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A dual-process account of the development of scientific reasoning: The nature and development of metacognitive intercession skills

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ABSTRACT

Metacognitive knowledge of the dual-processing basis of judgment is critical to resolving conflict between analytic and experiential processing responses [Klaczynski, P. A. (2004). A dual-process model of adolescent development: Implications for decision making, reasoning, and identity. In R. V. Kail (Ed.), *Advances in child development and behavior, Vol. 31* (pp. 73–123). San Diego, CA: Academic Press]. Such conflict is ubiquitous when reasoning scientifically. Three studies explored the nature, development, and stability of this metacognitive knowledge. In each study, participants completed the ratio-bias judgment task, which assessed their tendency to make analytically based responses, and the ratio-bias evaluation task, which assessed their metacognitive knowledge of the processing basis of judgments on the task (Metacognitive Status). In Study 1, college students' judgment performance was related to metacognitive status but not to general cognitive ability. In Study 2, metacognitive status was related to age and mathematics-related changes. Metacognitive status again predicted participants' tendency to make analytically based judgments. In Study 3, college students' judgments, but not metacognitive status, were affected by task conditions. The evidence suggests that assessing metacognitive knowledge is important for understanding how conflict between analytically and experientially based judgments is resolved.

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The present research explores the development of scientific reasoning from a dual-process theoretical perspective. Although relatively new to developmental theorizing, dual-process theories are prevalent in social psychology (Chaiken & Trope, 1999), cognitive psychology (Barrett, Tugade, & Engle, 2004; Evans, 2003, 2008; Hogarth, 2005; Sloman, 1996, 2002), and personality psychology (Epstein & Pacini, 1999; Kirkpatrick & Epstein, 1992). Dual-process theories[1] propose that multiple independent but interacting processing systems underlie thought, judgment, and decision-making (Evans, 2003, 2008; Epstein & Pacini, 1999).

Although there are a number of ways to characterize the two processing systems, we distinguish between *experiential* and *analytic* (see Evans, 2003, 2008; Epstein & Pacini, 1999, Klaczynski, 2004; Stanovich & West, 2000 for more details of the general account presented here). The *experiential processing* system is automatic, emotional, and cognitively economical. Experiential processing generally relies on concrete and contextualized task representations, rich in content from the situation, prior knowledge, experiences, or associations which, in turn, results in responses that are based on potentially misleading heuristics and beliefs (Evans, 2003, 2008; Stanovich & West, 2000). *Analytic processing* is formal, systematic, and cognitively effortful. Analytic processing may involve constructing decontextualized task representations, which require knowledge and skills that are acquired in culturally specific contexts, often resulting in responses that are normatively justified by formal logic or mathematics (Evans, 2003, 2008; Stanovich & West, 2000).

1. Dual-process theory and the development of scientific reasoning

Dual-process theory challenges traditional accounts of the development of scientific reasoning, defined as the ability to consistently and systematically coordinate theory and evidence in experimentation and evaluation contexts (Klahr, 2000; Koslowski, 1996; Kuhn, 1989; Lehrer & Schauble, 2006; Zimmerman, 2000, 2007). Since Inhelder and Piaget (1958), theories of the development of scientific reasoning have addressed the acquisition of more adequate and normatively justified scientific reasoning abilities which replace less adequate and non-normative ones. The "replacement" view of development is akin to Harris' (2001) characterization of the "veridical assumption," which holds that children develop toward increasingly rational, logical, and normatively justified conceptions of the world.

The replacement account of scientific reasoning development is not without challenges (for an early critique see Shaklee, 1979), which can be readily accounted for by dual-process theory. Complicating the replacement view of development is the finding that scientific reasoning skills are not unitary but include a range of general logical reasoning skills, discipline-specific causal and conceptual knowledge, forms of activities and practices that are related to the institutional practice of science, and metacognitive and process-oriented understandings of the foundation, nature, and meaning of formal inquiry (Lehrer & Schauble, 2006; Zimmerman, 2000, 2007). There is *age-related* variability in when and how these skills, knowledge, practices, and understandings emerge. Some skills may be acquired in childhood, leaving young children relatively immune from irrational judgments and biased beliefs for particular forms of reasoning (Carey, 1985; Gopnik, Sobel, Schulz, & Glymour, 2001; Wellman & Gelman, 1998). Other skills, knowledge, practices, and understandings emerge later, in some cases only with specific instruction, leaving untrained adolescents and adults relatively susceptible to irrational judgments and biased beliefs (Jacobs & Klaczynski, 2005; Klahr, 2000; Kuhn, 1989; Kuhn, Garcia-Mila, Zohar, & Andersen, 1995). Furthermore, there is *task-related* variability in the expression of underlying scientific reasoning competence. For example, Kuhn's (1989; Kuhn, Amsel, & O'Loughlin, 1988) claim that children lacked competence in evidence evaluation skills was challenged by studies demonstrating young children's abilities on tasks that minimized performance variables (Amsel & Brock, 1996; Gopnik et al., 2001; Koerber, Sodian, Thoermer, & Nett, 2005; Ruffman, Perner, Olson, & Doherty, 1993; Schulz & Bonawitz, 2007; Sodian, Zaitchik, & Carey, 1991; Waters, Siegal, & Slaughter, 2000).

[1] "Dual-process theory" may actually be a misnomer as many theorists now claim the existence of multiple implicit processing systems (Evans, 2008; Stanovich, 2004).

Dual-process theory can account for findings challenging the traditional replacement view of scientific reasoning development by proposing the co-development of both analytically based competencies and experientially based heuristics and beliefs. Some of the analytically based skills, abilities, practices, and understandings constituting scientific reasoning competence may be available to young children and others may be acquired with age and education, if they are ever acquired. As experientially based heuristics and beliefs are typically acquired through experience, their diversity, strength, and ease of activation may increase from childhood to adolescence (Klaczynski, 2000, 2004). The co-development of analytically and experientially based responses has been documented in a growing literature demonstrating positive associations between age/education and experientially based automatic responses on decision-making and scientific reasoning tasks (Brainerd, 1981; Jacobs & Potenza, 1991; Klaczynski, 2000; Klaczynski & Narasimham, 1998; Markovits & Dumas, 1999; Reyna & Ellis, 1994; Reyna & Farley, 2006; Wildman & Fletcher, 1977). These data demonstrate that experientially based responses on scientific reasoning tasks are not eliminated, even after analytically based responses are acquired, suggesting that development is not merely the replacement of the experientially based responses by the analytically based ones.

The co-development of analytic and experiential processing systems affords coherent explanations for and predictions of task- and age-related variability in cognitive performance (Klaczynski, 2000, 2004; Reyna & Farley, 2006; Reyna, Lloyd, & Brainerd, 2003). Notably, such variability is not treated as a challenge to an underlying competence, but as evidence of dynamic and adaptive responses from a contextually sensitive dual-process system. For example, rather than an indictment of adults' reasoning competence, biased responses on Wason's selection task have been shown to be a product of an interaction between experientially based pragmatic processes and analytically based probabilistic inferences (see reviews by Evans & Over, 2004; Poletiek, 2001). Similarly, Klaczynski (2000, 2001b; Klaczynski & Lavallee, 2005) found an interaction between experiential and analytic processing in adolescents' and young adults' evaluation of evidence for strongly held beliefs. Although there occurred an increase with age in analytically based judgments, there was minimal evidence of a decrease in bias, suggesting that experiential processes continued to influence judgments, despite growing analytic competence. However, individual difference (e.g., metacognitive) factors were found to minimize the influence of bias.

