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The role of epistemic emotions in mathematics problem solving

Krista R. Muis *, Cynthia Psaradellis, Susanne P. Lajoie, Ivana Di Leo, Marianne Chevrier

McGill University, Montreal, Quebec, Canada

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ABSTRACT

The purpose of this research was to examine the antecedents and consequences of epistemic and activity emotions in the context of complex mathematics problem solving. Seventy-nine elementary students from the fifth grade participated. Students self-reported their perceptions of control and value specific to mathematics problem solving, and were given a complex mathematics problem to solve over a period of several days. At specific time intervals during problem solving, students reported their epistemic and activity emotions. To capture self-regulatory processes, students thought out loud as they solved the problem. Path analyses revealed that both perceived control and value served as important antecedents to the epistemic and activity emotions students experienced during problem solving. Epistemic and activity emotions also predicted the types of processing strategies students used across three phases of self-regulated learning during problem solving. Finally, shallow and deep processing cognitive and metacognitive strategies positively predicted problem-solving performance. Theoretical and educational implications are discussed.

1. Introduction

"Mathematics" and "anxiety" are two words that often go together when individuals are asked to think about their experiences when learning mathematics. Indeed, a rich literature on test anxiety (see Zeidner, 1998) demonstrates researchers' interest in this particular topic over the past five decades (Schutz & Pekrun, 2007). Research on test anxiety has explored the structure, antecedents, and effects that anxiety has on students' health and well-being, and on learning outcomes in general. Despite the prominence of test anxiety research, with the exception of causal attributions as antecedents to achievement emotions (Weiner, 1985), only recently have educational psychologists considered the role that various types of emotions play in educational contexts. Today, emotions are recognized as being critically important to students' learning, motivation, and academic achievement as well as teachers' productivity (Efklides & Volet, 2005; Linnenbrink, 2006; Schutz & Pekrun, 2007).

In contemporary educational research, theorists define emotions as multifaceted phenomena that involve cognitive, affective, physiological, motivational, and expressive processes (Scherer, 2000). For example, the anxiety a student experiences about a mathematics exam may consist of worrying about failing the exam (cognitive), feelings of nervousness (affective), increased cardiovascular activation (physiological), impulses to flee the situation (motivational), and anxious facial expression (expressive) (Pekrun & Stephens, 2012). Over the past ten years, research has focused on what kinds of emotions are experienced in educational settings, as well as how both positive and negative emotions relate to achievement and personal growth (Efklides & Volet, 2005; Linnenbrink, 2006; Linnenbrink-Garcia & Pekrun, 2011; Pekrun, Goetz, Titz, & Perry, 2002a; Schutz & Lanehart, 2002). Research has shown that positive emotional experiences relate to students' academic achievement and success in an academic domain (Pekrun, Elliot, & Maier, 2009), whereas the converse is found for negative emotional experiences (Pekrun, Goetz, Frenzel, Barchfeld, & Perry, 2011). Emotions such as enjoyment, hope, and pride positively predict academic achievement, whereas negative emotions like boredom and hopelessness can lead to a decrease in achievement (Pekrun et al., 2011). Additionally, both positive and negative emotions play an important role in self-regulated learning, strategy use, and motivation (Op't Eynde, De Corte, & Verschaffel, 2007; Pekrun, Goetz, Titz, & Perry, 2002b).

Given the role that emotions play in learning and achievement, theoretical models have been developed to describe both the antecedents of students' emotional experiences, as well as their consequences. For example, Pekrun and colleagues (Pekrun, 2000, 2006; Pekrun, Frenzel, Goetz, & Perry, 2007) proposed the control-value theory of achievement emotions to explore the antecedents and consequences of emotions experienced in academic settings.

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* Corresponding author. McGill University, 3700 McTavish Street, Montreal, Quebec, Canada H3A 1Y2. Fax: +1 5143986968.

E-mail address: krista.muis@mcgill.ca (K.R. Muis).

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Achievement emotions are defined as emotions that are linked to achievement activities or achievement outcomes. Activity emotions are emotions experienced during engagement in an activity (e.g., solving a mathematics problem), whereas outcome emotions include both prospective outcome emotions (e.g., related to possible successes or failures) and retrospective outcome emotions (e.g., linked to prior success and failure). Achievement, activity, and outcome emotions fall under the broader category of academic emotions.

Recently, theorists have expanded the range of emotions to include epistemic emotions which, following R. Pekrun's suggestion (personal communication, June 4, 2015), we define as emotions that arise when the object of their focus is on knowledge and knowing (see also Pekrun & Linnenbrink-Garcia, 2012; Pekrun & Stephens, 2012). The word *epistemic* refers specifically to facets of knowledge and knowing. Like epistemic beliefs, individuals' beliefs about knowledge and knowing (Hofer & Pintrich, 1997), and epistemic cognition, cognitive manifestations of individuals' epistemic beliefs in context (Muis, Trevors, & Chevrier, in press), the object focus for epistemic emotions is on knowledge and processes of knowing. Typical examples include surprise, curiosity, and confusion that arise when there is unexpected information or cognitive incongruity (Kang et al., 2009). Cognitive incongruity might entail conflicting information (e.g., a student recalculates her solution but derives two different answers), or information that is counter to what one believes to be true (e.g., a student believes an acute angle is greater than 180 degrees but is told that it is less than 180 degrees). When individuals experience conflicting information, their first reaction may be surprise. Individuals may then experience curiosity about the conflicting information and attempt to resolve it, or they may experience confusion if the incongruence cannot be resolved.

Philosophers have also considered the role that epistemic emotions play during knowledge acquisition (Brun, Doğuoğlu, & Kuenzle, 2008; Morton, 2010), and have focused primarily on three: curiosity, surprise, and confusion. From an epistemological standpoint, these three affective states represent epistemic emotions because they relate to the knowledge-generating aspects of tasks and activities (see Brun et al., 2008 and Morton, 2010 for overviews). As philosophers have argued, they represent a major category of human emotion that serves an evolutionary-based purpose of acquiring knowledge about the world and the self (Brun et al., 2008). Brun and Kuenzle (2008) differentiate epistemic emotions from other types of emotions such as social, moral, or achievement emotions in terms of their specific object focus. For epistemic emotions, the object of the emotion is knowledge and knowledge generation. In contrast, for social, moral, or achievement emotions, other individuals, moral norms, or success and failure, respectively, are their object focus.

Additionally, as Brun and Kuenzle (2008) suggest, surprise, curiosity, and confusion are epistemic by their very nature, whereas other emotions can belong to different categories of emotions depending on their object focus. For example, frustration at not deriving a correct solution to a mathematics problem may be regarded as an epistemic emotion if the focus is on the cognitive incongruity that resulted from the unsolved problem. If, however, the focus is on personal failure and the inability to solve the problem, then the emotion is considered an achievement emotion. However, since epistemic emotions occur during learning and pertain to the features of ongoing knowledge-generating activities, like achievement emotions, epistemic emotions can be considered activity emotions. As such, epistemic emotions should share similar features to activity emotions with regard to their role in self-regulated learning, which is defined as "learning that results from students' self-generated thoughts and behaviors that are systematically oriented toward the attainment of their learning goals" (Schunk, 2001, p. 125).

