association*, *35*(8), 781–792. doi: 10.1037/hea0000384

Brainerd, C. J., Reyna, V. F., & Howe, M. L. (2009). Trichotomous processes in early memory development, aging, and neurocognitive impairment: A unified theory. *Psychological Review*, *116*(4), 783-832. doi:10.1037/a0016963

Broniatowski, D. A., Klein, E. Y., & Reyna, V. F. (2015). Germs are germs, and why not take a risk? Patients' expectations for prescribing antibiotics in an inner-city emergency department. *Medical Decision Making: An International Journal of the Society for Medical Decision Making*, *35*(1), 60–67. doi: 10.1177/0272989X14553472

Buckholtz, J. W., Treadway, M. T., Cowan, R. L., Woodward, N. D., Benning, S. D., Li, R,…, & Smoth, C. E. (2010). Mesolimbic dopamine reward system hypersensitivity in individuals with psychopathic traits. *Nature Neuroscience, 13*(4), 419-421. doi: 10.1038/nn.2510

Carre, J. M., Hyde, L. W., Neumann, C. S., Viding, E., & Hariri, A. R. (2013). The neural signatures of distinct psychopathic traits. *Social Neuroscience, 8*(2), 122-135. doi: 10.1080/17470919.2012.703623

Casey, B. J., Galvan, A., & Somerville, L. H. (2016). Beyond simple models of adolescence to an integrated circuit-based account: A commentary. *Developmental Cognitive Neuroscience, 17*, 128-130. doi: 10.1016/j.dcn.2015.12.006

Casey, B.J., Somerville, L.H., Gotlib, I.H., Ayduk, O., Franklin, N.T., Askren, M.K., & Shoda, Y. (2011). Behavioral and neural correlates of delay of gratification 40 years later. *Proceedings of the National Academy of Sciences, 108(36),* 14998-15003. doi: 10.1073/pnas.1108561108

Chick, C.F., Reyna, V.R., Corbin, J. C. (2015). Framing effects are robust to linguistic disambiguation: A critical test of contemporary theory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, in press.

Chochon, F., Cohen, L., Van De Moortele, P. F., & Dehaene, S. (1999). Differential contributions of the left and right inferior parietal lobules to number processing. *Journal of Cognitive Neuroscience, 11*(6), 617-630. doi: 10.1162/089892999563689

Clithero, J. A., & Rangel, A. (2013). Informatic parcellation of the network involved in the computation of subjective value. *Social Cognitive and Affective Neuroscience, 9*(9), 1289-1302. doi: 10.1093/scan/nst106

Cohen, A.O. & Casey, B.J., (2014) Rewiring juvenile justice: The intersection of developmental neuroscience and legal policy. *Trends in Cognitive Sciences*, 18, 63-65.

Cohn, M. D., Veltman, D. J., Pape, L. E., van Lith, K., Vermeiren, R. R., van den Brink, W.,…& Popma, A. (2015). Incentive processing in persistent disruptive behavior and psychopathic traits: A functional Magnetic Resonance Imaging study in adolescents. *Biological Psychiatry, 78*(9), 615-624. doi: 10.1016/j.biopsych.2014.08.017

Corbin, J. C., Reyna, V. F., Weldon, R. B., & Brainerd, C. J. (2015). How reasoning, judgment, and decision making are colored by gist-based intuition: A fuzzy-trace theory approach. *Journal of Applied Research in Memory and Cognition, 4*, 344-355. doi: 10.1016/j.jarmac.2015.09.001

Cox, R. W. (1996). AFNI: software for analysis and visualization of functional magnetic resonance neuroimages. *Computers and Biomedical Research, 29*(3), 162-173. doi: 10.1006/cbmr.1996.0014

Defoe, I. N., Dubas, J. S., Figner, B., & Van Aken, M. A. (2015). The origins of probability

judgment: A review of data and theories. *Psychological Bulletin, 141*(1), 48-84. doi: 10.1037/a0038088

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20*(3-6), 487-506. doi: 10.1080/02643290244000239

DeMartino, B., Harrison, N. A., Knafo, S., Bird, G., & Dolan, R. J. (2008). Explaining enhanced logical consistency during decision making in autism. *Journal of Neuroscience*, *28*(42), 10746–10750. doi: 10.1523/JNEUROSCI.2895-08.2008

DeWitt, S. J., Aslan, S., & Filbey, F. M. (2014). Adolescent risk-taking and resting state functional connectivity. *Psychiatry Research: Neuroimaging, 222*(3), 157-164. doi: 10.1016/j.pscychresns.2014.03.009

Ernst, M., Nelson, E. E., Jazbec, S., McClure, E. B., Monk, C. S., Leibenluft, E., . . . Pine, D. S. (2005). Amygdala and nucleus accumbens in responses to receipt and omission of gains in adults and adolescents. *NeuroImage, 25*(4), 1279-1291. doi: 10.1016/j.neuroimage.2004.12.038

Fraenkel, L., Peters, E., Charpentier, P., Olsen, B., Errante, L., Schoen, R. T., & Reyna, V. (2012). Decision tool to improve the quality of care in rheumatoid arthritis. *Arthritis Care & Research*, *64*(7), 977–985. doi: 10.1002/acr.21657

Fraenkel, L., Matzko, C. K., Webb, D. E., Oppermann, B., Charpentier, P., Peters, E., … Newman, E. D. (2015). Use of decision support for improved knowledge, values clarification, and informed choice in patients with rheumatoid arthritis. *Arthritis Care & Research*, *67*(11), 1496–1502. doi: 10.1002/acr.22659

Frederick, S. (2005). Cognitive reflection and decision making. *The Journal of Economic*

Perspectives, 19(4), 25-42. doi: 10.1257/089533005775196732

Freeman, S. M., Clewett, D. V. Bennett, C. M., Kiehl, K. A., Gazzaniga, M. S., & Miller, M. B. (2015). The posteromedial region of the default mode network shows attenuated task-induced deactivation in psychopathic prisoners. *Neuropsychology, 29*(3), 493-500. doi: 10.1037/neu0000118

Galvan, A., Hare, T. A., Voss, H., Glover, G., & Casey, B. J. (2007). Risk-taking and the adolescent brain: Who is at risk? *Developmental Science, 10,* F8–F14.

Gao, Y., & Raine, A. (2010). Successful and unsuccessful psychopaths: a neurobiological model. *Behavioral Sciences & the Law*, *28*(2), 194–210. doi: 10.1002/bsl.924

Gilaie-Dotan, S., Tymula, A., Cooper, N., Kable, J. W., Glimcher, P. W., & Levy, I. (2014). Neuroanatomy predicts individual risk attitudes. *Journal of Neuroscience*, *34*(37), 12394-12401. doi: 10.1523/JNEUROSCI.1600-14.2014

Glenn, A. L., & Raine, A. (2014). Neurocriminology: implications for the punishment, prediction and prevention of criminal behaviour. *Nature Reviews Neuroscience, 15*, 54-63. doi: 10.1038/nrn3640

Gullone, E., Moore, S., Moss, S., & Boyd, C. (2000). The Adolescent Risk-Taking Questionnaire: Development and psychometric evaluation. *Journal of Adolescent Research*, *15*(2), 231-250. doi:10.1177/0743558400152003

Hare, T. A., Camerer, C. F., & Rangel, A. (2009). Self-control in decision-making involves modulation of the vmPFC valuation system. *Science, 324*(5927), 646-648. doi: 10.1126/science.1168450

Harenski, C. L., Harenski, K. A., Shane, M. S., & Kiehl, K. A. (2010). Aberrant neural

processing of moral violations in criminal psychopaths. *Journal of Abnormal Psychology*, *119*(4), 863–874. doi: 10.1037/a0020979

