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A new intuitionism: Meaning, memory, and development in Fuzzy-Trace Theory

Valerie F. Reyna *

Abstract

Combining meaning, memory, and development, the perennially popular topic of intuition can be approached in a new way. Fuzzy-trace theory integrates these topics by distinguishing between meaning-based gist representations, which support fuzzy (yet advanced) intuition, and superficial verbatim representations of information, which support precise analysis. Here, I review the counterintuitive findings that led to the development of the theory and its most recent extensions to the neuroscience of risky decision making. These findings include memory interference (worse verbatim memory is associated with better reasoning); nonnumerical framing (framing effects increase when numbers are deleted from decision problems); developmental decreases in gray matter and increases in brain connectivity; developmental reversals in memory, judgment, and decision making (heuristics and biases based on gist increase from childhood to adulthood, challenging conceptions of rationality); and selective attention effects that provide critical tests comparing fuzzy-trace theory, expected utility theory, and its variants (e.g., prospect theory). Surprising implications for judgment and decision making in real life are also discussed, notably, that adaptive decision making relies mainly on gist-based intuition in law, medicine, and public health.

Keywords: fuzzy-trace theory, prospect theory, dual-process theory, choice, gist, memory, heuristics and biases, developmental reversal, framing effect.

1 Introduction

What are the cutting-edge approaches to judgment and decision making that will be influential in the next decade? Which hot topics today will turn into the enduring foundational assumptions of tomorrow? These questions concern new investigators, as they place bets with their most precious commodity, their time, by choosing topics in hopes of making an impact on the field. However, although new investigators strive to be original and forward thinking, they are also counseled to conduct programmatic and cumulative research. That is, to make progress on important topics, scientists must build on prior accomplishments, their own and those of others.

In this essay, I provide an overview of recent developments in one theory, and their origins in prior scientific research. Moreover, the topics were chosen with a view to the future. These are my bets about which approaches have been productive and are gathering momentum. Fortunately, these prognostications are more than simply my opinions (barely more than that perhaps) because they are based on the behavior of a community of scholars. These ideas continue to gain greater currency as our field searches for new paradigms and preoccupations (e.g., Burson, Larrick, & Lynch, 2009; De Neys & Vanderputte, 2011; Kühberger & Tanner, 2010; Stanovich & West, 2008).

What are the topics that I, and others, believe are taking off and will continue to progress? Among the new trends, the most established topic—one that draws on a rich supply of prior research—is memory. Researchers are increasingly turning to memory for explanations of judgment and decision making (for a review of the literature illustrating this point, see Weber & Johnson, 2009). Memory is much more than memorization, as I presently explain. A growing number of contemporary theories have memory as a common denominator (e.g., see Dougherty, Franco-Watkins, & Thomas,

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*Cornell University, Center for Behavioral Economics and Decision Research, Human Development, Psychology, Cognitive Science, and Neuroscience (IMAGINE Program), Cornell University, Ithaca, NY 14853. Email: vr53@cornell.edu

2008; Pleskac & Busemeyer, 2010; Ratcliff & McKoon, 2008; Schooler & Hertwig, 2005; Weber, Johnson, Milch, Chang, Brodschool, & Goldstein, 2007).

Development, defined as changes across the lifespan, is another topic that has gained ground. Because of links to aging and to adolescent risk taking in psychiatry, public health, and neuroscience, this topic has surged in popularity, although it is less established within judgment and decision making (e.g., see Baron, 2007; Casey, Getz, & Galvan, 2008; Figner, Mackinlay, Wilkening, & Weber, 2009; Jacobs & Klaczynski, 2005; Lejuez et al., 2002; Levin & Hart, 2003; Mikels & Reed, 2009; Steinberg, 2008; see also Brainerd, Reyna, & Howe, 2009). Notwithstanding that Tversky and Kahneman (1983) drew on Piagetian cognitive illusions to characterize heuristics and biases (e.g., Bruner, 1966), theories of adult judgment and decision making are only now incorporating developmental results in their core assumptions. Developmental results inform conceptions of whether choices are rational, adaptive, or good (Reyna & Farley, 2006). These results have been surprising. Knowing that children reason rationally (in the classic sense) and that adults forego rational reasoning—which they are capable of—in favor of heuristics and biases casts explanations of judgment and decision making in an entirely new light (Reyna & Brainerd, 1994; 2011).[1]

Last, the topic of meaning is the least established among the new trends. Nevertheless, the concept of meaning has tremendous potential to organize thinking about judgment and decision making, to propel the field forward in new and original directions, and to effect practical changes in real-world behavior (e.g., Peters et al., 2006; Sunstein, 2008). As Sunstein (2008) advises, "understanding of meaning and its malleability…suggests some tools that policymakers might use" (p. 146) and he exhorts public and private institutions to employ "meaning entrepreneurs" to move behavior in better directions.[2]

Combining meaning, memory, and development, the perennially popular topic of intuition can be approached in a new way. Fuzzy-trace theory integrates these topics by distinguishing between meaning-based memory representations—gist—and superficial verbatim representations of information. (People use their memories to represent information even when the information is visible.) Intuition, in this view, relies on the meaning-based gist representations, but it is not developmentally primitive (Barrouillet, 2011a). On the contrary, intuitive thinking underlies the most advanced thinking (e.g., Adam & Reyna, 2005; Reyna & Lloyd, 2006).

However, intuition produces meaning-based distortions in memory and reasoning. These distortions *increase* from childhood to adulthood, creating "developmental reversals" (i.e., children "outperform" adults under conditions that elicit meaning-based biases; Reyna & Farley, 2006, Table 3). These findings were predicted by the framework described here (e.g., Reyna & Ellis, 1994), but they violate core assumptions of other dual-process and developmental theories (despite recent acknowledgement of their reality and attempts at post hoc reconciliation; e.g., for illuminating discussions, see the recent special issue on dual-process theories in *Developmental Review*: Barrouillet, 2011a; Stanovich, West, & Toplak, 2011).

In the section below on Origins, I describe how this integrated account of meaning, memory, and development came about. Before that account, however, I summarize the central premises of fuzzy-trace theory; provide examples of how these premises are supported by critical tests of explicit hypotheses; and describe how these theoretical ideas differ from others.

1.1 Preamble

1.1.1 Verbatim and gist representations

Fuzzy-trace theory encompasses memory, reasoning, judgment, and decision making—and their development across the life span (see Reyna & Brainerd, 1995a, 1995b). Although I provide a summary of the basic tenets of the theory here, the evidence for it comes from a very large literature; so no single study tests the entire theory. The basic tenets are fairly simple, however: The central tenet is that people encode, store, retrieve, and forget verbatim and gist memories separately and roughly in parallel. (My colleagues and I have conducted experiments, and constructed models, that differentiate retrieval from storage, storage from forgetting, and so on; e.g., Brainerd, Reyna & Howe, 2009; Reyna & Brainerd, 1995a.) The distinction between verbatim and gist memory was established in psycholinguistics (for an overview, see Clark & Clark, 1977). Verbatim memory is memory for surface form, for example, memory representations of exact words, numbers and pictures. Verbatim memory is a symbolic, mental representation of the stimulus, not the stimulus itself. Gist memory is memory for essential meaning, the "substance" of information irrespective of exact words, numbers, or pictures. Hence, gist is a symbolic, mental representation of the stimulus that captures meaning.

However, psycholinguists did not consider verbatim and gist memory representations to be independent; the

[1] By "heuristics and biases", I refer to the vast literature illustrating such empirical effects in adults as the representativeness heuristic, framing biases, and so on (Gilovich, Griffin, & Kahneman, 2002). Many of these effects have been shown to increase developmentally (i.e., from childhood to adulthood; see Table 3 in Reyna & Farley, 2006, for a summary; Reyna & Brainerd, 2011).

[2] See also, "The Meaning of Consumption," an interdisciplinary conference at Cornell University, August 14–17, 2008.

independence idea was introduced in fuzzy-trace theory. (For summaries of critical tests of this idea, see Reyna, 1992; 1995; Reyna & Brainerd, 1995a.) Instead, psycholinguists assumed that gist memories were derived from verbatim memories, and the latter faded away—the kernel of meaning (gist memory) was extracted from information and the husk of the surface form (verbatim memory) was discarded (see also Kintsch, 1974). This notion that gist is extracted from verbatim memory remains a popular misconception.

Disproving this claim that verbatim and gist are derived in tandem, many experiments have shown that verbatim and gist memory representations are actually extracted in parallel from the same stimulus (e.g., Reyna & Brainerd, 1992; 1995a). Thus, fuzzy-trace theory falls into the class of parallel models (Sloman, 2002), as opposed to the class of default-interventionist models (Evans, 2008; Kahneman, 2003; but, for discussion of fuzzy-trace theory's assumptions about monitoring and inhibition, see Reyna, in press; Reyna & Mills, 2007b; Reyna, Estrada et al., 2011). For example, independent storage is exemplified in experiments on subliminal semantic priming, showing that semantic priming can occur (e.g., presenting the word "doctor" increases processing speed for the word "nurse") even when exemplar words ("doctor") are presented so fast that they cannot be encoded (i.e., verbatim memory for exemplar words is at chance). (Research on subliminal semantic priming and its relation to gist is summarized in chapter 4 of Brainerd & Reyna, 2005.) Conversely, storage of verbatim memories can occur without storage of gist; for example, when nonsense syllables are presented (rather than meaningful words or sentences), memory fades quickly and meaning-based false memory effects disappear (Brainerd, Reyna, & Brandse, 1995). That is, false recognition of similar (but never-presented) nonsense syllables is not stable over time, but gist-based false recognition is stable over time.

In addition, retrieval dissociation has been dramatically demonstrated in experiments that test whether recognition of verbatim and gist memories of sentences covary (if gist were derived from verbatim memories, such covariance should be detected; Reyna & Kiernan, 1994; 1995). Crucially, memory dependency is assessed by examining contingencies within subjects and within problems: The question is whether *gist* memory for presented sentences ("recognition" of novel sentences that express meaning) depends on *verbatim* memory for those same sentences? Under typical recognition testing conditions (testing after a short buffer and controlling for word familiarity and a host of other factors), the answer is no. Verbatim memory for presented sentences is stochastically independent of gist memory for those sentences (i.e., independent of erroneous "recognition" of gist-consistent paraphrases and inferences). (Even when more than a dozen experiments from different investigators were examined, no verbatim-gist covariance was detected; Brainerd & Reyna, 1992.) After one week, recognition of these same presented sentences and gist-consistent paraphrases/inferences becomes positively dependent—converging evidence demonstrated that recognition after a week was based on gist (Reyna & Kiernan, 1994; 1995). After a delay, gist memory is being used to accept *both* presented items and meaning-consistent gist items.

However, when verbatim memory is stronger (e.g., through repetition of presented items and more immediate testing), negative dependency is detected between recognition of presented items and meaning-consistent items, the opposite of dependency results after a delay. Negative dependency is detected because verbatim memory is being used to both *accept* presented items and to *reject* meaning-consistent gist items (e.g., Reyna & Kiernan, 1995; see Reyna & Brainerd, 1995a). Thus, the gamut of relations between presented and meaning-consistent (never-presented) items—independence, positive dependency, and negative dependency—has been demonstrated for the very same items under predicted conditions. Each of these studies was designed to test predictions of fuzzy-trace theory (i.e., predictions were deduced from a finite set of premises), rather than stumbling on these effects and explaining them after the fact. Certainly, science can progress by stumbling on effects, but my remarks pertain to the viability and generativeness of the present theory.

One might argue that gist-based results, such as erroneous recognition of meaning-consistent items (corrected for response bias) and positive dependency between presented and unpresented items after a delay, occur because memory is constructive or schematic (e.g., Bransford & Franks, 1971; Loftus & Doyle, 1987). "Constructive" memory usually refers to the classic idea discussed earlier that people extract meaning from presented information (discarding surface form) later using what they remember of the meaning to infer what actually occurred (i.e., memories are constructed from meaning). The idea of "schematic" memory is similar; memories are said to be selectively encoded, stored, and retrieved based on prior knowledge organized into "schemas" (e.g., Alba & Hasher, 1983).