Findings such as Klaczynski's have highlighted the importance of metacognitive skills in regulating the co-developing analytic and experiential cognitive processes in the development of scientific reasoning. Traditionally, metacognitive skills are considered central in accounts of the development of scientific reasoning by providing the epistemological basis, conceptual motivation, and cognitive control for individuals to deploy underlying competence on scientific-reasoning tasks (Hogan & Maglienti, 2001; Kuhn, 2000; Kuhn & Pearsall, 1998; Kuhn & Pease, 2006; Pintrich, Marx, & Boyle, 1993; Schauble, Klopfler, & Raghavan, 1991; Zimmerman, 2000, 2007). In dual-process theory, metacognitive skills function to regulate conflicts between analytically and experientially based responses. Default experientially based responses are at least temporarily available in working memory, which provides opportunities to reflect on and evaluate the adequacy and utility of the response (De Neys & Glumicic, 2008; Evans, 2007; Klaczynski, 2004; Stanovich & West, 2000). This process of *metacognitive intercession* (Klaczynski, 2004) requires the ability to (a) inhibit automatically activated "default" experientially based responses, (b) distinguish responses generated by analytically and experientially based processing, and (c) compare responses from the dual processes to determine the most appropriate response given the context. As a result of engaging in this process, individuals may rely on default experiential responses, suppress such responses and rely instead on analytical responses, or rely on a compromise or integration between these responses.

In summary, dual-process theory provides an alternative to traditional accounts of the development of scientific reasoning competence, which assume that the more adequate and normatively justified reasoning competencies replace less adequate and non-normative ones. Evidence across a variety of tasks suggests the co-development of and interaction between experiential and analytic processes, which can account for age- and task-related variability in scientific reasoning performance. A key aspect of the theory is the process of metacognitive intercession, which involves regulating conflict between analytically and experientially based responses. However, little is known about this process as it has been only minimally assessed (De Neys & Glumicic, 2008) and not studied developmentally.

2. The present studies

The present research examined the nature, development, and stability of metacognitive intercession skills, using Kirkpatrick and Epstein's (1992) ratio-bias task. In a standard presentation of the task, participants are presented with a pair of gambles having equivalent ratios but one with one a larger (10/100) and one with a smaller (1/10) absolute number of winners. Then, they are asked to select a gamble from which to make a single draw or express *no preference* between the gambles. A majority of participants prefer the 10/100 over the 1/10 gamble because the concrete nature of experiential processing predisposes them to favor gambles with a greater absolute number of winners even if the ratios are equivalent (Kirkpatrick & Epstein, 1992). The finding of a preference for gambles with more absolute winners has been replicated using different versions of the ratio-bias task (Denes-Raj & Epstein, 1994; Kokis, Macpherson, Toplak, West, & Stanovich, 2002; Stanovich & West, 2008), which are presented in different conditions (Amsel, Close, Sadler, & Klaczynski, in press; Dale, Rudski, Schwarz, & Smith, 2007; Epstein & Pacini, 2000/2001; Rudski & Volksdork, 2002) and with samples of different ages (Alonso & Fernandez-Berrocal, 2003; Klaczynski, 2001b). Expressing a preference on the task is treated as less optimal compared to expressing *no preference* as the latter respects the meaning of the mathematical equivalence between the gambles. As a *no preference* response generally requires the abstract processing of ratio information and an appeal to the formal and normative meaning of mathematical equivalence, it is treated as analytically based (Klaczynski, 2001b; Amsel et al., in press).[2]

The ratio-bias task is traditionally considered a decision-making, not a scientific reasoning, task. However, it a taps relevant evidence evaluation skills by requiring participants to interpret the relative strength of patterns of data, a topic of a good deal of research (Amsel & Brock, 1996; Koerber, Sodian, Thoermer, & Nett, 2005; Kuhn, Amsel, & O'Loughlin, 1988; Masnick & Morris, 2008; Shaklee & Paszek, 1985; Schauble, 1996). Interpreting ratio data correctly has been shown to be challenging for children and adults, whether the data are presented as fractions, proportions, risks, or probabilities (Hecht, Vagi, & Torgesen, 2007; Reyna & Brainerd, 2008).

The task also provides the opportunity to explore participants' metacognitive intercession skills for resolving conflict between responses generated by the dual processes. As noted, such skills are relevant on any scientific reasoning task, as theory-evidence coordination typically involves skills to resolve conflicting tendencies to base evidence evaluations on experientially based heuristics and beliefs or analytically based normative strategies and knowledge. Amsel et al. (in press) explored the relation between participants' performance on the ratio-bias task and their metacognitive knowledge of responses generated by each processing system, which is central for successful metacognitive intercession to resolve conflicts between responses. To assess metacognitive knowledge, participants evaluated whether each ratio-bias response option (1/10, 10/100, or *no preference*) reflected analytical processing (i.e., a rational response based on a formal and deliberate analysis of the logic of the situation). Amsel et al. (in press) found that judgments on the ratio-bias task were strongly predicted by participants' metacognitive knowledge. Two thirds of the sample could not recognize *no preference* as the only analytically based response on the task. Approximately a third had partial (Conflicted metacognitive status) and another third had no (Poor metacognitive status) metacognitive knowledge about the responses associated with each processing system. Few of these participants made analytically based *no preference* responses on the task. In contrast, most of those with complete metacognitive knowledge (Competent metacognitive status) made *no preference* responses on the task. But one third of the Competent participants had a gambling preference, even though they recognized such a response as experientially based and suboptimal.

[2] Research demonstrates the challenge of acquiring a formal normative understanding of mathematical equivalence (Knuth, Stephens, McNeil, & Alibali, 2006; McNeil & Alibali, 2005), supporting the view that *no preference* is an analytic-based ratio-bias response. However, the characterization of *no preference* as analytically based may be limited to participants without mathematical expertise who have automatized their processing of mathematical information and for whom *no preference* may be an automatic experientially based response (Schoenfeld & Herrmann, 1982). As participants in the present studies were middle school students and college undergraduates (who were novices in Schoenfeld and Hermann study) we are confident that for most if not all of them, *no preference* responses were analytically based ratio-bias responses.

Amsel et al.'s (in press) findings are generally consistent with those of others who found that greater metacognitive knowledge about cognitive processes predicts normatively valid responses on scientific reasoning tasks (Kuhn & Pearsall, 1998; Kuhn & Pease, 2006). However, the finding of participants who made ratio-bias preference responses despite having metacognitive knowledge that such responses were experientially based and suboptimal, may be seen as challenging the view that metacognitive knowledge inevitably, permanently, and irreversibly leads to optimal task performance. Bullock and Ziegler (1999) similarly found suboptimal control of variables task performance among participants who demonstrate an understanding of the control of variables strategy. The finding underscores the difficulties inherent in regulating conflicting analytic and experientially based responses.

Three studies examined the nature (Study 1), development (Study 2), and stability (Studies 1–3) of metacognitive status and explored the role of metacognitive status in ratio-bias task performance. It was predicted that there would be age- and education-related changes in metacognitive status, reflecting participants' growing insight about the processing sources of response options on the task. It was also predicted that greater metacognitive knowledge would be related to more effective *regulation* of conflicting dual experientially and analytically based responses and not necessarily to the *replacement* of the former by the latter.

3. Study 1

The ratio-bias judgment task has been used to directly test whether individuals rely on experientially based processing of absolute values rather than the analytically based processing of ratio information (Alonso & Fernandez-Berrocal, 2003; Amsel et al., in press; Dale, Rudski, Schwarz, & Smith, 2007; Denes-Raj & Epstein, 1994; Epstein & Pacini, 2000/2001; Kirkpatrick & Epstein, 1992; Klaczynski, 2001a; Rudski & Volksdork, 2002). In a different use of the task, Kokis et al. (2002) examined sources of individual differences in the tendency to respond analytically (also see Stanovich & West, 2008). Of particular interest was whether relying on analytically based responses on tasks was related to basic computational abilities or to cognitive style and metacognitive dispositions. Normal and educationally gifted 10–14 year olds were given five ratio-bias judgment trials (among other tasks), each of which presented a choice between two unequal ratios (e.g., 1/10 vs. 9/100 or 1/10 vs. 8/100). The task pits a ratio with higher chance of winning (10%) against one with a larger absolute number of winners (e.g., 8 or 9 winners). Analytically based responses (1/10 ratio) were associated with computational abilities and cognitive style (i.e., metacognitive dispositions), a finding replicated in an adult sample (Stanovich & West, 2008). The data were interpreted as evidence of the cognitive challenge in overriding experientially based and sustaining analytically based responses on the ratio-bias task.