Heller, S. B., Shah, A. K., Guryan, J., Ludwig, J., Mullainathan, S., Pollack, H. A. (2015). Thinking fast and slow? Some field experiments to reduce crime and dropout in Chicago. *National Bureau of Economic Research.*

Huettel, S. A., Stowe, C. J., Gordon, E. M., Warner, B. T., & Platt, M. L. (2006). Neural signatures of economic preferences for risk and ambiguity. *Neuron*, *49*(5), 765–775. doi: 10.1016/j.neuron.2006.01.024

Kaufman, L., Wood, G., Rubinsten, O., & Henik, A. (2011). Meta-analyses of developmental fMRI studies investigating typical and atypical trajectories of number processing and calculation. *Developmental Neuropsychology, 36*(6), 763-787. doi: 10.1080/87565641.2010.549884

Krall, S. C., Rottschy, C., Oberwelland, E., Bzdok, D., Fox, P. T., Eickhoff, S. B., … Konrad, K. (2015). The role of the right temporoparietal junction in attention and social interaction as revealed by ALE meta-analysis. *Brain Structure & Function*, *220*(2), 587–604. doi: 10.1007/s00429-014-0803-z

Kucian, K., von Aster, M., Loenneker, T., Dietrich, T., & Martin, E. (2008). Development of neural networks for exact and approximate calculation: A fMRI study. *Developmental Neuropsychology, 33*(4), 447-473.

Küberger, A., & Tanner, C. (2010). Risky choice framing: Task versions and a comparison of prospect theory and fuzzy-trace theory. *Journal of Behavioral Decision Making, 23(3),* 314-329. doi: 10.1002/bdm.656

Kwak, Y., Payne, J.W., Cohen, A.L., & Huettel, S.A. (2015). The rational adolescent: Strategic information processing during decision making revealed by eye tracking. *Cognitive Development, 36,* 20-30. doi:10.1016/j.cogdev.2015.08.001

Larson, C. L., Baskin-Sommers, A. R., Stout, D. M., Balderston, N. L., Curtin, J. J., Schultz, D. H.,…, & Newman, J. P. (2013). The interplay of attention and emotion: top-down attention modulates amygdala activation in psychopathy. *Cognitive, Affective, & Behavioral Neuroscience, 13*(4), 757-770. doi: 10.3758/s13415-013-0172-8

Lejuez, C. W., Aklin, W. M., Zvolensky, M. J., & Pedulla, C. M. (2003). Evaluation of the balloon analogue risk task (BART) as a predictor of adolescent real-world risk-taking behaviors. *Journal of Adolescence, 26,* 475–479. doi:10.1016/S0140-1971(03)00036-8

Levin, I. P., Bossard, E. A., Gaeth, G. J., & Yan, H. (2014). The combined role of task, child's age and individual differences in understanding decision processes. *Judgment and Decision Making*, *9*(3), 274.

Levin, I. P., Gaeth, G. J., Schreiber, J., & Lauriola, M. (2002). A new look at framing effects: Distribution of effect sizes, individual differences, and independence of types of effects. *Organizational Behavior and Human Decision Processes, 88*, 411–429.

Levin, I. P., & Hart, S. S. (2003). Risk preferences in young children: early evidence of individual differences in reaction to potential gains and losses. *Journal of Behavioral Decision Making, 16*(5), 397-413. doi: 10.1002/bdm.453

Leyton, M., Boileau, I., Benkelfat, C., Diksic, M., Baker, G., & Dagher, A. (2002). Amphetamine-induced increases in extracellular dopamine, drug wanting, and novelty seeking: A PET/[11C]Raclopride study in healthy men. *Neuropsychopharmacology, 27*, 1027-1035. doi: 10.1016/S0893-133X(02)00366-4

Liberali, J. M., Reyna, V. F., Furlan, S., Stein, L. M., & Pardo, S. T. (2012). Individual differences in numeracy and cognitive reflection, with implications for biases and fallacies in probability judgment. *Journal of Behavioral Decision Making, 25*(4), 361-381. doi: 10.1002/bdm.752

Louie, K., & Glimcher, P. W. (2010). Separating value from choice: delay discounting activity in the lateral intraparietal area. *The Journal of Neuroscience, 30*(16), 5498-5507. doi: 10.1523/JNEUROSCI.5742-09.2010

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science (New York, N.Y.)*, *288*(5472), 1835–1838.

Marsh, A. A., & Cardinale, E. M. (2012), When psychopathy impairs moral judgments: neural responses during judgments about causing fear. *Social Cognitive and Affective Neuroscience, 9*(1), 3-11. doi: 10.1093/scan/nss097

Matsueda, R. L. (2013). Rational Choice Research in Criminology: A Multi-Level Framework. In R. Wittek, T. Snijders, & V. Nee (Eds.), *The Handbook of Rational Choice Social Research* (pp. 283-321). Palo Alto, CA: Stanford University Press.

Mayka, M. A., Corcos, D. M., Leurgans, S. E., & Vaillancourt, D. E. (2006). Three-dimensional locations and boundaries of motor and premotor cortices as defined by functional brain imaging: a meta-analysis. *NeuroImage*, *31*(4), 1453–1474. doi: 10.1016/j.neuroimage.2006.02.004

Mills, B., Reyna, V.F., & Estrada, S. (2008). Explaining contradictory relations between risk perception and risk taking. *Psychological Science, 19(5),* 429-433. doi: 10.1111/j.1467-9280.2008.02104.x

Moffitt, T. E. (1993). Adolescence-limited and life-course-persistent antisocial behavior: a developmental taxonomy. *Psychological Review*, *100*(4), 674. doi: 10.1037/0033-295X.100.4.674

Mohr, P. N., Biele, G., & Heekeren, H. R. (2010). Neural processing of risk. *The Journal of Neuroscience, 30*(19), 6613-6619. doi: 10.1523/JNEUROSCI.0003-10.2010

Peters, E., Västfjäll, D., Slovic, P., Mertz, C. K., Mazzocco, K., & Dickert, S. (2006). Numeracy and decision making. *Psychological Science*, *17*(5), 407–413. doi: 10.1111/j.1467-9280.2006.01720.x

Peters, E., Dieckmann, N., Dixon, A., Hibbard, J. H., & Mertz, C. K. (2007). Less is more in presenting quality information to consumers. *Medical Care Research and Review: MCRR*, *64*(2), 169–190. doi: 10.1177/1077558707064002030l

Pinel, P., Dehaene, S., Riviere, D., & LeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *Neuroimage, 14*(5), 1013-1026. doi: 10.1006/nimg.2001.0913

Pinel, P., Le Clec'H G., Van de Moortele, P. F., Naccache, L., Le Bihan, D., & Dehane, S. (1999). Event related fMRI analysis of the cerebral circuit for number comparison. *Neuroreport, 10*(7), 1473-1479.

Platt, M. L., & Glimcher, P. W. (1999). Neural correlates of decision variables in parietal cortex. *Nature, 400*, 233-238. doi: 10.1038/22268

Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in Cognitive Sciences*, *10*(2), 59–63. doi: 10.1016/j.tics.2005.12.004

Pujara, M., Motzkin, J. C., Newman, J. P., Kiehl, K. A., & Koenigs, M. (2013). Neural correlates of reward and loss sensitivity in psychopathy. *Social Cognitive and Affective Neuroscience, 9*(6), 794-801. doi: 10.1093/scan/nst054

Pujol, J., Baralla, I., Contreras-Rodriguez, O., Harrison, B. J., Pera, V., Hernandez-Ribas, R.,…,& Lopez-Sola, M. (2012). Breakdown in the brain network subserving moral judgment in criminal psychopathy. *Social Cognitive and Affective Neuroscience, 7*(8), 917-923. doi: 10.1093/scan/nsr075

Reyna, V.F. (2012). A new intuitionism: Meaning, memory, and development in fuzzy-trace Theory. *Judgment and Decision Making, 7(3),* 332-359.