If words such as "constructive" and "schematic" are taken merely as descriptions of *some* memory effects (i.e., gist effects), then they are not theoretical claims about underlying mechanisms. However, when these words characterize memory at a theoretical level, then these theories have been shown to be resoundingly false by many investigators (e.g., for one summary, see Reyna & Lloyd, 1997). For example, Alba and Hasher's 1983 review of the literature asked, "Is memory schematic?"

and many experiments were presented demonstrating that the answer to this question is "no." In those days, two theoretical camps contended with one another to explain memory: constructive or schema theorists versus verbal learning or associative activation theorists (Anderson, 1971; 1975). In this article, I focus on psychological claims (e.g., the definition of association psychologically as a stimulus-stimulus or stimulus-response pairing), as opposed to ways in which psychological claims might be formalized or represented, as in associative activation networks, propositional logic, or production rules. (It is not that those formalizations are unimportant, but the mechanics of implementation should not overshadow the psychological substance.) Associative activation models (in which association is a psychological claim) characterize memory as mindless stimulus-stimulus associations (strengthened through pairing in experience) (e.g., Robinson & Roediger, 1997). Research on fuzzy-trace theory has cataloged many effects that cannot be explained by association models (e.g., Brainerd & Reyna, 2005). Although each side of the memory debate concluded that their criticisms of the other side were sound, their predictions and results often contradicted one another (e.g., Reyna & Brainerd, 1995a). The experiments presented earlier (e.g., Reyna & Kiernan, 1994, 1995; and other experiments) demonstrated that both sides were "right" inasmuch as each side had half of the story–gist-consistent results and verbatim-consistent results–sometimes for the same stimuli.

Note that attempts to "postdict" opposing results are not evidence for a theory's truth in either memory or in judgment and decision making; postdictions do not compare favorably to actual predictions (Glöckner & Betsch, 2011). So, summarizing this conflicting literature by saying that memory is constructive, except when it is not constructive, is not an argument that favors constructive memory theories because there is no mechanism in those theories that predicts when memory is constructive versus not. Parachuting in concepts such as "tags" to accommodate conflicting findings, as in schema-plus-tag models, was ultimately unsuccessful, weakening the core assumptions of the approach and reducing falsifiability. Analogous criticisms can be made of association theories that characterize memory as associative except when it is not associative.

Association models, and corresponding simulation models, have many strengths (McClelland & Rumelhart, 1981), but they also have weaknesses in failing to capture meaning (associations can *mimic* understanding but through mindless memorization of what has been paired with what). Simulation models of known effects are sophisticated examples of postdiction (e.g., Dougherty, Getty, & Ogden's, 1999, impressive MINERVA-DM model incorporates known effects). Some simulations have too many assumptions relative to the degrees of freedom in the data (or assumptions are opaque—it is not clear how effects are simulated) to be falsifiable. Models that are not falsifiable cannot be assumed to be true because there is no way to determine whether they are true. Naturally, all models have boundary conditions and gray areas in which predictions are not fully specified; otherwise, scientific knowledge would be complete and perfect, which it surely is not.

However, association models fail to predict a host of observed phenomena, such as stability of false memories over time (both associative activation at study and at test have been ruled out as explanations for this phenomenon; e.g., Brainerd, Yang, Reyna, Howe, & Mills 2008). Association—mindless memorization of learned answers to stock questions—also cannot predict far transfer of learning to novel instances (e.g., Reyna & Brainerd, 1992). Can some post hoc explanation using associations be constructed to account for these results?; yes, but by that measure all theories can account for all results. Association is an inherently meaningless relation (by definition), and hence does not easily explain phenomena caused by meaning. Therefore, successful simulations do not protect association models from empirical counterexamples. Considering the evidence as a whole, *central* features of both traditional constructivist (or schema) and associative memory models have been disputed by results from many experiments, even taking into consideration legitimate methodological critiques of the critiques.

Fuzzy-trace theory carefully built on the foundations and results of both memory-model traditions, but it makes specific predictions about the conditions under which verbatim versus gist memory will control performance (Brainerd et al., 1999; Reyna & Brainerd, 1995a, 2011; it also drew on earlier efforts such as Pennington & Hastie's, 1992, story model). For example, verbatim memory is more accessible immediately after stimulus presentation (compared to after a long-term retention interval); for cues that re-present stimuli (compared to unpresented meaning-consistent cues and even less so for unrelated cues); for adults (compared to children; both gist and verbatim memory ability develop in childhood); for novel metaphors (compared to less distinctive literal language); and for tasks that explicitly instruct subjects to base responses on verbatim memory (as opposed to gist) (see Brainerd & Reyna, 2005; Reyna & Brainerd, 1995a; Reyna & Kiernan, 1994; 1995).

In addition to many experiments that explicitly tested opposing predictions (e.g., of fuzzy-trace theory vs. schema theory or vs. association theories), mathematical models have been developed, and tested, for a variety of memory, judgment, and decision making tasks (e.g., models of recognition, recall, disjunction fallacies, decision making, and so on; e.g., Brainerd, Reyna, & Howe, 2009; Reyna & Brainerd, 2011). These models capture very simple assumptions about verbatim and gist representations, such as the definition of what verbatim and gist memories are, the assumption of independence, and differential forgetting of verbatim relative to gist memory over time, which not only fit data but also predict paradoxes in memory, judgment, and decision making.

For example, these assumptions predict that meaning-based "false" memories will be more consistent over time than true memories (Gallo, 2006; Reyna & Brainerd, 1995a). Interviewed immediately after study, recognition of true memories is based on verbatim representations, whereas "recognition" of meaning-based false memories is based on gist (measures control for response bias). After a delay, both recognition judgments are based on gist memories. Therefore, the conditional probability (second interview conditional on first interview) of saying "yes" to a true memory is lower than the conditional probability of saying "yes" to a false memory. All other factors equal, witnesses telling the truth will be less consistent on subsequent interviews, compared to those whose testimony is based on false memories (Reyna, Mills et al., 2006).

Figure 1 provides an overview of how the verbatim-gist distinction plays out in a variety of tasks. Each type of representation that I have discussed—verbatim and gist—supports a different kind of processing. The precise details of verbatim representations support precise processing, such as analyses or computations using exact numbers. Processing (as opposed to representation) involves retrieving reasoning principles and applying those principles to representations (e.g., see Reyna & Brainerd, 1992; 1995a). A small number of reasoning principles seem to cover a large number of reasoning, judgment, and decision-making tasks. These principles are often engaged without conscious deliberation, even before formal computational rules such as multiplication are learned in school (as shown by functional measurement research, e.g., Acredolo et al., 1989). When careful methodological controls are used, children as young as five or six exhibit the basic *competence* underlying many reasoning principles, even though their *performance* continues to improve and become less variable from childhood to adulthood (see Reyna, Estrada et al., 2011; Van Duijvenvoorde, Jansen, Bredman, & Huizenga, 2012).

To take one example relevant to probability, the ratio principle is a commonly used reasoning principle (e.g., probability depends on the ratio of the frequency of target events to the total frequency of target and non-target events, or, alternatively, to their odds; see Reyna & Brainerd, 1994). For people who are adept at computation, ratios seem to be calculated quickly and automatically (for a review of the literature on numeracy—how people understand and use numbers—see Reyna, Nelson, et al., 2009). When people lack understanding of the gist of task information, these ratios have been shown to be imported mechanically into judgment-and-decision-making tasks by people high in numeracy, even when the ratios make no sense and produce wrong answers. The latter is an example of verbatim-based analysis: processing exact information in a rote fashion rather than in a meaningful fashion. In contrast, as I discuss below, gist representations support the fuzzy and impressionistic, but meaningful, processes of intuition.

In general, adults encode both verbatim and gist representations in parallel, and they default to relying on gist representations to generate responses whenever the task permits (i.e., adults have a fuzzy-processing preference). Different task requirements are illustrated from left to right in Figure 1: When memory tasks *require* exact matches to presented information, verbatim representations are used to reject meaning-consistent distractors (i.e., verbatim trumps gist). Presented with "The bird is in the cage" and "The cage is under the table" a person with this task instruction should reject the test probe "The bird is under the table." These tasks go against the grain of normal thinking, the fuzzy-processing preference. Thus, they are difficult and unnatural; gist-based responses routinely bleed through in these tasks. For example, even in verbatim memory tasks, gist-based "false" memories (e.g., recognizing "The bird is under the table" as having been presented) are reported erroneously (e.g., Reyna & Kiernan, 1995).

Continuing to the right in Figure 1, when a memory task requires recognizing the meaning of presented information, both verbatim representations of presented information *and* gist representations of meaning-consistent distractors produce correct acceptances. People can recognize "The bird is in the cage" as being "true" either by remembering it verbatim or by recognizing that it is consistent with the gist of what was presented. Thus, even "memory" tasks such as recognition involve both verbatim and gist memories, if task instructions do not limit responses to only verbatim (directly studied) answers (e.g., Reyna & Kiernan, 1994; Reyna & Mills, 2007b; see also Brainerd et al., 2009). After a delay, such recognition responses are governed primarily by gist—as most recognition tasks are in real life (e.g., Reyna, 2008; Reyna, Mills et al., 2006).

In concert with the fuzzy-processing preference, reasoning, judgment, and decision-making tasks generally rely on gist representations, as shown in the second row, in the third box to the right, in Figure 1. In fact, when the task requires non-literal comprehension, gist representations of meaning are used to reject literal responses based on verbatim representations (rote memory for presented information) (i.e., gist trumps verbatim). For example, simply retrieving the exact words of a poem or a textbook

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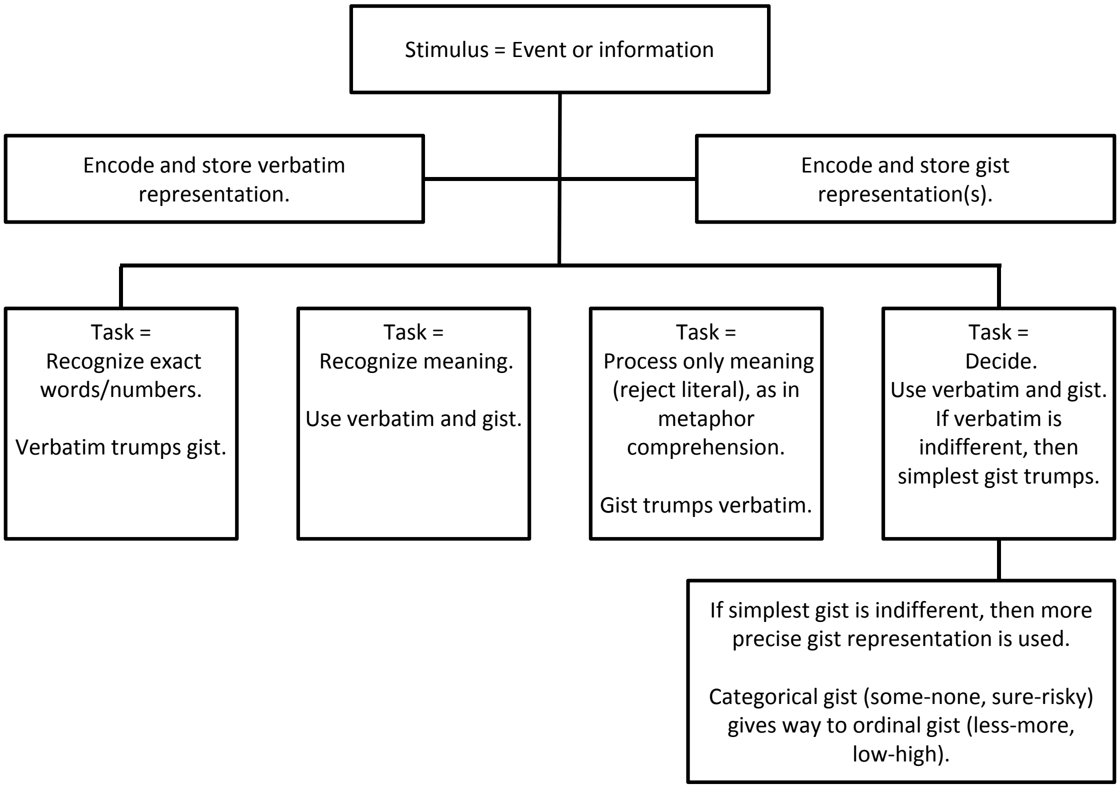
Figure 1: Tenets of fuzzy-trace theory tested in research on memory, judgment, and decision making