The present study explores the relation between general cognitive abilities, metacognitive status (Competent, Conflicted, and Poor), and ratio-bias judgments. The goal was to test whether a measure more directly tapping metacognitive intercession skills (metacognitive knowledge) would better predict analytically based ratio-bias performance than the measures used by Kokis et al. (2002) and Stanovich and West (2008). To assess general cognitive skills, self-reported ACT (American College Test) scores were collected. Self-reported ACT scores are reliable indicators of actual ACT scores (Payne, Harper, Quandt, & Campbell, 1995) and correlate with measures of general intelligence (Booth, 1983; Koenig, Frey, & Detterman, 2008; Lewis & Johnson, 1985; for a similar argument regarding self-reported SAT scores see Stanovich & West, 2008). Amsel et al. (in press) found higher ACT mathematics scores among those identified as having a Competent metacognitive status in one of their samples, but not in another. However, performance in that research was based on a single ratio-bias task trial. In the present study, self-reported ACT mathematics scores were collected and participants completed four trials of the ratio-basis judgment and evaluation task.

Unlike Kokis et al. (2002) and Stanovich and West (2008), participants in the present study were presented with pairs of gambles of equivalent ratios (1/10 vs. 10/100), told that they were equivalent, and asked to express a preference for one, the other, or neither gamble (Amsel et al., in press). To additionally assess the tendency toward experientially based responses, participants indicated their willingness to pay for a preferred gamble (Kirkpatrick & Epstein, 1992). We characterize a decision to pay for a preferred gamble among two equal gambles, particularly if the equality between them is made clear, as a non-normative, experientially based response.

4. Method

4.1. Participants

A total of 352 Introductory Psychology students (67% female, *M* age = 20.53 years, S.D. = 5.43 years) participated for research credit, with most participants being university freshmen (74%). A majority of participants reported their ACT mathematics (66%, *M* = 22.4, S.D. = 4.30) score. The mean score was slightly above the university-reported average for incoming freshmen ($M = 21.3$, $t(231) = 4.11$, $p < .001$) and less than half a standard deviation above the state mean (ACT, 2007). To further analyze the reliability of the self-reported ACT scores, self-reported ACT mathematics scores and permission to access actual ACT mathematics scores was requested from a separate sample of 75 Introductory Psychology students from the same university. The correlation between self-reported and actual scores was positive and significant, $r = .82$ ($p < .001$) and the mean self-reported ($M = 22.2$) and actual ($M = 21.8$) ACT mathematics scores did not differ significantly.

4.2. Tasks and procedure

A five-page questionnaire was developed, patterned on vignettes and questions from previous studies (Amsel et al., in press; Epstein & Pacini, 2000/2001; Kirkpatrick & Epstein, 1992). The cover page requested demographic (age, sex, and student status) and academic (ACT mathematics scores) information and introduced the ratio-bias task. The task was presented as a series of carnival games that could be played for free, so as to elicit no additional cost-benefit analysis by participants (Dale et al., 2007).

On the subsequent four pages, the participants were presented with four ratio-bias task trials, with each trial consisting of the ratio-basis judgment and evaluation tasks. The order of the two tasks within a trial was fixed, as previous research showed that counterbalancing task order did not influence judgments or evaluations (Amsel et al., in press). Each trial began with a vignette describing a game of chance in which the participants had the hypothetical opportunity to win $50. The first vignette, or "jellybean game," was presented as follows:

> You play a "jellybean" game in which you can win $50.00 if you reach into a jar (blindfolded of course) of mostly white jellybeans and pull out a black one. There are two similar jars to choose from and you can select to draw a jellybean from one or the other jar. In Jar A there are 10 jellybeans, only 1 of which is black and the rest are white. In Jar B there are 100 jellybeans, only 10 of which are black and the rest are white. The odds of selecting a black jellybean from Jar A are 1/10 (10%), which is the same as the odds of selecting a black jellybean from Jar B (10/100, 10%). Even though the odds of selecting a black jellybean are the same for the two jars, some people may have a preference as to which jar they would rather choose from to win the $50.00.

Other vignettes described the possibility of winning $50 by playing the "spinning wheel game" where wheel A had 12/144 and wheel had B 1/12 winning spaces (equivalent 8.33% odds of winning); the "sock drawer game" where drawer A contained 8/64 and drawer B contain 1/8 winning socks (equivalent 12.5% odds of winning), and the "marble drop game" in which Box A has 1/15 and Box B has 15/225 winning slots for marbles to drop into (equivalent 7% odds of winning). The ratio with the larger absolute number of winners is associated with option A in the first and last games and with option B in the second and third games. Participants were told of the equivalence between the gambles to remove any computational demands the task may pose.

4.2.1. Ratio-bias judgment task

After reading each vignette, participants made judgments about the options presented in the vignette. In the case of the jellybean task, participants were asked which jar, if either, they would select in order to have a better chance of winning. They were then given three response options from which they were to select one: *Jar A*, *Jar B*, or *It would not matter to me*. Participants were then given an opportunity to explain their response.

For each vignette, participants were then presented with the following statement and question (based on Kirkpatrick & Epstein, 1992):

> Let's say you didn't have a choice between Jar A and Jar B. One of them is going to be selected for you. In that case, would you be willing to pay for the privilege of choosing which jar you will draw from, rather than having the jar picked for you?

Participants made a forced *Yes* or *No* choice regarding whether they would be willing to pay for a choice between response options. If they answered *Yes*, they were asked to indicate in dollars and cents how much they would be willing to pay. Affirming the question and offering a payment to secure a choice between two mathematically equivalent gambles provides additional evidence of participants' tendency to make experientially based responses on each trial (Kirkpatrick & Epstein, 1992).

4.2.2. Ratio-bias evaluation task

After completing each question for each vignette on a given trial, participants were asked to respond to three evaluation questions, following Amsel et al. (in press). In the case of the jellybean game, the explanation and questions are as follows:

> Some answers on the task may be based on a logical, reflective, and mathematically sound analysis of the situation. Other choices may be based instead on an automatic reaction to or gut feelings about the situation. For *each* of the following responses, judge how sure you are that it is a logical, reflective, and mathematically sound analysis of the situation [emphasis in original].

Participants were then asked how sure they were that it is logical, reflective, and mathematically sound to have (a) a preference for and then choose Jar A that has a 1/10 chance of winning, (b) a preference for and then choose Jar B that has a 10/100 chance of winning, and (c) no preference for either jar, and not care which jar is chosen. Responses on each question were made on a four-point scale labeled Not At All Sure (1), A Little Sure (2), Mostly Sure (3), and Very Sure (4).

At the beginning of regularly scheduled Introduction to Psychology classes, students were informed about the study and asked if they would be willing to participate in order to earn required research credit. Interested students were given the 4-page questionnaire and a one-page consent form. They were required to return the packet within 1 week of its distribution to receive research credit.

5. Results and discussion

Overall, analytically based *no preference* responses made up 30% ($M = 1.20$ on 4 trials, S.D. = 1.55) of ratio-bias task responses. There was a tendency for participants to prefer gambles with a larger ($M = 1.49$) than a smaller ($M = 1.30$) number of absolute winners, however the difference only approached significance, $t(348) = 1.59$, $p = .057$, 1-tailed. A total of 24% of participants affirmed at least once that they would pay for a preferred gamble. This pattern of biased and suboptimal ratio-bias task performance replicates previous studies using similar tasks in the same condition (Amsel et al., in press; Epstein & Pacini, 2000/2001; Klaczynski, 2001b).