Reyna, V. F., & Brainerd, C. J. (1994). The origins of probability judgment: A review of data and theories. In G. Wright & P. Ayton (Eds.), Subjective probability (pp. 239-272). New York: Wiley.

Reyna, V.F., & Brainerd, C.J. (2011). Dual processes in decision making and developmental neuroscience: A fuzzy-trace model. *Developmental Review, 31(2),* 180-206. doi: 10.1016/j.dr.2011.07.004

Reyna, V. F., & Casillas, W. (2009). Development and dual processes in moral reasoning: A fuzzy-trace theory approach. *Psychology of Learning and Motivation, 50*, 207-236. doi: http://doi.org/10.1016/S0079-7421(08)00407-6

Reyna, V.F., Chick, C.F., Corbin, J.C., & Hsia, A.N. (2014). Developmental reversals in risky decision making, intelligence agents show larger decision biases than college students. *Psychological Science,* 2013. doi: 10.1177/0956797613497022

Reyna, V.F., & Ellis, S.C. (1994). Fuzzy-trace theory and framing effects in children's risky decision making. *Psychological Science, 5(5),* 275-279. doi: 10.1111/j.1467-9280.1994.tb00625.x

Reyna, V.F., Estrada, S.M., DeMarinis, J.A., Myers, R.M., Stanisz, J.M., & Mills, B.A. (2011). Neurobiological and memory models of risky decision making in adolescents versus young adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37(5),* 1125-1142. doi: 10.1037/a0023943

Reyna, V. F., & Farley, F. (2006). Risk and rationality in adolescent decision making: implications for theory, practice, and public policy. *Psychological Science in the Public Interest, 7*(1), 1-44. doi: 10.1111/j.1529-1006.2006.00026.x

Reyna, V.F., & Huettel, S.A. (2014). Reward, representation, and impulsivity: A theoretical framework for the neuroscience of risky decision making. In V.F. Reyna & V. Zayas (Eds.). *The Neuroscience of Risky Decision Making* (pp. 11-42). Washington, DC: American Psychological Association.

Reyna, V. F., & Mills, B. A. (2014). Theoretically motivated interventions for reducing sexual risk taking in adolescence: A randomized controlled experiment applying fuzzy-trace theory. *Journal of Experimental Psychology: General, 143*(4), 1627-1648. doi: 10.1037/a0036717

Reyna, V. F., Wilhelms, E. A., McCormick, M. J., & Weldon, R. B. (2015). Development of risky decision making: Fuzzy-trace theory and neurobiological perspectives. *Child Development Perspectives, 9*(2), 122-126. doi: 10.1111/cdep.12117

Schlottmann, A. (2001). Children's probability intuitions: Understanding the expected value of complex gambles. *Child Development, 72,* 103–122.

Schonberg, T., Fox, C. R., Mumford, J. A., Congdon, E., Trepel, C., & Poldrack, R. A. (2012). Decreasing ventromedial prefrontal cortex activity during sequential risk-taking: An fMRI investigation of the balloon analog risk task. *Frontiers in Neuroscience, 6*(80). doi: 10.3389/fnins.2012.00080

Shannon, B. J., Raichle, M. E., Snyder, A. Z., Fair, D. A., Mills, K. L., Zhang, D., ... Kiehl, K. A. (2011). Premotor functional connectivity predicts impulsivity in juvenile offenders. *Proceedings of the National Academy of* Sciences *of the* United *States of America, 108,* 11241-11245. doi: l0.1073/pnas.1108241108

Shulman, E.P., Smith, A.R., Silva, K., Icenogle, G., Duell, N., Chein, J., & Steinberg, L. (2016). The dual systems model: Review, reappraisal, and reaffirmation. *Developmental Cognitive Neuroscience*, *17*, 103-117. http://dx.doi.org/10.1016/j.dcn.2015.12.010

Simmonds, D. J., Pekar, J. J., & Mostofsky, S. H. (2008). Meta-analysis of Go/No-go tasks demonstrating that fMRI activation associated with response inhibition is task-dependent. *Neuropsychologia*, *46*(1), 224–232. doi: 10.1016/j.neuropsychologia.2007.07.015

Somerville, L.H., & Casey, B.J. (2010). Developmental neurobiology of cognitive control and motivational systems. *Current Opinion in Neurobiology, 20(2),* 236-241. doi: 10.1016/j.conb.2010.01.006

Steinberg, L. (2008). A social neuroscience perspective on adolescent risk taking. Developmental Review, *28 (1)*, 78–106. doi: 10.1016/j.dr.2007.08.002

Sugrue, L. P., Corrado, G. S., & Newsome, W. T. (2004). Matching behavior and the representation of value in the parietal cortex. *Science, 304*(5678), 1782-1787. doi: 10.1126/science.1094765

Swann, N. C., Cai, W., Conner, C. R., Pieters, T. A., Claffey, M. P., George, J. S., … Tandon, N.

(2012). Roles for the pre-supplementary motor area and the right inferior frontal gyrus in stopping action: electrophysiological responses and functional and structural connectivity. *NeuroImage*, *59*(3), 2860–2870. doi: 10.1016/j.neuroimage.2011.09.049

Sweeten, G., Piquero, A. R., & Steinberg, L. (2013). Age and the explanation of crime, revisited. *Journal of Youth and Adolescence, 42*(6), 921-938. doi: 10.1007/s10964-013-9926-4

Tversky, A., & Kahneman, D. (1986). Rational choice and the framing of decisions. *Journal of Business, 59(4),* S251-S278.

Venkatraman, V., Rosati, A. G., Taren, A. A., & Huettel, S. A. (2009). Resolving response, decision, and strategic control: Evidence for a functional topography in dorsomedial prefrontal cortex. *The Journal of Neuroscience, 29*(42), 13158-13164. doi: 10.1523/JNEUROSCI.2708-09.2009

Weller, J. A., Levin, I. P., & Denburg, N. L. (2011). Trajectory of risky decision making for potential gains and losses from ages 5 to 85. *Journal of Behavioral Decision Making, 9,* 331–344.

White, C. M., Gummerum, M. and Hanoch, Y. (2015). Adolescents' and young adults' online risk taking: The role of gist and verbatim representations. *Risk Analysis, 35*, 1407–1422. doi:10.1111/risa.12369

Wolfe, C. R., Reyna, V. F., Widmer, C. L., Cedillos, E. M., Fisher, C. R., Brust-Renck, P. G., & Weil, A. M. (2015). Efficacy of a web-based intelligent tutoring system for communicating genetic risk of breast cancer: a fuzzy-trace theory approach. *Medical Decision Making: An International Journal of the Society for Medical Decision Making*, *35*(1), 46–59. doi: 10.1177/0272989X14535983

Zuckerman, M. (1994). *Behavioral Expressions and Biosocial Bases of Sensation Seeking*. Cambridge: Cambridge University Press.

