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Development of intuitive rules: Evaluating the application of the dual-system framework to understanding children's intuitive reasoning

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Theories of adult reasoning propose that reasoning consists of two functionally distinct systems that operate under entirely different mechanisms. This theoretical framework has been used to account for a wide range of phenomena, which now encompasses developmental research on reasoning and problem solving. We begin this review by contrasting three main dual-system theories of adult reasoning (Evans & Over, 1996; Sloman, 1996; Stanovich & West, 2000) with a well-established developmental account that also incorporates a dual-system framework (Brainerd & Reyna, 2001). We use developmental studies of the formation and application of intuitive rules in science and mathematics to evaluate the claims that these theories make. Overall, the evidence reviewed suggests that what is crucial to understanding how children reason is the saliency of the features that are presented within a task. By highlighting the importance of saliency as a way of understanding reasoning, we aim to provide clarity concerning the benefits and limitations of adopting a dual-system framework to account for evidence from developmental studies of intuitive reasoning.

There is a strong philosophical (e.g., Plato, Aristotle, Pascal, Hume, Kant, and Frege) and psychological (e.g., Freud, 1900/1953, and James, 1890/1950) tradition behind the assertion that there are two modes of thinking (i.e., logical and intuitive). These forms of thinking are described as being in conflict with each other, with logical thought confounded by primitive intuitions. The dualist framework still pervades current thinking, and in recent developments in the psychology of reasoning, a similar framework has been used (e.g., Evans & Over, 1996; Sloman, 1996; Stanovich & West, 2000). The current view is that one mode of reasoning generates inferences automatically, without any step-by-step, logically defensible basis. The other mode of reasoning is deliberate and slow, because it allows individuals to hypothesize—that is, to think about possibilities that do not necessarily have a referent in the world. Because of these characterizations, the different modes of reasoning cannot be reconciled within a single reasoning mechanism.

The dichotomy has been investigated in the adult-reasoning domain, and although the evidence that is compatible with this distinction has been growing, Osman (2004) has provided arguments that call into question the empirical and theoretical status of dual-system theories of reasoning. In addition, although this framework has also been used to accommodate evidence from developmental studies of reasoning, research in adult reasoning and research in child reasoning have remained relatively separate, and there has been no examination of the different dual-system frameworks in both domains. Therefore, our main objectives in this article are to contrast the different claims made by dual-system theories of adult and child reasoning and then to evaluate their claims against evidence from developmental research on reasoning.

The article will begin with an introduction to the main dual-system theories of adult reasoning (Evans & Over, 1996; Sloman, 1996; Stanovich & West, 2000) and the principal dual-system theory of developmental reasoning and memory (Brainerd & Reyna, 2001). We then will draw on research in which children's reasoning has been examined in the domains of mathematics and science and will evaluate the claims made by the theories described. Here, we will discuss the tenets of the research program—

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in particular, the significance it places on the role of salient task properties in understanding the development of rules that children apply automatically to a range of problems. We then will return to the main claims made by dual-system theories of reasoning and will evaluate them according to the findings we have described. In the final section, we will argue that although the evidence is consistent with some hypotheses of the dual-system framework, the conditions under which intuitive rules are applied and the reasoning phenomena that ensue are best characterized by a framework that has as its central tenet the dynamic relationship between consciousness and reasoning, and that proposes that implicit, explicit, and automatic forms of reasoning are different manifestations of a single reasoning system.

DUAL-SYSTEM THEORIES OF REASONING

The dual-system theories of reasoning discussed presently differ according to the labels they use to refer to the different reasoning systems. We will avoid using the terms *intuitive* and *analytic*, because different dual-system theories attach different meanings to each of these terms. In addition, the research program discussed in the next section refers to *intuitive* in a different way from the dual-system theories. To avoid confusion, we will use the term *primary* to refer to the system that the theorists describe as *associative* (Sloman, 1996; Stanovich & West, 2000), *heuristic* (Evans & Over, 1996), *System 1* (Evans & Over, 1996; Sloman, 1996; Stanovich & West, 2000), and *intuitive* (Brainerd & Reyna, 2001) and the term *secondary* to refer to the system that theorists label *analytic* (Brainerd & Reyna, 2001; Evans & Over, 1996), *System 2* (Evans & Over, 1996; Sloman, 1996; Stanovich & West, 2000), *logico-deductive* (Brainerd & Reyna, 2001), and *rule based* (Sloman, 1996; Stanovich & West, 2000).

All the theories are introduced according to three central aspects: (1) how the two reasoning systems encode information, (2) their functional role, and (3) how they interact with each other. At the end of this section, we will summarize the main claims that the theories make (Table 1) but will save contrasting their different positions on various aspects of reasoning until the empirical section of this review.

Encoding

Evans and Over (1996) have claimed that the primary system operates over representations that are the most relevant to a particular problem space; that is, they follow their first (cognitive) principle of relevance: "Human cognitive processes are aimed at processing the most relevant information in the most relevant way" (Evans & Over, 1996, p. 48). This includes representations that are contextual (e.g., rooted in everyday experiences of the world) and pragmatic (i.e., carry linguistic information about, e.g., shared beliefs, prior knowledge, presuppositions of motives). The primary system is said to operate over preattentive representations that include both selective features of the problem content and relevant associated knowledge retrieved from long-term memory. The secondary system is described as operating over the representations in the primary system, as well as representations of possibilities that can be abstract and purely hypothetical.

In Sloman's (1996, 2002) account, the primary system is based on representations held in long-term memory, but it is also able to operate over representations generated online during the solution of a task; that is, because the systems can generalize automatically on the basis of similarity, a computation of similarity between novel stimuli can occur while the reasoner is solving a task. In essence, the representations carry structural information and contextualized information. The secondary system operates over representations that have extracted the key features of the problem; but in this case, unlike representations in the primary system, the structural information is constrained, and ingrained in these representations are abstract concepts, such as necessity and sufficiency.

Stanovich and West (2000) have characterized the primary system as operating over representations that are highly contextualized, personalized, and socialized; these are global properties of stimuli. Stanovich (2004) also has claimed that normatively appropriate knowledge can be automatized and, so, become imbued in the primary system, as the result of practice that is often initiated due to the metacognitive abilities instantiated in the secondary system. Like Evans and Over (1996), Stanovich and West (2000) proposed that the secondary system operates over representations in the primary system, but also over representations that are abstract (i.e., decontextulaized, depersonalized, and desocialized), in order to support hypothetical thinking.

Brainerd (Brainerd & Reyna 1992, 2001; Reyna & Brainerd, 1995) has proposed that the primary system operates over *gist* memory traces. These are memory traces that preserve the underlying meaning of a task and contain relational or pattern-like information that is also tagged with episodic information. The secondary system is characterized as logico-deductive, and it often involves implementing a formal principle over precise and accurate representations. This system operates using *verbatim* memory traces; these generally preserve the precise surface details of the task.

Functioning

Evans and Over (1996, 2004) have described the primary system as retrieving and applying experiential-based representations to a problem automatically. There is no conscious reflection involved in the application of the representations to the problem, because relevance enables the automatic retrieval of prior knowledge about a problem—particularly, if it is contextualized. The secondary system generates inferences and decisions in a slow sequential manner because it supports hypothetical thinking. It is involved in the evaluation of a model (a concept, theory, rule, or inference) used to implement the *satisficing principle*. This principle states that instead of optimizing a decision/choice among possible alternatives, the current model is maintained if it sufficiently satisfies

Table 1
Summary of the Main Claims of Dual-System Theories of Reasoning and the Intuitive Rules Research Program

Study	Flexible	Consciously Accessible	Involves Global Concepts	Metarepresented	Automatic	Computationally Expensive	Encoding	Functioning	Relationship Between Systems
Dual-System Theories									
Primary System									
Evans & Over (1996, 2004)	×	×	✓	×	✓	×	Relevant representations (reps), pragmatic, Gricean implicatures	Processes subjectively relevant reps	Supplies reps to S.S.
Sloman (1996, 2002)	✓	×	✓	×	✓	×	Concrete and generic concepts, images, feature sets, stereotypes	Processes similarity and contiguity	P.S. reps. dominate
Stanvich & West (2000)	×	×	✓	×	✓	×	Contextualized, personalized, and socialized reps	Process subjectively relevant reps	Supplies reps to S.S.
Brainerd & Reyna (2001)	✓	✓	✓	✓	✓	×	Episodic instantiations of concepts (relations, meanings, patterns	Processes relational properties of reps	Inhibiting irrelevant S.S. reps
Secondary System									
Evans & Over (1996, 2004)	✓	✓	✓	✓	×	✓	Reps of possibilities, metareps, P.S. reps	Hypothetical thinking rationalizing behavior determined by P.S.	Override P.S.
Sloman (1996, 2002)	✓	✓	✓	✓	×	✓	Concrete, generic, and abstract concepts, compositional symbols	Symbol manipulator	Override P.S.
Stanvich & West (2000)	✓	✓	✓	✓	×	✓	Rules and principles, P.S. reps, abstract concepts, metareps	Decontextualized and depersonalized problems and hypothetical thinking	Override P.S.
Brainerd & Reyna (2001)	✓	✓	×	✓	×	✓	Precise surface information	processes precise reps	Editing out irrelevant P.S. reps
Intuitive Rules Research Program									
Stavy & Tirosh (2000)	✓	×	✓	×	✓	×	Stimulus driven bottom-up salient task features	Intuitive rules	
	✓	✓	✓	✓	✓	×	Knowledge and experiential top-down salient task features		

the constraints set by the individual but that it can be overturned if there is contrary evidence that shows the model to be unsatisfactory. The secondary system is, therefore, a resource-bound system that is highly demanding of executive functions and is also effortful, because it serves to inhibit responses automatically generated by the primary system. In addition, because the primary system reveals only the end products (i.e., the response) of processing to consciousness, the secondary system serves to invent rationalizations (i.e., justifications for the response) of the inferential steps that might have contributed to the generating of the end products.

Sloman (1996) describes the primary system as typically reproductive; that is, the system relies on representations that are based on past experiences. However, as has already been mentioned, the system is also able to reason from newly experienced stimuli through a similarity-based method of generalization. Therefore, there is some flexibility in this system, because pattern matching can occur without employing any deliberate intentional goal-directed manner. This can lead to the generation of inferences on the basis of representations newly acquired during the solution of a task. The secondary system is productive and systematic and, so, can generate an unlimited number of new representations because it is rule based; that is, it is an operator that connects two representations that can be generalized to other representations that are different, as well as similar. Unlike the primary system, it involves deliberate analysis and, so, is strategic and goal directed. In this way, it abstracts the most relevant properties of a problem. In addition, although the primary system generates responses to problems quickly, the representations that are often processed in a characteristically serial manner require monitoring and are, therefore, metarepresented, which is why the secondary system is slower.

Stanovich (2004) has described the primary system as a collection of processes referred to as *the autonomous set of systems* (TASS). They are executed without any conscious reflection and operate in parallel with each other and the secondary system. Once they are triggered, they run to completion, which makes it difficult to override the inferences that are automatically generated. Also, because TASS involves representations that are well practiced, it does not make any demands on executive functions while the system is running. The secondary system is slow, cumbersome, and computationally expensive, because the reasoner must keep conscious track of the representations that are operated over. The secondary system enables hypothetical thinking. Decoupling (i.e., making contextualized representations abstract) is thus critical, because it requires thinking about possibilities that are dissociated from belief-laden representations that have a referent in the world.