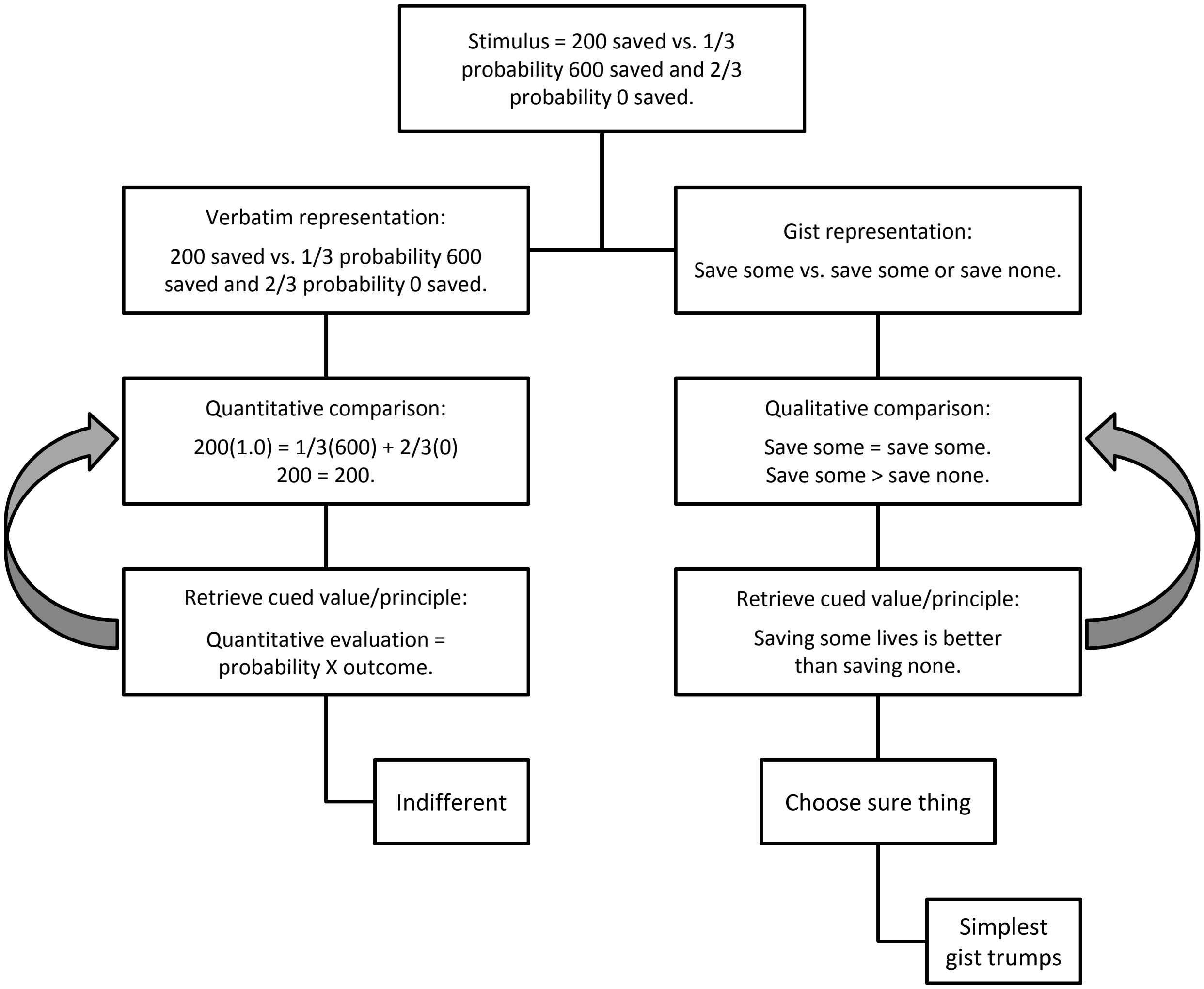
does not suffice to demonstrate understanding. Processes that manipulate rote, verbatim information fall short in such tasks (e.g., "The prison guard is a hard rock" literally interpreted as the guard had hard muscles or "The man is wearing a loud tie" literally interpreted as the man is wearing a tie that plays loud music; Reyna, 1996b). People with Asperger's syndrome or autism, for example, tend to rely on verbatim-based processes; they have difficulty with non-literal language, such as metaphor, but are less subject to gist-based biases in reasoning, judgment, and decision-making (Reyna & Brainerd, 2011).

The three examples of tasks in Figure 1 that I have discussed so far correspond to three instructional requirements: accept only presented information (reject meaning), accept either presented information or its meaning, and accept only meaning (reject presented information) (e.g., Brainerd et al., 1999; Reyna, Holliday, & Marche, 2002; Reyna & Kiernan, 1994, 1995). The first instruction is given to witnesses in the courtroom; the second instruction applies to tests in the classroom; and the third instruction applies to creative endeavors that incorporate the past but do not recapitulate it (e.g., new patents or fashion design).

Finally, the right-most box in Figure 1 illustrates how information is processed when a task does not *require* verbatim or gist representations. Again, both verbatim and gist representations are encoded in parallel, but gist is preferred by most adults (the fuzzy-processing preference). Adults begin with the lowest (categorical) level of gist and only proceed to higher (more precise) levels if the lower levels do not allow them to perform the task (e.g., to differentiate between options in a choice task). For example, as shown in Figure 1, nominal or categorical gist (e.g., some lives are saved; some money is won; no lives are saved; no money is won) is the simplest gist of numbers, such as numerical outcomes and probability values. If categorical distinctions fail to discriminate options, ordinal distinctions (e.g., more lives are saved; more money is won; fewer lives are saved; less money is won) are used, and so on until options can be discriminated (see Figure 2 for a worked example). Gist reflects meaning, and so does not map one-to-one to verbatim quantities: a non-zero amount can be categorized as nil; a 20% chance of rain is low, whereas a 20% chance of a heart attack is high (Reyna, in press; Stone, Yates, & Parker, 1994).

When verbatim and gist representations conflict (e.g., analysis of exact numbers favors one option and qualitative intuition favors the other option), most people still prefer to rely on gist, but people with high need for cognition are likely to monitor this conflict and *inhibit* in-

Figure 2: Example of fuzzy-trace theory explanation of decision making for a gain-framed option



coherent responses (e.g., Stanovich & West, 2008). In fuzzy-trace theory, intuition and impulsivity (lack of *inhibition*) are distinct processes; for example, gist-based intuition increases with development from childhood to adulthood, whereas impulsivity decreases (e.g., Reyna, in press; Reyna & Brainerd, 2011; Reyna & Rivers, 2008). This development occurs because of experience in life, analogous to the development for adults from novice to expert in a domain of expertise (Reyna & Lloyd, 2006). As noted earlier, when people lack understanding of information, as, for example, patients do when they first receive a rare medical diagnosis, they fall back on verbatim representations (as subjects did in the nonsense syllable experiment; see also Reyna, 2008). Within the limits of their knowledge, however, people strive to extract the gist and base their decisions on the simplest gist that allows them to accomplish the task (Reyna, 2012).

In sum, fuzzy-trace theory's tenet about independent "dual" verbatim and gist representations has survived strong tests, including tests of single and double dissociation, overcoming shortcomings identified for standard dual-process theories (e.g., Keren & Schul, 2009). Therefore, one crucial way that fuzzy-trace theory differs from other dual-process theories is that it has passed empirical tests that are required to assert dual systems or processes (e.g., see Reyna & Brainerd, 2008, for a recent summary of evidence concerning Epstein, 2008's, cognitive-experiential-self theory, or CEST, among other dual-process approaches; see also, Reyna, in press; Reyna & Brainerd, 2011; Reyna, Nelson et al., 2009). Nevertheless, earlier approaches have informed fuzzy-trace theory (e.g., Anderson, 1971; Estes, 1980; Fischhoff, 2008; Hogarth & Einhorn, 1992; Kahneman, 2003; MacGregor & Slovic, 1986; Tversky & Kahneman, 1981 and others). For instance, gestalt theorists mounted devastating criticisms of association theories that remain relevant to such theories today. However, gestalt theory incorporated nativist assumptions and lacked the concept of retrieval cuing; these and many other features distinguish gestalt theory from fuzzy-trace theory, despite embracing the former's distinction between nonproductive (associative) and productive thought (Wertheimer, 1938). Adaptive decision-making models were a major influence on fuzzy-trace theory because they link memory to decision making, but they lack the verbatim-gist distinction and thus cannot account for required crossover effects and other gist results (e.g., Payne et al., 1993). These and many other theories have inspired breakthroughs in psychology and cognate fields; fuzzy-trace theory has been held to account for the results generated from these approaches, while striving to go beyond them in terms of new effects and new predictions.

1.2 Origins

My first duty in discussing the origins of fuzzy-trace theory is to thank the teachers whose work had a tremendous influence on me: my graduate-school mentors, William K. Estes, for his memory models, and George A. Miller, for his work in psycholinguistics. Not coincidentally, Miller was the maven of meaning. The seminal exposure to psycholinguistics, however, occurred under the tutelage of my undergraduate advisor, the developmental psychologist Rachel Joffe Falmagne, notably, Kintsch's (1974) classic, *The Representation of Meaning in Memory*. This work brought memory and psycholinguistics together, relying on the distinction between verbatim and gist representations, later central to fuzzy-trace theory (see also Clark & Clark, 1977). The surface form—the exact words of a sentence—constitutes the verbatim level of representation; the text-based representation (generated through comprehension and inference) and situation models (incorporating extra-textual information, such as world knowledge) together are what would now be called a *hierarchy of gist* in fuzzy-trace theory (Reyna & Brainerd, 1995a). A hierarchy of gist is a collection of gist representations for the same stimulus at multiple levels of specificity and involving multiple levels of information—from the semantics of a word or sentence, to inferences derived deductively from sets of sentences, to pragmatic inferences that integrate world knowledge with textual information (e.g., Kinstch, 1974; Reyna & Kiernan, 1994).

Therefore, prior work on meaning and memory informed the origins of fuzzy-trace theory. The concept of gist addressed the criticisms aimed at the concept of schema, while conserving many of its useful features, and extending them to non-linguistic stimuli, such as numbers (e.g., Alba & Hasher, 1983). Predictions of fuzzy-trace theory, then, overlap somewhat but also differ in important ways from those of schema theory (e.g., Reyna & Lloyd, 1997). Mental models have more in common with fuzzy-trace theory than schema theory does, and were also a formative influence, but they lack the duality (and, thus, opposing predictions) of gist versus verbatim representations (see Barrouillet, 2011b; Johnson-Laird, 2010). Dual opposing predictions (opposing under conditions specified by the theory) are required to account for otherwise paradoxical results (e.g., Reyna & Brainerd, 1995a; Reyna & Kiernan, 1994; 1995).

With training in both memory and psycholinguistics, I embarked on a postdoctoral fellowship with Amos Tversky and my formal foray into judgment and decision making. The success of the Tversky-Kahneman research program provoked disputes about rationality that were heated and instructive (e.g., at the Foundations and Applications of Utility, Risk and Decision Theory Conference at Duke University in 1990). Amos was the first person to teach me about a scientific approach to intuition and to intuitionism, rounding out my preparation. In the following, I explain how these intellectual influences regarding memory, meaning, and development led to a theory of intuition, fuzzy-trace theory.