Table 1: Noncriminal Risky Behavior Covariate Clusters Surviving Family Wise Error Correction

Contrast	**Area of Brain (AAL Label)**	**Brodmann/Anatomical Areas**	**Voxels in Label**	**Mean *t***	**Voxels in Cluster**	**Co-ordinates (Peak) *X Y Z***
Verbatim Reverse Framing> Mixed Framing	Putamen_L	Putamen, 13.	12	3.7834	208	-26 0 26
	Caudate_L		7	3.5373		
Verbatim + Mixed GainRisky >	**Amygdala_L**	**Amygdala,**	**50**	**4.0243**	**251**	**-30 -4 -12**
Verbatim + Mixed GainSure	**Hippocampus_L**	**Putamen**	**36**	**3.7481**		
	Putamen_L		**32**	**4.1887**		
	Insula_L		**3**	**3.6548**		
	Palidum_L		**3**	**3.7653**		
	Caudate_L	Putamen, 12,	43	4.1363	455	-30 -10 22
	Insula_L	Caudate Body	34	3.8145		
	Putamen_L		22	3.6735		
	Thalamus_L		4	3.7344		
	Rolandic_Oper_R		1	3.5890		
	Postcentral_L	7, 40, 5, 3, 4	160	3.9278	448	-30 -38 54
	Parietal_Sup_L		97	3.8155		
	Parietal_Inf_L		43	3.7032		
	Precuneus_L		38	3.6232		
	Precentral_L		2	3.4137		
	Postcentral_R	31, 40, 5, 3, 7	159	3.8297	449	18 -30 42
	Cingulum_Mid_R		33	3.9148		
	Parietal_Sup_R		17	3.6393		
	Parietal_Inf_R		8	3.7366		
	Precuneus_R		7	3.6776		
	Supramarginal_R		5	3.7826		
	Cuneus_L	Corpus	29	4.0793	292	-20 -54 26
	Precuneus_L	Callosum,	7	3.7125		
	Angular_L	31	3	3.4382		

Note: AAL = Anatomical Automatic Labeling. Clusters in bold indicate that the cluster peak is also significant after family wise error correction.

Table 2: Criminal Risky Behavior Covariate Clusters Surviving Family Wise Error Correction in Framing Inconsistent Contrasts

Contrast	**Area of Brain (AAL Label)**	**Brodmann/Anatomical Areas**	**Voxels in Label**	**Mean *t***	**Voxels in Cluster**	**Co-ordinates (Peak) *X Y Z***
Verbatim Reverse Framing > Gist Framing	Temporal_Mid_R	13, 22, 41	123	3.9980	234	56 -50 14
	Temporal_Sup_R		94	3.7657		
Mixed Reverse Framing > Gist Framing	Angular_R	40,2,13	155	3.9114	350	54 -52 34
	SupraMarginal_R		122	3.6392		
	Temporal_Sup_R		31	3.5306		
	Temporal_Mid_R		25	3.5226		
	Parietal_Inf_R		10	3.6980		
Gist Reverse Framing>Gist Framing	Lingual_L	18,19,30,29	239	3.9010	285	-18 -58 -2
	Calcarine_L		39	3.6514		
	SupraMarginal_R	13	72	3.8875	244	48 -42 26
	Supramarginal Gyrus					
	Temporal_Sup_R		50	3.8162		
	Temporal_Mid_R		26	3.8924		
	Angular_R		20	3.6017		
Gist + Mixed LossSure > Gist + Mixed LossRisky	Anterior Cingulate	24,33,32	94	3.7784	239	4 30 4
	Extra Nuclear		56	3.8523		
	Cingulate Gyrus		16	3.6446		
	Inferior parietal lobule	40,2,13,1	219	3.8357	282	56 -34 28
	Postcentral Gyrus		46	3.7439		
	Insula		8	3.6120		
	Supramarginal Gyrus		8	3.6023		
Gist LossSure > Gist LossRisky	**Inferior Parietal Lobule**	**40,21,13,37,42,22,19,39**	**342**	**4.3882**	**1108**	**42 -46 18**
	Temporal_Mid_R		**269**	**4.1548**		
	Temporal_Sup_R		**173**	**4.1520**		
	Supramarginal_R		**139**	**4.0404**		
	Postcentral Gyrus		**87**	**4.2665**		
	Sub-Gyral		**52**	**4.6382**		
	Insula		**36**	**4.2253**		
	Middle Occipital Gyrus		**6**	**3.9825**		
	Temporal_Inf_R		**3**	**3.7031**		
	Precuneus	7,31,18,19,17	417	4.1080	890	-22 -58 18
	Cuneus		256	3.9605		
	Sub-gyral		164	4.5057		
	Posterior Cingulate		25	3.8609		
	Extra-Nuclear		16	4.1283		
	Middle Occipital Gyrus		12	3.7304		

Note: AAL = Anatomical Automatic Labeling. Clusters in bold indicate that the cluster peak is also significant after family wise error correction.

Table 3: Criminal Risky Behavior Covariate Clusters Surviving Family Wise Error Correction in Framing Consistent Contrasts

Contrast	**Area of Brain (AAL Label)**	**Brodmann/Anatomical Areas**	**Voxels in Label**	**Mean *t***	**Voxels in Cluster**	**Co-ordinates (Peak) *X Y Z***
LossRisky > LossSure	Pre-Supplementary Motor Area					
	Supp_Motor_Area_L	6,8,32	210	4.3855	229	-4 6 58
	Supp_Motor_Area_R		15			
Verbatim LossRisky >Verbatim LossSure	Right DLPFC	10		3.9996	199	36 54 8
	Frontal_Mid_R		158	4.0875		
	Frontal_Sup_R		41	3.9511		
	Left DLPFC	10, 46		3.9961	228	-34 54 14
	Frontal_Mid_L		222	3.9576		
	Frontal_Inf_Tri_L		6	3.6039		

Note: AAL = Anatomical Automatic Labeling. Clusters in bold indicate that the cluster peak is also significant after family wise error correction.

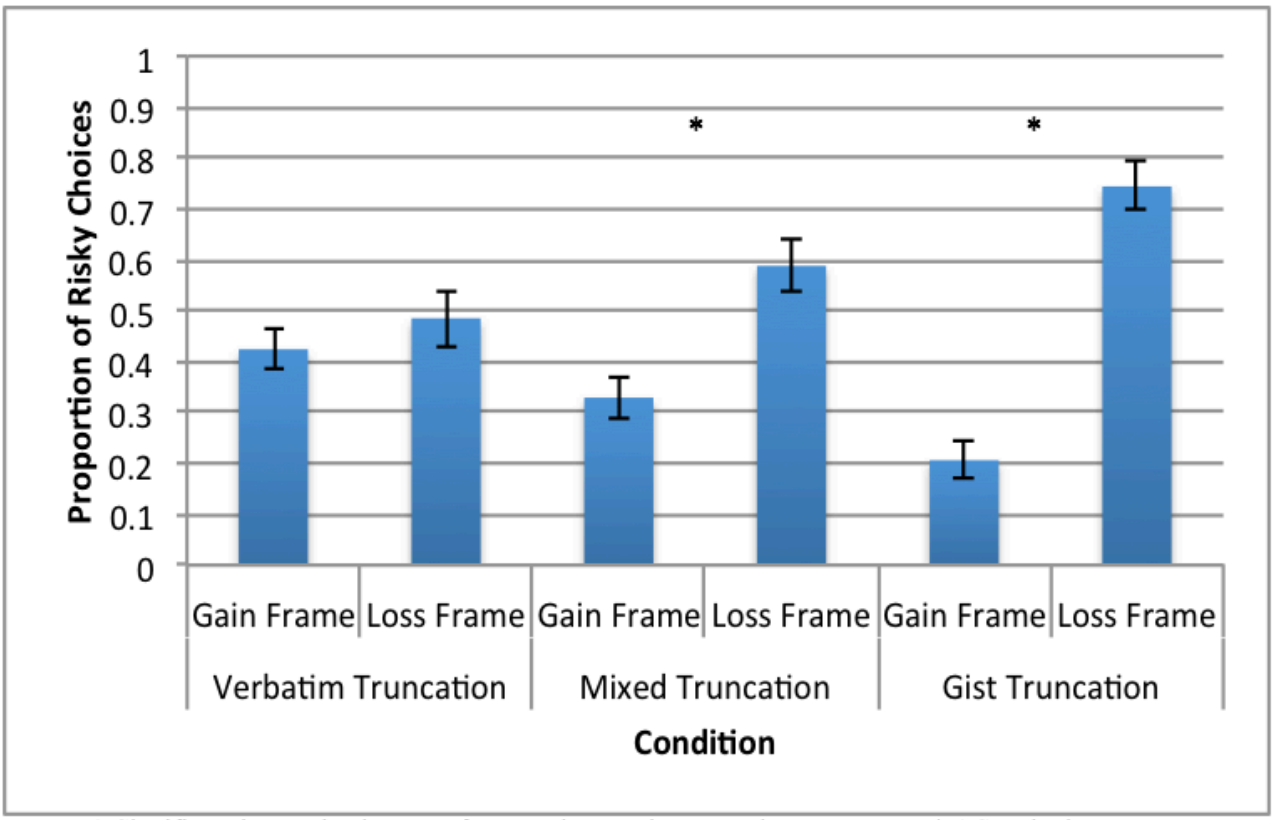


Figure 1. Significant interaction between frame and truncation. Error bars represent +/- 1 Standard Error.