Brainerd and Reyna (2001) have claimed that the functioning of the systems is integral to the kinds of representations they operate over. The primary system involves gist representations and, so, operates over the essential (relational, semantic, and structural) properties of a problem, which are later used to generate inferences automatically. Brainerd and Reyna (2001) also proposed that because of this, there is a bias toward relying on the primary system for most reasoning, judgment, decision-making, and problem-solving tasks. The primary system generates responses quickly and efficiently because of the kinds of representations it operates over, which is why reasoning performance cannot be reliably indexed by working memory capacity or indexes of cognitive ability. The primary system is flexible in order to accommodate the developmental changes in the extraction and abstraction of different gist representations. The secondary system functions when the task demands the application of rules to precise details—for example, mathematical calculations. In such cases, the solution is valid only if the correct operation and the precise values of the problem are accurately combined.

Interactive Relationship

Evans and Over (1996) claimed that there are conditions in which the secondary system inhibits responses generated by the primary system. Often, the systems compete, because the initial belief-based response, generated by the primary system, is flagged as inappropriate to the task by the secondary system. The outcome of the conflict depends on the individual. Some reasoners' final responses will be belief based, whereas individuals with higher cognitive abilities or experience with the particular task domain will succeed in overriding their belief-based responses and will give a logic-based answer. However, given the relevance principle that Evans and Over (1996) proposed, the relationship between the primary and the secondary systems is highly interactive, particularly because, as a default, the primary system will determine the relevant representations that the secondary system operates over.

Sloman (1996) claimed that, because of the efficiency and speed of execution of the primary system, it normally precedes the secondary system in generating responses to a problem. However, the secondary system is able to suppress the primary system in situations in which the problem format is familiar to the individual. Often, the systems operate in a complementary manner, which is why it is difficult to identify conditions in which one operates exclusively. However, although both systems can generate the same response to a problem, there are situations in which the task cues both systems and the responses are contrary to each other. Sloman (1996) refers to these conditions as *Criterion S*, which are tasks that invite conflicts between the systems. Typically, the primary system is invoked first, and either spontaneously or through instruction, the secondary system generates a contradictory response, and because the properties of the task invoke both systems strongly, they compete.

Similarly, Stanovich and West (2000) claimed that as well as supporting hypothetical thinking, the secondary system functions to override the representations that are automatically generated by the primary, default system. The secondary system's ability to decouple (depersonalize, decontextualize, and desocialize) the representations supplied by the primary system develops with other cognitive ability (working memory, digit span, and IQ). This is why individuals with higher cognitive ability are able to override responses generated by the primary system, because the inhibitory mechanism is effective and alternative correct representations are readily available.

Brainerd (Brainerd & Reyna 1992; Reyna & Brainerd, 1995) claimed that accurate reasoning develops under conditions that demonstrate the interaction between the primary and the secondary systems. This involves encoding the appropriate gist information from the problem, inhibiting inferences that are likely generated from verbatim representations, avoiding irrelevant gists, and, finally, retrieving and implementing the correct formalism (rule, principle, or mathematical operation). Brainerd (2004) also outlined the relationship between the primary and the secondary systems under U-shaped and inverted U-shaped patterns of development. Brainerd proposed that in U-shaped curves, increases in a particular treatment variable (e.g., forgetting or varying the exposure duration of stimuli in subliminal semantic activation tasks) will lead to increases in the influence of the primary system (i.e., gist memory), which decreases performance on a behavioral measure (e.g., recalling a word list). Increases in the treatment variable produce larger increases in the influence of the secondary system (i.e., verbatim memory) than in that of the primary system. Increases in the treatment create an equilibrium, represented as the plateau on the developmental curve. Eventually, increases in the treatment, in turn, increase the influence of the secondary system, which then dominates the primary system. The same principle works in reverse for inverted U-shaped curves.

Preliminary Summary

Table 1 summarizes the main characteristics of the primary and secondary systems that dual-system theories of reasoning propose. The table also includes a summary of the claims made by the research program; these will be discussed in the next section. The greatest disparity between the theories is based on the types of representations that are thought to be encoded in the primary system. In contrast, the dual-system theories of adult reasoning agree on many of the properties of the secondary system. However, Brainerd and Reyna's dual-system theory differs in a number of fundamental ways from the other dual-system theories' characterizations of both systems.

In the next section, we will introduce the developmental research program from which we evaluate the various claims made by dual theorists. We will set out the paradigm used to examine the development of intuitive rules and will define the kinds of phenomena that are investigated. A detailed discussion of the main claims made by the dual-system theories of reasoning and the contrasts between adult and developmental theories will then follow.

DEVELOPMENTAL RESEARCH PROGRAM: INTUITIVE RULES

One of the many research routes that has been pursued, in an effort to understand the development of the reasoning process, is the investigation of intuitive inferences (e.g., Dixon & Dohn, 2003; Dixon & Moore, 1996, 1997; Siegler, 1999, 2004; Stavy & Tirosh, 2000). Stavy & Tirosh's (2000) research program examines intuitive reasoning extensively in the educational domain. In particular, Stavy and Tirosh (2000) detail the development and application of *intuitive rules* in a variety of scientific and mathematical disciplines. They show that specific features of a given task encourage children to rely on a domain-general rule that is automatically invoked to generate a response. The rules are pervasive, and although they can generate responses efficiently, they are employed in tasks that are conceptually unrelated and may, therefore, lead to erroneous responses. Moreover, they do not diminish with cognitive development but, instead, persist into adulthood. In the following discussion, we will describe in more detail what intuitive rules are and the conditions in which they are applied.

Intuitive Rules

The rules referred to by Stavy and Tirosh (2000) are *intuitive* because children often experience them as self-evident and self-consistent cognitions (Fischbein, 1987). That is, children's responses generated from these rules appear to be prima facie, much like a reflex to a given set of task stimuli. The *rules* themselves (e.g., *more A–more B*, *same A–same B*, *everything comes to an end*, or *everything can be divided*) are operations that translate some property of the task and generalize it to make an inference about another property. There is no preplanning involved in retrieving them. They are simply implemented as a result of the task's properties.

For example, an intuitive rule such as *more of A* (e.g., weight, height, volume, width, density, size, area, time, or distance) *implies more of B* generates quick judgments in situations in which an individual is comparing quantities by drawing on task properties (e.g., area) that help discriminate between two items (e.g., a square and a triangle). It is then used by extension to form a judgment about another property (e.g., a perimeter) (N. H. Anderson, 1987; Piaget, Inhelder, & Szeminska, 1960; Stavy & Tirosh, 1996, 2000). The application of the rule is observed in a host of tasks that are based on conservation (e.g., one in which the taller of two containers is considered to have more water, despite the fact that they contain equal amounts) and comparison (e.g., one in which an angle with longer arms is judged as greater than an equivalent angle with shorter arms). These types of erroneous inferences are made by children and adults (Zaskis, 1999; Zaskis & Campbell, 1996a, 1996b). The intuitive *everything comes to an end* and *everything can be divided* rules are expressed in many repeated division problems (e.g., repeated halving, decreasing series such as serial dilution, radioactive decomposition, etc.) in which children are asked whether the repeated division will terminate. Many young children tend to respond that such processes are finite, thereby demonstrating use of the *everything comes to an end* rule (Stavy & Tirosh, 2000; Tirosh & Stavy, 1996; Yair and Yair, 2004). Many older subjects claim that such processes are infinite, thereby demonstrating use of the *everything can be divided* rule, regardless of whether the object is mathematical (where the process is actually infinite), physical, or biological (where the process is finite).

Saliency. To understand the role of saliency in child reasoning—and in particular, how it relates to the application of intuitive rules—we first will describe what we take saliency to mean and then will discuss its relevance to how intuitive rules are invoked. Since no precise definition of saliency has been provided in reasoning research, we will draw on evidence from perception research to provide an operational definition of saliency. A salient stimulus is arousing. Attention and behavioral resources are preferentially directed toward a given stimulus for two reasons. First, the features of a task capture attention without the intention of the observer (e.g., Lamy, Leber, & Egeth, 2004; Zink, Pagnoni, Martin-Skurski, Chappelow, & Berns, 2004), which is referred to as *bottom-up* or *stimulus-driven* saliency. Second, behavioral resources are also directed toward stimuli that have intrinsic properties that are relevant to the individual. This occurs through top-down factors—that is, according to the individual's prior knowledge and experience and his or her goals or intentions (e.g., Lamy et al., 2004; Lleras & Von Mühlenen, 2004; Sobel & Cave, 2002).

Bottom-up saliency. The allocation of attention and behavioral resources to a particular (salient) stimulus in a task depends largely on its relationship to the other stimuli contained in the task (Reingold & Stampe, 2004; Rothermund & Wentura, 2004; Treisman, 1998; Wolfe, 2001). That is, the more an item of a task differs from other stimuli in the task, the more salient it becomes, and the more easily a response based on it can be generated (Cave & Wolfe, 1990; Wolfe, 2003; Wolfe, Cave, & Franzel, 1989). To illustrate, there is a mathematical problem in which children's responses are based entirely on the perceptual, rather than the conceptual, features of the task—specifically, the most salient task feature.

The task (see Figure 1) involves presenting children with two rows containing the same number of counters; both rows are equally spaced. Then the distance between the counters of one row is increased (the task has also been demonstrated with other stimuli—e.g., flowers, chocolates, money, and geometric shapes). The status of one row has now become salient; that is, there is a perceptible difference between the two rows, and this is more conspicuous than the fact that the objects in both rows are of the same number. Children under the age of 6–7 years believe that altering the spatial layout of a line of objects changes its numerosity; hence, they infer that the longer the line, the greater the number of counters, invoking the intuitive rule *more A–more B*. Theorists (e.g., Bryant, 1974; Karmiloff-Smith, 1992; Stavy & Tirosh, 2000) have shown that this is because children are unable to distinguish between relevant (e.g., equivalent numerosity) and irrelevant (spatial layout) perceptual cues. Thus, the relationship between salient and other task stimuli determines the ease of processing (i.e., the speed at which a response is generated), because the salient feature is easily discriminable from other task features (Brainerd & Reyna, 1993; Napolitant & Sloutsky, 2004; Rothermund & Wentura, 2004). In summary, bottom-up activation is a measure of how different an item is from its neighbors. Thus, in tasks in which responses are stimulus driven, intuitive rules are invoked as a result of perceptual, not conceptual, task properties.

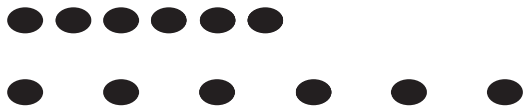

Figure 1. Examples of spatial arrays of counters.

Top-down saliency. Sobel and Cave (2002) have shown that the saliency of a stimulus is determined by prior experience of it or by goal-orientated knowledge of the task. Thus, exposure to a stimulus that has been repeatedly experienced in other learning instances will generate a response, regardless of its relationship to other stimuli in the task. To illustrate, in Livne's (1996) task, biology majors (Grades 10, 11, and 12) were told that a babysitter overheated the milk in a pan. She filled two feeding bottles that each contained 100 ml of milk but differed in shape: One was spherical, and the other was cylindrical (these were represented pictorially in the task). She immersed both in ice water. The students were asked whether the bottles would cool at the same rate or not and to provide explanations. The students focused on the equivalence in quantity between the bottles, ignoring the perceptually discernable differences between the stimuli, and erroneously invoked the intuitive *same A* (same quantity), *therefore same B* (same rate of cooling) rule, rather than considering the ratio between surface area and volume. Typically, they responded that "the time needed to cool the milk in both bottles is equal because the amounts of milk in each bottle are equal." In this example, there was perceptual information available that had students chosen to base their answers on it would have helped to generate a correct response by cuing relevant taught knowledge. Instead, the students matched the equivalence of objects with their prior knowledge of ratios to generate responses: These appeared consistent and sensible because they could be justified through the misapplication of taught knowledge and their experiences of ratios. In summary, the application of intuitive rules via top-down salient task features depends on the degree of match between the conceptual properties of an item and similar experiential-based knowledge of the set of target properties of that item.