Patterns of evaluation task responses for each participant on each trial were categorized as Competent, Conflicted, Poor, or Other. Competence was defined as ratings of *moderately* (score of 3) or *very* (score of 4) certain that *no preference* is an analytically based response and ratings of *not at all* (score of 1) or *a little* (score of 2) certain that preferring either or both gambles was an analytically based response. Overall, a total of 34% of evaluation response patterns were Competent ($M = 1.35$ competent patterns on 4 trials). In contrast, 29% of the response patterns were Poor ($M = 1.15$), defined as ratings of *moderately* or *very* certain that preferring either or both gambles was an analytically based response, but a rating of *not at all* or *just a little* certain that *no preference* was an analytically based response. Another 22% of the response patterns were Conflicted ($M = .87$), defined as scores of *moderately* or *very* certain that both responses of *no preference* and preferring either or both gambles were analytically

Table 1
Metacogntive status, *no preference* judgments, and payment judgments by study.

Study and variable	metacognitive status			
	Competent	Conflicted	Poor	Other
Study 1				
Status distribution[1] (%)	36	21	29	14
No preference judgment[2]	2.28[a]	.99[b]	.17[c]	.89[b]
Payment judgments[2]	.28[b]	.58[b]	1.11[a]	.79[a,b]
Study 2				
Status distribution[1] (%)	34	24	22	21
No Preference judgments[2]	2.56[a]	1.39[b]	.32[c]	1.50[b]
Payment judgments[2]	.19[c]	.60[b]	1.24[a]	.70[b]
Study 3				
Status distribution[3] (%)	39	33	17	11
No preference judgments[3] (%)	75[a]	54[b]	17[c]	42[b,c]
Payment judgments[3] (%)	8[a,b]	7[b]	23[a]	21[b]

Note: Different superscripts on judgments denote significally different means in *post hoc* tests.
[1] Distribution of Metacognitive Status for participants whose responses were consistent.
[2] Average *no preference* and payment judgment scores range from 0 to 4.
[3] Scores reflect percentages of the sample for each variable.

based responses. The final 15% of response patterns were labeled as other, defined as scores of *not at all* or *a little* certain that each response option was analytically based. The other response pattern reflects a misrepresentation of the analytical nature of *no preference* responses. This distribution of metacognitive patterns replicates Amsel et al. (in press).

A total of 86% of the participants had the same metacognitive status on three or four of the trials. The probability of participants being so consistent was .31, with a binomial probability of $p < .001$ of obtaining the observed consistency[3]. The percentage of consistent participants by metacognitive status (see Table 1) parallels the overall distribution of patterns described above. Participants categorized into different metacognitive status groups were no different in age, sex, or student status. However, a one-way ANOVA with Fisher LSD (Least Significant Difference) *post hoc* tests revealed significantly higher self-reported ACT scores, $F(3, 191) = 4.31$, $p < .01$, among those categorized as consistently Competent ($M = 23.66$) or Conflicted ($M = 23.14$) than those identified as Poor ($M = 21.79$) or Other ($M = 20.63$). The findings suggest that metacognitive status is stable and associated with general cognitive abilities.

To systematically assess the impact of general cognitive abilities and metacognitive status on analytic reasoning performance, a median split of ACT scores was performed. A 4 (metacognitive status) by 2 (ACT Level) ANOVA was performed on the frequency of *no preference* responses. There was only a significant effect of metacognitive status, $F(3, 187) = 24.64$ $p < .001$, with Competent participants making more *no preference* responses than Conflicted and Other participants, who made more than Poor participants (see Table 1). To more sensitively assess the impact of key predictor variables on analytically based *no preference* responses, a stepwise multiple regression was run with interval- or ratio-scaled predictor variables. Self-reported ACT mathematics scores, frequency of each metacognitive pattern, and demographic variables (age, sex, and student status) served as predictor variables. The regression analysis revealed that *no preference* responses were positively related to the number of Competent metacognitive patterns ($\beta = .43$) and negatively to number of Poor patterns ($\beta = -.19$), $R = .55$, $F(2, 225) = 49.21$, $p < .001$, but not to ACT scores.

Overall, Competent participants, who had metacognitive knowledge that preference responses were *not* a “logical, reflective, and mathematically sound analysis of the situation” made preference judgments 41% of the time (1.65 preferences responses of 4). Most of the Competent participants

[3] There were 8 (2^3) possible response patterns on a given evaluation trial, including 1 Competent and Other pattern, 3 Conflicted and Poor patterns. The probability of randomly responding on 3 or 4 trials with a Competent or Other pattern is .007 and Conflicted or Poor pattern is .15, for a total $p = .31$.

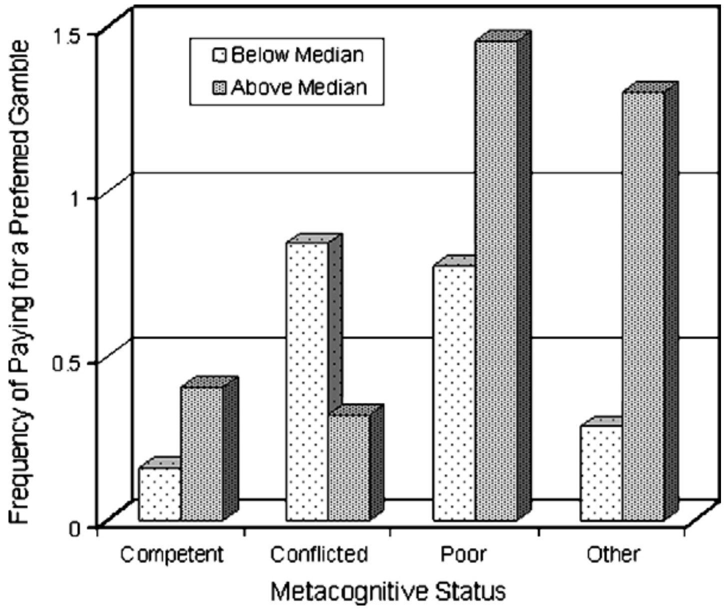

Fig. 1. Average frequency of paying for preferred gamble by metacognitive status and mathematics ACT median split score.

(59%) made a ratio-bias preference judgment on at least one trial, with 36% making such judgments on 3 or 4 of the trials. When they made preference judgments, they did so without bias; that is, equally for gambles with more (M = .85) or fewer (M = .79) absolute winners. There was no difference in ACT score or other demographic (sex, age, and student status) variables between Competent participants who made at least one ratio-bias preference judgment and those who made none.

We doubt that the tendency for these participants to give preference responses was due to confusion or bias resulting from being *told* that the gambles were equivalent but asked to make a choice between them. The 30% rate of *no preference* responses among college undergraduates in the present study was higher than the 21% found by Klaczynski (2001b), who did not explicitly tell participants that the gambles were equivalent. If telling these participants that the gambles were equivalent and then asking them to make a choice was confusing or biasing, one would have expected fewer optimal *no preference* responses on the present task than found by Klaczynski (2001b).

A 4 (metacognitive status) by 2 (ACT Level) ANOVA performed on the frequency of payment responses revealed a significant main effect of metacognitive status, $F(3, 185) = 4.63$, $p < .01$, and an interaction between metacognitive status and ACT Level, $F(3, 185) = 2.74$, $p < .05$. Poor metacognitive status participants were willing to pay for a preferred gamble more often than Conflicted and Competent ones, with Other participants no different from any other group (see Table 1). The interaction effect demonstrated that Conflicted participants were an exception to the pattern of higher ACT scores associated with more payment responses (see Fig. 1). A regression analysis revealed that the frequency of Poor ($\beta = .20$) metacognitive patterns, but not self-reported ACT mathematics scores, predicted payment responses, $R = .20$, $F(1,222) = 9.13$, $p < .01$.