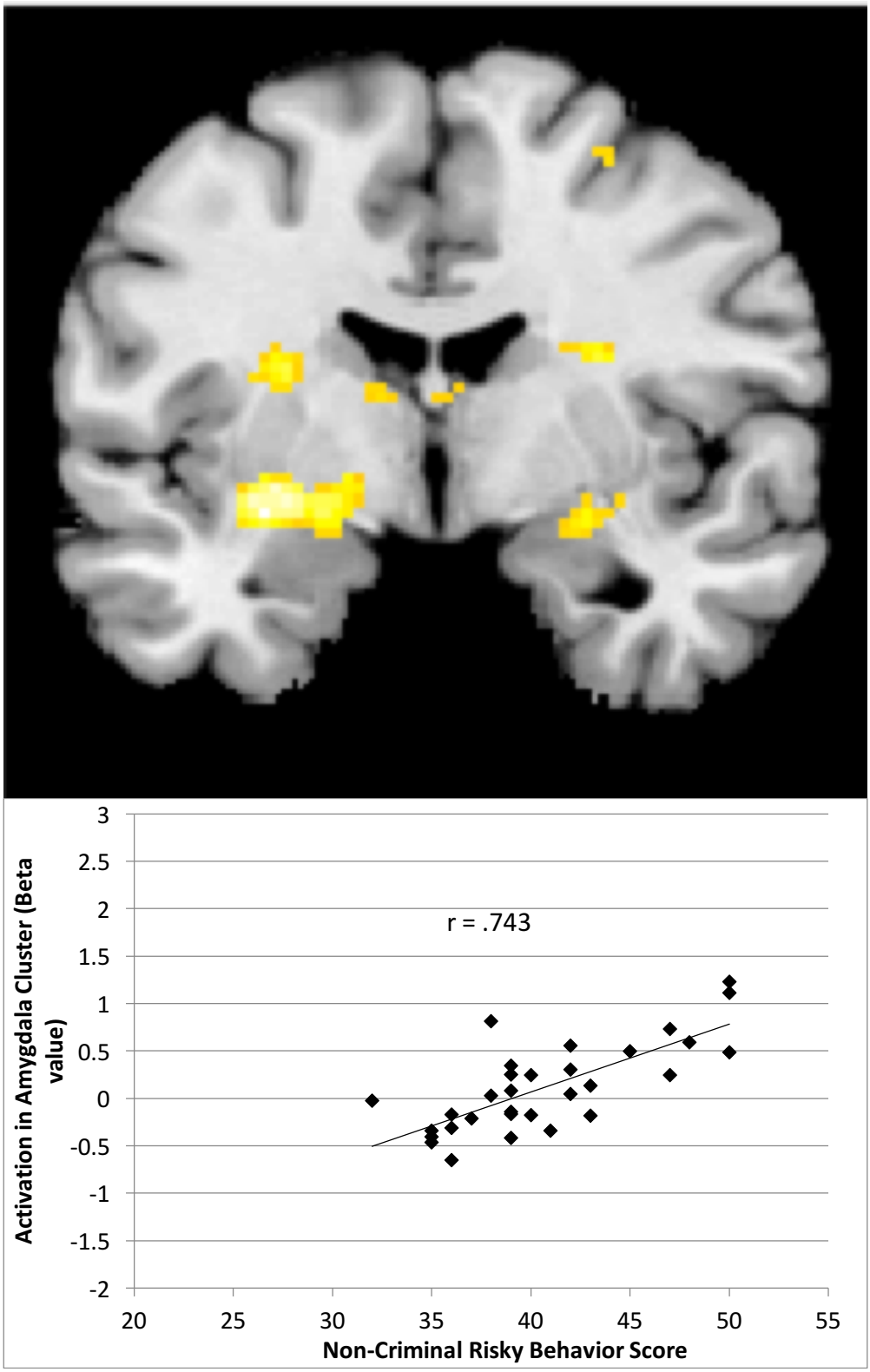


Figure 2: Covariation of cluster with peak in amygdala with noncriminal risky behavior in Verbatim + Mixed GainRisky > Verbatim + Mixed GainSure (activation at p<.001).

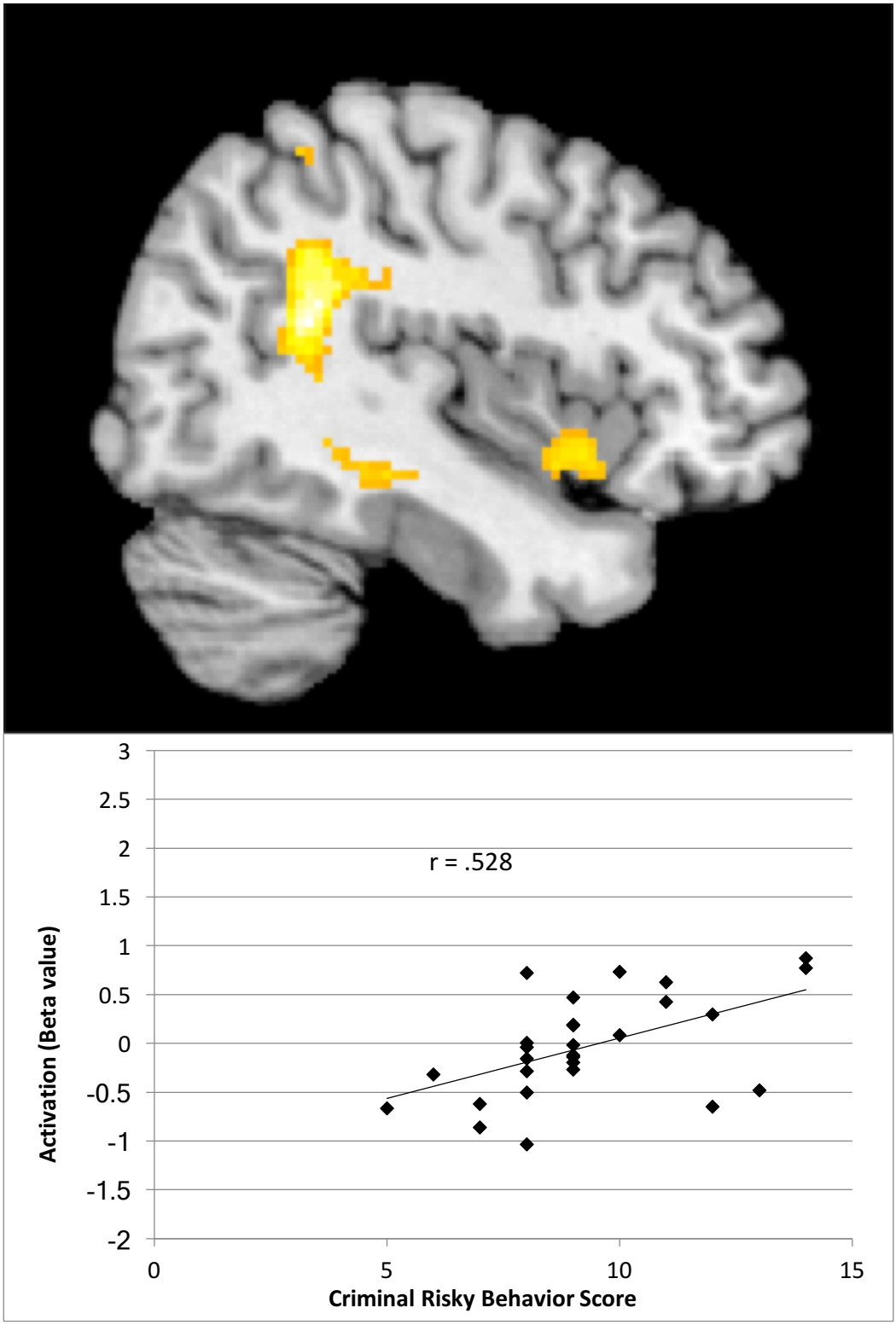


Figure 3: Covariation of parietal cluster with criminal risky behavior in Gist LossSure > Gist LossRisky (activation at p<.001).