1.3 A road less traveled: Three themes that organize the evidence

The empirical evidence that culminated in the current version of fuzzy-trace theory can be organized into three themes. Given my influences, it makes sense that the early work began with the question, "Does judgment and decision making process memory?" I refer to "memory" in the Simon (1955) sense that memory resources (or capacity) constrain rationality, an assumption that most of us take for granted today, but which must be amended in important respects to capture the data. That is, does memory, including working memory capacity, influence the quality of judgment and decision making (e.g., Corbin, McElroy, & Black, 2010)? The answer to that question turned out to be "no", no in the narrow sense of processing exact memories for numbers and no in the traditional sense of memory capacity. (For a review of experiments distinguishing dual-task interference from processing capacity and traditional memory capacity, see Reyna, 1995; Reyna & Brainerd, 1995a; for an overview, see Reyna, 2005.)

Another major theme of my work was the relation between the two kinds of memory that are important in judgment and decision making–verbatim and gist memory (Brainerd & Reyna, 1990; for summaries, see Reyna & Mills, 2007a; 2007b). Definitions of verbatim and gist memory were operationalized and formalized, building on research in psycholinguistics per the earlier discussion (e.g., Brainerd et al., 1999; Reyna & Brainerd, 1995b; Reyna & Kiernan, 1994). The relation between true (verbatim-based) and "false" (gist-based) memory occupied this middle period because it offered an opportunity to study the fuzzy boundary between memory as traditionally defined (exact memory for information), on the one hand, and reasoning, judgment and decision making, on the other hand. "False" memories, it turned out, were often the product of gist-based reasoning, judgment, or decision-making processes, mistakenly attributed to actual experience (e.g., Kim & Cabeza, 2007; Reyna, Holliday, & Marche, 2002). These verbatim-gist distinctions have figured extensively in neuroscience research on memory (e.g., Dennis, Kim, & Cabeza, 2008; Schacter, Guerin, & St. Jacques, 2011; Slotnick & Schacter, 2004).

Most recently, I have focused on a third theme, whether gist-based intuition is primitive, as assumed in standard dual-process theories, or advanced, as suggested in gestalt theory (Reyna & Brainerd, 1998). Research concerning intuitive processes in judgment and decision making has shown that advanced cognition relies on gist-based intuition (e.g., Reyna & Farley, 2006; Reyna & Hamilton, 2001; Reyna & Lloyd, 2006). Table 1 summarizes major domains of evidence gathered under each of the three themes. Before I proceed to specific findings, however, it is useful to explain basic concepts and relate them to intuition.

2 Terms and concepts

2.1 What is intuition?

Intuition has remained a hot topic, both in the field and in the popular press (Baron, 1998; Gigerenzer, 2007; Glöckner & Witteman, 2010; Hogarth, 2001; Plessner, Betsch, & Betsch, 2007). The standard view of intuition is captured in dual-process approaches pitting intuition and emotion against logic and deliberation: the old reptilian brain and limbic system (intuition) versus the neocortex (rationality; e.g., De Martino, Kumaran, Seymour, & Dolan, 2006). This familiar dualism harkens back to Descartes and to Freud's primary and secondary processes (Reyna, Nelson, Han, & Dieckmann, 2009). In this standard view, intuition is the old system of animal impulses and low-level decision making (the experiential system "1" to reflect its primacy in evolution) as contrasted with conscious cognition and high-level decision making (the rational system "2" to reflect its recency in evolution; Epstein, 1994; Stanovich & West, 2008).

The problem with this familiar dualism is that the data do not consistently support it. People higher in self-reported rational, as opposed to intuitive, thinking do not consistently show fewer biases and heuristics; in fact, they are more prone to certain biases (Peters et al., 2006; Reyna & Brainerd, 2008; Reyna et al., 2009). These results are a problem for dual-process models because they directly contradict explicit predictions of those models (e.g., Epstein's rational-experiential inventory, REI, is supposed to explain and predict biases; see Reyna & Brainerd, 2008). Indeed, a major motivation for dual-process theories has been to account for both logical or rational thinking and violations of logic and probability theory as manifested in heuristics and biases; the latter were said to originate chiefly through intuition (e.g., Epstein, 1994; Kahneman, 2003; Peters et al., 2006). (Again, the question is not whether standard intuition theorists can provide post hoc rationalizations of results that run counter to their core mechanisms, but, rather, the question is what the mechanisms of those theories actually predict.) Not all intuition theorists are standard dualists, however (e.g., Betsch & Glöckner, 2010).

As fuzzy-trace theory predicts, unconscious gist-based intuition often produces superior reasoning (when there is a gist to uncover) compared to conscious analytical thought that focuses on superficial details (Dijksterhuis, Bos, van der Leij, & van Baaren, 2009). The overall developmental shift, according to fuzzy-trace theory, is from greater reliance on verbatim-based analysis to greater reliance on gist-based intuition in reasoning, judgment, and decision making (e.g., Reyna & Brainerd, 1995a, 2011). Rather than facilitating reasoning (or being neutral) as classic decision theories assume, verbatim memory can interfere with reasoning. To take one example of a counterintuitive effect of verbatim memory on reasoning, experiments on fuzzy-trace theory showed that removing numbers and other background information (so that verbatim memory faded) systematically *improved* reasoning involving those numbers, especially in reasoners likely to focus on superficial details. In these problems, quantitative information suggested the wrong answer, but the qualitative gist supported the right answer (Brainerd & Reyna, 1995). Therefore, worse memory for numbers was associated with better reasoning performance (this effect was not about a few data points; rather, there was a negative dependency, an inverse correlation, between memory accuracy and reasoning performance across the range of data points; Reyna & Brainerd, 1995a). Conversely, increasing cognitive load to high levels has been shown to leave gist-based reasoning unimpaired (e.g., see Brainerd & Reyna, 1992; Reyna, 1995; Reyna & Brainerd, 1990).

Rather than discard the classic distinction between intuition and analysis entirely, fuzzy-trace theory refined and augmented it. (For a review of how the theory handles conflicts between emotion and inhibition, see Rivers et al., 2008.) Two kinds of reasoning—verbatim-based analysis and gist-based intuition—were retained in the theory, accompanied by developmental and individual differences in impulsivity (or lack of inhibition; Reyna,

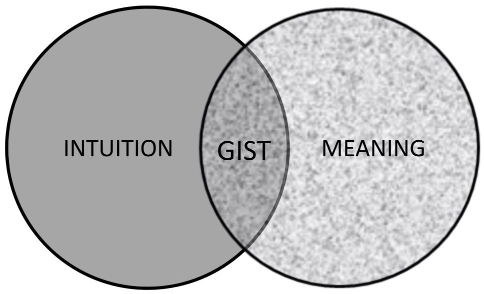
Table 1: Examples of domains of evidence for fuzzy-trace theory with illustrative references (core judgment-and-decision-making overviews are Reyna, 2008; Reyna & Brainerd, 1995a; 2008; 2011; Reyna, Estrada et al., 2011)

Comprehension and reasoning
Logical reasoning (e.g., transitive inference; Reyna & Brainerd, 1990)
Pragmatic inference (Reyna & Kiernan, 1994)
Moral reasoning (Reyna & Casillas, 2009)
Metaphor comprehension (Reyna & Kiernan, 1995)
Recognition and recall
True and false memory (Reyna, Mills, Estrada, & Brainerd, 2006)
Effects of emotion on memory (Brainerd, Holliday, Reyna, Yang, & Toglia, 2010)
Probability judgment
Conjunction and disjunction fallacies (Wolfe & Reyna, 2010)
Base-rate neglect (Reyna, 2004)
Hindsight bias (Reyna, 2005)
Denominator neglect (Reyna & Brainerd, 2008)
Conversion errors in conditional probability judgment (Lloyd & Reyna, 2001)
Risk perception
Gist-based distortions in risk perception (Reyna, 2008)
Opposite correlations between risk perception and risk taking (Mills, Reyna, & Estrada, 2008)
Effects of knowledge and cuing on risk perception (Reyna & Adam, 2003)
Decision making
Framing effects and variations (Reyna, Estrada et al., 2011)
Preference reversals (Reyna & Brainerd, 1995a)
Effects of emotion on judgment and decision making (Rivers et al., 2008)
Effects of expertise on judgment and decision making (Reyna & Lloyd, 2006)
Effects of numeracy on risk perception and decision making (Reyna, Nelson et al., 2009)
Development
Adolescent risk taking (Reyna & Farley, 2006)
Developmental increases in intuition (i.e., developmental reversals; Brainerd, Reyna, & Ceci, 2008)
Developmental reversals in risky decision making (Reyna & Brainerd, 2011)

Estrada, et al., 2011; Reyna & Rivers, 2008). Note that there is a role for rote stimulus-response (or stimulus-stimulus) associations in fuzzy-trace theory. These kinds of mindless associations or rote computations would fall under verbatim-based processes, as opposed to gist-based processes (e.g., matching bias, Evans, 2011; see also Liberali et al., 2011; Wolfe, Reyna, & Brainerd, 2005). Association, as in stimulus-response driven choice, is an example of rote processing, and, thus, are verbatim-based processes, as opposed to intuition as defined in fuzzy-trace theory (see Glöckner & Witteman, 2010). These fuzzy-trace theory distinctions are not simply opinions, but, instead, are justified by specific findings (e.g., see Brainerd et al., 1999; Reyna & Brainerd, 1995a, 1995b).

Intuition in fuzzy-trace theory is similar to the old ideas about intuition in some ways: It is fuzzy rather than precise, operates in parallel rather than being serial, and typically is unconscious and automatic (a conclusion resting on evidence from mathematical models and experiments). However, intuition is not necessarily primitive and it is not a result of rote stimulus-response (or stimulus-stimulus) associations, in contrast to Sloman's (1996, 2002) and others' conceptions (e.g., Gilovich, Griffin, & Kahneman, 2002; Glöckner & Witteman, 2010). Rather than being mindless and low-level, the core construct of cognition in fuzzy-trace theory (the fuzzy trace, also called gist) is based on meaning—on extracting the essential, bottom-line meaning of information.

Figure 3: A new intuitionism: Fuzzy meaning



Hence, fuzzy-trace theory differs from standard views of intuition, which is what is new about this new intuitionism. On the one hand, there is the classical view of intuition as an unconscious, fuzzy, parallel process, and then, on the other hand, there are notions of meaning, and usually meaning and intuition do not go together. However, in this theory, gist—the central construct—is at the intersection between intuition and meaning (Figure 3). In real life, in natural decision making, people are meaning makers. They look for meaning (e.g., for patterns that can be interpreted), and they base their judgments and decisions on that essential meaning (e.g., Gaissmaier & Schooler, 2008; Proulx & Heine, 2009; Reyna, 2012; Wolford, Newman, Miller, & Wig, 2004). What is the meaning of the event or the information, in the broad sense? Typically, people encode multiple meanings for a given stimulus. The gist representations of a stimulus encompass the meaning to us as individuals, the meaning to us based on our life history, and the meaning in our culture (Reyna, 2004, 2008; Reyna & Adam, 2003; Reyna et al., 2009). In the following section, I discuss how this concept of gist representations of information plays out in specific psychological phenomena, and how representations are combined with retrieval of social values and moral principles, which are then applied to those representations to produce judgments and decisions.

3 Sample phenomena

3.1 Risk-taking: Framing effects in adults

In this section, I discuss examples of phenomena studied under the rubric of fuzzy-trace theory. As noted, the early work on framing was aimed at the question, "Do judgment and decision making process memory in the narrow sense?", and the answer was, surprisingly, no. As an example, precise verbatim information (e.g., exact numbers) was neither necessary nor sufficient to observe framing effects (e.g., Kühberger & Tanner, 2010; Reyna & Brainerd, 1991, 1995a). I first discuss psychophysical predictions of traditional approaches, such as prospect theory, followed by predictions from fuzzy-trace theory for these same manipulations (see Figure 2). The main point of these comparisons is not whether prospect theory might accommodate some of these results after the fact, but whether the psychophysics of numbers is both necessary and sufficient to observe the range of observed framing effects.