The findings demonstrate that participants' metacognitive knowledge about the processing sources of responses on the ratio-bias task is stable and predictive of analytically based *no preference* and experientially based payment responses on the task. Although higher ACT mathematics scores were associated with a Competent metacognitive status, metacognitive status predicted task performance independently of such scores. Nonetheless, the majority of Competent participants still made at least one preference judgment on the task. They were unbiased in the gamble they selected, showed minimal tendency to pay for their preferred gamble, did not appear confused or biased in selecting a preferred gamble, and demonstrated no cognitive or demographic difference from those who did not make preference judgments. It seems that these participants appreciate at some level that in preferring a gamble they were not maximizing their chances of winning, reflecting a compromise between analytically and experientially based response tendencies (or, as one reviewer put it, an attempt to integrate rationality and superstition).

The suboptimal responses by those with a Competent metacognitive status can be distinguished from the same responses of those with a Conflicted or Poor status. These participants consistently judged that responses preferring one or the other gamble were based on analytic processing and so made preference responses assuming that they were "mathematically sound." Those with a Poor status so strongly believed that they were maximizing their chances of winning that many were willing to pay for the privilege of selecting a gamble.

The results replicate Amsel et al.'s (in press) finding that many participants with metacognitive knowledge about the processing sources of responses on the task were not constrained from making responses that they knew were suboptimal. Such a constraint would be expected if metacognitive insight into task responses resulted in the *replacement* of experientially based responses by analytic-based ones. The findings support a dual process model, which proposes that metacognitive knowledge serves to *regulate* conflicting dual processes responses but not necessarily to *replace* less adequate and non-normative responses by more adequate and normative ones.

6. Study 2

Study 2 was conducted to examine developmental changes in performance on the ratio-bias task. Previous research has focused on the development of analytically based responses, but results are not consistent. Klaczynski (2001b) found an increase in the frequency of analytically based *no preference* responses among preadolescents, adolescents, and college students on a ratio-bias task. However, no corresponding decrease was found in the frequency of experientially based preferences for the gambles with more absolute winners. Also, analytically based *no preference* responses were made infrequently among each group, including college students. Kokis et al. (2002) found no difference in analytically based responses among 10–11 year olds and 13–14 year olds. Kokis et al.'s (2002) task was a ratio-bias task with unequal ratios (1/10 vs. 9/100) whereas Klaczynski's (2001b) task was a ratio-bias task with equal ratios (1/10 vs. 10/100). However, neither study explored the change in participants' metacognitive knowledge about the processing basis of ratio-bias responses.

Study 2 assesses differences by age and education in both the analytically based *no preference* responses and metacognitive status. Perhaps analytically based *no preference* responses are not the only or most important index of change in dual-process reasoning occurring over adolescence, which may be better indexed by the development of metacognitive knowledge necessary for metacognitive intercession.

The results of Study 1 demonstrated that, although not directly influencing the frequency of analytically based responses on the ratio-bias task, general cognitive skills, particularly in mathematics, may be related to metacognitive status. The present study thus explores both the role of age and mathematics background by including middle-school students and university young adult students enrolled in parallel mathematics classes. These groups allow for a comparison between participants of different ages but similar mathematics level. A group of university students enrolled in upper-division statistics courses allowed an additional comparison between similarly aged university students who varied in mathematics level. Together, these three groups permitted inferences regarding age-related differences in metacognitive status independent of mathematics background and of mathematics-related differences independent of age.

7. Method

7.1. Participants

A total of 304 students served as participants. There were 115 (65 female) middle-school students (M = 13 years old, S.D. = .74 year) who were sampled from pre-algebra (n = 52) and beginning algebra (n = 63) courses. Another 114 (55 female) university students (M = 23.3 years old, S.D. = 5.42 years) were sampled from similar pre-algebra (n = 44) and beginning algebra (n = 70) courses in a university-level Developmental Mathematics program. The algebra courses were similar in content to the middle-school classes and prepared students for the intermediate algebra and the university Quantitative Literacy courses, which were a requirement for taking upper-division courses and for graduation.

University students were assigned to developmental mathematics classes on the basis of a formula which includes performance on a placement test, years since their last mathematics class, ACT scores, and students' own preferences. Finally, 75 (44 female) university students (*M* = 24.6 years, S.D. = 5.90 years) were sampled from Psychology Statistics students. Psychology statistics course students had to have passed the university Quantitative Literacy requirement. Distribution by sex was equivalent across the three groups.

7.2. Task and procedure

Participants were presented with similar demographics questionnaire and ratio-bias judgment and evaluation tasks (Jellybean, Spinning Wheel, Sock Drawer, and Marble Drop) to those used in Study 1. The demographics questions asked about anticipated grade in the English and Mathematics course rather than ACT scores. A slightly different set of ratios were used on the ratio-bias task (1/10 vs. 10/100, 1/12 vs. 12/144, 1/8 vs. 8/64, 1/14 vs. 14/196), and the order of presentation of the four ratio-bias task trials was varied. The participants were block randomized into one of the four different ratio-bias task trial orders. Subsequent analyses revealed no effect of questionnaire order on the judgment or evaluation task performance, so the data were collapsed over order. The college students completed the questionnaire and consent forms outside of class and returned them to their instructor to earn extra class credit. Middle-school students completed the questionnaire in their mathematics class as an assignment for which they received class credit.

8. Results and discussion

Overall, analytically based *no preference* responses were made 38% of the time (*M* = 1.50 on 4 trials, S.D. = 1.62). Participants preferred gambles with a larger (*M* = 1.47) rather than a smaller (*M* = 1.03) number of absolute winners, a difference that was statistically significant $t(298) = 3.74$, $p < .001$, 1-tailed, and showed no difference by age group. The tendency to pay for a preferred gamble was made at least once by 30% of the sample. As in Study 1, this pattern of biased and suboptimal ratio-bias task performance replicates previous studies.

There were no group differences in *no preference* responses, with 34% of Middle School, 40% of the Developmental Mathematics, and 39% of the Psychology Statistics students making analytically based *no preference* responses. However, there was a weak trend toward younger participants making more experientially based payment responses, $F(2, 291) = 2.47$, $p = .087$. More Middle School (42%) than Developmental Mathematics (27%) or Psychology Statistics (20%) students were willing to pay for a preferred gamble on at least one trial, $F(2, 291) = 5.57$, $p < .01$. The findings are consistent with Kokis et al.'s (2002) finding of no developmental changes in analytically based responses, but inconsistent with Klaczynski's (2001b) finding of such changes, although the low frequency of analytically based responses in each group is consistent with Klaczynski (2001b)'s findings.

Participants' response patterns on each of the four ratio-bias evaluation trials were coded into one of the 4 metacognitive patterns described in Study 1. The frequency of each pattern was summed over trials for each participant. A total of 74% of the adolescents, 83% of the Developmental Mathematics students, and 84% of the Psychology Statistics students responded with the same pattern on 3 or 4 trials, with all binomial *ps* < .001 (see Table 1). The distribution of consistent responders was no different across Study 1 and 2, $X^2(3) = 6.87$, *ns*. Sex was distributed differently across metacognitive status in Study 2, $X^2(3) = 8.45$, $p < .05$, with females (representing 56% of the entire sample of consistent responders) overrepresented in the Poor (68%) and underrepresented in the Conflicted (42%) metacognitive status groups.