TENETS OF THE INTUITIVE RULES RESEARCH PROGRAM

Five main claims have been borne out by the research program developed by Stavy and Tirosh (2000). First, attentional and behavioral resources are allocated to particular properties of a task. This is the result of salient properties that are stimulus driven (bottom-up saliency) or based on prior experience and knowledge (top-down saliency).

Second, salient properties that are stimulus driven invoke intuitive rules implicitly—that is, without the individual's control and without his or her awareness of the application of the rule. This is not to say that individuals are unaware of the stimuli at encoding; since the stimuli are salient, they will have conscious experience of them. Rather, there is a lack of awareness of how these stimuli are combined to produce a response. In contrast, because top-down salient features invoke intuitive rules through their match to relevant prior experiences and knowledge, the rules are invoked automatically, without the individual's control, but are accessible; that is, the reasoner has metaknowledge of the rule and of the products of that operation. However, the responses generated are based on representations that have accumulated strength through repeated exposure and are often endorsed by formal knowledge. For these reasons, it is difficult to correct responses that are generated by automatically invoked intuitive rules. Third, automatically invoked intuitive rules are examples of skilled reasoning and allow the reasoner to make inferences in a range of different contexts without deliberately computing each sequence of inferences. Fourth, for this reason, intuitive rules do not diminish with age and cognitive development but actually persist into adulthood. Finally, the research program is concerned with investigating reasoning phenomena that elicit responses without deliberation. This is not to say that children do not engage in reasoning that involves deliberate evaluative thinking. The research program also includes examples in which children are introduced to new scientific or mathematical principles or are prompted to reexamine familiar stimuli in the light of alternative hypotheses (e.g., Clement, 1993; Stavy, 1991; Stavy & Tirosh, 1993; Tsamir, Tirosh, & Stavy, 1997). This form of reasoning is different with respect to intuitive rules, because the representations are being manipulated deliberately, which is why reasoning from them is executed slowly. This redescription of representations is crucial in development (Karmiloff-Smith, 1992), because it gives rise to flexibility in the way information is encoded and utilized. Reasoning of this kind is not treated as belonging to a system separate from the implicit or automatic forms described here, because what appear to change across these forms of reasoning are the representations, not the inferential process itself (Karmiloff-Smith, 1992).

The Dynamic Graded Continuum

We will introduce Cleeremans and Jiménez's (2002) dynamic graded continuum (hereafter, DGC) framework, recently discussed by Osman (2004). Osman used this framework to unify different forms of reasoning identified in the adult-reasoning literature. It is introduced here because it shares many of the claims made by the intuitive rules research program. In particular, the DGC framework describes a single reasoning system that includes different forms of reasoning (implicit, explicit, and automatic). There are different forms of reasoning because of variations in the quality of representation. Representations increase in quality (i.e., according to their strength, distinctiveness, and stability) along a continuum that leads to an equivalent progression in the type of reasoning, from implicit to explicit to automatic, for which consciousness has different functional roles. As a result of the variation in the representations and, consequently, in the different functional roles that consciousness plays, the framework makes an important distinction between implicit and automatic reasoning. The DGC framework describes implicit reasoning as involving weakly represented representations that are not stable. The resultant abstractions or inferences are made without a concomitant awareness of them. The inferences occur unintentionally and cannot be consciously controlled but, through priming, are still capable of influencing explicit processes (Osman, 2004). Explicit reasoning involves representations that are stable, strong, and distinctive and, so, involve awareness of the abstractions or inferences that are made. Because the representations have a high rate of activation and are stable enough to become registered in working memory, they can be reliably recalled and expressed as declarative knowledge. Therefore, metaknowledge of the representations allows them to be controlled and manipulated. In contrast, individuals possess metaknowledge of the representations in automatic reasoning but do not have the opportunity to control them (J. R. Anderson, 1993). This form of reasoning is skill based and is acquired through frequent and consistent activation of relevant information that becomes highly familiarized. This is why the representations are enduring and well defined, and become stable through repeated use, but are difficult to modify.

What Are the Similarities Between the DGC Framework and the Intuitive Rules Program?

Both the OGC framework and the intuitive rules program make an important distinction between implicit and automatic forms of reasoning, which, although they are beyond the control of the individual, differ according to whether the reasoner has metaknowledge of the inferences made. In addition, the DGC framework describes the properties of the representations and how they differ between these forms of reasoning, whereas the intuitive rules program complements this by setting out the task conditions that invoke implicit and automatic reasoning. The lack of control that is characteristic of the implicit and automatic application of intuitive rules results from exposure to particular task scenarios that include salient features (bottom up and top down) that reliably invoke intuitive rules. In the DGC framework, there is no conscious control of implicit- or automatic-based inferences because, in the former, the representations are weak and not stable enough to be reliably recalled in memory, whereas in the latter, the representations are so well practiced that they are highly active in memory. The function of metaknowledge is to offer the child flexibility (Karmiloff-Smith, 1994; Stavy & Tirosh, 2000). Both the DGC framework and the intuitive rules account treat automatic forms of reasoning as skill based and, therefore, knowledge based. Thus, the reason intuitive rules are pervasive and the application of certain rules increases with age into adulthood is that there are contexts in which they have provided efficient and accurate responses quickly and have, through repeated exposure, become reinforced. Moreover, this representational change leads to U-shaped and inverted U-shaped developmental curves. For example, performance follows an inverted U-shaped developmental curve because, initially, children's intuitive rules are invoked through bottom-up salient task properties, which lead to a correct response. Once children have acquired explicitly taught mathematical or scientific principles, they misapply them to the same task, but through practice, they become able to discriminate which principles apply to the task and to respond correctly. Like the DGC framework, representational change over time is critical for the intuitive rules account: This is explained on the basis of which properties of a task become salient and how the saliency of these properties changes. Changing the saliency of task features elicits different responses and can improve performance but does not invoke a different reasoning system. Rather, it helps to reconceptualize the task and to make relevant task features that were previously treated as irrelevant.

What Are the Differences Between Dual-System Theories of Reasoning and the Intuitive Rules Program?

The intuitive rules program differs from a dual-system framework in a number of critical ways. Principally, it differentiates implicit from automatic forms of reasoning, a distinction not made by dual-system theories of reasoning. Second, the intuitive rules program outlines differences in the source of salient task information. Although saliency is an important aspect of the dual-system theories, they make no distinction between bottom-up and top-down saliency and between the types of reasoning that follow from them. Finally, intuitive rules are claimed to develop with cognitive development and age: This is necessary for skill development, particularly because cognitive development advances so that processes can be executed automatically (Cleeremans & Jimenez, 2002; Karmiloff-Smith 1986, 1992, 1994; Osman, 2004). This issue divides the dual-system theories. Brainerd and Reyna (2001) claimed that reasoning matures in such a way that accurate reasoning is carried out by the primary system, whereas Sloman (1996) claimed that mastering rules and the contexts in which they apply makes it possible to make inferences with less effort and is a necessary aspect of development. In contrast, Stanovich (1999) and Evans and Over (1996) suggested that the development of the inhibitory mechanism of the secondary system is critical for producing accurate and controlled processing styles that inhibit biases found in the primary system.

We return to Table 1, which summarizes the critical properties of each of the systems described by the dual-system framework and which will be used in evaluating the theories in the following discussion. The evidence presented in the empirical section of this review is divided into three parts: encoding, functioning, and interaction between systems. Each subsection will begin with the hypotheses that follow from the different dual-system theories presented in Table 1 and then will describe evidence from the intuitive research program, which later will be used to evaluate the success of the hypotheses.

EMPIRICAL SECTION

Encoding

Hypotheses. Adult dual-system theories (Evans & Over, 1996; Sloman, 1996; Stanovich, 2004) claim that representations that become automatically encoded in the primary system are stimulus driven or knowledge based (including pragmatic knowledge [e.g., deontic rules], Gricean implicatures, and feature sets). In contrast, Brainerd and Reyna (1990, 2004) have distinguished between stimulus- and knowledge-based representations and the task situations that generate them, although, as in adult dual-system theories, the primary system operates over both types of salient representations. Brainerd and Reyna predicted that in stimulus-driven tasks, some representations pop out and others sink into the background and that, in these cases, accurate reasoning is influenced by the visual distinctiveness of critical information. In conceptually driven salient tasks, which involve *schematic situations* (i.e., situations that involve mature social concepts, such as ethnicity and emotional relationships), young children do not extract salient meanings from target items, because the meanings are not yet understood. Reyna and Brainerd (1995) and Sloman (1996) made explicit that the primary system encodes information about concepts that include its internal structure and that the information is encoded and stored as patterns and includes relational information, which can be construed as rule-like. This is compatible with the claims made by the intuitive rules program and the DGC framework. However, unlike the dual-system theories, there are implicitly and automatically invoked intuitive rules: In the latter, children have metaknowledge of the operation. None of the dual-system theories predicts that reasoners possess knowledge of processes that follows from representations that are available automatically, even if they are skill based (Stanovich, 2004).

Evidence. The following is an example of a task in which the intuitive rule (*more A–more B*) is invoked in response to stimuli-driven salient task features. Brecher (2005; Babai, Brecher, Stavy, & Tirosh, 2006) presented high school students majoring in science with a probability task. In the task, the students were shown two boxes, both of which contained black and gray counters, and they were asked to judge from which of the two boxes they were more likely to select a black counter. In tasks of this kind, it has been shown that the black counters are the salient task feature (e.g., Babai & Alon, 2004; Falk, Falk, & Levin, 1980; Green, 1983). Brecher included two versions of the task. In congruent versions, the frequency of the black counters was varied: When the frequency of the black counters increased, so did the probability of their selection, relative to the number of gray counters. In incongruent versions, as the number of black counters increased, the probability of selecting a black counter decreased (see Figure 2).

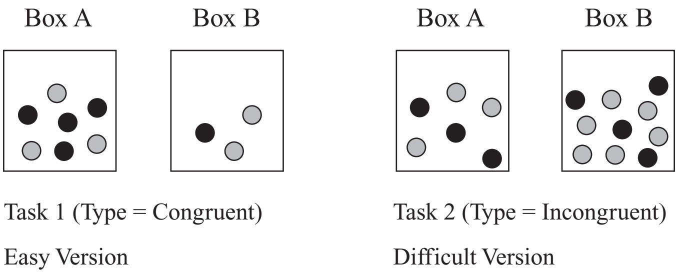

Figure 2. Examples of Brecher's (2005) probability task.

Task difficulty was varied, along with the congruency of the task features. In easy tasks, the difference between the probability of selecting a blue counter from Box A and the probability of selecting it from Box B was perceptually distinguishable, whereas in difficult tasks, it was not, because the difference between the probability of selecting a blue counter from Box A and the probability of selecting it from Box B was small. Given that the salient feature is the frequency of black counters, the children's answers were based on the intuitive *more A–more B* rule. That is, of the two boxes, the children focused on the one that contained more black counters and inferred that it was more probable that a black counter could be picked from it. In addition, because the salient task feature was perceptually based, saliency was determined by the discriminability between black and gray counters. Therefore, in incongruent and difficult versions, in which discriminability was manipulated, the participants' performance and speed of response were adversely affected. If, for example, responses to the difficult and easy tasks had been based solely on the frequency of black counters, no differences between difficult and easy tasks would have been observed, because the children could use the *more A–more B* rule in both versions. Instead, the findings indicated that the children based their answers on the black counters, relative to their differentiation from the other task properties (the frequency of gray to black counters), and that because they were more sensitive to both types of stimuli in the difficult task, they spent a longer time generating their responses, thus providing evidence that the status of perceptually salient task stimuli is dependent—on their relationship to the surrounding task stimuli. Consistent with this, Stavy's (Stavy, Goel, Critchley, & Dolan, in press; Stavy & Tirosh, 1996, 2000; Stavy, Tirosh, Babai, & Levyadun, in press) findings show that reasoning based on intuitive rules that are invoked via perceptually salient features leads to longer responses times when the discriminability between salient and other task stimuli is reduced. Moreover, similar findings have been reported in studies in which tasks involve making judgments about perimeters (Azhari, 1998; Stavy & Tirosh, 1996, 2000; Stavy, Tirosh, Babai, & Levyadun, 2006), and geometric concepts (e.g., angles; Stavy & Tirosh, 1996; Tsamir et al. 1997).