Framing effects describe shifts in risk preferences, for instance, from risk aversion when prospects are described in terms of gains (e.g., money won or number of people saved) to risk seeking when the same prospects are described in terms of losses (e.g., money lost or number of people who died; Tversky & Kahneman, 1986; cumulative prospect theory predicts risk seeking for gains with small probabilities and risk aversion for losses with small probabilities, but the decisions in Figures 4 and 5 do not involve small probabilities). Most theories of framing effects rely on the psychophysics of quantities, exemplified in perceived diminishing returns as quantities, such as money, increase. (Technically, the concept is diminishing marginal utility.) Expected utility theory, subjective expected utility theory, prospect theory, cumulative prospect theory and so on rely on the general psychophysical account of diminishing returns for outcomes, and that outcomes trade off with probabilities (i.e., are combined multiplicatively); in some accounts probabilities are processed nonlinearly, too (Tversky & Kahneman, 1986; 1992). Experiments show that adults process both outcomes and probabilities (so failing to encode or process probability does not account for results presented below), and that they combine numerical outcomes and probabilities multiplicatively (see Reyna & Brainerd, 1994; Figures 1 & 2). Although adults process outcomes and probabilities multiplicatively (i.e., they compute something like expected value), the issue is whether framing effects arise from this numerical processing.

Early research on fuzzy-trace theory challenged the predictions of psychophysical theories (e.g., Reyna & Brainerd, 1991; Reyna & Ellis, 1994). For example, how could framing effects derive from the psychophysics of quantities if numbers could be removed from the problems and framing effects *in*creased? This effect is called the *nonnumerical framing effect* (see Reyna & Brainerd, 1995a). If one ignores the psychophysical mechanisms through which framing effects are produced in prospect theory, non-numerical loss-versus-gain differences can be explained by invoking evaluation from a reference point and loss aversion. However, it is difficult, to explain *larger* framing effects under some deletion conditions compared to when numbers are present. The issue at hand, nonetheless, is whether the psychophysics of numerical quantities (e.g., dollars, probabilities) is necessary to observe framing effects.

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Figure 4 shows results from three different conditions in which numerical information was deleted. In some problems, we took outcomes out and put vague phrases in (e.g., a 1/3 probability of saving many people and 2/3 probability of saving no one); in some problems, we only took the probabilities out and put in vague phrases (e.g., some probability of saving 600 people and a higher probability of saving no one); and in some problems, we took them both out and put in vague phrases (Reyna & Brainerd, 1991, 1995a). As is evident from Figure 4, framing effects were preserved in all conditions, and were largest when both numerical outcomes and probabilities were deleted. If all of the numbers are taken out of these problems, and replaced with vague phrases, the necessary ingredients according to expected utility theory, prospect theory, and so on, have been deleted. The nonlinear perception of the numbers is supposed to cause the framing effect. However, nonnumerical framing effects demonstrate that numbers are not necessary to observe the effect. These results cannot be explained by ambiguity aversion because a) in some conditions, subjects preferred the ambiguous option, but moreover b) preference ratings remained high even when both options were ambiguous.

But, are these numbers *sufficient* to cause framing effects? Again, the most popular and enduring theories of decision making have assumed that the psychophysics of these numbers was sufficient to cause framing effects. To test the sufficiency hypothesis, another class of manipulations was implemented called *selective attention effects* (e.g., Reyna & Brainerd, 1995a, 2011). It is not obvious how to explain all of the critical selective attention results using prospect theory or any of the other expected utility variants (Table 2; see also Kühberger & Tanner, 2010): For example, how could deleting zero make framing effects *disappear*? Deleting zero focuses attention on the specific numbers critical to either to prospect theory or to utility theory; yet, it eliminates framing effects.

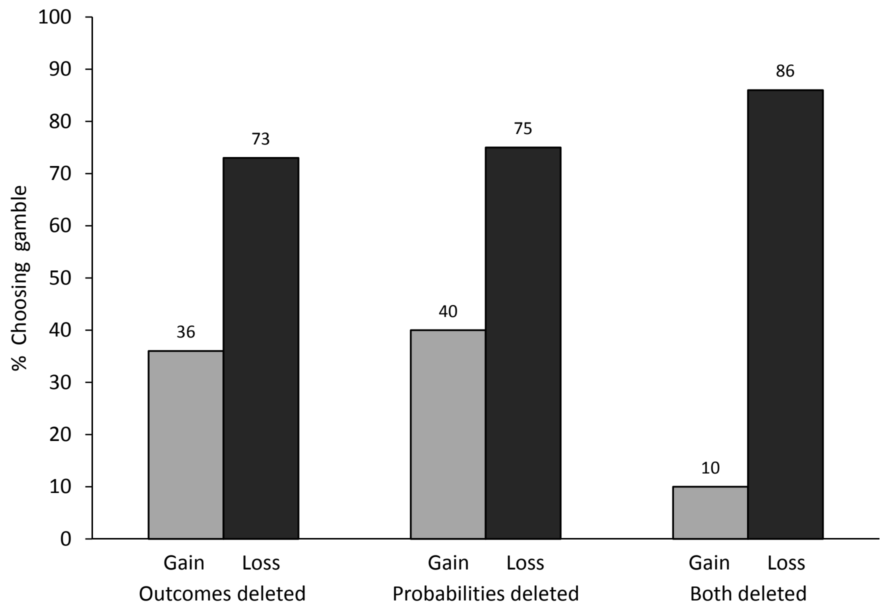
Figure 5 shows effects of selectively focusing attention on parts of the gamble; two variations on selective attention effects are displayed. (Note that missing parts of the gamble were presented in the preamble to eliminate ambiguity; thus, when all three groups had the same information, the pattern shown in Figure 5 is observed; Reyna & Brainerd, 1995a; 2011.) These experiments address the question of whether supposedly key numbers are sufficient to observe framing effects. For example, in the gain frame of the Asian disease problem, the key numbers, according to expected utility and prospect theory, are 200 saved versus a 1/3 probability of 600 saved. In the loss frame, the key numbers according to these theories are 400 die versus 2/3 probability that 600 die. These numbers are supposed to provide everything needed to show framing effects. (The zero complement of the gamble literally multiplies out to equal zero.) Thus, focusing attention on these numbers should produce *identical* framing effects (compared to full-complement, traditional versions of the problem), according to psychophysical theories.

In contrast, according to fuzzy trace theory, an attenuation of framing should be observed under this condition of focusing on "key" numbers because the decision maker does not focus on the categorical contrast between some and none, a simple gist (discussed below). As you can see in Figure 5, there is little or no framing effect when attention is focused on the supposedly critical numbers, an effect that has been replicated in different languages and cultures (e.g., Betsch & Kraus, 1999; Kühberger, 1995; Kühberger & Tanner, 2010; Mandel, 2001; Stocké, 1998). When the categorical contrast is put in the background, the decision becomes about "six of one versus half a dozen of another" (as the aphorism goes), and no framing effect is observed.

What happens if the opposite truncation of the gamble is performed, another selective attention manipulation (Table 2)? In this variation of the gain frame, for example, the 1/3 probability of 600 saved is put in the background information, and the focus is on the contrast between 200 saved and none saved. According to fuzzy trace theory, this variation highlights the some-none contrast: some people are saved or there is a categorical possibility that no one is saved. Therefore, an increase in the framing effect should be observed, and, in fact, this is what the studies showed (Figure 5). As noted earlier, this categorical gist is encoded in parallel with verbatim analysis of something like expected value; so the claim is not that people are insensitive to expected value, on the contrary (see Reyna & Brainerd, 1995a; Figures 1 & 2). When the expected values of the options are equal (or close to it), however, focusing attention on categorical contrasts between options produces sharp preferences, in spite of the equivalence in expected value.

This series of experiments on selective attention effects pits predictions characterizing decision making in terms of psychophysical transformations of probabilities and outcomes, which trade off, against predictions that decision making boils down to essential meaning: simple categorical or ordinal distinctions (e.g., better to save some lives than to save none; for a recent summary of these effects and a model, see Reyna & Brainerd, 2011). The effects shown in Figures 4 and 5—making framing effects disappear and making these effects larger—fall out of the assumptions of fuzzy-trace theory. It is possible to explain some of these findings with prospect theory (or cumulative prospect theory) by going beyond its psychophysical mechanisms, but it is not obvious how all of the effects in Figures 4 and 5 can be accommodated by that approach.

Figure 4: Nonnumerical framing effects. Deleting numbers from framing problems and replacing them with vague words, “some” and “none” (probabilities deleted = 200 saved vs. some probability of saving 600 and a higher probability of saving none; outcomes deleted = some saved vs. 1/3 probability of saving many and 2/3 probability of saving none; both deleted = some saved vs. some probability of some saved and some probability none saved); Reyna & Brainerd, 1991, 1995



Fuzzy-trace theory’s assumptions built directly on those of prospect theory, not only about gain-loss distinctions, but also about editing and cancellation (Tversky & Kahneman, 1986; 1992). Prospect theory seems to capture what people do when they process numbers, but more often than not, people make decisions based on crude qualitative contrasts (some-none or low-high) rather than on numerical details (Reyna, 2008). How people mentally represent quantities in judgments and decisions, along with the social and moral values that they retrieve and apply to their representations, determine behaviors, such as choices.

Moreover, the level of representation is not arbitrary, but, rather, begins at the lowest or simplest level of gist (the nominal, or categorical, level) and proceeds up the hierarchy of gist (increasing in precision) until a choice can be made (e.g., Hans & Reyna, 2011). Applying this principle, the representation of the gamble “1/3 probability of saving 600 lives and 2/3 probability of saving no one” in the Asian disease problem is most simply characterized in categorical terms: save some people or save none. Similarly, the simplest representation of the sure option of “200 saved” in the Asian disease problem is some saved. The fuzzy-processing principle stipulates that the lowest level of gist, the categorical or some-none distinction, is attempted first because it is the simplest gist (e.g., Reyna & Brainerd, 1995a). That is, if one thinks of any kind of numerical quantity, the simplest distinction that can be made is at the nominal (some vs. none) level, corresponding to the lowest scale of measurement. This level is sufficient to discriminate options, so the decision maker does not proceed to more precise representations (as would be required to discriminate between two gambles; see Reyna & Brainerd, 1995a; 2011). Thus, the gist of the Asian disease problem boils down to a choice between saving some people versus saving some people or saving none, favoring the selection of the sure option in the gain frame; the same simple dichotomization favors selection of the gamble option in the loss frame (Reyna, 2008).

However, implicit in these preferences is a principle of valuing human life (Reyna & Casillas, 2009). (Other decisions cue other values, such as valuing money or health, which are then applied to representations of the decision options in order to generate a preference.) Retrieving and applying a value for human life (e.g., for the Asian disease problem) is required in order to generate a preference between the sure option (save some people) and the gamble (save some people or save none). If decision makers had this some-none representation, but did not have this human-life value, they would not necessarily have a preference, even though the representation was simple. It is this value, retrieved in the context of choice, that allows someone to decide between the sure option versus

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Table 2: Predictions of prospect theory and fuzzy-trace theory for three selective attention conditions (one example shown, but effects have been replicated for many problems).