To explore age and mathematics level effects on metacognitive status, 4 separate one-way ANCOVAs were conducted on the percentage of participants in each metacognitive status by Group (Middle School, Developmental Mathematics, Psychology Statistics) controlling for sex and using LSD *post hoc* tests (see Fig. 2). There were both age and mathematics effects for the Competent status, $F(2, 233) = 9.78$, $p < .001$, with more participants identified as Competent in Psychology Statistics than in Developmental Mathematics and more in Developmental Mathematics than in Middle School. There was an age effect for the Poor status, $F(2, 233) = 8.56$, $p < .001$, with more participants categorized as Poor in Middle

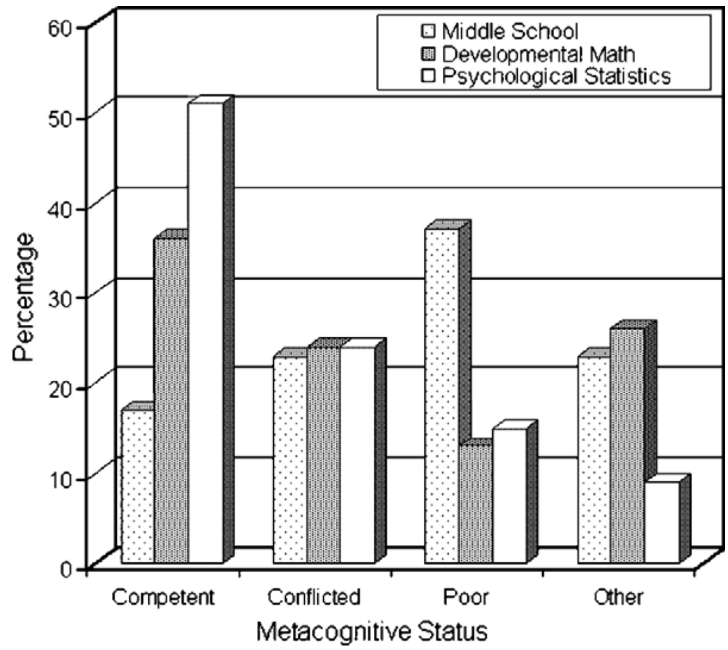

Fig. 2. Distribution of metacognitive status across age and mathematics level.

School than in Developmental Mathematics or Psychology Statistics. There was a mathematics level effect for the Other status, $F(2, 233) = 3.55$, $p < .05$, with more in the Other status in Middle School and Developmental Mathematics than in Psychology Statistics. There was no Group effect for Conflicted.

Metacognitive status was associated with unique patterns of responses, with results largely replicating the findings from Study 1 (see Table 1). One-way ANCOVAs demonstrated metacognitive status effects on *no preference* responses, $F(3,227) = 20.69$, $p < .001$, and payment responses, $F(3, 227) = 7.39$, $p < .001$, independently of age and sex. Competent metacognitive status participants made more *no preference* responses than did Conflicted and Other, who made more such responses than Poor participants. In contrast, Poor metacognitive status participants were willing to pay for their preferred choice at twice the rate as Conflicted or Other participants, who in turn paid at a rate more than three times higher than Competent participants. A final analysis tested the percentage of students by metacognitive status who anticipated a grade of A in their mathematics and English classes, independently of age and sex. Only the percentage of expected *A* grades in mathematics varied by metacognitive status, $F(3, 231) = 3.97$, $p < .01$, with twice as many Competent (40%) expecting an *A* in mathematics than Conflicted (19%), Poor (22%) and Other (17%) participants.

Overall, Competent participants made preference judgments 38% of the time (1.53 preferences responses of 4). Most of the Competent participants (51%) made a ratio-bias preference judgment on at least one trial, with 33% making preference judgments on 3 or 4 of the trials. These participants were again unbiased in their preference, selecting the gamble with the larger absolute number of winners ($M = .90$) as often as the gamble with smaller absolute number of winners ($M = .63$). There was no difference in age, sex or group between Competent participants who made at least one ratio-bias preference judgment and those who made none. These results closely resemble the findings from Study 1.

The findings of Study 2 point to extensive age- and mathematics-related differences in metacognitive knowledge but minimal differences in ratio-bias judgments. Analytical-based *no preference* judgments were unaffected by age and mathematics level, although the percentage of participants willing to pay to secure a choice of gambles demonstrated a weak age effect. As noted, this finding confirms that of Kokis et al. (2002), who found no age difference in a sample with a narrower age-range (10–13 years) and a different task. Kokis et al. (2002) used the ratio-bias task with unequal gambles (e.g., 1/10 vs. 9/100) and found a strong preference (43% of all judgments) for a gamble with more absolute number of winners (9/10) even if it had lower odds of winning than a gamble with fewer absolute number of winners (1/10) (also see Alonso & Fernandez-Berrocal, 2003; Denes-Raj & Epstein, 1994; Stanovich & West, 2008, who used the same task). The present study replicates the finding of age-related stability in preferring gambles with larger than smaller absolute number of winners, despite participants being told that the two gambles were equivalent. A parallel statement of the inequality between the gambles was not given by Kokis et al. (2002), suggesting that dissimilar tasks and procedures tapped the same experiential processing of absolute values which, for many participants, predominated over analytic processing of abstract ratios.

In sharp contrast to their *judgments*, there were a host of differences between middle school and college participants' *metacognitive knowledge*. Most middle-school students were challenged to correctly identify *no preference* as an analytically based response (Poor or Other Metacognitive Status) and to identify having a preference as an experientially based response (Poor or Conflicted). A majority of Psychology Statistics students were classified as Competent and could correctly identify the processing source of both kinds of responses. The Developmental Mathematics students were distributed more evenly across the four metacognitive status groups, reflecting students who were quite diverse in metacognitive knowledge about dual processes. Generally, the growth of metacognitive knowledge regarding analytically and experientially based responses parallels the growth of other metacognitive skills during adolescence (Klaczynski, 2005; Kuhn, 2000).

The acquisition of metacognitive knowledge was shown to have an impact on judgments. Correctly making analytically based *no preference* judgments and avoiding experientially based payment judgments on the ratio-bias task were strongly related to participants' metacognitive status, independently of cognitive abilities (Study 1) and a range of demographic variables (Studies 1 and 2). Moreover, in both studies, metacognitive status was found to be stable over multiple trials. Study 2 provides further validity to the measure of metacognitive status by its association with students' anticipated mathematics grades.

The acquisition of metacognitive knowledge over age and mathematics level has a profound impact on how ratio-bias judgment performance can be understood. The opportunity to learn the limits of experiential responding is unavailable to younger and mathematically lower-level participants, whose ratio-bias preference judgments were often made with the belief that they were a mathematically sound response in the situation. These participants will require a great deal more metacognitive development regarding the cognitive source of their responses and when to rely on one cognitive system or the other (Hogarth, 2005). Nonetheless, having metacognitive knowledge that ratio-bias preference judgments are analytically based was not a guarantee that such responses would be made. A majority of those with a Competent metacognitive status responded on the ratio-bias task with a preferred gamble in at least one trial but they did not demonstrate the ratio bias effect, preferring each gamble equally often. The findings replicate the results of Study 1 and support the claim that preference responses from Competent participants may reflect a compromise between analytically and experientially based judgments. This result further points to the role of metacognitive knowledge in promoting the *regulation* but not necessarily the *replacement* of experientially based responses by analytically based ones.

9. Study 3

Dual-process theory proposes that *external* conditions can result in the predominance of one system of processing over the other (Alonso & Fernandez-Berrocal, 2003; Epstein & Pacini, 2000/2001; Kirkpatrick & Epstein, 1992; Klaczynski, 2001b). For example, Kirkpatrick and Epstein (1992) found evidence that under certain conditions, analytically or experientially based responses can be elicited on the ratio-bias task. Similar findings have been found by others varying participant's perspective (their own, other people's, and a logical person's) or consensus information (others' tendency to have a preference on the task) (Alonso & Fernandez-Berrocal, 2003; Epstein & Pacini, 2000/2001; Klaczynski, 2001b). But no study as yet systematically varied these two conditions (perspective and consensus) simultaneously.

Study 3 directly tests the effect of perspective and consensus information on ratio-bias judgments and evaluations. The perspectives varied were whether participants responded from their own (Self) or a Logical Person's perspective. The manipulation has been found to be effective in promoting analytic responses in previous research using within-subjects designs but has not been tested in a between-subjects design. The consensus information varied was others' tendency to have a preference (Negative) or no preference (Positive) for a gamble on the task. Consensus information was varied in order to assess whether social cues alone could sway participants' mathematical judgments and evaluations in comparison to perspective, which carries with it a sense eliciting normative responses in the Logical Person condition. It was predicted that task conditions may affect ratio-bias judgments but not alter participants' metacognitive status, which has shown to be stable over tasks.