The following is an illustration of the application of an intuitive rule through top-down saliency. Fischbein and Schnarch's (1997) probability task is based on Tversky and Kahneman's (1972) law-of-large-numbers *hospital problem*. The law of large numbers states that as the sample size (or the number of trials) increases, the relative frequencies tend toward the theoretical probabilities (.5). In Fischbein and Schnarch's version, children assessed whether the probability of getting heads at least twice when three coins are tossed is greater than, equal to, or less than that of getting at least 200 heads out of 300 tosses. Here, the salient property of the task is the ratio between the number of heads and the number of tosses. The results from Fischbein and Schnarch's (1997) study are presented in Table 2. The figures show that most of the students in each grade level claimed that the probabilities are equal, because the proportions 2/3 and 200/300 are equal. Interestingly, the frequency of this erroneous response increased with age.

Fischbein and Schnarch (1997) showed that the "equal" response increases with age because it tracks the acquisition and stabilization of the proportion scheme and, without this scheme, children do not infer *same A* (ratio)–*same B* (probability). Although the evidence suggests that a logical scheme (proportion) is incorrectly applied to solve the task, it also demonstrates that there is a relationship between intuitive reasoning and formal knowledge. Children apply the *same A–same B* rule in a variety of tasks, because the concept of equivalence is generalized to a variety of contexts. Mendel (1998) presented 11th grade students with a problem in which a rectangle was shown. They were told that the length of it was decreased by 20% and the width was increased by 20%. The changes to the rectangle were visually represented. The students were asked what difference these changes made to the perimeter. Most students (72%) responded erroneously, claiming that the perimeter remained the same because "you add 20% and removed the same percentage, so they compensate each other." Only 8% of the students understood that the length

Table 2
Reaction Times (RTs in Seconds) and Proportion of Errors (Percentage Incorrect) in Congruent and Incongruent Probability Tasks

	Easy		Difficult		All tasks	
Tasks	RT	% Error	RT	% Error	RT	% Error
Congruent	1,410	7.6	1,769	9.5	1,620	8.7
Incongruent	2,267	18.7	2,616	23.4	2,475	21.5

of the rectangle is longer than the width, so that a 20% reduction in length and a 20% increase in width would not keep the perimeter constant. In these and other, similar problems, there is perceptual information available that if students choose to base their answers on it, will generate a correct response by cuing relevant taught knowledge. Instead, students make a match between their knowledge of the equivalence of objects and of percentages to generate responses. These appear consistent and sensible because they can be rationalized by taught knowledge.

The findings discussed involve studies of children's inability to avoid the saliency of task features. The following is an illustration of a task in which adults make errors similar to those of children, by basing their responses on perceptually salient information. In the free-fall task, children and adults are shown two matchboxes—one filled with sand, the other empty—and are asked to predict what will happen when both are dropped from the same height. Children and adults argue that the heavier matchbox will reach the ground first. Both groups are influenced by the difference in weight of the matchboxes and erroneously reason that the heavier the box is, the faster it will reach the ground (*more A–more B*). Similar studies conducted on first-year college physics students (Champagne, Klopfer, & Anderson, 1979; Gunstone & White, 1981) showed that although they were aware of Newton's second law of motion, which states that the speed of a falling body depends on the height from which it falls and is independent of the mass of the body, most based their answers on the perceptually salient property, claiming that the heavier box would reach the ground sooner.

Discussion. All the dual-system theories distinguish between the information encoded by the primary system and that encoded by the secondary system. In fact, they make distinctions based on the content of the representations. The evidence from the studies shows that the kinds of rule-based inferences that are invoked from formal-based knowledge and from perceptually salient task features are the same. In addition, in contrast to dual-system theories of reasoning, this distinction is independent of the content of the stimuli. The evidence shows that the particular properties of a task that are salient will change throughout the course of development (e.g., Fischbein & Schnarch, 1997). Because of this, salient features in themselves are unlikely to be associated with particular forms of reasoning, because they can invoke both intuitive schemes and formal scientific, mathematical, and logical schemes. For example, tasks in which bottom-up salience invokes intuitive rules (typically, the *more A–more B* rule) include physical, chemical, or biological attributes, such as weight (Stavy & Stachel, 1985), temperature (Stavy & Berkovitz, 1980), concentration (Strauss, Stavy, Orpaz, & Carmi, 1982), cellular size (Stavy & Tirosh, 2000), and speed (Stavy & Tirosh, 2000). For bottom-up saliency, the discriminability of salient stimuli from other task features is critical to invoking the application of intuitive rules, and these rules are not dependent on the content of the salient task features.

Sloman's (1996) Criterion S, which other dual-system theorists endorse (i.e., Evans & Over, 1996; Stanovich & West, 2000), describes conditions under which both primary and secondary systems cue contradictory responses in the same task. Reducing the discriminability between salient and other features present in the task generates conflicts. Under these conditions, children are slower to invoke intuitive rules to generate a response, and the processing is not automatic, because the children are evaluating more than just the salient task feature. Is this support for Criterion S? It appears that there is a conflict, but there is little to suggest that the conflict reflects competing reasoning systems. Instead, the evidence suggests that the conflicts that are identified in incongruent tasks do not arise from distinct reasoning systems but can, instead, consistent with the DGC framework, be interpreted as a result of the varying strengths of the representations utilized while reasoning (Osman, 2004). The discriminability between salient and other task stimuli can be manipulated gradually, and it is not shifts in reasoning that occur; children simply encode the stimuli differently and are forced to pay closer attention to other stimuli that were previously neglected. The attentional status of salient task properties changes because other task stimuli are similar to the salient stimulus (i.e., the discriminability is reduced); therefore, recovery from capture is possible only after an extended time, in order to allow for disengagement and redirection from the other task stimuli and back to the salient task properties (Azhari, 1998; Babai, Levyadun, Stavy, & Tirosh, in press; Stavy & Tirosh, 1996, 2000).

We will turn now to the second source of saliency: top down. Consistent with evidence from studies of saliency in perception (e.g., Greenberg, 1966; Kim & Cave, 1999; Pratto & John, 1991; Wentura, 2000; Wentura, Rothermund, & Bak, 2000), the evidence presented in this section will suggest that children match some property of the task with their knowledge. Examples of this kind of reasoning demonstrate how advanced knowledge, intentions, and goals automatically guide attention through a task, until a match is made between the properties of the task and knowledge and prior experience. The findings show that these salient properties can have a formal abstract basis (e.g., proportion or equivalence) and that a particular scientific or mathematical concept is matched to a variety of stimuli from a range of tasks and is not restricted to one domain. These are characteristics of representations that are consistent with the dual-system theories of reasoning hypothesis of primary (e.g., global, structural, or relational) representations and secondary systems (e.g., formal or abstract). Another problematic aspect of intuitive rules invoked from top-down salient stimuli is that children show awareness of using them (e.g., Livne, 1996; Mendel, 1998; Stavy & Tirosh, 2000) and can provide formal justifications for their responses because of the logical basis of their answers (e.g., Tirosh & Stavy, 1996). Finally, the acquisition of formally taught logical, scientific, and mathematical principles can increase the application of particular intuitive rules (e.g., Fischbein & Schnarch, 1997), because children are able to generalize their knowledge and match this to problem information in a variety of domains, which sustains the application of intuitive rules into adulthood. Only Brainerd and Reyna (2001) have claimed that children learn to rely on gist representations that are operated over by the primary system for accurate and efficient reasoning and that this persists into adulthood.

Functioning

Hypotheses. Sloman (1996) and Reyna and Brainerd (1995) have posited that there is a level of flexibility in the functioning of the primary system, whereas Stanovich and West (2000) and Evans and Over (1996) have described the system as invariant and have claimed that only the secondary system is flexible, because it is conscious and dependent on executive functions. Consequently, dual-system theorists are divided according to whether the systems can be indexed by measures of executive functions (e.g., working memory span, digit span, reading comprehension, and Scholastic Aptitude Test scores). Evans and Over (1996) and Stanovich and West (2000) hypothesized that performance that is based on the secondary system is predicted by cognitive ability measures, because measures of cognitive capacity directly reflect the likelihood of the secondary systems overriding the response primed by the primary system, in cases in which the two systems conflict. Therefore, they predicted that individuals that achieve high scores on tests of executive functions will perform better on a variety of reasoning tasks that lead both systems to generate contradictory responses. Individuals with poorer cognitive ability will perform poorly on these tasks, because the secondary system is unable to inhibit erroneous responses generated by the primary system.

Stanovich and West (2000) and Evans and Over (1996) also proposed that because the primary system is robust, it is spared by aging (Gilinksy & Judd, 1994) and neurological damage (e.g., Deglin & Kinsbourne, 1996). Because of this, they predicted that inverted U-shaped development occurs, in which the development of executive functions tracks improvements in performance in reasoning tasks but declines as executive functions become impaired through aging. Only Brainerd and Reyna have explicitly described the basis on which U-shaped and inverted U-shaped development occurs. Finally, all dual-system theorists agree that the secondary system involves metarepresentations and is under the conscious control of the individual. This is why it operates much more slowly than the primary system.

Evidence. The following studies have used comparison tasks that were based on formally taught schemes, such as volume, weight, and area. The examples that will be discussed illustrate a range of different patterns in performance, in which it increases with age, decreases with age, and shows a U-shaped developmental curve. All of these are dependent on the application of the intuitive *more A–more B* and *same A–same B* rules. In the cylinders task (Stavy & Tirosh, 2000; Tirosh & Stavy, 1999), students are presented with two identical rectangular sheets of paper, one of which is rotated by 90° (see Figure 3).

They are then asked to judge whether the area of Sheet 1 is equal to, larger than, or smaller than the area of Sheet 2

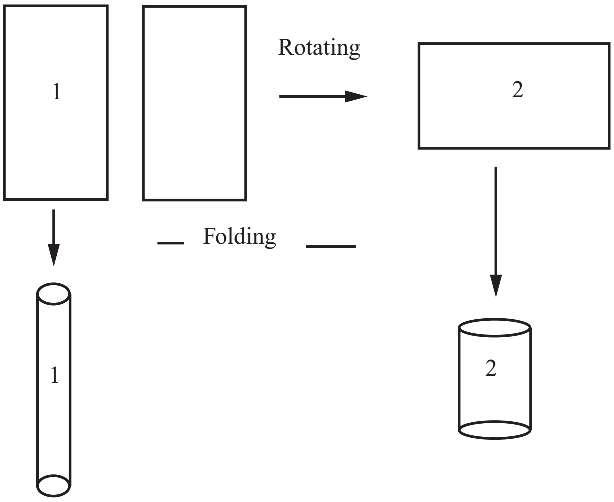

Figure 3. Example of the cylinders conservation task.

(Piaget et al., 1960). Many studies (e.g., Piaget et al., 1960; Tirosh & Stavy, 1999) have shown that for young children, the salient feature is the difference in either the length or the width of the two sheets (bottom-up saliency), whereas for older children and adults, the salient feature is the identical area of both sheets of paper (top-down saliency; Stavy & Tirosh, 2000; Tirosh & Stavy, 1999). After the presentation of the rectangular sheets, each sheet is then rolled to form a cylinder (see Figure 3), and the students are asked to judge whether the volume of Cylinder 1 is equal to, larger than, or smaller than the volume of Cylinder 2. For young children, the salient property is the difference in either the height or the width of the two cylinders (bottom-up saliency), whereas older children and adults focus on the equivalent area of the original sheets that form the cylinders (top-down saliency).