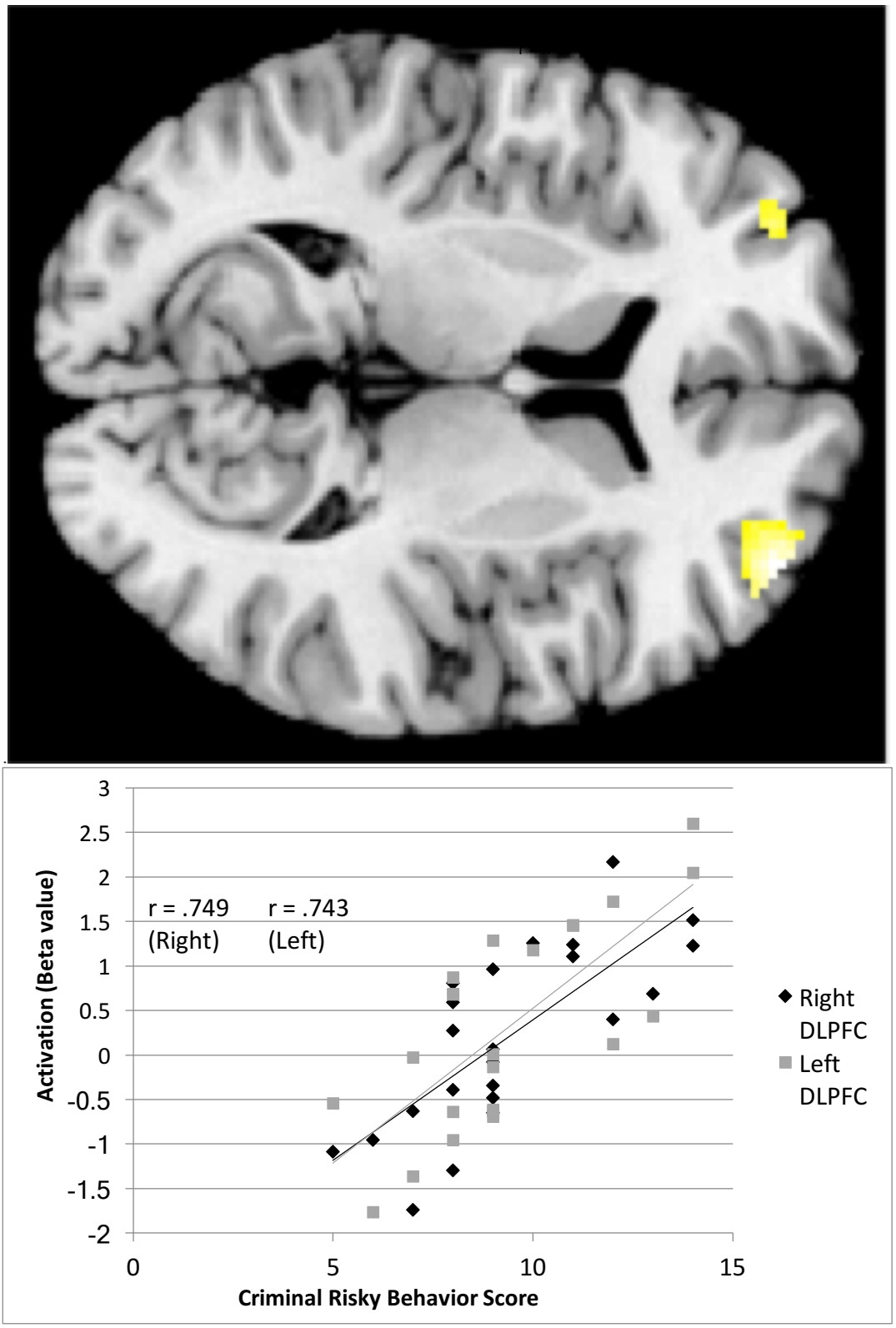


Figure 4. Covariation of activation in the left and right dlPFC with criminal risky behavior in Verbatim LossRisky > Verbatim LossSure (activation at p<.001).

Supplemental Materials

Table 1S: Noncriminal Risky Behavior Covariate Clusters Surviving Family Wise Error Correction

Contrast	Area of Brain (AAL Label)	Brodmann/Anatomical Areas	Voxels in Label	Mean *t*	Voxels in Cluster	Co-ordinates (Peak) *X Y Z*
Verbatim Reverse Framing> Mixed Framing	Putamen_L	Putamen, 13.	12	3.7834	208	-26 0 26
	Caudate_L		7	3.5373		
Verbatim + Mixed GainRisky > Verbatim + Mixed GainSure	**Amygdala_L**	**Amygdala,**	**50**	**4.0243**	**251**	**-30 -4 -12**
	Hippocampus_L	**Putamen**	**36**	**3.7481**		
	Putamen_L		**32**	**4.1887**		
	Insula_L		**3**	**3.6548**		
	Palidum_L		**3**	**3.7653**		
	Cerebelum_6_L	18, Dentate	259	3.7563	693	0 -78 -28
	Cerebelum_Crus1_L		120	3.5936		
	Vermis_7		101	4.0132		
	Vermis_6		100	4.0021		
	Cerebelum_6_R		37	3.7477		
	Cerebelum_Crus2_L		16	3.8476		
	Lingual_R		11	3.6369		
	Cerebelum_4_5_L		6	3.5223		
	Cerebelum_8_L		3	3.5397		
	Fusiform_L		2	3.5441		
	Vermis_8		2	3.5518		
	Cerebelum_Crus1_R		1	3.7766		
	Caudate_L	Putamen, 12, Caudate Body	43	4.1363	455	-30 -10 22
	Insula_L		34	3.8145		
	Putamen_L		22	3.6735		
	Thalamus_L		4	3.7344		
	Rolandic_Oper_R		1	3.5890		
	Postcentral_L	7, 40, 5, 3, 4	160	3.9278	448	-30 -38 54
	Parietal_Sup_L		97	3.8155		
	Parietal_Inf_L		43	3.7032		
	Precuneus_L		38	3.6232		
	Precentral_L		2	3.4137		
	Postcentral_R	31, 40, 5, 3, 7	159	3.8297	449	18 -30 42
	Cingulum_Mid_R		33	3.9148		
	Parietal_Sup_R		17	3.6393		
	Parietal_Inf_R		8	3.7366		
	Precuneus_R		7	3.6776		
	Supramarginal_R		5	3.7826		
	Cuneus_L	Corpus	29	4.0793	292	-20 -54 26

	Precuneus_L	Callosum,	7	3.7125		
	Angular_L	31	3	3.4382		
Gist LossSure > Gist LossRisky	Cerebelum_6_R	19	130	4.0668	247	18 -66 -16
	Cerebelum_4_5_R		77	3.7754		
	Vermis_4_5		18	3.7813		
	Lingual_R		11	3.8349		
	Fusiform_R		6	3.7065		
	Vermis_3		3	3.7686		
	Cerebelum_3_R		2	3.7343		

Note: AAL = Anatomical Automatic Labeling. Clusters in bold indicate that the cluster peak is also significant after family wise error correction.