10. Method

10.1. Participants

The sample included 173 students (57% female, $M = 21$ years, S.D. = 5.88 years) from Introductory Psychology courses. Most participants were freshmen (68%) who completed the task for research credit.

10.2. Task and procedure

A single page questionnaire was distributed to participants. The questionnaire presented a series of demographic questions (age, sex, student status, and high school GPA) and the two ratio-bias tasks in a fixed order. The ratio-bias judgment task was presented first. Participants imagined being offered a free lottery in which they can win $50 if they choose a winning ticket from a jar. They were given two jars to choose from: Jar A had 1 winning ticket and 9 losing ones, and Jar B had 10 winning tickets and 90 losing ones. They were told that the odds of winning (10%) were equivalent for each jar and then asked which jar they preferred (e.g., 1/10 or 10/100 gamble) or to express *no preference* between them. Participants were also asked whether, and how much, they would be willing to pay to secure a choice between jars rather than having one chosen for them.

The second task was the ratio-bias evaluation task. Participants were first given a definition of analytically based processing (*a reflective, mathematically sound, and well reasoned analysis of the situation*). Then participants were asked to evaluate their certainty that choosing each response option (e.g., preferring *1/10*, *10/100*, and *no preference*) reflected the product of an analytic process. The certainty judgment for each response option was made on the same 4-point scale used in Studies 1 and 2.

Participants were randomly assigned to one of four conditions, reflecting a complete crossing of two levels of Perspective (Self or Logical Person) and Consensus Information (Negative or Positive). There were approximately 43 participants in each cell. The groups did not differ in any demographic characteristic. Consensus Information specified that most people had no preference (Positive Consensus) or had a preference (Negative Consensus) for one jar or the other. Consensus information was provided directly before the judgment task questions. Perspective varied whether participants were to answer both the judgment and evaluation questions from either their own (Self) or a Logical Person's perspective. Participants were requested to entertain a perspective just prior to answering both questions on both tasks. Participants signed a consent form, were block randomized into one of the four experimental conditions, and completed the questionnaire in their Introductory Psychology class.

11. Results and discussion

To test whether Perspective and Consensus Information affected performance on the ratio-bias task, separate 2 (Perspective) by 2 (Consensus) ANOVAs were conducted on the tendency to give analytically based *no preference* and experientially based payment responses. The analysis revealed only a main effect of Perspective on analytically based judgments, $F(1, 169) = 4.64$, $p < .05$. There were more analytically based responses by participants in the Logical Person ($M = 62\%$) than Self ($M = 46\%$) conditions. There was no main effect of Consensus or interaction of Perspective and Consensus on participants' *no preference* judgments, and no main or interaction effect of Perspective or Consensus on payment judgments.

The results replicate others' finding that perspective influences the use of analytically based responses on the ratio-bias judgment task (Alonso & Fernandez-Berrocal, 2003; Epstein & Pacini, 2000/2001; Klaczynski, 2001b). However, the effect was small, resulting in only a 16% difference in analytically based *no preference* judgments. The finding is consistent with that of Klaczynski (2001b), who

Table 2
The distribution of metacogntive status by perspective (self or logical person) and consensus (positive or negative) conditions, Study 3.

	Metacognitive status			
	Competent	Conflicted	Poor	Other
Consensus: negative[a]				
Self	14	7	9	7
Logical person	16	17	7	3
Consensus: positive[b]				
Self	19	16	8	6
Logical person	18	17	6	3
Total *N*	67	57	30	19
Fisher exact *p*[*]	.81	.18	1.00	1.00

[a] Negative consensus information specified that most people had a preference for one gamble or the other.
[b] Positive consensus information specified that most people had no preference for one gamble or the other.
[*] 2-tailed test.

found an improvement of 21% in a within-subjects version of the same manipulation among college students, although others have found much larger effects in similar studies (Alonso & Fernandez-Berrocal, 2003; Epstein & Pacini, 2000/2001).

To assess the impact of condition on metacognitive status, participants were again categorized into one of four metacognitive status groups using the same procedure as in Studies 1 and 2 (see Table 1). The results largely replicate the previous findings. There were no Metacognitive Status differences in demographic variables (age, sex, student status, or self-reported High School GPA). None of the four Fisher Exact tests on the distribution of each Metacognitive Status by Perspective and Consensus Information was significant (see Table 2). This finding provides evidence that metacognitive status is stable not only over trials (Studies 1 and 2) but also over contexts, which otherwise produce differences in ratio-bias judgments (Study 3). Moreover, the finding suggests that the Perspective effect on task performance was not only small but also superficial, having no impact on deeper aspects of participants' thinking about the task.

As expected and confirming Studies 1 and 2, *no preference* judgments were made more often by Competent participants than Conflicted and Other, and more by Conflicted than Poor participants, $F(3, 169) = 11.54$, $p < .001$. Those with Poor metacognitive status were willing to pay for a preferred jar more often than Competent and Conflicted participants, with Other participants no different than any other group $F(2, 169) = 2.69$, $p < .05$. These patterns suggest that internal metacognitive status, rather than the external conditions, accounted for much of the performance variance on the ratio-bias task.

Of the 67 participants with Competent metacognitive status, 17 (25%) had a preference for a gamble; these were equally distributed across the 1/10 ($n = 8$) and 10/100 ($n = 9$) gambles. There were no demographic differences (age, sex, student status, High School GPA) between those identified as Competent who made or did not make a ratio-bias preference judgment. However, Competent participants gave a preference judgments more often in the Self (12/33 or 36%) than the Logical Person (5/34 or 15%) condition, $t(65) = 2.07$, $p < .05$. This result points to the role of metacognitive knowledge in *regulating* the selection of the most appropriate response on a task, given the conditions, rather than *replacing* experientially based responses by analytic ones irrespective of condition. Interestingly, Conflicted and Poor or Other (combined to increase sample size) participants showed no perspective effect in their rate of preference judgments, suggesting perhaps that they lack the metacognitive knowledge to effectively intercede to make analytic responses.

12. General discussion

The present study explored the nature, development, and stability of preadolescents' and young adults' metacognitive knowledge regarding task responses. Such knowledge was theorized to be necessary for successful metacognitive intercession skills, which involve regulating conflicting experientially and analytically based responses. Circumstances in which there are conflicting dual-processing responses are ubiquitous when reasoning scientifically, ranging from the simple comparison of the relative strength of probabilities to the complex coordination of belief-based expectations with evidence. The conflicts between experientially and analytically based responses arise not only in laboratory-based scientific reasoning tasks but also in the laboratories of practicing scientists (Chinn & Brewer, 1998; Fugelsang, Stein, Green, and Dunbar, 2004; Hogan & Maglienti, 2001).

Metacognitive knowledge was explored on the ratio-bias task, which permitted the analysis of participants' ability not only to rely on experientially or analytically based task responses, but to distinguish between them as well. The ratio-bias task taps scientific reasoning skills as it requires participants to interpret patterns of data and to make decisions or take actions based on those interpretations. A reliable finding across three studies involving over 825 participants was that many participants (a majority in Studies 1 and 2 and a sizable minority in study 3) expressed a preference for one of two gambles with an equivalent likelihood of winning. This finding is obtained despite informing participants that the two gambles were equivalent. Moreover, participants expressed a preference for the gamble with the larger absolute number of winners in Studies 1 and 2. The finding of a preference for a gamble with the larger absolute number of winners replicates previous studies using similar tasks, as does the finding that such a preference further motivates some participants to pay for a preferred gamble (Amsel et al., in press; Kirkpatrick & Epstein, 1992). The explanation for this ratio-bias effect is that participants, who may understand the two gambles are equivalent, are compelled by the differences in the absolute number of winners on a task and make irrational preference and payment judgments. The findings add to the scientific reasoning (Zimmerman, 2007), judgment and decision-making (Reyna & Brainerd, 2008), and mathematics education (Hecht et al., 2007) literatures regarding the challenges posed when reasoning about ratios.