For example, Morton (2010) delineates how curiosity is a driving force behind how individuals approach solving a complex problem. When individuals are curious about answers to complex problems, this influences how they plan to solve the problem, which goals they set, and the strategies they use to achieve their goals. When confusion arises, individuals will attempt to resolve the confusion by evaluating the source of confusion, adjusting strategies, and monitoring whether the confusion has been resolved. Planning, goal setting, strategy use, and metacognitive monitoring and control are all key features of models of self-regulating within the educational psychology literature (Puustinen & Pulkkinen, 2001). In this regard, similar to Pekrun's (2006) delineation of the role of activity emotions in self-regulated learning, we hypothesize that epistemic emotions should also be related to various phases of self-regulated learning. Indeed, recent empirical work supports this contention.

Specifically, research on epistemic emotions has shown that curiosity positively predicts the use of deep processing cognitive and metacognitive strategies, including metacognitive monitoring and evaluation of learning, as well as critical thinking and elaboration of content, whereas surprise negatively predicts critical thinking (Muis et al., accepted). D'Mello, Lehman, Pekrun, and Graesser (2014) found that confusion is beneficial for learning when that confusion can be resolved through the use of appropriate learning strategies. Despite these promising new lines of research, very little is known with regard to the antecedents and consequences of epistemic emotions, particularly with younger students. Moreover, with regard to self-regulated learning, the majority of research on achievement emotions has focused solely on the learning strategies that learners adopt during the enactment phase of self-regulated learning. To better understand the role that emotions play in self-regulated learning, a logical next step in this line of research is to examine whether emotions predict processes that occur across several phases of self-regulated learning (Muis, 2007). Our research addresses these gaps in the literature by extending research on academic emotions and their link to theoretical models of self-regulated learning. Specifically, the purpose of our research was to examine the role that epistemic emotions play in complex mathematics problem solving during various phases of self-regulated learning with a sample of elementary students. Prior to delineating our research questions and hypotheses, we first describe relevant theoretical frameworks and empirical work. We begin with Pekrun's (2006) control-value theory of achievement emotions.

1.1. *Pekrun's (2006) control-value theory of achievement emotions*

Pekrun (2006) proposed that the types of emotions individuals experience in an achievement setting depend on their perceptions of control (both action control and outcome control) as well as their value appraisals, both of which arise as a function of the environment (e.g., cognitive quality, motivational quality, goal structures, et cetera). That is, both control and value are considered important antecedents to the kinds of emotions individuals experience during an achievement situation. Control appraisals refer to the perceived controllability of the achievement-related actions and outcomes, whereas value refers to the subjective importance of the achievement-related activities and outcomes and include both intrinsic and extrinsic value (Pekrun et al., 2011). Perceptions of control and value are theorized to initiate different kinds of achievement emotions, both prospectively and retrospectively, as well as during learning. For example, for activity emotions (e.g., experienced during engagement in a learning task), when individuals perceive high levels of control and value for learning mathematics, they will experience enjoyment during mathematics problem solving. However, anger and frustration may arise during complex problem solving if individuals do not place much value on mathematics and the task demands are high, or they may experience anxiety when perceived value is high but control is low. Finally, boredom is experienced when individuals perceive low control and low value in contexts under which individuals are over-challenged.

1.1.1. Epistemic emotions

According to Graesser, Ozuru, and Sullins (2010), surprise, curiosity, and confusion are very likely to arise during complex learning tasks. For example, in cases of complex mathematics problem solving, individuals must first attempt to understand the problem, generate relevant prior knowledge, coordinate informational sources, make comparisons, and generate inferences to correctly solve the problem (Schoenfeld, 1985). At any point during these processes, discrepant events may arise that induce cognitive incongruity, which can entail obstacles to goals, impasses, or unexpected feedback such as an incorrect answer (Graesser, Lu, Olde, Cooper-Pye, & Whitten, 2005; VanLehn, Siler, Murray, Yamauchi, & Baggett, 2003). Indeed, within the mathematics education literature, researchers have documented the importance of productive struggle to facilitate students' understanding of mathematics (Brown, 1993; Hiebert & Grouws, 2007; Kapur, 2008; Kapur & Bielaczyc, 2012). They describe productive struggle as occurring in situations when students expend effort to make sense of a mathematics problem when the solution is not immediately apparent. Confusion arises when solving a problem that is within students' reach, but does not lead to extreme levels of frustration that may arise when a problem is too challenging. When confusion arises, students attempt to resolve this confusion to reduce cognitive dissonance (Festinger, 1957). As Brown (1993) argued, confusion is viewed as facilitating the process of understanding given that students must make mental connections among mathematical facts, ideas, and procedures to resolve the confusion to subsequently solve the problem.

As such, given the likely prevalence of these emotions during complex mathematics problem solving, research is needed to further explore under which conditions these emotions likely arise, and to establish the antecedents and consequences of these emotions when they do arise. Results from this initial foray into the role that epistemic emotions play during complex learning can then be used to develop learning environments that foster better learning outcomes.

1.1.2. Antecedents and consequences

What might be the antecedents and consequences of epistemic emotions? Drawing from the philosophical literature, Morton (2010) suggests that epistemic emotions arise when individuals attempt to acquire accurate beliefs (in the philosophical sense of a justified true belief). Individuals are curious when the answers to questions have practical importance to them. Certainly, individuals can engage in problem solving without being curious, but curiosity drives deeper engagement during problem solving. Take, for example, a problem that has important implications for the safety of many individuals (e.g., correctly designing a bridge that connects two cities), and several factors must be taken into consideration when solving the problem (e.g., wind, earthquakes, traffic volume). If it is important to the individual that a correct answer is achieved, that individual will be driven by curiosity to correctly solve the problem. In this situation, the individual is more likely to be vigilant while solving the problem, ensuring to understand the problem and its various components, generating relevant prior knowledge, coordinating informational sources, making comparisons, and generating inferences, which are considered deep processing strategies. The individual is also more likely to continually evaluate progress, and check answers against set goals, which are key metacognitive processes for successful problem solving (Jacobse & Harskamp, 2012). The importance placed on correctly solving the problem may also result in anxiety if issues arise when solving the problem, confusion or frustration if the issue cannot be resolved, or enjoyment if there is resolution. Moreover, if high value is placed on mathematics problem solving, but individuals perceive low control, they are more likely to experience higher levels of anxiety. Finally, given that surprise is considered a neutral emotion that is triggered in response to events during the learning task, neither control nor value is hypothesized to be antecedents to this emotion (surprise is considered a neutral activating emotion (Mauss & Robinson, 2009)).