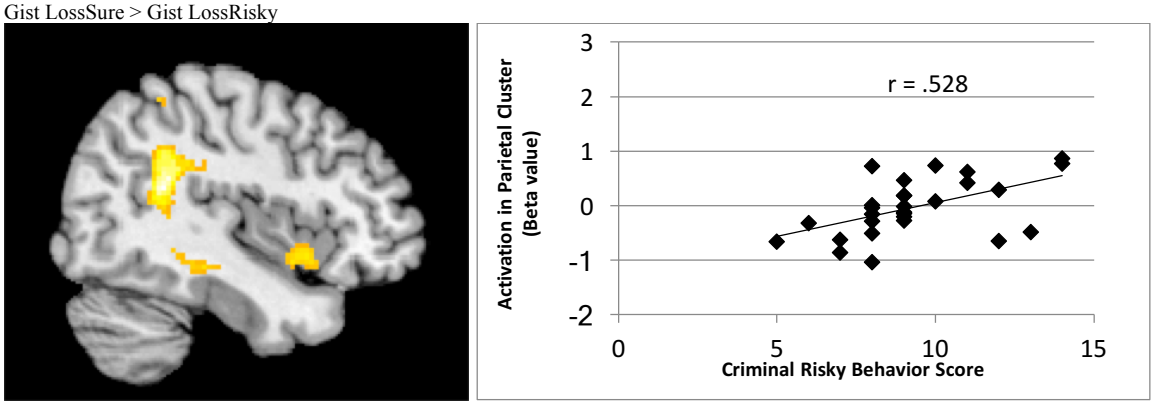
Table 2S: Criminal Risky Behavior Covariate Clusters Surviving Family Wise Error Correction in Framing Inconsistent Contrasts

Contrast	Area of Brain (AAL Label)	Brodmann/Anatomical Areas	Voxels in Label	Mean *t*	Voxels in Cluster	Co-ordinates (Peak) *X Y Z*
Verbatim Reverse Framing > Gist Framing	Temporal_Mid_R	13, 22, 41	123	3.9980	234	56 -50 14
	Temporal_Sup_R		94	3.7657		
	Lingual_R	19,18	243	3.7480	281	12 -48 -8
	Cerebelum_4_5_R		38	3.9250		
	Cuneus_R	18,7	270	3.6168	652	20 -72 24
	Calcarine_R		124	3.6829		
	Precuneus_R		94	3.6853		
	Cuneus_L		65	3.5374		
	Occipital_Sup_R		51	3.5327		
	Calcarine_L		37	3.5945		
Mixed Reverse Framing > Gist Framing	**Calcarine_L**	**18,17,23,30**	**242**	**4.1853**	**598**	**-10 -86 12**
	Calcarine_R		**138**	**3.8392**		
	Cuneus_L		**118**	**4.1180**		
	Cuneus_R		**51**	**3.8690**		
	Occipital_Supp_L		**42**	**3.6780**		
	Lingual_L		**6**	**3.4600**		
	Angular_R	40,2,13	155	3.9114	350	54 -52 34
	SupraMarginal_R		122	3.6392		
	Temporal_Sup_R		31	3.5306		
	Temporal_Mid_R		25	3.5226		
	Parietal_Inf_R		10	3.6980		
Gist Reverse Framing>Gist Framing	Lingual_L	18,19,30,29	239	3.9010	285	-18 -58 -2
	Calcarine_L		39	3.6514		
	Lingual_R		592	3.9693	2005	10 -74 32
	Cuneus_L		349	3.7861		
	Cuneus_R		337	4.0014		
	Calcarine_R		190	3.6840		
	Precuneus_R		136	3.9274		
	Calcarine_L		129	3.7136		
	Cerebelum_6_R		61	3.6693		
	Precuneus_L		52	3.7752		
	Occipital_Sup_L		48	3.8671		
	Cerebelum_4_5_R		33	3.5935		
	Vermis_6		31	3.6854		
	Fusiform_R		20	3.6440		
	Vermis_4_5		12	3.7008		
	Occipital_Mid_L		7	3.5691		
	SupraMarginal_R Supramarginal Gyrus	13	72	3.8875	244	48 -42 26
	Temporal_Sup_R		50	3.8162		
	Temporal_Mid_R		26	3.8924		
	Angular_R		20	3.6017		
Gist + Mixed LossSure > Gist + Mixed LossRisky	Anterior Cingulate	24,33,32	94	3.7784	239	4 30 4
	Extra Nuclear		56	3.8523		
	Cingulate Gyrus		16	3.6446		
	Sub-Gyral		1	3.4854		

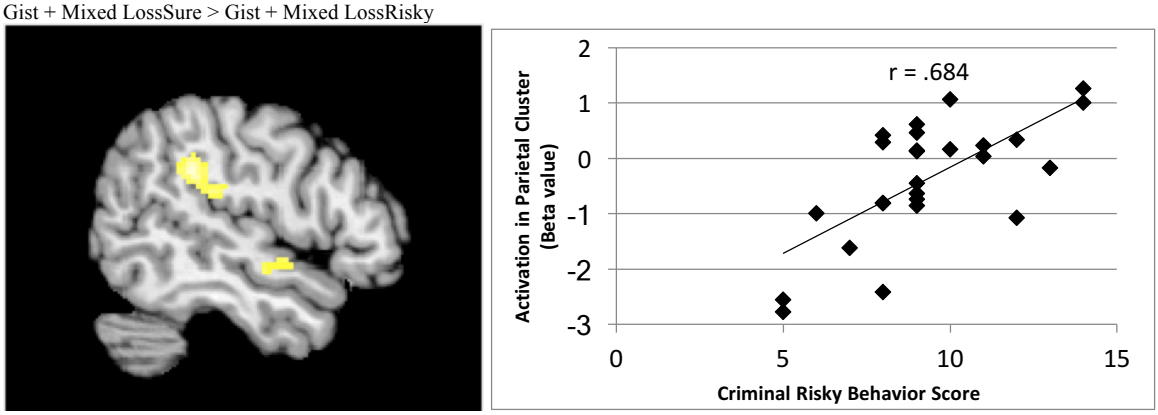
	Inferior parietal lobule	40,2,13,1	219	3.8357	282	56 -34 28
	Postcentral Gyrus		46	3.7439		
	Insula		8	3.6120		
	Supramarginal_R		8	3.6023		
	Temporal_Sup_R		1	3.5715		
	Lingual Gyrus	18,19	137	3.7783	231	14 -64 -4
	Culmen		21	3.6370		
	Declive		19	3.6911		
	Fusiform Gyrus		8	3.7005		
	Sub-gyral		3	3.5885		
	Cuneus		2	3.5443		
Gist LossSure > Gist LossRisky	**Inferior Parietal Lobule**		**342**	**4.3882**	**1108**	**42 -46 18**
	Temporal_Mid_R		**269**	**4.1548**		
	Temporal_Sup_R		**173**	**4.1520**		
	Supramarginal_R		**139**	**4.0404**		
	Postcentral Gyrus		**87**	**4.2665**		
	Sub-Gyral		**52**	**4.6382**		
	Insula		**36**	**4.2253**		
	Middle Occipital Gyrus		**6**	**3.9825**		
	Temporal_Inf_R		**3**	**3.7031**		
	Extra Nuclear		**1**	**3.7688**		
	Precuneus		417	4.1080	890	-22 -58 18
	Cuneus		256	3.9605		
	Sub-gyral		164	4.5057		
	Posterior Cingulate		25	3.8609		
	Extra-Nuclear		16	4.1283		
	Middle Occipital Gyrus		12	3.7304		

Note: AAL = Anatomical Automatic Labeling. Clusters in bold indicate that the cluster peak is also significant after family wise error correction.