The area question has been used to examine whether students have a concept of conservation based on area. The volume question has been used to examine whether students can correctly avoid generalizing the concept of conservation to volume. Responses to the questions (see Figure 4) in Stavy and Tirosh's (2000) study have been consistent with Piaget et al.'s (1960) original findings. They have shown that the conservation scheme does not emerge until Grade 2. Children without the conservation scheme tend to erroneously invoke the intuitive *more A* (length)–*more B* (area) rule, based on perceptually salient task features. However, they also rely on perceptually salient features to respond to the volume question and infer *more A* (width)–*more B* (volume), which generates the correct response. After the second grade, children now correctly answer the first question, using the logical conservation scheme, and use identity, reversibility, addition, and compensation to support their decision. However, there is a sharp increase in erroneous responses to the volume question, in which they invoke the intuitive *same* (paper area)–*same* (cylinder volume) rule. To support their answers, many students give such explanations

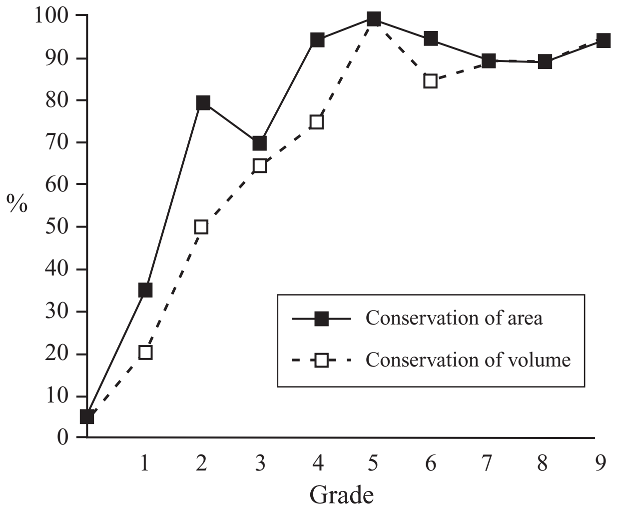

Figure 4. Distribution of equality judgment (percentages of correct responses), by age, to the task involving the surface area and volume of the two cylinders.

as "the volumes of the two cylinders are the same because they are made from identical sheets of paper." Educated adults presented with this task also give the same incorrect answers to the volume question. Tirosh and Stavy (1999) claimed that the development and stabilization of the conservation scheme replaces the intuitive *more A–more B* rule because conceptual knowledge, rather than stimulus-driven saliency, guides responses. Consequently, the salient feature of the task now becomes the "equivalence" between the areas of both shapes. The findings demonstrate that the application of intuitive rules changes as a result of an overlearned logical scheme that, in this case, is applied inappropriately.

A similar version of the cylinders problem is the containers problem, in which children reason about weight and volume (Bruner, 1966; Piaget & Inhelder, 1974; Stavy & Tirosh, 2000; Tirosh & Stavy, 1999). Students are typically presented with two containers with equal amounts of water. One of the containers is later heated, and the students observe the water level rising. They are asked to judge whether the weight and the volume of the water in the containers differ before and after heating. This is another example in which the saliency of task properties changes with age and, in this case, with the acquisition of particular taught schemes (Stavy & Tirosh, 2000). The task was originally designed to examine whether children show knowledge that, after heating, weight is conserved ($W_1 = W_2$) but volume is not ($V_2 > V_1$). As Figure 5 shows, performance in response to the weight question increases with age and tracks the acquisition and stabilization of the conservation scheme leading children to infer *same A* (weight before heating)–*same B* (weight after heating). In the case of the volume question, after Grade 6, the majority of students respond correctly. At this stage, students are formally taught the *particulate nature of matter* (i.e., understanding how particles react under different states), which is endorsed by the perceptual information from the task, (i.e., the volume is larger in the heated container, and visibly so), which facilitates correct responding. Students in Grades 2 and 3 are also able to answer the volume question correctly but rely on the perceptually salient features of the task and have no metaknowledge of the basis for their inferences.

In contrast, in Grades 4–6, the conservation scheme for weight stabilizes, and so students respond by applying the intuitive *same A* (weight)–*same B* (volume) rule and often justify their answer by claiming that "it's the same water; therefore, it's the same volume." The striking aspect of this result is that they ignore the most visually salient information in favor of the abstract concept *equivalence*, in order to invoke the intuitive rule.

Formal knowledge can help strengthen the application of an intuitive rule in a correct context, but also inappropriately and independently of perceptually salient features. In addition, the application of intuitive rules is independent of measures of cognitive capacity. To illustrate, Babai and Alon (2004) examined the relationship between cognitive ability and the application of intuitive rules. A variety of tasks that invoked intuitive rules were correlated with cognitive ability, measured by validated Piagetian-based tests (Adey, Shayer, & Yates, 2001). These included tests of number, area and conservation, spatial perception, seriation, reversibility, and proportionality. Babai and Alon (2004) reported that the intuitive *more A–more B* rule decreased as cognitive ability increased (especially in tasks that relied on logical schemes, such as conservation or proportion). However, Babai and Alon also reported that the intuitive *same A–same B* and *everything can be divided* rules increased as cognitive ability increased. Younger students' answers to a variety of problems were based on concrete perceptual features (e.g., conservation-volume tasks), whereas older students learned to ignore these in favor of taught logical schemes. Many of the findings from studies of cognitive ability have shown that the application of logical schemes can often hinder students' performance, because they are overgeneralized to inappropriate task domains (e.g., Fischbein & Schnarch, 1997; Tirosh & Stavy, 1996).

Discussion. The evidence presented here suggests that the application of intuitive rules changes and that the reasoning process is flexible. Children use formal rules to help assert their intuitive rules, as has been shown with the containers and cylinders tasks, because they learn to reinforce their experiences of intuitive rules with relevant, formally taught knowledge (e.g., Dixon & Moore, 1996; Siegler, 1999; Siegler & Jenkins, 1989; Stavy & Tirosh, 2000). That is, children's intuitive rules adapt over the course of development: Some are enhanced and persist into adulthood, and new intuitive rules are generated to accompany newly acquired, formally taught knowledge (Dixon & Moore, 1996; Siegler & Jenkins, 1989; Stavy & Tirosh, 2000; Tirosh & Stavy, 1999). Studies of intuitive reasoning also have shown that the development and function of intuitive rules is closely related to the acquisition of formal knowledge. Conversely, the availability of

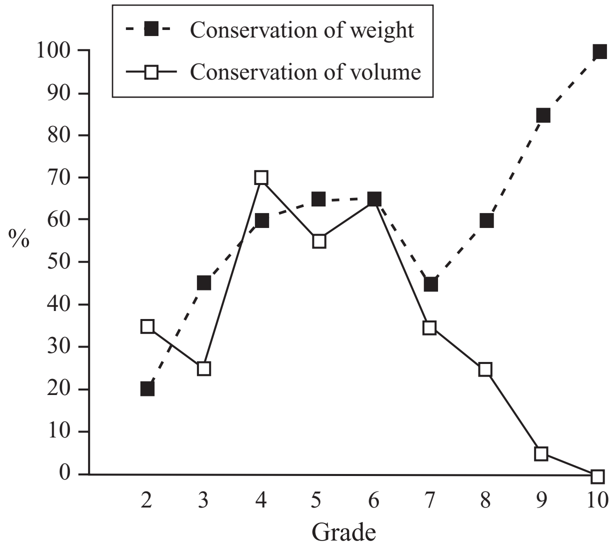

Figure 5. Distribution of equality judgment (percentages of correct responses), by age, to the task involving the weight and volume of water.

formally taught knowledge and its application to new and familiar task domains are related to the intuitive principles that the individual has acquired. Stanovich and West (2000) and Evans and Over (1996) have claimed that the primary system is inflexible. However, consistent with this evidence, Sloman (1996) and Reyna and Brainerd (1995) have claimed that the primary system is flexible because of the kinds of representations that it operates over.

In the cylinders problem, performance on the volume question decreases with age (Stavy & Tirosh, 2000), whereas in the containers problem, performance on the volume question follows a U-shaped curve (Stavy & Tirosh, 2000; Tirosh & Stavy, 1999). The latter pattern of performance has also been supported by other studies, in which reasoning that involves intuitive rules in very young and older students converges (e.g., Bedard et al., 2002; Kail & Salthouse, 1994; Sloutsky & Fisher, 2004; Stavy, 1981; Stavy & Berkovitz, 1980; Strauss & Stavy, 1982; Strauss et al., 1982). Moreover, U-shaped patterns of development have been found for a variety of processes: face perception (Cashon & Cohen, 2004), memory consolidation (e.g., Brainerd, Reyna, & Kneer, 1995; Seamon et al., 2002), and retrieval (e.g., Dosher, 1984; Dosher & Rosedale, 1991). Thus, many cognitive processes are nonmonotonic, and this is why studies are unable to reliably index performance on reasoning tasks through measures of cognitive ability (e.g., Babai & Alon, 2004). Unlike dual-system theories of adult reasoning (i.e., Evans & Over, 1996; Stanovich & West, 2000), fuzzy-trace theory (Brainerd, 2004) does not relate accurate reasoning to examples of accurate executive functioning (e.g., memory accuracy). Consistent with the evidence from intuitive rules, Brainerd and Reyna have shown that certain biases (e.g., framing effects; i.e., even when formally identical, instructional changes can have marked effects on responses) increase with age (Reyna, 1996; Reyna & Ellis, 1994) and with cognitive development (e.g., Davidson, 1995).

The principal characteristic of the primary system that is shared by all of the dual-system theories is that it is executed automatically and that there is no accompanying metaknowledge of the inferential steps that are carried out. Studies in which the cylinder and containers tasks have been used have shown that children reason through the application and coordination of logical inferences and that these can be guided by justifiable formal norms (Moshman, 2004). This particularly raises problems for dual-system theories that consign all examples of automatic reasoning to the primary system. The DGC framework and the account offered by the intuitive rules program predict differences between skill-based learning (e.g., overgeneralized, formally taught knowledge) and implicit-based reasoning. This position is able to accommodate the evidence from studies showing U-shaped developmental curves and the properties of the reasoning that emerges across the curve. For instance, although, in the containers task, the responses of children in Grades 2 and 11 are the same and the intuitive rules that are invoked are the same, the source of the information encoded is different. In the older age group, the inferences are based on differences at the particle level, which relies on explicitly taught rules that are rehearsed and later applied automatically. The relationship between automatic reasoning processing and analytical processing is inconsistent with many of the dual-system theories, because they attribute formal abstract knowledge to the secondary system. Although there are examples in which intuitive rules are invoked quickly, without awareness of the rule, inconsistent with dual-system theorists' claims, there are examples in which intuitive rules are rationalized, correctly, through formal-based knowledge.

Interaction Between the Systems

Hypotheses. It is difficult to evaluate the dual-system theories' hypotheses concerning the interaction between the systems, because these theories posit a close relationship between the primary and the secondary systems and posit that, because the systems complement each other in most tasks, the systems cannot be independently identified in a given task (Brainerd & Reyna, 1990; Sloman, 1996; Stanovich & West, 2000). However, because all the theories predict conflicts between the systems and because the systems are said to cue different responses under conditions that fulfill Criterion S, the evidence from the intuitive rules program will be evaluated in the light of these hypotheses.