With regard to consequences, a number of empirical studies have explored the role that emotions play during learning, and have found that emotions influence a wide range of cognitive and metacognitive processes, including attention, perception, social judgment, cognitive problem solving, decision making, and memory processes (see Pekrun & Linnenbrink-Garcia (2012) for a review). Given the relationship that researchers have found between emotions and learning strategies, Pekrun (2006) proposed that emotions predict the types of cognitive and metacognitive strategies individuals use during learning. Specifically, Pekrun proposed that positive activating emotions (curiosity, enjoyment) result in deep processing learning strategies, including generating inferences and metacognitive strategies (see Pekrun & Stephens, 2012, for a review of supporting evidence). In contrast, negative activating emotions (anxiety, frustration) result in shallow processing strategies such as rereading (Pekrun & Stephens, 2012), whereas confusion and surprise result in an increase in metacognitive strategies to reduce cognitive incongruity (Pekrun & Stephens, 2012). Negative deactivating emotions, such as boredom, can impair systematic use of learning strategies (Pekrun, Goetz, Daniels, Stupnisky, & Perry, 2010) and therefore result in reduced cognitive and metacognitive strategies. Finally, from a self-regulatory perspective (e.g., Muis, 2007), and drawing from Pekrun's (2006) model, use of deep learning strategies is theorized to have positive effects on learning outcomes, particularly with complex learning material. Several empirical studies support these hypotheses (e.g., Azevedo & Chauncey Strain, 2011; Azevedo et al., 2013; Murayama, Pekrun, Lichtenfeld, & vom Hofe, 2013; Pekrun et al., 2010, 2011).

1.1.3. Extending theoretical considerations

We further posit that the consequences of academic emotions need not be limited to the enactment phase of self-regulated learning. That is, as Muis (2007) proposed, emotions are activated during the task definition phase (the first phase) of self-regulated learning. Similar to most models of self-regulated learning (Puustinen & Pulkkinen, 2001), Muis (2007) proposed four phases of learning: 1) task definition, 2) planning and goal setting, 3) enactment, and 4) evaluation. In the first phase of learning, an individual constructs a perception of the task, which is influenced by external conditions, such as context, and internal conditions, such as prior knowledge, motivation, and emotions. During the second phase, components from the first phase influence the types of goals an individual sets for learning and the plans made for carrying out the task. The third phase begins when an individual carries out the task by enacting the chosen learning strategies. In the last phase, individuals evaluate the successes or failures of each phase or products created for the task, or perceptions about the self or context. Products created during learning are compared to the standards set via metacognitive monitoring. Key to the evaluation phase is metacognition, but metacognitive processes can occur during any phase of self-regulated learning, and individuals may cycle through any phase as learning progresses. This reflects the cyclical nature of her model. Accordingly, given that emotions are activated during the task definition phase of learning, we propose that emotions predict the plans and goals that students set for learning, the learning strategies students use (enactment phase), as well as the metacognitive processes used to monitor progress and evaluate products (evaluation phase) created during learning. In the next section, we focus specifically on empirical evidence of the consequences of epistemic emotions.

1.2. Empirical evidence of epistemic emotions

With a specific focus on epistemic emotions (e.g., curiosity, surprise, confusion), a few studies have explored the role they play in complex learning (e.g., Craig, Graesser, Sullins, & Gholson, 2004; D'Mello & Graesser, 2011; Graesser, Chipman, King, McDaniel, & D'Mello, 2007; Muis et al., accepted). For example, D'Mello et al. (2014) tested a theoretical model, which posits that confusion, triggered by cognitive conflict, can be beneficial for learning if appropriately induced, regulated and resolved. Confusion was experimentally induced via an animated agent that presented contradictory information, and participants were required to decide which opinion had more scientific merit. Results revealed that contradictions had no effect on learning when learners were not confused by the manipulations. However, when confusion did arise, participants' performance on multiple-choice and transfer tests was substantially higher than the control (no contradiction) condition.

Based on these results, D'Mello et al. (2014) argued that confusion is beneficial for learning when individuals are driven by the need to reduce that confusion. That is, once an impasse is detected, learners may engage in more effortful learning strategies to resolve the confusion (enactment phase), such as careful deliberation of the situation, evaluation of progress made (evaluation phase), or reconsideration of the problem space (task re-definition phase). However, D'Mello et al. (2014) also warned that not all confusion leads to greater learning gains. In the context of mathematics problem solving, a learner may become confused about the problem, make several unsuccessful attempts to resolve the issue, but not succeed. In this case, the individual may resort to shallow processing strategies given the limited cognitive resources available, which may then result in little learning gains.

In another study, D'Mello, Lehman, and Person (2010) measured the emotions students experienced during a series of effortful problem solving activities, and assessed whether various emotions predicted achievement outcomes. Forty-one undergraduate students solved challenging analytic reasoning problems, and emotions were measured at random and specific times throughout the problem-solving session. Results revealed the primary emotions that students experienced included curiosity, happiness, confusion, frustration, boredom, and anxiety. Moreover, curiosity was a positive predictor of problem solving performance, whereas frustration was a negative predictor of performance.

Given this set of studies, and those within the mathematics education literature (e.g., Kapur, 2008; Kapur & Kinzer, 2009), it appears that curiosity and confusion can be beneficial for complex learning tasks by driving deep processing cognitive and metacognitive strategies to resolve cognitive conflict that arises during learning. What is still unknown, however, is whether these relations extend to other phases of self-regulated learning and whether similar patterns would result with younger elementary students in authentic learning contexts. Specifically, to date, research on the role of confusion has been conducted solely with adolescent and adult samples. Given the important function of emotions in authentic educational contexts (see Pekrun, 2006), research is needed to assess the role epistemic emotions play during complex learning with younger students. As Butler and Winne (1995) and Zimmerman and Martinez-Pons (1990) noted, younger students are not very good at self-regulating their learning, nor are they necessarily accurate at judging how well they are carrying out a task. As such, in the face of an impasse during complex problem solving, it could be the case that younger students do not adjust their strategies, redefine the problem space, or implement deeper processing cognitive and metacognitive strategies to resolve conflict. Confusion that arises may result in the reduction of processing strategies altogether. Moreover, to date, research has not empirically investigated possible antecedents to curiosity, surprise and confusion, such as control and value, or whether confusion arises due to cognitive conflict regardless of students' perceptions of control and value for mathematics problem solving. We addressed these gaps in the literature.

2. The current study

As previously noted, during complex problem solving, confusion is likely to arise given that mathematics is inevitably coupled with making mistakes and recovering from those mistakes. Students may experience confusion when mistakes arise, or when they are not able to successfully solve one or more aspects of a complex problem. Curiosity may drive them to persist in the face of difficulty, to use more deep processing cognitive and metacognitive strategies to resolve issues, and ultimately successfully solving the problem. Alternatively, students may experience anxiety, frustration, and boredom when issues are not resolved, which may negatively affect subsequent learning processes and learning outcomes. As such, it is paramount for researchers to assess what the antecedents and consequences are with regard to epistemic emotions, and to academic emotions more generally, during complex mathematics problem solving.