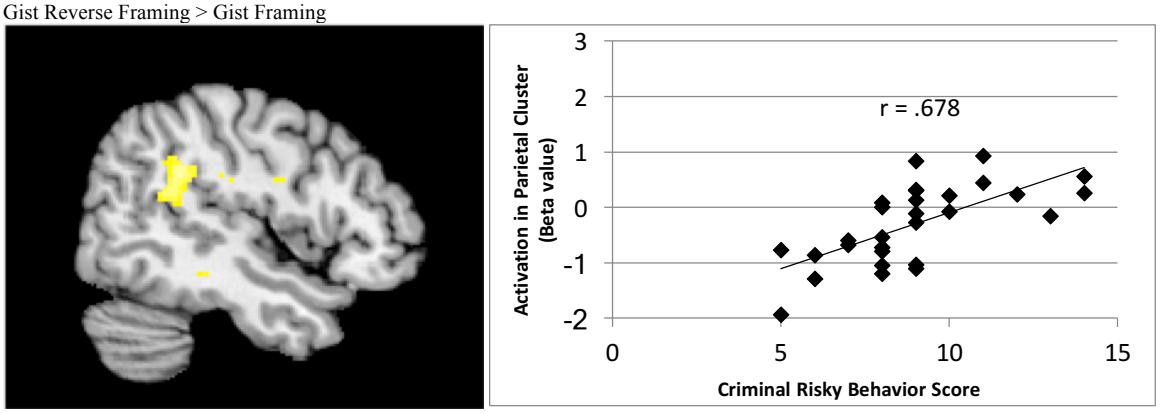
Gist LossSure > Gist LossRisky



Gist + Mixed LossSure > Gist + Mixed LossRisky



Gist Reverse Framing > Gist Framing



Mixed Reverse Framing > Gist Framing

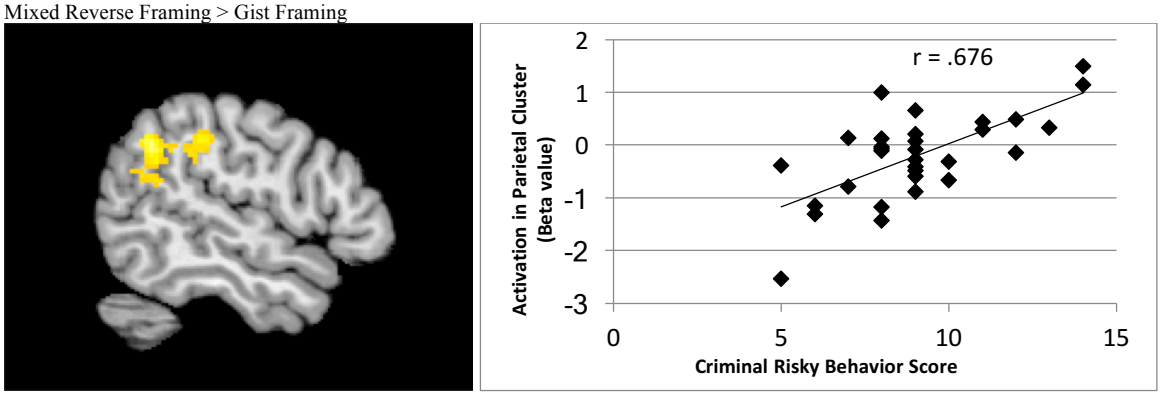


Figure 1S: Covariation of parietal activations with criminal behavior in framing-inconsistent contrasts (activation at p<.001).

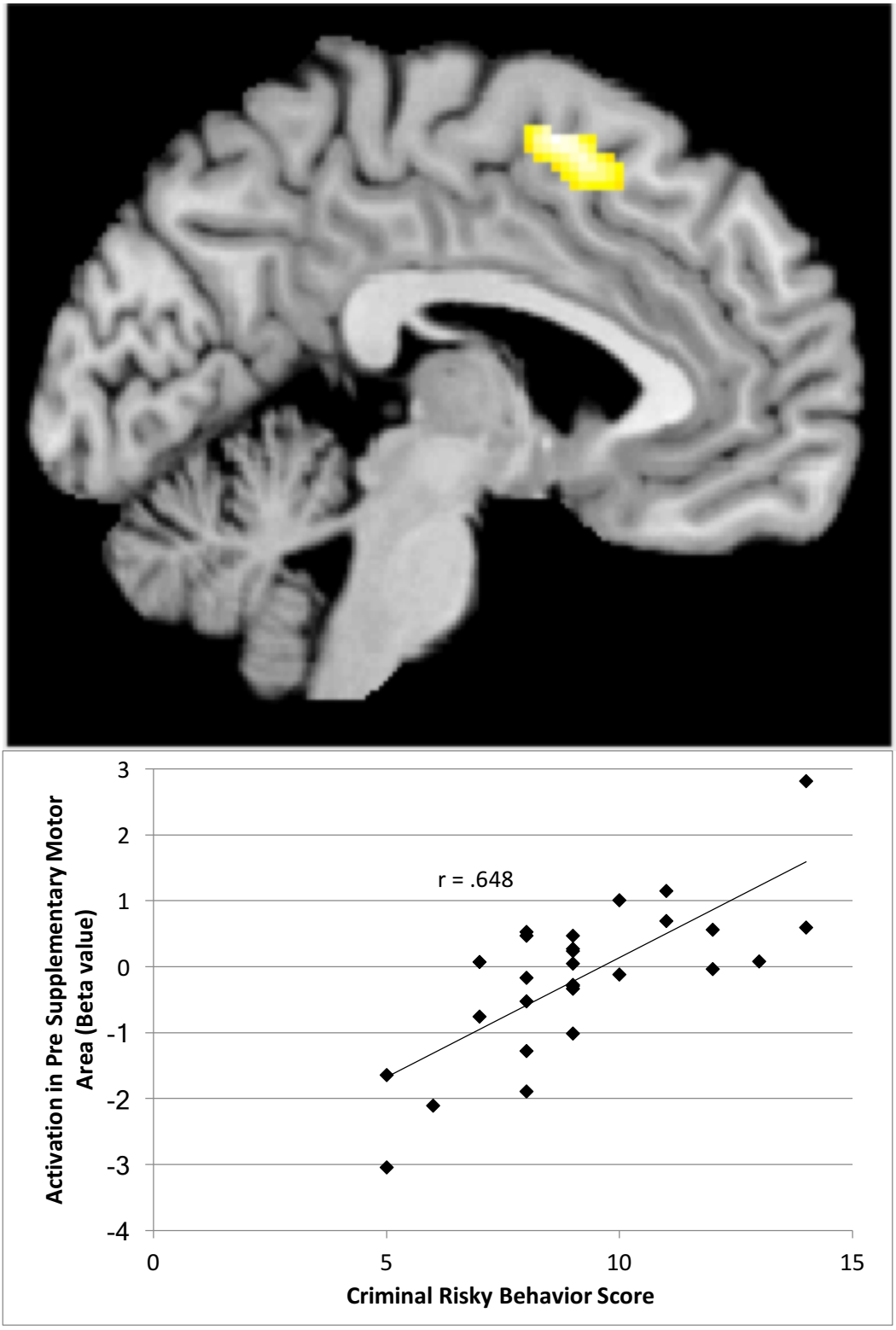


Figure 2S. Covariation of activation in supplementary motor area with criminal risky behavior in LossRisky > LossSure (activation at p<.001).