Evidence. The evidence presented here focuses on examples in which conflicts are generated between different sources of knowledge that children rely on and on how they are resolved. Tutoring studies (e.g., Clement, 1993; Stavy, 1981, 1991; Tsamir et al., 1997) have shown that children gain insight into their erroneous reasoning in tasks in which conflicts are generated between their own knowledge and task information. To illustrate, Tirosh and Tsamir (1996) presented students (Grades 10–12) with a problem with two infinite sets, Set 1{1, 2, 3, 4, …} and Set 2{1, 4, 9, 16, …}, and asked whether the number of elements in the sets was the same. To answer the problem correctly, children should focus on the one-to-one correspondence between the elements in Set 1 and Set 2. However, instead, they focus on the differences between the sequences of numbers in the sets, basing their responses on the fact that there are missing elements in the sequence of the elements in Set 2. Students make the *more A–more B* inference, claiming that Set 1 contains more elements because Set 1 includes the numbers in Set 2 and those missing from Set 2. The students were then presented with an equivalent problem, but with Sets A{1, 2, 3, 4, …} and B{1^2, 2^2, 3^2, 4^2, …}. In this version, the equivalence between the sets was inferred because *n* is matched to n^2. When the students were asked to reexamine their responses to Sets 1 and 2, a conflict was generated between their initial tendency to treat the sets as different and their awareness of the one-to-one correspondence between the elements, which was emphasized by their responses to Set A and Set B. However, they were able to correct their answers, because they understood the source of conflict between the two equivalent tasks.

In Siegler's (1976) study, children were presented with a series of tasks that measured their knowledge of the arithmetical rules that governed a balance beam. Included in these were conflict-based problems: *conflict-weight*, in which the side with more weight always tipped down; *conflict-distance*, in which the side with the weight furthest from the fulcrum would tip down; and *conflict-balance*, in which the two factors, weight and distance, would cancel out and the beam would balance. Depending on which properties of the task the children focused on, Siegler (1976) was able to predict performance on the various problems. He argued that the children focusing only on weight to make predictions about whether the beam would balance or tip reasoned "more weight, then more likely to fall" (Rule 1). The children focusing on weight and distance used Rule 1 as a default, and then, if this was not fulfilled, they inferred "more distant from the fulcrum, then more likely to fall" (Rule 2). The children following Rule 3 used a combination of both, "more weight + distance from the fulcrum, then more likely to fall," by trying to incorporate their knowledge of proportionality, which is also necessary in creating balance in the beam. However, they did include the composition rule of summing the products of weight and distance on each side of the fulcrum (Rule 4), which was evident in children 16–17 years of age.

Siegler (1976) found that there was good performance on the conflict-weight tasks by the children following Rules 1, 2, and 4, whereas only the children following Rule 4 correctly solved the conflict-distance and conflict-balance tasks. In the conflict-distance tasks, the children's performance was poor for different reasons: Rule 1 followers used only weight as a property on which to base their answers, whereas followers of Rules 2 and 3 took distance into account but their understanding of these concepts was incorrect. Conflict-balance tasks created the most difficulty among the children, particularly followers of Rules 2 and 3. The reason for this was that the problems generated an equilibrium outcome but the rules the children used focused their attention on both cues (weight and distance), either of which suggested that the beam would tip (e.g., three weights on second peg vs. six on first peg), and so, because the children did not have the correct rule to integrate this knowledge, they inferred that the beam would tip, because of either the weight or the distance. Siegler (1976) showed that a task can generate conflicts that arise from competing rules that the reasoner finds difficult to reconcile.

Similarly, Stavy (2006) showed that competing intuitive rules could arise in reasoning tasks performed by adults. In a version of the probability task similar to that in Brecher (2005), Stavy (2006) presented adults with two boxes with pink and white drops of paint. On the basis of the ratio of white to pink, the reasoners had to decide whether, after combining the different colored paints in each box, the color would be equivalent in both or whether the paint in one of the boxes would be darker. In congruent versions, the quantity of red drops was larger in the box that would yield the darker paint (i.e., there was a larger ratio of red to white), therefore invoking the intuitive *more A–more B* rule. In incongruent versions of the two boxes, the one containing the more red drops either yielded equal darkness or was lighter in color than the other box (i.e., there was a larger ratio of white to red). Because the participants focused on the frequency of red drops in each box, responses to congruent versions were quicker and more accurate than those to incongruent versions, consistent with previous studies (e.g., Brecher, 2005; Falk et al., 1980; Stavy & Tirosh, 1996). However, Stavy (2006) included a series of congruent versions with ratios that included, for example, Box A (Red 2: White 3) and Box B (Red 3: White 4). Although the box with the larger number of red drops also yielded the darkest color, the difference between this and the other congruent versions was that the number of white drops also increased with the number of red drops. This radically reduced performance to chance. Stavy (2006) was able to show that the adults spent longer solving these congruent versions because two intuitive rules were cued in the same task; that is, conflicts arose between the intuitive *more A* (red drops)*–more B* (darker) and *more A* (white drops)*–more B* (lighter color) rules. Thus, Stavy (2006) demonstrated that adults were susceptible to the same kinds of salient task properties as children, which, in this case, generated conflicts between the outcomes of the different intuitive rules.

Discussion. In this review, the discussion of the evidence for different forms of encoding suggests that conflicts can arise between competing representations. The evidence presented here also shows that conflicts can occur between competing rules. The rules appear to be mutually exclusive because there is no other relevant knowledge that can reconcile or integrate the possibilities (e.g., Siegler, 1976; Tirosh & Tsamir, 1996). This is also why children spend a longer time generating responses (e.g., Stavy, 2006) and performance is at chance (Siegler, 1976; Stavy, 2006). Dual-system theorists claim that reasoners lack the necessary information to resolve conflicts, which is why they take longer to solve tasks that generate them. However, the evidence suggests that it is not the case that children are required to inhibit erroneous responses generated by the primary system. Rather, they do not have the requisite knowledge, or they fail to apply such knowledge in order to integrate the conflicting information (e.g., Tirosh & Tsamir, 1996) or rules (e.g., Diamond, Kirkham, & Amso, 2002; Siegler, 1976; Stavy, 2006).

Evidence of conflicts between representations and rules does not fit precisely with the kind of conflicts described by dual-system theories of reasoning. With the exception of Reyna and Brainerd (1995), who predicted conflicts between representations (i.e., gist vs. verbatim) because they are based in separate memory stores, dual-system theories of reasoning predict conflicts only between reasoning systems. However, competition between two seemingly relevant rules, or representations, cannot be ruled out under a dual-system framework. For example, a task (e.g., the balance beam) in which there are conflicts between rules could be the result of the reasoner's retrieving two relevant, associated rules from long-term memory. Similarly, Evans and Over's (1996, 2004) relevance principle does not exclude the possibility that more than one representation or model is relevant in the current context. What the evidence presented here does suggest is that conflicts per se cannot reliably be taken as evidence of competing reasoning systems, and this is true not only of developmental research. There have been many examples of people reasoning about mutually exclusive possibilities (e.g., Newcomb's paradox, and the liar's paradox) that have demonstrated competition between abstract concepts. Under the dual-system framework, these would have to be construed as competition within the secondary system, which is inconsistent with the claims of any dual-system theory of reasoning.

Another property of Criterion S tasks is that they induce sudden insight that can momentarily lead to correct responding, but the dominance of the primary system makes reasoners unable to inhibit it, and so they return to their default erroneous response. Consistent with this, there are examples from studies of intuitive rule use in which the insights gained during tutoring tasks are sudden (e.g., Dembo, Levin, & Siegler, 1997; Zietsman & Clement, 1997). However, there are also examples in which insight occurred gradually (e.g., Siegler & Stern, 1998; Stavy, 1981; Tsamir et al., 1997). What is common to tasks that generate both sudden and gradual insights is that they generate insight by manipulating the saliency of task features. Repeated exposure to the correct task property cues children to examine and evaluate the task based on it (e.g., Dixon & Moore, 1996; Siegler & Jenkins, 1989) or degrades the saliency of irrelevant task features (e.g., Clement, 1993; Stavy, 1991; Tsamir, Tirosh et al., 1997). In younger children (Grades 2 and 3), insight occurs because children become overly familiar with the task environment from which the original intuitive rule developed and this forces a change (Dixon & Moore, 1996; Siegler & Jenkins, 1989). Older children learn to seek out new strategies because their repertoire of strategies has broadened and, so, they can combine them in novel ways (Crowley & Siegler, 1999; Siegler, 1999; Siegler & Jenkins, 1989).

Sudden insight is taken as indicative of shifts in reasoning systems, whereas the evidence suggests that although this occurs, it is the result of children's reconceptualizing the task (Karmiloff-Smith, 1994), either through techniques that are taught to them when they encounter an impasse or through actively trying to motivate a change in their understanding of a given task. This process does not need to be considered to be the result of changes in reasoning systems, and the evidence suggests that often, children are simply evaluating task properties that were not salient when they initially embarked on solving the task.

SUMMARY

The objectives of this review were twofold. First, the aim was to contrast the claims made by dual-system theories of adult reasoning with a developmental account that also incorporates the same framework. Second, the approach undertaken in this review has been hypothesis driven, and through this, the aim was to evaluate dual-system theories of reasoning in the light of evidence from a developmental research program. The motivation for this approach was based on the simple assumption that a successful theory of reasoning needs to account for reasoning behavior in children, as well as in adults. Thus, a rigorous evaluation of the claims made by dual-system theories of reasoning could be achieved by standing them up against a relevant body of research that has not previously been aligned with either a single- or a dual-system framework of reasoning.

Evidence in Agreement With Dual-System Theories of Reasoning

Children invoke intuitive rules as early as Grade 2, and typically, children generate solutions rapidly and without intention. Consequently, the ubiquity of intuitive rules can be costly, because they are often misapplied and this produces erroneous responses. Intuitive rules are also robust, and children have difficulty overcoming the application of intuitive rules, which is why some such rules strengthen, rather than diminish, with age. These characteristics provide strong evidence that intuitive rules share many characteristics with the primary reasoning system proposed by dual-system theories of reasoning.

Evidence Consistent With *Some* Claims Made by Dual-System Theories of Reasoning

Stavy and Tirosh (2000) have shown that children use formal rules to help assert their intuitive thinking, because they reinforce their experience with relevant, formally taught knowledge (e.g., Dixon & Moore, 1996; Siegler, 1999; Siegler & Jenkins, 1989; Stavy & Tirosh, 2000). Conversely, intuitive processing increases the generation of formal representations (Ahl, Moore, & Dixon, 1992; Carraher, Carraher, & Schliemann, 1985; Ceci & Liker, 1986; Stavy & Tirosh, 2000). This evidence points to the flexibility of the process that relies on intuitive rules. If one assumes that intuitive rules are invoked by processes that dual-system theories treat as primary, this evidence is consistent with Sloman (1996), who proposed that the primary system is able to reason from newly experienced stimuli through a similarity-based method of generalization. In addition, Reyna and Brainerd (1995) also claimed that the primary system is flexible, but for the reason that it accommodates developmental changes in the extraction and abstraction of different gist representations.

Evidence Inconsistent With *Some* Claims Made by Dual-System Theories of Reasoning

Dual-system theories of adult reasoning claim that individual differences in measures of cognitive ability can be used to identify different reasoning systems. Some developmental studies have shown that with cognitive development comes the ability to override the application of heuristics through executive functions (e.g., Handley, Capon, Beveridge, Dennis, & Evans, 2004; Klaczynski & Robinson, 2000; Kokis, MacPherson, Toplak, West, & Stanovich, 2002). However, there is also evidence that as cognitive ability increases, so does the use of the intuitive *same A–same B* and *everything can be divided* rules. In addition, college students and adults fail the Piagetian concrete operational conservation task, by applying the intuitive *more A–more B* rule (e.g., Winer, Craig, & Weinbaum, 1992; Winer & McGlone, 1993). These findings raise problems for dual-system theories of adult reasoning for two reasons. First, given that measures of cognitive ability track decreases and increases in the application of intuitive rules, it follows that intuitive and formal analytic reasoning must share some functional properties that are indexed by these measures. Second, U-shaped developmental curves are not predicted by some dual-system theories of reasoning (Evans & Over, 1996, 2004; Stanovich & West, 2000). These indicate nonmonotonic increases in performance in a variety of cognitive and motor skills that are inconsistent with explanations of monotonic increases in the development of basic capacities—for example, working memory, metacognition, content knowledge, and analytical skills.