Specifically, following Pekrun's (2006) control-value theory of achievement emotions, we sought to explore whether perceived value (intrinsic interest value, importance, and utility value) and control during mathematics problem solving were antecedents to students' epistemic and activity emotions during mathematics problem solving, and whether emotions predicted planning and goal setting (Phase 2), and actual use of shallow and deep cognitive strategies (Phase 3), as well as deep metacognitive strategies (Phase 4). We further explored whether learning processes mediated relations between control and value and achievement, or between emotions and achievement. Seventy-nine fifth grade elementary students participated, and were given a complex mathematics problem to solve over a period of several days. We targeted grade five students given that the provincially mandated mathematics curriculum includes multi-faceted complex mathematics problems that all students are required to complete and that count as a percentage of their final grades (30%).

We addressed the following research questions: (1) Are perceived control and value antecedents to students' epistemic and activity emotions? (2) Do epistemic/activity emotions mediate relations between control and value and achievement? (3) What is the relationship between epistemic/activity emotions and learning processes across three of the four phases of self-regulated learning during complex mathematics problem solving? (4) Do learning processes mediate relations between emotions and achievement? (5) Are learning processes predictors of mathematics problem solving achievement? Based on theoretical (Morton, 2010; Pekrun, 2006) and empirical considerations, we hypothesize that both perceived value and control will be significant predictors of students' epistemic and activity emotions. Specifically, value and control will both positively predict curiosity and negatively predict confusion. Additionally, coupled with low levels of control, higher value will predict higher levels of anxiety and frustration, whereas both high control and high value will predict enjoyment. In contrast, low levels of control and value will predict boredom. Finally, greater perceived control will predict higher levels of curiosity and lower levels of confusion. We further hypothesize that emotions would predict planning and goal setting (Phase 2), cognitive strategies employed during the enactment phase of self-regulated learning (Phase 3), as well as metacognitive strategies employed during the evaluation phase (Phase 4). Specifically, higher levels of curiosity, enjoyment, and confusion will positively predict use of plans and goals (or adjustments to plans and goals, given the cyclical nature of self-regulated learning), and deeper cognitive and metacognitive strategies, whereas surprise, anxiety and frustration will positively predict shallow

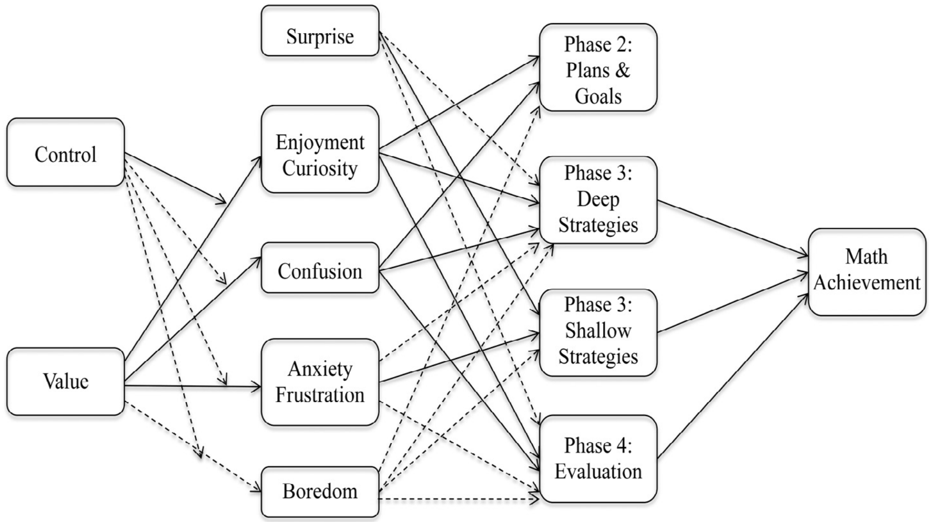

Fig. 1. Hypothesized model. Solid lines indicate positive relationships, whereas dotted lines denote negative relationships.

processing strategies and negatively predict deep processing cognitive and metacognitive strategies. Given that boredom results in disengagement in learning (Linnenbrink-Garcia & Pekrun, 2011), we hypothesize that boredom would negatively predict use of planning and goal setting, and cognitive and metacognitive learning strategies. Finally, we predict that deep processing cognitive and metacognitive strategies will result in higher levels of problem solving achievement, and will mediate relations between emotions and achievement. Our hypothesized model is presented in Fig. 1.

3. Methodology

3.1. Participants

Seventy-nine fifth-grade students (n = 34 females) from two different schools across four classrooms participated. All students were from the same school board. These two schools were chosen given their eclectic mix of low- through high-income families within each school and inclusion of approximately 30% of students on individualized education plans in each classroom. Variability in student characteristics allowed for a broader generalization of the results. There were 41 students (n = 20 females) from one school, and 38 (n = 14 females) students from the other school. The mean age of the sample was 11 years (*SD* = .31). All grade 5 students in both schools were invited to participate and 95% assented to participate (parental consent was also obtained).

3.2. Materials

3.2.1. Prior knowledge

Students' standardized achievement score on the 2013 compulsory provincial exam was used to obtain a measure of prior knowledge. The 2013 provincial exam was completed one week prior to the beginning of the research study (in the first week of April, which is the eighth month of the school year). Commencement of the research study was intentionally chosen to immediately follow the provincial exam to ensure a valid assessment of students' prior knowledge. The exam included a series of multiple-choice questions that assessed students' knowledge of the mathematics content covered over the school year. Reliability of the prior knowledge test was .94.

3.2.2. Global emotions about mathematics

To measure students' global emotions about mathematics, we used Pekrun, Lichtenfeld, Killi, and Reiss's (2007) Achievement Emotions Questionnaire (AEQ)—Elementary Version, which assesses students' enjoyment, boredom, and anxiety for mathematics class (12 items, e.g., "I enjoy math class"), mathematics homework (eight items, e.g., "Math homework bores me to death"), and mathematics tests (eight items, e.g., "I get very nervous during math tests"). Students rated each item on a 5-point scale ranging from "Not at all" (a rating of 1) to "very much" (a rating of 5). These emotions were used as a baseline measure of students' general emotions about mathematics prior to solving the problem and to ensure equivalence across schools. Cronbach's alpha reliability estimates for the three subscales were acceptable: .92 for enjoyment, .90 for boredom, and .72 for anxiety in class; .79 for enjoyment, .85 for boredom, and .70 for anxiety for homework; and, .86 for enjoyment and .88 for anxiety during tests.

3.2.3. Task value

Pekrun and Meier's (2011) Task Value Measure (adapted from Eccles, Wigfield, Harold, & Blumenfeld, 1993) was used to measure students' value for learning mathematics in general, as well as their perceptions specifically for mathematics problem solving. This seven-item Likert scale measures three dimensions of task value: intrinsic interest value (two items, e.g., "In general, I find learning about math very interesting"), importance (two items, e.g., "Learning more about math is very important"), and utility value (three items, e.g., "In general, learning about math is useful"). At four different time points, students rated each item on a 5-point scale ranging from "Not at all true of me" (a rating of 1) to "Very true of me" (a rating of 5). The first time (general context) was done two weeks prior to being given the mathematics problem. Students were instructed to think about mathematics in general (again, to assess similarity across schools). The second and subsequent times were conducted during each problem solving session. Students were instructed to respond to items based on their immediate experience of solving the mathematics problem. Because previous research has shown that younger students do not differentiate between the three types of value (see

Wigfield, 1994 for a complete review), all items were summed and averaged for an overall estimate of students' task[1] value for both general mathematics learning and specific to the problem-solving context for each of the three days. Higher values represent higher perceptions of task value. Cronbach's alpha reliability estimates were .88 for the general responses, and .88, .84, and .86 for each of the three days of mathematics problem solving specifically.