Condition	Focus on **nonzero** complement	Focus on **both** complements: Traditional presentation	Focus on **zero** complement
Stimulus: Gains	200 lives saved vs. 1/3 probability of 600 lives saved	200 lives saved vs. 1/3 probability of 600 lives saved and 2/3 probability of 0 lives saved	200 lives saved vs. 2/3 probability of 0 lives saved
Stimulus: Losses	400 people die vs. 2/3 probability that 600 die	400 people die vs. 2/3 probability that 600 die and 2/3 probability that 0 die	400 people die vs. 2/3 probability that 0 die
Ambiguity	No ambiguity: Deleted information provided in preamble/instructions and subjects tested afterwards.	No ambiguity: Subjects tested afterwards.	No ambiguity: Deleted information provided in preamble/instructions and subjects tested afterwards.
Predicted result: Prospect theory	Framing effect: Identical to traditional presentation	Framing effect	Framing effect (or larger?)
Predicted result: Fuzzy-trace theory	No framing effect	Framing effect	Larger framing effect
Observed result	No framing effect	Framing effect	Larger framing effect

the gamble option. Stored in long-term memory is a qualitative social value for human life—a moral value—that saving some people is better than saving none (Reyna & Casillas, 2009; see also Mills et al., 2008; Reyna, Estrada et al., 2011).

Therefore, in the gain frame, because saving some people is better than saving none, one prefers the sure option. In the loss frame, the mental processes are analogous to those in the gain frame, but the resulting preference is exactly the opposite. If some people die for sure, and none dying is preferred over some dying, now one chooses the gamble option. Algorithmically applying the same representation and retrieval processes (e.g., retrieval of social/moral values) to the loss frame produces the framing effect—and accounts for its variations. Additional variations include that framing effects increase, rather than disappear, with repeated choices presented within subjects (e.g., in contrast to decision field theory's predictions; see Reyna & Brainerd, 1995a). Also, framing effects disappear if people are told that whatever they choose will be re-enacted many times, effectively removing the zero outcome of the gamble, and, hence, removing the categorical contrast between some and none (Reyna, 2008; Reyna & Brainerd, 1995a). These effects, as well as the nonnumerical and selective attention effects discussed earlier, are predicted by the representational and retrieval assumptions of fuzzy-trace theory.

3.2 Risk-taking: Framing effects in children and adolescents

After the initial demonstrations of nonnumerical framing and selective attention effects, Ellis and I conducted the first study on framing in children—showing that framing effects developed with age (Reyna & Ellis, 1994). This result mirrored other emerging developmental results for similar reasons. Reyna and Ellis argued that the representativeness heuristic and other biases increased with age, too, because of an increased reliance on gist-based intuition (e.g., Davidson, 1995; Jacobs & Potenza, 1991). Young children were found to be loss averse, as adults are (Reyna, 1996a), but they roughly calculated and re-

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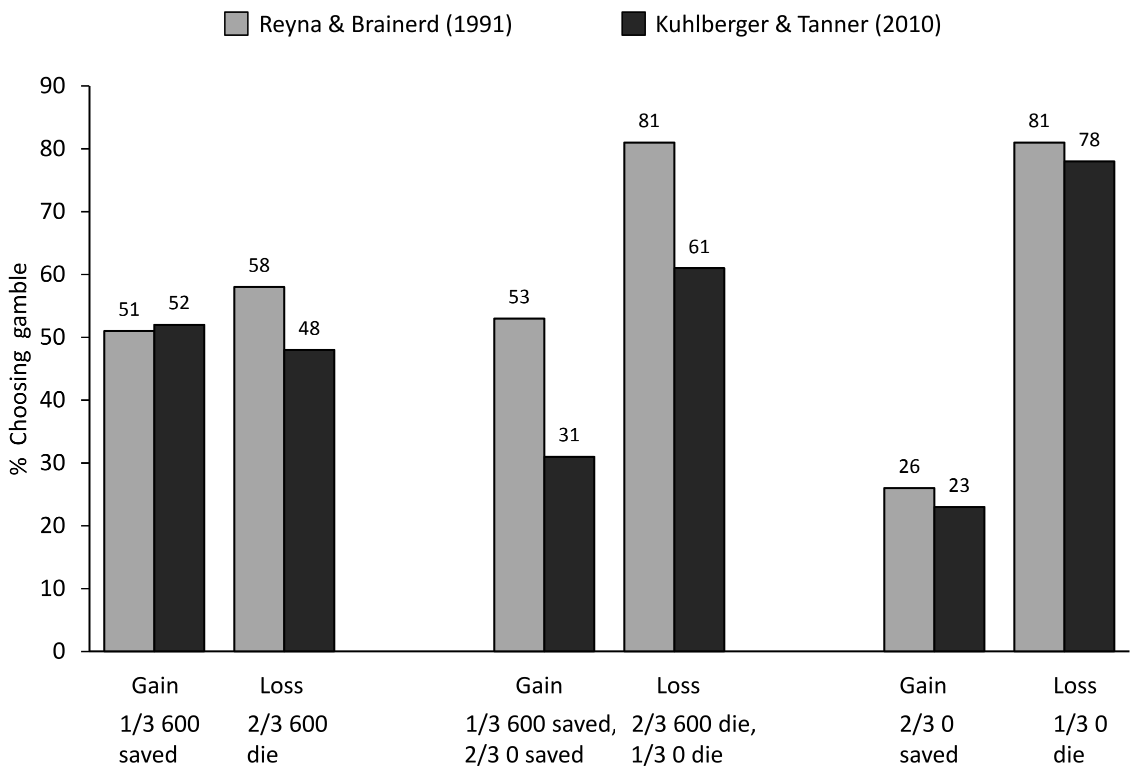
Figure 5: Selective attention effects. Framing problems with variations in gambles—focusing on nonzero complement shown at the left, both complements (traditional presentation) shown in the middle, or zero complements shown at the right. Labels are shown for the Asian disease problem, but the data are from multiple problems (each of which shows the effect).



sponded similarly to gain and loss frames in *true* framing (as opposed to reflection) problems: when net gains are the same for gains and for so-called "losses" problems (for reflection problems, gains are compared to actual losses). In particular, young children did not show framing effects for true framing problems when "losses" were explicitly displayed in front of them, eliminating the need to subtract or to remember outcomes (for discussion, see Reyna, Estrada, et al., 2011). Rather than show gist-based framing effects, young children appear to roughly calculate expected value, and they modulate their choices based on the magnitudes of risks and rewards (e.g., Figner et al., 2009; Reyna & Farley, 2006; Schlottmann & Anderson, 1994).

However, fuzzy-trace theory does not assume that verbatim-based analysis (e.g., of risk and reward) is replaced by gist-based intuition in development. Instead, fuzzy-trace theory incorporates a duality: numerical calculation (verbatim-based analysis) and gist-based intuition *both* develop from childhood to adulthood. When instructions are simplified and tasks are clear, young children (four to six years of age, depending on the study) behave rationally, in the sense that they traded off risks and rewards (for a review, see Reyna & Farley, 2006). Their ability to calculate—to multiply magnitudes of risks and rewards—improved during roughly the same period that framing biases and other numerical fallacies also emerged (Reyna & Brainerd, 1994).

Therefore, cuing and context elicited mathematically astute judgments early in development (e.g., Acredolo et al., 1989; Rakow & Rahim, 2009; Siegler, 1981) followed by heuristics and biases later in development that, thus, coexisted with mathematical *competence*. Furthermore, mathematical *performance* improved during the same period in which heuristics and biases emerged for seemingly mathematical tasks, such as probability judgment and decision making (i.e., framing problems in which expected value, as a function of numerical probabilities and numerical outcomes, varied; Figner et al., 2009; Levin, Hart, Weller, & Harshman, 2007; Levin, Weller, Pederson, & Harshman, 2007; Reyna & Brainerd, 1993, 1994, 2008). In sum, framing and other judgment-and-decision-making biases grew with age during childhood, consistent with fuzzy-processing preferences being present in adulthood (see also Markovits & Dumas, 1999 and Morsanyi & Handley, 2008, but see Klaczynski, 2005).

3.3 Gist-based intuition increases with age and experience

More generally, the emergence of framing effects is an example of how reliance on gist-based intuition increases with age and experience. If one considers theories of the development of reasoning from childhood to adulthood, there are many reasons to expect that reasoning should only get better (in the traditional sense of being more quantitatively sophisticated and less biased). Working memory capacity increases, inhibition and cognitive control improve, and metacognition develops during that age period (e.g., Bjorklund, 2012). A person becomes a better computer all the way around, from childhood, to adolescence, to adulthood. In all standard developmental and dual process theories — if an age difference is observed — it should generally reflect improvement in reasoning and judgment-and-decision-making performance. However, there are many demonstrations of the opposite developmental trend–the framing example is only one of them–of increases in biases with age (Reyna & Brainerd, 2011; Reyna & Farley, 2006). Increases in biases or distortions are called *developmental reversals* because they reverse the usual expectation of developmental progress (e.g., Brainerd, Reyna, & Ceci, 2008; Reyna & Ellis, 1994; Reyna & Farley, 2006).

Developmental reversals were predicted by fuzzy-trace theory, but they have been found serendipitously, too. According to the theory, these increases are predicted because they reflect gist-based meaning biases. Shown in false memory as well as in reasoning, meaning-based processing increases with age from childhood to adulthood. (For a review of studies on developmental increases in memory distortion, see Brainerd, Reyna, & Zember, 2011.) A study conducted by Markovits and Dumas (1999) is instructive for understanding increases in reasoning biases. They presented transitive inference problems to young children (transitive inference questions are on IQ tests—A is bigger than B, B is bigger than C, therefore A is bigger than C). Young children generally get these problems right (Reyna & Brainerd, 1990; Reyna & Kiernan, 1994). For example, "Paul is taller than Harry, and Harry is taller than Sam; is Paul is taller than Sam?" Young children get that problem right. What if Paul is a friend of Harry, and Harry is a friend of Sam, is Paul necessarily a friend of Sam? Young children say, "No! That's not logical," which is correct.

As children get older, systematic errors go up in the friendship version of the problems. Older children are more likely to conclude *erroneously* that Paul is a friend of Sam. That erroneous inference increases with pragmatic knowledge, social knowledge, and so on, because knowledge supports the processing of meaning (e.g., Reyna, 1996a). However, as the emergence of framing effects shows, knowledge differences are not essential to observing increases in gist-based intuition. Older theories acknowledge the possibility of meaning-based distortions, but they claim either that reasoning is inherently biased or that such biases are artifacts (e.g., Liben, 1977). Both verbatim analysis (e.g., calculating expected value) and gist-based intuition (e.g., belief bias as illustrated in inferences about friendship) coexist in the adult mind, according to fuzzy-trace theory. The interplay of these two kinds of processing has been used most recently to explain adult biases in conjunction and disjunction judgments (e.g., Brainerd & Reyna, 2008; Brainerd, Reyna, & Aydin, 2010; Brainerd, Reyna, Holliday, & Nakamura, 2012; Reyna & Brainerd, 2008; Wolfe & Reyna, 2010).

To summarize, during childhood, despite increasing skill in calculation, including in calculating probabilities and expected value, the tendency to use the bottom-line meaning in many situations goes up faster than the tendency to rely on computational ability. Mathematical models are useful in testing such predictions involving opposing processes, in this instance, verbatim-based analysis versus gist-based intuition (e.g., Reyna & Brainerd, 2011). Models incorporating simple assumptions from fuzzy-trace theory have been tested for goodness-of-fit to real data and evaluated against alternative models (e.g., see Brainerd, Reyna, & Howe, 2009; Brainerd et al., 1999). The heart of a mathematical model of a psychological process, such as decision making, is not the mathematics, but, rather, the interpretation of the mathematics in terms of core constructs. The core constructs in fuzzy-trace theory are verbatim and gist representations that are encoded and processed in parallel, and which support analysis versus intuition, respectively. Verbatim and gist representations compete against each other for control of task performance; the winner depends on which memory is more accessible and the constraints of the task (see Figure 1). In general, gist is more accessible and more useful than verbatim representations—especially when gist is informed by age and experience.