One of the conceptually important findings of the present research is that not all suboptimal experientially based preference judgments on the ratio-bias task were the same. Participants with a Poor metacognitive status made preference judgments with relative certainty that they were the only analytically based and mathematically sound response that could be made on the task. Participants with a Poor metacognitive status represented approximately a quarter of the sample across the three studies (ranging from 17% in Study 3–29% in Study 1). Although those with a Poor status were willing to pay for a preferred gamble more often than others, and even gambled more often (Amsel et al., in press), they were not lacking in mathematical, academic, or cognitive abilities. Poor metacognitive status participants expected an A in their Mathematics classes at the same rate as Conflicted and Other participants and they had similar self-reported High School GPA and ACT mathematics scores as most others.

In contrast, a subset of those identified as having a Competent metacognitive status made preference judgments when relatively certain that *no preference* responses were the only analytically based and mathematically sound response. The proportion of such judgments made by those identified as Competent was 41, 38, and 25% in Studies 1, 2, and 3, respectively, close to the 36% found by Amsel et al. (in press). It is notable that in all three studies these participants showed no bias in their preferred gamble, selecting the gamble with the larger (10/100) and smaller (1/10) absolute number of winners equally often. These findings reflect these participants' regulation of their conflicting response tendencies perhaps by combining or integrating analytical and experiential processing. Moreover, Study 3 demonstrated the tendency for those with metacognitive competence to make fewer preference judgments in the Logical Person than the Self-condition, suggesting that those identified as Competent readily modulate their suboptimal responses when the context strongly elicits an optimal one.

The present findings are difficult to explain by the *replacement* of experientially based responses by analytically based ones, as is assumed in traditional accounts of the development of scientific reasoning. There was no evidence of developmental change in analytically based *no preference* responses despite extensive age-related and education-related differences in metacognitive knowledge. Moreover, more analytically based *no preference* responses were given in conditions that were designed to elicit normative responses, particularly by those with a Competent metacognitive status (Study 3). These results are more consistent with a view of development as involving co-development of experiential and analytically processing systems and the acquisition of skills to regulate these processes. There is a good deal of evidence of the latter in Study 2, which demonstrated the decrease over age in those having no metacognitive knowledge (Poor metacognitive status) and an increase over age and mathematics level in those having complete knowledge (Competent metacognitive status). The finding that competent metacognitive knowledge was associated with advanced cognitive skills (ACT mathematics scores), mathematics achievement (A grades in mathematics classes), and ratio-bias judgments performance is generally consistent with claims of a connection between general intelligence, academic skills, and reasoning ability (Perkins & Grotzer, 1997). However, most participants with a Competent metacognitive status did not completely abandon making experientially based ratio-bias responses, and instead they continued to make such responses knowing that they were suboptimal. The findings suggest the importance of metacognitive knowledge in the development of scientific reasoning but deny that such knowledge inevitably, permanently, and irreversibly leads to optimal task performance.

The dual-process account of ratio-bias task performance provides a unique perspective from which to understand the stability of and variability in performance on other scientific reasoning tasks. For example, optimal performance which has proven difficult for adolescents and adults on certain evidence evaluation tasks can be demonstrated by young children on other evidence evaluation tasks (Amsel & Brock, 1996; Gopnik et al., 2001; Koerber et al., 2005; Ruffman et al., 1993; Shultz & Bonawitz, 2007; Sodian et al., 1991; Waters et al., 2000). Rather than treating the latter tasks as superior to the former by revealing earlier scientific reasoning competence, the findings of the present study suggest that the performance variance may merely reflect differences in the dual-process regulatory skills demanded by each task.

More generally, the findings suggest that even the same response on a scientific reasoning task cannot be interpreted in the same manner, unless participants' metacognitive knowledge about the sources of their judgments (or other measures of metacognitive intercession skills) are assessed. For example, consider situations in which data are treated differently depending on whether they are consistent or anomalous with individuals' beliefs. Although such responses violate canons of scientific consistency, evidence suggests that differential responses are made by children (Amsel & Brock, 1996; Koerber et al., 2005), adolescents and young adults (Klaczynski & Lavallee, 2005; Kuhn & Pearsall, 1998; Kuhn & Pease, 2005; Schauble, 1996), and practicing scientists (Chinn & Brewer, 1998; Dunbar, 1999; Fugelsang et al., 2004). Although these groups may respond similarly to one another, their metacognitive knowledge regarding their responses may be quite different. This parallels the present finding that those with Poor and Competent metacognitive status may each generate the same judgments but hold different metacognitive knowledge regarding the nature and significance of such responses. At one extreme, scientists may be aware of their differential responses but have metacognitive knowledge regarding their responses that justify their violation of the canons of scientific consistency (Fugelsang et al., 2004; Hogarth, 2005). At the other extreme, even if children are aware of their differential responses to data, they may lack metacognitive knowledge about the extent to which experientially based processing influenced their responses or of the normative standards that might justify such responses. Adolescents and young adults may be somewhere between the children and scientists, reflecting partially developed metacognitive knowledge.

12.1. Limitations and future research

The present study suggests a number of directions for future research. It focused on assessing one particular component of metacognitive intercession skills. Participants' metacognitive knowledge about responses on the ratio-bias task was claimed necessary for successful metacognitive intercession to resolve conflicting analytically and experientially based responses. Other skills and abilities associated with metacognitive intercession likely include cognitive speed and efficiency (Kail, 2007; Kail & Ferrer, 2007), additional kinds of metastrategic knowledge (Kuhn, 2000; Klaczynski, 2005), executive processing skills (Lamm, Zelazo, & Lewis, 2006; Zelazo, Craik, & Booth, 2004), and an epistemological stance broadly valuing normative standards (Chandler, Hallett, & Sokol, 2001) and scientific inquiry (Lehrer & Schauble, 2006). Additionally, the present research suggests that skills to successfully intercede on the ratio-bias task likely involve mathematics-specific knowledge, decontextualization abilities (Stanovich & West, 2000), and a grasp of mathematical equivalence (Knuth et al., 2006). Future research can more carefully relate metacognitive status to other metacognitive intercession skills and assess each in predicting analytic performance.

The present study focused on metacognitive status on only one particular task. Future research could focus on whether the role of metacognitive status on the ratio-bias task is similar on other tasks. Of particular interest is whether the tendency for some to knowingly make suboptimal judgments is a disposition that is demonstrated on a variety of different tasks.

Performance on the ratio-bias task was based on hypothetical lotteries that may not have motivated participants to reason at a level that they would have had they been actually confronted with such a situation. Studies have replicated the ratio-bias effect on hypothetical and actual gambling tasks (Kirkpatrick & Epstein, 1992). Nonetheless, assessing metacognitive status and its relation to performance on highly motivating and engaging tasks would be an important research direction.

The present study does not explore how or why individuals detect a conflict between experientially and analytically based responses (De Neys & Glumicic, 2008). Recognizing that a conflict exists is the trigger for metacognitive intercession. We speculate that appreciating that dual-process responses conflict with each other may require metacognitive abilities (Samarapungavan, 1992) and cognitive dispositions (Klaczynski, 2005, 2009) that are related to metacognitive intercession skills. Future research could explore the relation between metacognitive intercession skills and the detection of response conflict.

As noted initially, dual-process theory is relatively new to developmental theorizing in general and to scientific reasoning in particular (Klaczynski, 2000; Klaczynski & Lavallee, 2005). The significance of the theory is its focus on not only the development of analytical processing but also the regulation of analytical and experiential responses. This is in contrast to a focus on the replacement of less adequate and non-normative responses by more adequate and normative ones. Finally, the dual-process account of development of scientific reasoning presented here is not the only one available (see Reyna & Brainerd, 2008; Stanovich, Toplak, & West, 2008) and future research should be directed to testing differences between the accounts.

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