3.2.4. *Academic control*

To measure their perceived control (both action and outcome) for learning mathematics in general as well as specifically for mathematics problem solving, students completed Perry, Hladkyi, Pekrun, and Pelletier's (2001) Academic Control Scale, modified for elementary students, over four sessions. For the first session, two weeks prior to being given the problem to solve, students rated their level of agreement to each of the eight items, ranging from "Strongly disagree" (a rating of 1) to "Strongly agree" (a rating of 5). Sample items included, "I have a lot of control over my grades in math" and "The more effort I put into learning math, the better I do." Instructions for the first self-report session focused on mathematics in general. For the second and subsequent sessions, completed immediately following each day of problem solving, students were instructed to complete the scale with a specific focus on their perceptions of control during the problem solving session. Following previous research (Muis et al., accepted), all items were summed and averaged for an overall estimate of students' perceived control prior to (general context) and during problem solving (specific context). Higher values represent higher perceptions of control. Cronbach's alpha reliability estimates were acceptable at .75 for the general responses, and .71, .78, and .78 for each of the three days with a specific focus on mathematics problem solving.

3.2.5. *Epistemic and activity emotions*

The epistemic and activity emotions students experienced while solving the complex mathematics problem were measured using the Epistemic Emotions Scale (EES; Pekrun & Meier, 2011), adapted for elementary students (four items were removed from the original scale as elementary students would not likely understand their meaning, e.g., "muddled"). This 17-item self-report questionnaire is designed to measure three epistemic emotions and four activity emotions including curiosity (two items; e.g., interested), surprise (two items; e.g., shocked), confusion (two items; e.g., puzzled), and enjoyment (three items; e.g., joyful), anxiety (three items; e.g., nervous), frustration (two items; e.g., irritated), and boredom (two items; e.g., dull). Each item consisted of a single word describing one emotion (e.g., "excited"). Students were instructed to report the emotions they experienced when solving the mathematics problem. To assess emotions as they occurred during problem solving, students completed the scale at defined intervals across the three days of problem solving. All students completed the scales at the same time intervals (e.g., 10 minutes into problem solving, followed by 20, 30, 60 and 90 minutes). Students were asked to rate along a 5-point Likert scale how strongly they felt each of the emotions. Responses ranged from "Not at all" (a rating of 1) to "Very strong" (a rating of 5). Cronbach's alpha reliability estimates were within an acceptable range across each of the days, from .78 to .96. Specific values were as follows: surprise (.78 day one, .80 day two, and .79 for day three), curiosity (.87 day one, .83 day two, and .89 day three), enjoyment (.82 day one, .90 day two, .96 for day three), anxiety (.94 day 1, .89 day two, .78 day three), frustration (.80 day one, .84 day two, .79 day three), and boredom (.85 day one, .86 day two, .84 day three).

3.2.6. *Situational problem*

The situational problem, *Start Your Engines*, was drawn from the 2009 compulsory Quebec Exam in Mathematics. The objective is to have students develop a coherent solution to a situational problem that meets the following conditions: (1) the procedure required to solve the situational problem is not obvious, since it involves choosing a significant number of previously acquired mathematical concepts and processes and using them in a new way; (2) the situation focuses on obstacles to overcome, which requires various learning strategies; and, (3) the instructions do not suggest a procedure to be followed or the mathematical concepts and processes to be used (Ministère de l'Éducation, due Loisir et du Sport, 2009). For this particular problem, students had to: create a seven-sided polygon for the racetrack design that ranged in length between 4.5 km and 5 km; include at least one acute angle, one obtuse angle, and one angle greater than 180 degrees; create spectator areas with 15 squares per section to seat 120,000 spectators; draw a starting line frieze pattern that was one-third white, reflected twice; and, calculate the cost of the paint for the starting line.

3.3. *Procedure*

Parental consent and student assent were obtained, which included permission to participate in the study as well as permission to audio-record students' thought processes. Basic demographic data were also collected, which included students' gender, age, first language and other languages spoken at home. Following this, one week prior to giving students the complex mathematics problem, students completed the AEQ—Elementary Version (Pekrun, Lichtenfeld et al., 2007), followed by the Task Value Measure (Pekrun & Meier, 2011), and the Academic Control Scale (Perry et al., 2001) during regular class time. During regular class time, the first author explained to students how to respond to the items, provided definitions of the various emotions that students might experience, had students provide examples of what the various emotions might feel like to ensure they understood the qualifying words on the emotions scale, and then read all items for all questionnaires out loud to students. Then, one day prior to being given the mathematics problem, students were trained to think out loud. The students then heard a practice think-aloud audio file that modeled what not to do followed by an appropriate think out loud example. Finally, students practiced thinking out loud while completing the following mathematics problem, "Kim can walk three kilometers in one hour. How far can she walk in two and a half hours?" Students practiced for approximately 15 minutes.

The following day after think aloud training, students were given the problem to solve (again, during regular class time, which students were told counted toward their grade in mathematics). Students were told that the problem was to be treated as if it were an exam, and were not allowed to work together or copy each other's work during problem solving. As such, students were seated in such a way as to prevent them from cheating (barriers were used, which is normal practice for math tests and for other tests like spelling), and headsets were used to capture their think alouds, with microphones placed close to students' mouths. The decibel level in the room was sufficiently loud that students could not hear one another as they worked on the problem.

Students worked on the problem on consecutive days over three to four days for approximately 1.5 to 2 hours each day (the vast majority of students completed the problem within three days). To ensure all students were thinking out loud, five trained research assistants and the first author were present to prompt students to continue to think out loud if they were silent for more than five

[1] We also conducted three CFAs to assess whether the measurement model resulted in one, two, or three value factors. Our results confirm previous research wherein the one-factor model fit was best with this particular age group.

seconds (a ratio of approximately three to four students per prompter). Each day, students completed the task value and control measures with a specific focus on the mathematics problem they were attempting to solve. At predetermined time intervals as noted above, students then completed the Epistemic Emotions Scale (Pekrun & Meier, 2011) each day. Once students completed the problem (after several days), they submitted their work to the research team. To thank students for their participation, each student received a $15 iTunes card.