3.4 Risk-taking from lab to life: Adolescents and young adults

As noted earlier, gist-based "false" memory has been a research theme, explained by the same processes discussed hitherto for judgment and decision making. False memory, occurring when people remember things that never happened as though they did happen, typically derives from unconscious meaning-based inferences (e.g., Brainerd & Reyna, 2005; Reyna, Holliday, & Marche, 2002). A lesson learned from the false-memory literature is that seemingly "artificial" laboratory tasks explain real-world forensic situations—when those tasks tap causal mechanisms (Brainerd, Reyna, & Estrada, 2006; Reyna, Mills, Estrada, & Brainerd, 2006). Indeed, the conclusions discussed below are drawn from an extensive review of the literature on real-life risk taking as well as from laboratory data from behavioral and brain studies (Reyna & Farley, 2006; Reyna, Chapman et al., 2012). Popular myths, such as that adolescents underestimate risks, have been studied extensively and ruled out by multiple investigators. Therefore, underestimation of risk, changes in beliefs, and other conventional wisdom do not account for the effects I now discuss.

Applying the lesson that laboratory findings bear on real life to the problem of risk taking, I have more recently examined risky decision making of adolescents, portrayed in the literature as paradigmatic examples of irrational decision makers (Reyna, et al., 2005; Steinberg, 2008). Extrapolating decision-making mechanisms from laboratory to life, is it possible to explain adolescent risk taking? Laboratory tasks reveal that overall risk taking (collapsing gains and losses) declines from childhood to adulthood, a robust pattern across studies (Boyer, 2008; Reyna & Farley, 2006). (Tasks that add the experience of actual outcomes—children experience wins and losses—cloud assessment of risk preferences per se: Figner et al., 2009; Reyna & Brainerd, 1994).

As noted earlier, around preschool age, there is no consistent difference between risk preferences for gains (e.g., win 2 prizes) and for identical net gains (e.g., have 4 prizes, then lose 2 prizes) phrased in terms of losses (in contrast, aversion to actual losses is present early in childhood, Reyna, 1996a). The biasing effect of context, that net gains were achieved as a result of losses, emerges in childhood (Galvan, 2012). Although risk preferences for gains versus gains framed as losses are similar in preschoolers, such preferences begin to diverge for elementary schoolers.

Specifically, a pattern of preferences begins to emerge around second grade that my colleagues and I have called *reverse framing* (Estrada & Reyna, 2011; Reyna & Ellis, 1994; Reyna, Estrada, et al., 2011; these problems do not involve small probabilities, and so results are not predicted by cumulative prospect theory). Reverse framing is the opposite of standard framing: It is a preference for the gamble option in the gain frame, but the sure option in the loss frame. Recall that, when expected value is equal, risk and reward trade off in these problems. Thus, in reverse framing, second graders choose the gamble more in the gain frame; they go for the larger rewards (i.e., the greater gains in the gamble; see also Reyna & Farley, 2006). Apparently, second graders compare numerical outcomes in the loss frame, too; they go for the smaller losses in the sure thing, relative to the losses in the gamble (focusing on probabilities would have produced opposite preferences). So, unlike younger children who process both risk and reward—two dimensions—older children mainly focus on the one dimension of reward outcomes. (To clarify, younger children are *capable* of processing both dimensions under carefully simplified conditions, but their *preferences* shift during this period to a focus on outcomes; and each of these developmental differences should be distinguished from the additional complexities of *strategy* selection as information value varies; see Mata, Helversen, & Rieskamp, 2011).

In early adolescence, the emergence of standard framing can be detected (e.g., Chien et al., 1996; Reyna & Ellis,1994; Reyna, Estada, et al., 2011). As the studies discussed in an earlier section show, standard framing is evidence for a qualitative processing strategy—the assimilation of different numerical outcomes into a categorical gist of "some," as opposed to none (and assimilation of probabilities into sure vs. variable). (Standard framing is evidence for qualitative processing because that hypothesis accounts for all of the effects reviewed earlier, as opposed to alternative hypotheses that do not account for all of the effects.) Consistent with this hypothesis, younger adolescents who are just beginning to exhibit standard framing, are more likely to assimilate outcomes when the outcomes are similar to one another than when they differ: Therefore, it makes sense that standard framing emerges first for smaller outcomes (e.g., *1* prize for sure vs. 50% chance of *2* prizes or nothing), but reverse framing remains for larger outcomes (e.g., *30* prizes for sure vs. a 50% chance of *60* prizes or nothing). In other words, the difference in outcomes is greater for larger (e.g., 60 – 30 = 30) than for smaller outcomes (e.g., 2 – 1 = 1). High school students also show reverse framing for larger outcomes (e.g., Estrada & Reyna, 2011; Reyna, Estrada et al., 2011).

Thus, children and adolescents are sensitive to quantitative differences between outcomes, manifest in a reverse framing pattern, whereas adults rarely exhibit reverse framing (e.g., DeMartino et al., 2006; Levin, Gaeth, Schreiber, & Lauriola, 2002; Reyna, Estrada et al., 2011). This developmental trend from a focus on quantitative differences to qualitative categories is consistent with fuzzy-trace theory's assumption of increases in gist-based intuition with age. Intriguingly, deviation from consistency across frames grows with age until the adult pattern of standard framing is evident. By traditional yardsticks (e.g., Tversky & Kahneman, 1986), then, irrationality grows from childhood to adulthood. Yet, youth are assumed to be more irrational in their risk taking in real life, compared to adults (Committee on the Science of Adolescence, 2011; Reyna & Farley, 2006; Steinberg, 2008). How can the risk preferences of lab and life be reconciled?

For gains, the downward trend across age in preference for risk, as measured objectively in the laboratory, is fairly stable. Most real-life risk taking in developed countries involves gains rather than losses, and thus preferences in the lab and in life can be somewhat reconciled (Reyna & Rivers, 2008). In addition, real-life increases in risk taking, such as in drunk driving and unprotected sex, are associated empirically with increased freedom and, hence, greater "risk opportunity" in older adolescence and young adulthood, compared to younger ages (Gerrard et al., 2008). However, as illustrated by reverse framing, adolescents also differ cognitively and motivationally from adults (e.g., see also Chick & Reyna, 2012; Galvan, 2012). Youth are more likely to compare reward magnitudes, and to take risks to achieve more positive outcomes. According to fuzzy-trace theory, their greater reliance on verbatim-based analysis (e.g., quantitative differences) aids and abets the motivational shifts in adolescence that support risk taking. The cognitive shift from greater reliance on verbatim-based analysis (e.g., quantitative differences) to gist-based intuition (qualitative contrasts) in adults discourages risk taking because it allows adults to avoid unhealthy outcomes–even when unhealthy outcomes are unlikely, such as HIV infection (Reyna, Estrada et al., 2011; Rivers et al., 2008).

In 2006, based on a review of the literature in many domains of adolescent risk taking, Reyna and Farley concluded that precise, hair-splitting calculation of risks and rewards promotes risk taking among adolescents, whereas simple, all-or-none gist protects against unhealthy risk taking—the opposite of most theories of risk taking (e.g., Fischhoff, 2008). This prediction was also borne out in subsequent studies (e.g., Mills, Reyna, & Estrada, 2008; Reyna, Estrada et al., 2011). Moreover, cognitive measures of verbatim-based analysis versus gist-based intuition (i.e., verbatim hairsplitting vs. simple categorical gist) predicted larger variance, and unique variance, in real-life self-reported risk taking, compared to motivational factors such as reward sensitivity (e.g., sensation seeking; Reyna, Estrada et al., 2011).

Reverse framing, in particular, loaded with other measures of verbatim-based analysis in principal component analyses, and these verbatim measures predicted greater vulnerability to real-life risk taking. In contrast, gist-based intuition was consistently associated with lower levels of unhealthy risk taking. For example, agreement with simple gist principles such as "Avoid risk" and with categorical gist statements such as "It only takes once to get pregnant" was associated with lower levels of sexual initiation, lower intentions to have sex, and fewer sexual partners (Reyna, Estrada et al., 2011). Consistent with fuzzy-trace theory, gist-based intuition was more "advanced" in the sense that it was associated with better outcomes (for discussion of coherence and correspondence criteria of rationality in fuzzy-trace theory, see Adam & Reyna, 2005; Reyna, 2008; Reyna & Adam, 2003; Reyna & Brainerd, 1994; Reyna, Lloyd & Brainerd, 2003; Reyna & Farley, 2006; Reyna & Lloyd, 2006).

Most theories of adolescent risk taking recognize that something like inhibition or cognitive control (which includes the ability to regulate emotions) also develops during this period. This assumption is shared by fuzzy-trace theory (e.g., Reyna, in press; Reyna & Mills, 2007b). However, fuzzy-trace theory parts company with traditional theories by assuming that such inhibition is a third factor, beyond the two types of reasoning referred to as verbatim-based analysis and gist-based intuition. Empirical evidence bears this out: behavioral inhibition increases with age during adolescence and young adulthood and accounts for unique variance beyond reasoning styles (Reyna, Estrada et al., 2011). The growth of inhibition is consistent with the development of fronto-striatal circuitry during this period (Casey et al., 2008; Giedd et al., 2012; see also Roiser et al., 2009).

Thus, mature adults differ from immature adolescents in more than the ability to rein in emotional and motivational responses (e.g., to tempting rewards), although such differences are important (Somerville et al., 2010). Adolescents also differ in the way in which they think about reward. If offered a million dollars to play Russian roulette, an adult quickly refuses. An adolescent appears to conduct a cost-benefit analysis, which is irrational under these circumstances, according to fuzzy-trace theory (e.g., Reyna et al., 2005). Compensatory reasoning—is the reward worth the risk—sounds smart and it fits traditional definitions of rationality. Many economists would make the argument that it is rational to play Russian roulette if the reward were large enough (or to smoke if the benefits outweighed the costs for that individual; Reyna & Farley, 2006). Others would say that the game has infinite disutility, which is another way to say that it seems categorically crazy, a gist-based, all-or-none intuition.

Therefore, investigating rationality through the lens of teenage behavior challenges basic assumptions (e.g., for a recent review of research on adolescent risk taking, see Reyna, Chapman, Dougherty, & Confrey, 2012; for a review of theory, including the neuroscience of risky decision making, see Reyna & Rivers, 2008). Although some theorists have argued that adolescents are more impulsive than adults are—but equivalent to adults cognitively—fuzzy-trace theory implies that there are important cognitive changes from childhood to adulthood. These cognitive changes should produce decreases in risk preference for gains (or rewards) (Reyna, Estrada et al., 2011). After reviewing the literature on children's and adolescents' risk taking (see Reyna & Farley, 2006), it became apparent that many take risks *because* they analyze and trade off risk and reward. Simple alternative explanations, such as that adolescents lack experience and thus must deliberate (Hogarth, 2001), are not antithetical to this hypothesis. However, they do not explain the range of results encompassed by the fuzzy-trace theory hypothesis that lacking experience contributes to reliance on a particular kind of processing, verbatim-based analysis of risk and reward, and a lack of fundamental insight into the gist of risky decisions (see Reyna, Estrada et al., 2011).

Explicitly, one-time risks (e.g., having unprotected sex one time) are often low and rewards (or benefits) are high; this imbalance promotes risk taking if one analyzes risk and reward. Drawing on results from both the framing task and other risk-taking research inside and outside of the lab, it appears that, as teens become adults, they do less analysis for the decisions that matter (e.g., Lenert, Sherbourne, & Reyna, 2001). They do not engage in compensatory reasoning, despite encoding risk and reward and despite being capable of multiplying them in a compensatory fashion. Rather, decisions are based on the bottom line gist, as adolescents grow up into mature adults (Committee on the Science of Adolescence; Board on Children, Youth, and Families; Institute of Medicine and National Research Council, 2011). A summary paper in *Medical Decision Making* reviews implications for prevention problems in public health, especially concerning teenagers and infectious diseases, such as HIV (Reyna, 2008). A randomized control trial of over 800 adolescents followed for one year found that inculcating gist-based intuitions using fuzzy-trace theory produced significant reductions in risk taking relative to a control curriculum and to another comprehensive risk-reduction curriculum (Reyna, Mills, & Estrada, 2008).