Evidence Inconsistent With Claims Made by Dual-System Theories of Reasoning

The evidence presented in this review suggests that implicit and automatic forms of reasoning are part of the same system but are invoked according to different types of salient properties. The difficulty in evaluating the hypotheses of dual-system theories of reasoning with the evidence presented in the review is that the intuitive rules program shows that although implicit and automatic forms of reasoning differ according to the accessibility of the representations that are utilized, the reasoning operation that follows from both is the same. Therefore, the alignment of the reasoning phenomena to one or the other system is problematic, because intuitive rules share properties of both the primary and the secondary systems. From this, the hypothesis that follows is that if dual-system theories of reasoning treat phenomena that have been described in this review as support for the primary system, the diversity of these phenomena call into question the unitary nature of the primary system.

In order to posit two systems of reasoning, the systems' functions must be computationally incompatible with each other, so that the same function cannot be carried out by both systems (Sherry & Schacter, 1987). If we take the evidence of skill-based reasoning (e.g., the acquisition of the concept of proportionality), the intuitive rules program shows that it is first acquired explicitly and, through practice, is applied and generalized automatically to a variety of task domains (e.g., Fischbein & Schnarch, 1997; Tirosh & Stavy, 1996). From this, the hypothesis that follows is that from a dual-system framework of reasoning, the evidence of skill-based reasoning, which demonstrates that formal knowledge can be acquired and used explicitly, can be taken to exemplify processing consistent with the secondary reasoning system. However, the same evidence also shows that processing is automatic, which from a dual-system framework is consistent with what is referred to as the primary reasoning system. If skill-based reasoning can be both formal and automatic, it shows that either the same function can be carried out by both systems or an expansion of the dual-system framework is needed in which there are four components (i.e., conscious–analytic, conscious–heuristic, unconscious–analytic, and unconscious–heuristic; Klaczynski, 2001). In the case of the latter, if we accept the need for parsimony, the four components that have been identified can be treated as different examples of the same underlying reasoning system. Therefore, the problems concerning where the interactive relationship between seemingly similar reasoning processes exists is avoided, because the evidence for intuitive rules is consistent with a single-system account of reasoning.

The very issues that cannot be reconciled within a dual-system framework are, however, entirely consistent with the DGC single framework of reasoning. The DGC framework has been developed to explain implicit and automatic learning and has been applied to explain reasoning phenomena (Osman, 2004), and it predicts the very differences reported in the intuitive rules program. The DGC framework proposes that automatic reasoning involves representations that are accessible because they are highly stable and distinctive and, thus, that the memory traces are difficult to overcome. Implicit reasoning involves weakly represented representations that have not accumulated strength through repeated exposure to the same types of learning environments as have automatic representations, which is why children are unaware of the intuitive rules that are implemented. Moreover, this is why conceptual-based errors resulting from intuitive rules invoked by top-down salient features are more difficult to overcome than perceptual-based errors resulting from intuitive rules invoked by bottom-up salient features. The framework proposes that all contexts are essentially learning environments in which extrapolation and generalization occur. In addition, children, like adults, develop useful rules that are supported by formal knowledge that demonstrates expertise in a given problem domain. On this basis, the review concludes that the challenge remains for dual-system theories of reasoning to develop an account that accommodates the range of findings discussed in this review alongside evidence from studies of adult reasoning.

REFERENCES

Adey, P., Shayer, M., & Yates, C. (2001). *Thinking science: The materials of the CASE project* (3rd ed.). Cheltenham, U.K.: Nelson Thornes.

Ahl, V. A., Moore, C. F., & Dixon, J. A. (1992). Development of intuitive and numerical proportional reasoning. *Cognitive Development*, **7**, 81-108.

Anderson, N. H. (1987). Function knowledge: Comment on Reeds and Evans. *Journal of Experimental Psychology: General*, **116**, 297-299.

Anderson, J. R. (1993). *Rules of the mind*. Hillsdale, NJ: Erlbaum.

Azhari, N. (1998). *Using the intuitive rule "same of A, same of B" in conservation tasks*. Unpublished manuscript, Tel Aviv University, Israel.

Babai, R., & Alon, T. (2004, month). *Intuitive thinking, cognitive level or grade level: What predicts students' incorrect responses in science and mathematics*. Paper presented at the National Association of Research in Science Teaching Conference, Vancouver.

Babai, R., Brecher, T., Stavy, R., & Tirosh, D. (2006). Intuitive interference in probabilistic reasoning. *International Journal of Science & Mathematics Education,* **4,** 627-639.

Babai, R., Levyadun, T., Stavy, R., & Tirosh, D., (in press). Intuitive rules in science and mathematics: A reaction time study. *International Journal of Mathematical Education in Science & Technology.*

Bedard, A. C., Nichols, S., Barbosa, J. A., Schachar, R., Logan, G. D., & Tannock, R. (2002). The development of selective inhibitory control across the life span. *Developmental Neuropsychology*, **21**, 93-111.

Brainerd, C. J. (2004). Dropping the other U: An alternative approach to U-shaped developmental functions. *Journal of Cognition & Development*, **5**, 81-88.

Brainerd, C. J., & Reyna, V. F. (1990). Inclusion illusions: Fuzzy-trace theory and perceptual salience effects in cognitive development. *Developmental Review*, **10**, 365-403.

Brainerd, C. J., & Reyna, V. F. (1992). Explaining "memory free" reasoning. *Psychological Science*, **3**, 332-339.

Brainerd, C. J., & Reyna, V. F. (1993). Memory independence and memory interference in cognitive development. *Psychological Review*, **100**, 42-67.

Brainerd, C. J., & Reyna, V. F. (2001). Fuzzy-trace theory: Dual processes in memory, reasoning, and cognitive neuroscience. *Advances in Child Development & Behavior*, **28**, 41-100.

Brainerd, C. J., Reyna, V. F., & Kneer, R. (1995). False-recognition reversal: When similarity is distinctive. *Journal of Memory & Language*, **34**, 157-185.

Brecher, T. (2005) *Application of the intuitive rule: "More A–more B" in probability task: A reaction time study*. Unpublished master's thesis, Tel Aviv University, Israel (in Hebrew).

Bruner, J. S. (1966). On the conservation of liquids. In J. S. Bruner, R. R. Olver, & P. M. Greenfield (Eds.), *Studies of cognitive growth* (pp. 183-207). New York: Wiley.

Bryant, P. (1974). *Perception and understanding in young children: An experimental approach.* London: Methuen.

Carraher, T. N., Carraher, D. W., & Schliemann, A. D. (1985). Mathematics in the streets and in schools. *British Journal of Developmental Psychology*, **3**, 21-29.

Cashon, C. H., & Cohen, L. B. (2004). Beyond U-shaped development in infants' processing of faces: An information-processing account. *Cognition & Development*, **5**, 59-80.

Cave, K. R., & Wolfe, J. M. (1990). Modeling the role of parallel processing in visual search. *Cognitive Psychology*, **22**, 225-271.

Ceci, S. J., & Liker, J. K. (1986). A day at the races: A study of IQ, expertise, and cognitive complexity. *Journal of Experimental Psychology: General*, **115**, 255-266.

Champagne, A. B., Klopfer, L. E., & Anderson, J. H. (1979). *Factors influencing the learning of classical mechanics.* Pittsburgh: University of Pittsburgh, Learning Research and Development Center.

Cleeremans, A., & Jiménez, L. (2002). Implicit learning and consciousness: A graded, dynamic perspective. In R. M. French & A. Cleeremans (Eds.), *Implicit learning and consciousness: An empirical, philosophical and computational consensus in the making* (pp. 1- 40). Hove, U.K.: Psychology Press.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching*, **30**, 1241-1257.

Crowley, K., & Siegler, R. S. (1999). Explanation and generalization in young children's strategy learning. *Child Development*, **70**, 304-316.

Davidson, D. (1995). The representativeness heuristic and the conjunctive fallacy in children's decision making. *Merrill-Palmer Quarterly*, **41**, 328-346.

Deglin, V. L., & Kinsbourne, M. (1996). Divergent thinking styles of the hemispheres: How syllogisms are solved during transitory hemisphere suppression. *Brain & Cognition*, **31**, 285-307.

Dembo, Y., Levin, I., & Siegler, R. S. (1997). A comparison of the geometric reasoning of students attending Israeli ultraothodox and mainstream schools. *Developmental Psychology*, **33**, 92-103.

Diamond, A., Kirkham, N., & Amso, D. (2002). Conditions under which young children can hold two rules in mind and inhibit a prepotent response. *Developmental Psychology*, **38**, 352-362.

Dixon, J. A., & Dohn, M. C. (2003). Redescription disembeds relations: Evidence from relational transfer and use in problem solving. *Memory & Cognition*, **31**, 1082-1093.

Dixon, J. A., & Moore, C. F. (1996). The developmental role of intuitive principles in choosing mathematical strategies. *Developmental Psychology*, **32**, 241-253.

Dixon, J. A., & Moore, C. F. (1997). Characterizing the intuitive representation in problem solving: Evidence from evaluating mathematical strategies. *Memory & Cognition*, **25**, 395-412.

Dosher, B. A. (1984). Discriminating pre-experimental (semantic) and learned (episodic) associations: A speed–accuracy study. *Cognitive Psychology*, **16**, 519-555.

Dosher, B. A., & Rosedale, G. (1991). Judgments of semantic and episodic relatedness: Common time-course and failure of segregation. *Journal of Memory & Language*, **30**, 125-160.

Evans, J. St. B. T., & Over, D. E. (1996). *Rationality and reasoning*. Hove, U.K.: Psychology Press.

Evans, J. St. B. T., & Over, D. E. (2004). *If.* Oxford: Oxford University Press.

Falk, R., Falk, R., & Levin, I. (1980). A potential for learning probability in young children. *Educational Studies in Mathematics*, **11**, 181-204.

Fischbein, E. (1987). *Intuition in science and mathematics*. Dordrecht: Reidel.

Fischbein, E., & Schnarch, D. (1997). The evolution with age of probabilistic, intuitively bad misconceptions. *Journal for Research in Mathematics Education*, **28**, 96-105.

Foxman, D., & Ruddock, G. (1984). Concepts, misconceptions and alternative conceptions: Changing perspectives in science education. *Studies in Science Education*, **10**, 9-13.

Freud, S. (1953). The interpretation of dreams. In J. Strachey (Ed., & Trans.), *The standard edition of the complete psychological works of Sigmund Freud* (Vols. 4 and 5). London: Hogarth. (Original work published 1900)

Gilinsky, A. S., & Judd, B. B. (1994). Working memory and bias in reasoning across the life-span. *Psychology & Aging*, **9**, 356-371.

Green, D. R. (1983). A survey of probability concepts in 3000 pupils aged 11–16 years. In D. R. Grey, P. Holmes, V. Barnett, & G. M. Constable (Eds.), *Proceedings of the First International Conference on Teaching Statistics* (pp. 766-783). Sheffield, U.K.: Teaching Statistics Trust.

Greenberg, J. H. (1966). *Language universals*. The Hague: Mouton.

Gunstone, R. F., & White, R. T. (1981). Understanding of gravity. *Science Education*, **65**, 291-299.

Hammond, K. R. (1996). *Human judgment and social policy*. New York: Oxford University Press.

Handley, S. J., Capon, A., Beveridge, M., Dennis, I., & Evans, J. S. T. (2004). Working memory, inhibitory control and the development of children's reasoning. *Thinking & Reasoning*, **10**, 175-195.