3.4. Coding and scoring

3.4.1. Self-regulatory processes

To capture students' self-regulatory processes, a concurrent think aloud protocol was used. Students wore Apple Ear Pods with remote and microphone to capture their voices on digital recording devices. Students' think alouds were then transcribed verbatim by four trained research assistants. Think alouds ranged in length from 90 minutes to 4.5 hours, which resulted in 1086 single-spaced pages of text (29,078 lines). Schoenfeld's (1982), Greene and Azevedo's (2009), and Muis's (2008) think aloud coding schemes and Muis's (2007) theoretical model of self-regulated learning were used as a guide to develop a micro-macro-level coding scheme specifically for mathematics problem solving. To develop the coding scheme, the two longest transcripts were selected. Each transcript was 34 single-spaced pages, for a total of 68 pages. The first author and five research assistants together spent four weeks analyzing the transcripts to identify the micro-level codes, which were then categorized into four macro-level processes based on Muis's (2007) model: task definition, planning and goal setting, enactment, and monitoring and evaluation.

Once these codes were established, the first author then selected three of the longest transcripts from each of the four classes, plus one of the shorter transcripts from each class to ensure comparability across length. The original two used to develop the coding scheme were included in the 16 transcripts chosen, which resulted in a total of 315 single-spaced pages of transcripts. The first author and five research assistants then spent an additional eight weeks working together to establish and modify the coding scheme, coding, and then recoding the transcripts until an acceptable level of inter-rater reliability was achieved. At the end of this process, inter-rater agreement was 85% for the 16 transcripts.

The first author and five research assistants then coded another four transcripts, one from each class, to ensure inter-rater reliability. Total page-length was 80 single-spaced pages. Inter-rater agreement was established at 82%, and disagreements were resolved through discussion. As such, 395 pages (37%) of the transcripts were coded to establish inter-rater reliability. The research assistants then coded the remaining transcriptions independently. Following this, frequencies of each of the strategies were examined, and strategies that occurred infrequently were removed from consideration (e.g., averages less than 3 over a 4.5 hour period). Following Greene and Azevedo's (2009) protocol, four macro variables were then created by summing each of the micro variables within that macro code: Phase 2—planning and goal setting, Phase 3—shallow cognitive strategies (e.g., coloring, rereading, calculating), Phase 3—deep cognitive strategies (e.g., summarizing, coordinating information sources, making inferences), and Phase 4—metacognitive strategies (e.g., monitoring, control, evaluation). See Table 1 for examples and definitions of each micro- and macro-level process.

3.4.2. Mathematics achievement

A rubric was developed to score each student's solution to the situational problem. Each element of the problem was given a particular value, and full points were awarded for successfully completing each element. Partial points were given when aspects were missing, or zero points were given if an element was completely missing or wrong. The total number of points was 50. The first and second author together coded 10 of the solutions to establish consistency in use of the rubric. Agreement was 100%. The two coders then coded 10 additional solutions independently to establish inter-rater agreement. Agreement was 100%. Given high inter-rater agreement, the second author then coded all remaining solutions. See the Appendix for the scoring rubric.

4. Results

4.1. Preliminary analyses

Skewness and kurtosis values were examined for normality for all variables. For kurtosis, all variables were within an acceptable range (using Tabachnick & Fidell, 2013 criteria of $<|3|$). For skewness, with the exception of plans and goal setting (5.29), variables were within an acceptable range. Given that plans and goals were calculated as an actual frequency with a meaningful zero point, scores were not transformed (see Tabachnick & Fidell, 2013).

Intraclass correlations were also examined for all variables across the two schools. All ICCs were less than .05. As such, nested analyses were not necessary. Collinearity diagnostics were also performed, and results revealed no multicollinearity.

We then examined whether there were gender differences across each of the variables. No gender differences were found for task value, control, or any of the global emotions, epistemic, or activity emotions (all $p > .10$). Gender differences were found, however, for prior knowledge, $F(1, 76) = 4.61$, $p < .05$, $\eta^2 = .06$, strategy use, $F(4, 72) = 9.98$, $p < .001$, $\eta^2 = .37$, and achievement, $F(1, 76) = 9.92$, $p < .01$, $\eta^2 = .12$, with girls scoring higher on all variables compared to boys. As such, prior knowledge was used as a covariate in all subsequent analyses. Moreover, to ensure level of specificity was equivalent across all variables and over time, students' task-specific value and control were used and were averaged across the three days of problem solving (no differences were found across each day for these two constructs). Similarly, for each epistemic and activity emotion, these were also averaged across the three days (again, due to no differences in these emotions across the three days, with the exception of confusion and anxiety, which significantly decreased over time [$F(2, 94) = 6.88$, $p < .01$, $\eta^2 = .13$, and $F(2, 94) = 3.52$, $p < .05$, $\eta^2 = .07$, respectively]. For self-regulatory strategies across the three phases of self-regulated learning, total frequency across the three days was used. Means and standard deviations of all variables averaged across the three days are presented in Table 2, and Table 3 presents the zero-order correlations.

4.2. Path analysis and mediation model

To test the mediation model presented in Fig. 1, we used Hayes and Preacher's (2013) MEDIATE SPSS macro, which is recommended with complex models and smaller sample sizes as it maintains higher levels of power while still controlling for Type I errors (see Preacher & Hayes, 2008). Although traditional path analytic approaches suffer from low power with small sample sizes (MacKinnon, Lockwood, Hoffman, West, & Sheets, 2002), this issue can be addressed by using a bootstrapping technique (Hayes & Preacher, 2013). The bootstrapping technique generates a sampling distribution of the effects by pretending the sample is a population, and then draws random resamples of size N with replacement a very large number of times (e.g., 10,000 times). This resampling of the original sample provides more precise estimates of the effects and yields far more power given the number of times the sample is resampled. The Monte Carlo method (Preacher & Selig, 2012) is then applied to estimate the path coefficients. Using

Table 1
Micro- and macro-level definitions, codes, and examples.