3.5 Risk-taking from lab to life: Experts

At the top of the developmental heap, experts have been a focus of research on fuzzy-trace theory (e.g., Adam & Reyna, 2005; Reyna, 2004; Reyna & Adam, 2003; Reyna & Lloyd, 2006; Reyna, Lloyd, & Brainerd, 2003). Experts are entrusted with decisions about health and safety, and, thus, their risk perception and decision processes are important to understand. For example, an emergency-room physician must decide whether a patient is at risk of a heart attack; a meteorologist must decide whether a community is at risk of being struck by a hurricane; and a lawyer must evaluate potential damage awards and decide whether a client should settle or risk going to trial (e.g., Hans & Reyna, 2011; Reyna, 2004). In addition to domain knowledge, conventional wisdom and many theories suggest that experts apply precise analytical and numerical reasoning skills to achieve the best outcomes, whereas novices are more likely to reason non-analytically and non-numerically (e.g. Epstein, 1994; Peters et al., 2006; but see Betsch & Haberstroh, 2005, for alternative views of expertise).

However, recent research on individual differences in analytical and numerical reasoning challenges conventional assumptions about advanced reasoning (e.g., Liberali et al., 2011; Reyna & Brainerd, 2008; for a review of the literature on numeracy, see Reyna, Nelson, Han, & Dieckmann, 2009). For example, even experts in quantitative fields struggle with concepts such as risk and probability (e.g., Nelson et al., 2008; Perneger & Agoritsas, 2011; Reyna & Brainerd, 2007; Reyna, Lloyd, & Whalen, 2001). Furthermore, those high in numeracy are prone to systematic errors when their processing is rote or verbatim (e.g., Peters et al., 2006; see Reyna et al., 2009).

According to fuzzy-trace theory, experts differ developmentally from novices, and should rely more often on gist-based intuition rather than verbatim-based analysis (see also Hogarth & Einhorn, 1992; Shanteau, 1992). This view is not unlike Hogarth's (2001) idea of educated intuition, which experts acquire as a result of experience that affords insight. As might be expected from our discussion of the gist origins of framing effects, a recent study comparing risk experts (i.e., experienced intelligence officers) to college students and to non-expert adults found that the framing bias was significantly *larger* among the experts who had extensive real-world experience with risk, even when sensation seeking and other factors were controlled (Reyna, 2011a). Thus, experts focus on the "deep structure" of decisions in their domain of expertise, on gist representations that eschew surface details, despite encoding both gist and verbatim (surface) representations (e.g., Chi & Feltovich,1981).

Consistent with this developmental expectation, my colleagues and I have found that experts used less information, and processed it less precisely, to make decisions, compared to novices (e.g., Reyna, 2004; Reyna & Lloyd, 2006; Reyna et al., 2003). For example, we have shown that more-expert physicians have better discrimination than less-expert physicians regarding predictions of medical outcomes, but the former rely on simpler gist-based representations to achieve this discrimination (Lloyd & Reyna, 2009; Reyna & Lloyd, 2006). Hence, precise information processing was not associated with better judgments of patient risks or better emergency-room decisions about patients—on the contrary.

Nevertheless, experts' risk and probability judgments violated internal coherence (e.g., Adam & Reyna, 2005; Reyna & Adam, 2003; Reyna & Lloyd, 2006). In particular, for judgments regarding emergency room admissions, about 1 out of 3 judgments were incoherent among physicians, for real as well as hypothetical patients. These physicians judged the probability that a patient was at risk of a myocardial infarction (heart attack) or had clinically significant coronary artery disease, or both, to be *lower* than the probability that the same patient had one or the other condition. The three elicited probability judgments were incoherent; the logic of their probabilities

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just did not make sense (see Reyna et al., 2003, for an overview). Yet, those physicians who displayed this internal incoherence, nevertheless, were able to discriminate low-risk from high-risk patients very effectively. My research team and I followed patient's actual outcomes after they had been seen in the emergency department and verified that more expert physicians (cardiologists) were better able to discriminate low versus high risk patients (based on practice guidelines and on subsequent cardiac outcomes within a year), but they were still as prone to heuristics and biases as generalist physicians.

More generally, experts show framing biases, conjunction and disjunction fallacies, and so on despite good correspondence (e.g., good discrimination of low vs. high risk; Adam & Reyna, 2005; Kostopoulo, 2009; Perneger & Agoritsas, 2011; Reyna, 2004; Reyna & Adam, 2003; Reyna, Lloyd, & Brainerd, 2003; Reyna, Lloyd, & Whalen, 2001). For example, physicians exhibit base-rate neglect: Suppose that the base rate of a disease is 10% and a diagnostic test for that disease is 80% accurate (i.e., an 80% chance of a "positive" result if the patient has the disease; an 80% chance of a "negative" result if the patient does not have the disease). If a patient has a positive test result, how likely is it that he or she has the disease; is it closer to 30% or to 70%? As Reyna (2004) reported for a sample of 82 physicians, only 31% of physicians selected the correct answer (of 30%), well below chance. Despite almost daily feedback about how base rates combine with diagnostic test results (and formal training in Bayes' theorem as part of medical education), these experts violated coherence. For these and other biases that violate coherence, coherence and correspondence do not appear to converge with experience over time, which makes sense given their explanations derived from fuzzy-trace theory. (See Reyna et al., 2003; for process models, see Reyna, 1991; Reyna & Brainerd, 2008; Reyna & Mills, 2007a; Wolfe & Reyna, 2010.) As predicted by fuzzy-trace theory, measures of coherence and correspondence are not the same thing. The intension, or gist, of probabilities does not obey the same rules as the extension, or reality, of the outcomes (see Reyna, 1991; Reyna & Brainerd, 2008; Reyna & Farley, 2006).

In sum, there are people who are logically coherent and those who have good outcomes, and these are not necessarily the same people. Coherence errors (internal inconsistency, such as violations of axioms of preference) are not necessarily related to correspondence errors (external correspondence to reality), such as good vs. bad medical outcomes. Fuzzy-trace theory provides a perspective on rationality that encompasses both coherence and correspondence (see also Reyna & Farley, 2006). Degrees of rationality are distinguished in fuzzy-trace theory based on process models identifying the cognitive loci of errors in different tasks; some errors are dumber than others and they tend to occur earlier in development (Reyna & Brainerd, 2011; Reyna et al., 2003; Reyna & Farley, 2006). Errors of both coherence and correspondence generally decrease with greater reliance on gist-based intuition. Therefore, the answer to the question, "Does the brain calculate [numerical] value?" is "yes" in fuzzy-trace theory (Vlaev, Chater, Stewart, & Brown, 2011), and this valuation sometimes wins out, but the more developmentally advanced brain relies mainly on the results of qualitative, meaning-based processes despite verbatim valuation.

4 Overview and future directions

The research reviewed here points up the importance of memory, meaning and development in judgment and decision making. Research on recall, recognition, and reasoning has shown that people mentally represent information in different types of representations—verbatim and multiple gist representations of the same information—and these representations are encoded, stored and retrieved roughly in parallel. Distinctions between verbatim and gist representations account for double dissociations, crossover interactions and developmental reversals and, moreover, predict such counterintuitive effects.

When people make judgments or decision based on information, they process both verbatim and gist representations, and sometimes the verbatim details (e.g., when expected values of options differ) carry the day. More often than not, however, adults rely on the essential meaning or gist of the options—and this tendency to rely on gist increases with development, that is, with age and experience. Much is known about the factors that influence meaning or gist extraction, based on research in psycholinguistics. Fuzzy-trace theory draws on this prior research, as well as research on emotion. Mood, valence, arousal, and discrete emotions shape the gist of information, consistent with theories of affect as information. Fuzzy-trace theory also builds on gestalt theory's distinction between rote (verbatim) versus meaningful (gist) processing, and on schema theory and mental models approaches, although it differs in important ways from each of these approaches.

The mental representations that people extract are not arbitrary. For numerical information, a hierarchy of gist representations is encoded, that are analogous to scales of measurement in terms of variations in precision: from nominal to ordinal to interval (or linear) representations of numerical valuation. Once information is mentally represented and depending on the cues in the environment, people retrieve values and principles that are stored in gist form in long-term memory (Figure 2). They apply these values and principles to mental representations to produce judgments and decisions. People retrieve moral values such as "Saving some people is better than saving none" or "Thou shalt not kill," and social norms such as the equity principle (all else equal, everyone should receive the same—the same pay, the same number of cookies, the same economic opportunity and so on). Together, these theoretical ideas explain task variability (that context and framing shifts judgment and decision making in predictable ways) and task calibration (that precise response formats and task requirements can shift the level of representation that is relied on away from a fuzzy-processing default).

Critical tests of expected utility theory, prospect theory, and fuzzy-trace theory have been conducted, producing multiple nonnumerical framing, selective attention, and other effects, which consistently support fuzzy-trace theory's predictions. Fuzzy-trace theory is the only dual-process theory that predicts developmental reversals—that biases based on fuzzy gist should *increase* with development (i.e., adults and experts should be more biased than children and novices, respectively). The first studies of framing effects in children and adolescents confirmed these predictions, and these results have been joined by a growing number of others illustrating developmental reversals for biases and heuristics (see Reyna & Brainerd, 2011). Both verbatim-based analysis and gist-based intuition develop in parallel during childhood, and both are available as modes of processing in adulthood, making fuzzy-trace theory a dual-process theory.

There is a "third" process in fuzzy-trace theory, however, that also varies with development and across individuals. Developmental increases in inhibition occur alongside developments in representation and retrieval, and counteract unhealthy risk taking. Although this review did not emphasize processing interference between overlapping classes (which accounts for denominator neglect and other errors in probability judgment, such as base-rate neglect, conjunction, and disjunction fallacies), developmental improvements in inhibition help to counteract these mental bookkeeping errors as well (see Reyna & Brainerd, 2008; Reyna & Mills, 2007a). Theory-based interventions have been used to reduce these errors, such as base rate neglect, implementing tagging manipulations originally discovered with children that reduce interference from overlapping classes. Supposed frequency effects have been shown to be a special case of "tagging" manipulations that do not depend on frequency formats (i.e., they work equally well with normalized probabilities to reduce errors, based on mechanisms delineated in fuzzy-trace theory; Reyna, 1991; Lloyd & Reyna, 2001; Wolfe & Reyna, 2010).

These tenets of fuzzy-trace theory also explain phenomena outside of the laboratory, such as false memory and legal decision making in the court room; risk perception and communication in health (e.g., cancer screening, HIV prevention, genetic testing, and vaccination); medical and surgical decision making by patients and physicians (e.g., informed consent for carotid endarterectomy, triage decisions for patients with chest pain, and choosing surgery to treat prostate cancer); and risk taking among adolescents (e.g., unprotected sex and underage drinking). The development of risky decision in childhood and adolescence has been a particular focus of the theory, with the surprising discovery that youth reason more rationally in the classic sense than adults do, inspiring new conceptions of rationality, assessed in terms of both coherence and correspondence (e.g., Reyna & Adam, 2003; Reyna & Farley, 2006).

Fuzzy-trace theory is being applied to develop new measures of financial literacy, of gist-based numeracy, and of intertemporal choice (i.e., delay discounting). Most important, the theory has been integrated with research on neurobiological development, for example, the massive pruning of gray matter that accompanies experience from childhood through young adulthood and the increased connectivity between prefrontal cortex and striatal regions during the same period (Reyna, Chapman, et al., 2012). Thus, to oversimplify, research on neurobiology and on fuzzy-trace theory supports the view that judgment and decision making become more streamlined and better integrated, rather than more detailed and elaborate, as development progresses (Reyna, Estrada et al., 2011). Neuroimaging evidence further suggests that qualitative gist-based intuition underlies framing biases in risky decision making, in contrast to traditional theories of quantitative valuation (Reyna, 2011b).

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