James, W. (1950). *The principles of psychology*. New York: Dover. (Original work published 1890

Kail, R., & Salthouse, T. A. (1994). Processing speed as a mental capacity. *Acta Psychologica*, **86**, 199-225.

Karmiloff-Smith, A. (1986). From meta-processes to conscious access: Evidence from children's metalinguistic and repair data. *Cognition*, **23**, 95-147.

Karmiloff-Smith, A. (1992). *Beyond modularity*. Cambridge, MA: MIT Press.

Karmiloff-Smith, A. (1994). Beyond modularity: A developmental perspective on cognitive science. *Behavioral & Brain Sciences*, **17**, 693-745.

Kim, M.-S., & Cave, K. R. (1999). Top-down and bottom-up attentional control: On the nature of interference from a salient distractor. *Perception & Psychophysics*, **61**, 1009-1023.

Klaczynski, P. A. (2001). Analytical and heuristic processing influences on adolescent reasoning and decision making. *Child Development*, **72**, 844-861.

Klaczynski, P. A., & Robinson, B. (2000). Personal theories, intellectual ability, and epistemological beliefs: Adult age differences in everyday reasoning biases. *Psychology & Aging*, **15**, 400-416.

Kokis, J. V., MacPherson, R., Toplak, M. E., West, R. F., & Stanovich, K. E. (2002). Heuristic and analytic processing: Age trends and associations with cognitive ability and cognitive styles. *Journal of Experimental Child Psychology*, **83**, 26-52.

Lamy, D., Leber, A., & Egeth, H. E. (2004). Effects of task relevance and stimulus-driven salience in feature-search mode. *Journal of Experimental Psychology: Human Perception & Performance*, **30**, 1019-1031.

Livne, T. (1996). *Examination of high school students' difficulties in understanding the change in surface area, volume and surface area/volume ratio with the change in size and/or shape of a body*. Unpublished master's thesis, Tel Aviv University, Israel.

Lleras, A., & Von Mühlenen, A. (2004). Spatial context and top-down strategies in visual search. *Spatial Vision*, **17**, 465-482.

Mendel, N. (1998). *The intuitive rule "same of A, same of B": The case of comparison of rectangles.* Unpublished master's thesis, Tel Aviv University, Israel (in Hebrew).

Moshman, D. (2004). From inference to reasoning: The construction of rationality. *Thinking & Reasoning*, **10**, 221-239.

Osman, M. (2004). An evaluation of dual-process theories of reasoning. *Psychonomic Bulletin and Review*, **11**, 988-1010.

Piaget, J., & Inhelder, B. (1974). *The construction of quantity*. London: Routledge & Kegan Paul.

Piaget, J., Inhelder, B., & Szeminska, A. (1960). *The child's conception of geometry*. London: Routledge & Kegan Paul.

Pratto, F., & John, O. P. (1991). Automatic vigilance: The attention-grabbing power of negative social information. *Journal of Personality & Social Psychology*, **61**, 380-391.

Reingold, E. M., & Stampe, D. M. (2004). Saccadic inhibition in reading. *Journal of Experimental Psychology: Human Perception & Performance*, **30**, 194-211.

Reyna, V. F. (1996). Conceptions of memory development, with implications for reasoning and decision making. *Annals of Child Development*, **12**, 87-118.

Reyna, V. F., & Brainerd, C. J. (1995). Fuzzy-trace theory: An interim synthesis. *Learning & Individual Differences*, **7**, 1-75.

Reyna, V. F., & Ellis, S. C. (1994). Fuzzy-trace theory and framing effects in children's risky decision making. *Psychological Science*, **5**, 275-279.

Rothermund, K., & Wentura, D. (2004). Underlying processes in the implicit association test: Dissociating salience from associations. *Journal of Experimental Psychology: General*, **133**, 139-165.

Seaman, J. G., Luo, C. R., Schwartz, M. A., Jones, K. J., Lee, D. M., & Jones, S. J. (2002). Reception can have similar or different effects on accurate and false recognition. *Journal of Memory & Language*, **46**, 323-340.

Sherry, D. F., & Schacter, D. L. (1987). The evolution of multiple memory systems. *Psychological Review*, **94**, 439-454.

Siegler, R. S. (1976). Three aspects of cognitive development. *Cognitive Psychology*, **8**, 481-520.

Siegler, R. S. (1999). Strategic development. *Trends in Cognitive Sciences*, **3**, 430-435.

Siegler, R. S. (2004). Learning about learning. *Merrill-Palmer Quarterly*, **50**, 353-368.

Siegler, R. S., & Crowley, K. (1991). The microgenetic method: A direct means for studying cognitive development. *American Psychologist*, **46**, 606-620.

Siegler, R. S., & Jenkins, E. (1989) *How children discover new strategies.* Hillsdale, NJ: Erlbaum.

Siegler, R. S., & Stern, E. (1998). Conscious and unconscious strategy discoveries: A microgenetic analysis. *Journal of Experimental Psychology: General*, **127**, 377-397.

Sloman, S. A. (1996). The empirical case for two systems of reasoning. *Psychological Bulletin*, **119**, 3-22.

Sloman, S. A. (2002). Two systems of reasoning. In T. Gilovich, D. Griffin, & D. Kahneman (Eds.), *Heuristics and biases: The psychology of intuitive judgment* (pp. 379-398). Cambridge: Cambridge University Press.

Sloutsky, V. M., & Fisher, A. V. (2004). When development and learning decrease memory: Evidence against category-based induction in children. *Psychological Science*, **15**, 553-558.

Sobel, K. V., & Cave, K. R. (2002). Roles of salience and strategy in conjunction search. *Journal of Experimental Psychology: Human Perception & Performance*, **30**, 1055-1070.

Stanovich, K. E. (1999). *Who is rational? Studies of individual differences in reasoning.* Mahwah, NJ: Erlbaum.

Stanovich, K. E. (2004). *The robot's rebellion*. Chicago: University of Chicago Press.

Stanovich, K. E., & West, R. F. (1998). Individual differences in rational thought. *Journal of Experimental Psychology: General*, **127**, 161-188.

Stanovich, K. E., & West, R. F. (2000). Individual differences in reasoning: Implications for the rationality debate. *Behavioral & Brain Sciences*, **22**, 645-665.

Stavy, R. (1981). Teaching the inverse function via the concentration of salt water solution. *Archives de Psychologie*, **49**, 267-287.

Stavy, R. (1991). Using analogy to overcome misconceptions of conservation of matter. *Journal of Research in Science Teaching*, **28**, 305-313.

Stavy, R. (2006). *Informational conflict in proportional reasoning.* Manuscript under review.

Stavy R., & Berkovitz, B. (1980). Cognitive conflict as a basis for teaching quantitative aspects of the concept of temperature. *Science Education*, **64**, 679-692.

Stavy, R., Goel, V., Critchley, H., & Dolan, R. (in press) Intuitive interference in quantitative reasoning. *Cognitive Brain Research*.

Stavy, R., & Stachel, D. (1985). Children's conception of changes in the state of matter: From solid to liquid. *Archives de Psychologie*, **3**, 331-334.

Stavy, R., & Tirosh, D. (1993). When analogy is perceived as such. *Journal of Research in Science Teaching*, **30**, 1229-1239.

Stavy, R., & Tirosh, D. (1996). Intuitive rules in science and mathematics: The case of "more of A more of B." *International Journal of Science Education*, **18**, 653-667.

Stavy, R., & Tirosh, D. (2000). *How students (mis-)understand science and mathematics: Intuitive rules*. New York: Teachers College Press.

Strauss, S., & Stavy, R. (1982). U-shaped behavioural growth: Implications for theories of development. In W. W. Hartup (Ed.), *Review of child development research* (pp. 547-599). Chicago: University of Chicago Press.

Strauss, S., Stavy, R., Orpaz, N., & Carmi, G. G. (1982). U-shaped behavioral growth in ratio comparisons, or that-'s funny I would not have thought you were U-ish. In S. Strauss & R. Stavy (Eds.), *U-shaped behavioural growth* (pp. 11-36). New York: Academic Press.

Tirosh, D., & Stavy, R. (1996). Intuitive rules in science and mathematics: The case of "everything can be divided by two." *International Journal of Science Education*, **18**, 669-683.

Tirosh, D., & Stavy, R. (1999). Intuitive rules: A way to explain and predict students' reasoning. *Education Studies in Mathematics*, **38**, 51-66.

Tirosh, D., & Tsamir, P. (1996). The role of representations in students' intuitive thinking about infinity. *International Journal of Mathematical Education in Science & Technology*, **27**, 33-40.

Treisman, A. (1998). Feature binding, attention and object perception. *Philosophical Transactions of the Royal Society of London: Series B*, **353**, 1295-1306.

Tsamir, P., Tirosh, D., & Stavy, R. (1997). Intuitive rules and comparison tasks: The grasp of vertical angles. In G. A. Makrides (Ed.), *Proceedings of the First Mediterranean Conference: Mathematics Education and Applications.* (pp. xxx-xxx) Nicosia, Cyprus: Cyprus Pedagogical Institute and Cyprus Mathematical Society.

Tversky, A., & Kahneman, D. (1972). Subjective probability: A judgment of representativeness. *Cognitive Psychology*, **3**, 430-454.

Tversky, A., & Kahneman, D. (1983). Extensional versus intuitive reasoning: The conjunction fallacy in probability judgment. *Psychological Review*, **90**, 293-315.

Wentura, D. (2000). Dissociative affective and associative priming effects in the lexical decision task: *Yes* versus *no* responses to word targets reveal evaluative judgment tendencies. *Journal of Experimental Psychology*: *Learning*, *Memory*, *& Cognition*, **26**, 456-469.

Wentura, D., Rothermund, K., & Bak, P. (2000). Automatic vigilance: The attention-gabbing power of approach- and avoidance-related social information. *Journal of Personality & Social Psychology*, **78**, 1024-1037.

Winer, G. A., Craig, R. K., & Weinbaum, E. (1992). Adults' failure on misleading weight-conservation tests: A developmental analysis. *Developmental Psychology*, **28**, 109-120.

Winer, G. A., & McGlone, C. (1993). On the uncertainty of conservation: Responses to misleading conservation questions. *Developmental Psychology*, **29**, 760-769.

Wolfe, J. M. (2001). Asymmetries in visual search: An introduction. *Perception & Psychophysics*, **63**, 381-389.

Wolfe, J. M. (2003). Moving towards solutions to some enduring controversies in visual search. *Trends in Cognitive Sciences*, **7**, 70-76.

Wolfe, J. M., Cave, K. R., & Franzel. S. L. (1989). Guided search: An alternative to the feature integration model of visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 419-433.

Yair, Y., & Yair, Y. (2004). "Everything comes to an end": An intuitive rule in physics and mathematics. *Science Education*, **88**, 594-609.

Zaskis, R. (1999). Intuitive rules in number theory: Example of "the more of A, the more of B" rule implementation. *Educational Studies in Mathematics*, **40**, 197-209.

Zaskis, R., & Campbell, S. (1996a). Divisibility and multiplicative structure of natural numbers: Preservice teachers's understanding. *Journal of Research in Mathematics Education*, **27**, 540-563.

Zaskis, R., & Campbell, S. (1996b). Prime decomposition: Understanding uniqueness. *Journal of Mathematical Behavior*, **15**, 207-218.

Zietsman, A., & Clement, J. (1997). The role of extreme case reasoning in instruction for conceptual change. *Journal of Learning Sciences*, **6**, 61-89.

Zink, C. F., Pagnoni, G., Martin-Skurski, M. E., Chappelow, J. C., & Berns, G. S. (2004). Human striatal responses to monetary reward depend on saliency. *Neuron*, **42**, 509-517.

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