Phase (Macro)/Micro	Code	Definition	Examples
Phase 1—Task Definition		A learner generates a perception about the task, context, and the self in relation to the task. External and internal conditions play a major role.	Prior knowledge activation, beliefs, motivation, and knowledge of strategies are activated during this phase.
Prior Knowledge Activation	PKA	Searching for or explicitly recalling relevant prior knowledge.	[reading problem] "Your track must have at least one acute angle. I know what that is. It's an angle that is less than 90 degrees." [after reading that a reflex angle needs to be included in the diagram] "I know that means an angle that is greater than 180 degrees." "A reflex angle. That's more than 180 degrees." "5 km, which is short for kilometre."
Identifying Important Information	I^3	Recognizing the usefulness of information.	"So that will help us figure out how many people are in each row…"
Phase 2—Planning and Goal Setting		The learner begins to devise a plan to solve the problem and sets goals.	e.g., Planning to use means–ends analysis, trying trial and error, identifying which part of the problem to solve first, solving it within a specific amount of time.
Making/Restating a Plan	P/RP	Stating what approach will be taken, what strategy will be used to solve the problem, or what part of the problem will be solved in some sequence. This includes restating plans.	"First, I have to figure out how many are in each row, then I can figure out how many people fit in each row to fit 120,000 people." "Lets just do trial and error." "So now I'm going to draw it on paper and see if it's between 4.5 and 5 km." "So I'm going to start with the track." "Now I am going to write 'have to draw rectangle.' "
Setting/Restating a Goal	G/RG	A goal is modeled as a multifaceted profile of information, and each standard in the profile is used as a basis to compare the products created when engaged in the activity. This includes restating goals.	"We have to have an acute angle, obtuse angle and one reflex angle." "We have to label these angles too." "I don't want to spend too much time figuring out the track." [time goal] "So I need 2, and then 5." "I want to make sure my calculations are neat." "Then I have to reflect it twice."
Phase 3—Enactment		Enactment occurs when the learner begins to work on the task by applying tactics or strategies chosen for the task.	
Hypothesizing	HYP	Making predictions.	"The next one is probably going to tell us the information about the design." [in reference to the learner's track being large enough] "I think it is going to be enough."
Summarizing	SUM	Summarizing what was just read in the problem statement.	"Next, the spectator seating area must be divided into sections each section must have seats for 15,000 people. So there, each section has 15,000 people." "The starting line must be painted with a frieze pattern, this pattern is a rectangular design that has to be, that has been reflected twice, so it has to be reflected twice." "So you need to draw circles and write down the required information."
Help Seeking – info – eval	HS	Asking for help from a teacher, peer, or other source. Help seeking for information (info) VERSUS help seeking for evaluation (eval).	[turns to teacher and asks a question] "But what if my track isn't exactly 5 km?" "Mrs. [teacher's name], for the reflex angle would I do it on the outside or the inside?" "So we're supposed to do something like this?" "What are we supposed to do next?" "Is this correct?"
Coordinating Informational Sources	CIS	Using other sources of information to help solve the problem.	"Lets go back to our popplet." [Popplet includes the concept map, and learner is going back to the concept map he created to help solve the problem].
Phase 3—Enactment continued		Enactment occurs when the learner begins to work on the task by applying tactics or strategies chosen for the task.	
Highlighting/Labeling/Coloring/ Drawing/(Writing)	HLC	Highlighting information, labeling information as part of the problem-solving process, or taking notes in reference to the problem. Making a drawing to assist learning or as part of solving the problem	"We can put the starting line just like right there." [labeling] [you can hear the learner's pencil] "So its two sides, 2 sides, 3, kind of look like a good drawing [evaluating quality of drawing], 4." "Like that, like that and like that." "This is a reflex angle." "4 C-M."
Calculating/Measuring	CAL	Solving equations, measuring, or other similar features.	[adding up the sides] "10 so that's like 1 km plus 1 km and 400 meters…" "4.4 plus 3.1 plus…equals…" "I'm measuring the starting line."
Re-Reading	R-R	Re-reading a section of the problem, word for word. Important that it is word for word, otherwise it is summarizing.	"I'm just going to re-read this…"

(*continued on next page*)

Table 1 (*continued*)

Phase (Macro)/Micro	Code	Definition	Examples
Making Inferences	MI	Making inferences based on information read or products created from solving the problem. (self-explanation) Explaining why something was done. Key word is "because."	"So it doesn't say it has to be irregular or regular." "I'm just, I'm multiplying 18 by 6.25 [calculating] because there are 6.25 per white squares." [self-explanation]
Goal-directed search			"I'm looking for another thing that might be useful."
Phase 4—Monitoring and Evaluation		Various types of reactions and reflections are carried out to evaluate the successes or failures of each phase or products created for the task, or perceptions about the self or context. Reaction and reflection also includes judgments and evaluations of performance on a task as well as the attributions for success or failure.	Products created are compared to the standards set via metacognitive monitoring. Monitoring and evaluation can include any facet listed above (e.g., progress, motivation, plans, goals, strategies, products like answers or drawings made).
Self-Questioning	SQ	Posing a question.	"But how much is that?" "What is the most important thing?" "So how do we turn meters into km?"
Monitoring	MON	Monitoring something relative to goals.	"I'm not sure there is a reflex angle in my drawing. Let me check." "I might forget that each section must have seats for 15,000 people." [learner is counting the number of sides for the polygon] "So we have 1 side 2 side 3 side 4 side 5 side 6 side 7 sides."
Judgment of Learning	JOL	Learner is aware that something is unknown, not fully understood, or difficult to do.	"That would be an acute angle, which is kind of hard to draw, this is hard to draw." "I don't really understand this." "I'm not sure." "This is going to be very hard to figure out." "I need help with this one. I don't understand." "So, I don't know."
Phase 4—Monitoring and Evaluation continued		Various types of reactions and reflections are carried out to evaluate the successes or failures of each phase or products created for the task, or perceptions about the self or context. Reaction and reflection also includes judgments and evaluations of performance on a task as well as the attributions for success or failure.	Products created are compared to the standards set via metacognitive monitoring. Monitoring and evaluation can include any facet listed above (e.g., progress, motivation, plans, goals, strategies, products like answers or drawings made).
Self-Correcting	SC	Correcting one's mistakes.	"Here are 4 km. Not 4 km. Sorry, 400 meters." "So the first thing was the track had to be has to be a 4 sided [summarizing], not a 4 sided sorry a 7 sided polygon [self-correcting]." "Never mind, I'm not going to put that." "Oops, that was actually an obtuse angle."
Evaluation	EVAL	Judging whether goals have been met, whether a particular strategy is working, whether the answer is correct, whether the work is neat, etc. Judgment of all facets that fall under monitoring.	After counting the number of sides of the polygon, the learner states, "Yes, I have 7 sides. Okay, we're good." "I measured the wrong thing by accident." [after adding up the sides] "3 km, that's way too little." "That's not very neat."
Control	CON	Changing strategy when monitoring or evaluating results in a determination that goal has not been met.	[after judging that polygon was not 7-sided] "I'm just going to erase this. It has to be a 7-sided polygon so let's do a different one."
Task Difficulty	TD	Statements reflecting the difficulty or easiness of a task.	"This is difficult." "This is easy."

this approach, we implemented a moderated mediation analysis to assess our predicted relations. Prior knowledge was included as a covariate for all variables in the model. Control was included as a moderator between value and enjoyment, anxiety, frustration, and boredom. Mediation was tested as a two-step process to assess whether emotions mediated relations between control/value and mathematics achievement, and then whether strategies mediated relations between emotions and mathematics achievement.

The path model with statistically detectable standardized estimates is presented in Fig. 2. We first analyzed whether control moderated relations between value and enjoyment, anxiety, frustration, and boredom. No moderated effects were found. We then modeled all effects as direct or mediated. The total effects model for the first mediation analysis (control and value, emotions, achievement, with strategies and prior knowledge as covariates) was significant, $F(3, 75) = 11.30$, $p < .001$, $R^2 = .31$. For our first research question, whether control and value served as antecedents to epistemic and activity emotions, value was a positive predictor of curiosity (B = .39, $t = 3.25$, $p = .001$) and enjoyment (B = .53, $t = 4.91$, $p < .001$), and a negative predictor of confusion (B = –.30, $t = –2.57$, $p = .01$), anxiety (B = –.23, $t = –2.00$, $p < .05$), frustration (B = –.40, $t = –3.45$, $p < .01$), and boredom (B = –.36, $t = –2.97$, $p = .004$). Control was a negative predictor of confusion (B = –.23, $t = –1.99$, $p < .05$), and anxiety (B = –.35, $t = –3.05$, $p = .004$). We then examined whether emotions mediated relations between control and value and achievement (our second research question). Results revealed that confusion mediated relations between both value and control and mathematics achievement (t = 2.15, $p < .03$ t = 2.28, $p = .02$, respectively), with point estimates of –1.11 and bias corrected bootstrap confidence intervals (95%) of –.08 to –3.19 for value, and –.87 and bias corrected bootstrap confidence intervals (95%) of –.0006 to –3.14 for control.

Table 2
Means and standard deviations for all variables.

	Mean	Standard Deviation
Prior Knowledge	86.06%	12.38
Control[a]	4.06	.62
Value[a]	3.91	.70
Surprise[a]	2.63	1.16
Enjoyment[a]	3.71	.95
Curiosity[a]	3.12	1.13
Confusion[a]	2.59	.89
Anxiety[a]	2.00	.76
Frustration[a]	1.65	.72
Boredom[a]	1.95	.84
Planning and Goal Setting[b]	50.24	23.58
Shallow Cognitive Strategies[b]	36.23	10.44
Deep Cognitive Strategies[b]	88.28	31.77
Metacognitive Strategies[b]	57.41	21.19
Mathematics Achievement	84.67%	11.61

Note: Cog = cognitive.
[a] Average based on a Likert scale ranging from 1 to 5.
[b] In raw frequency.

For the next analysis (emotions predicting learning strategies predicting achievement, with prior knowledge, control and value as covariates; our third and fourth research questions), bias corrected bootstrap results for the total effects model were significant, $F(8, 70) = 4.36$, $p < .002$, $R^2 = .30$. For direct effects of emotions on learning strategies, curiosity positively predicted shallow cognitive strategies (B = .34, $t = 2.46$, $p = .01$) and metacognitive strategies (B = .31, t = 2.08, $p < .05$). Surprise was a negative predictor for planning and setting goals (B = −.28, $t = -2.00$, $p < .05$), shallow cognitive strategies (B = −.39, $t = -3.08$, $p = .003$), and deep cognitive strategies (B = −.33, $t = -2.56$, $p < .01$). Confusion was a negative predictor of shallow cognitive strategies (B = −.45, $t = -2.93$, $p < .01$) and deep cognitive strategies (B = −.28, $t = -1.98$, $p < .01$). Interestingly, enjoyment did not predict any processing strategies, whereas frustration positively predicted shallow cognitive strategies (B = .33, $t = 2.25$, $p = .02$). Anxiety also positively predicted use of shallow cognitive strategies (B = .27, t = 2.21, $p < .05$) as well as metacognitive strategies (B = .27, $t = 1.98$, $p < .05$). Boredom negatively predicted planning and goal setting (B = −.39, $t = -2.52$, $p = .01$), deep cognitive strategies (B = −.23, $t = -1.60$, $p < .05$), and metacognitive strategies (B = −.25, $t = -1.65$, $p < .05$). Finally, for our last research question, whether learning strategies predicted mathematics achievement, there were three significant positive predictors, which included use of shallow cognitive strategies (B = .25, $t = 2.01$, $p < .05$), deep cognitive strategies (B = .28, $t = 2.23$, $p < .05$), and metacognitive strategies (B = .29, $t = -2.50$, $p < .01$). For mediation, results revealed that shallow cognitive strategies, deep cognitive strategies, and metacognitive strategies mediated relations between both confusion and curiosity and mathematics achievement (t = 2.05, $p < .05$, t = 2.02, $p < .05$, and t = 1.99, $p < .05$ respectively).

5. Discussion

The purpose of this study was to explore the antecedents and consequences of epistemic and activity emotions during complex mathematics problem solving. Pekrun's (2006) control-value theory and philosophical considerations (Morton, 2010) served as the foundations from which to develop specific testable hypotheses. Elementary students were given a complex mathematics problem to solve over a period of several days. Students' perceived control and value for learning mathematics were examined as antecedents to these emotions, and use of planning and goal setting, shallow and deep cognitive strategies, as well as metacognitive strategies were examined as possible consequences to these emotions. With the exception of surprise, we predicted that both control and value would relate to students' emotions during problem solving. We also posited that higher levels of curiosity, enjoyment, and confusion would positively predict use of deep cognitive and metacognitive strategies, whereas surprise, anxiety, and frustration would positively predict shallow cognitive strategies and negatively predict deep cognitive and metacognitive strategies. We also hypothesized that boredom would negatively predict use of all learning strategies. Finally, we predicted that deep cognitive and metacognitive strategies would result in higher levels of problem solving achievement, and would mediate relations between emotions and achievement.

5.1. Antecedents

For our first research question, whether perceived control and value serve as antecedents to students' epistemic and activity emotions, results from path analyses revealed support for the majority of the hypothesized relations. As predicted, value was an important antecedent to curiosity and enjoyment, wherein the more students valued mathematics the more curiosity and enjoyment they experienced during problem solving. Conversely, the more students valued mathematics, the less likely they were to experience confusion, frustration, anxiety, and boredom. For perceived control, the more students felt in control of their learning and learning outcomes, the less likely they experienced confusion and anxiety.

These results provide support for Pekrun's (2006) control-value theory of achievement emotions, and are consistent with previous research on the antecedents of students' enjoyment (Buff,

Table 3
Correlations for all variables.

	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Control	.46**	−.15	.21	.19	−.38	−.22*	−.20	−.15	.29*	.33*	.24*	.29*	.14	.31**
2. Value		−.02	.39**	.48**	−.41**	−.24*	−.38**	−.35**	.04	.13	.15	.03	.10	.18
3. Surprise			.37**	.38**	.08	.33**	.02	−.27*	−.14	−.20	−.18	.03	−.09	−.23*
4. Curiosity				.56**	−.16	.18	−.09	−.34**	.06	.27*	.21	.27*	.10	.22*
5. Enjoyment					−.36**	−.17	−.42**	−.64**	.07	.12	.15	.04	.13	.24*
6. Confusion						.31**	.51**	.47**	.03	−.34**	−.26*	.06	−.03	−.25*
7. Anxiety							.41**	.15	.08	.28*	.30*	.27*	.08	.36**
8. Frustration								.30*	.10	.27*	.30*	.15	.05	.21
9. Boredom									−.23*	−.19	−.23*	−.24*	.09	.14
10. Plans/Goals										.54**	.46**	.71**	.16	.22*
11. Shallow Cog											.36**	.47**	.23*	.29*
12. Deep Cog												.49*	.24*	.35**
13. Metacognitive													.15	.27*
14. Prior Knowledge														.47**
15. Achievement														

* $p = .05$.
** $p < .01$.

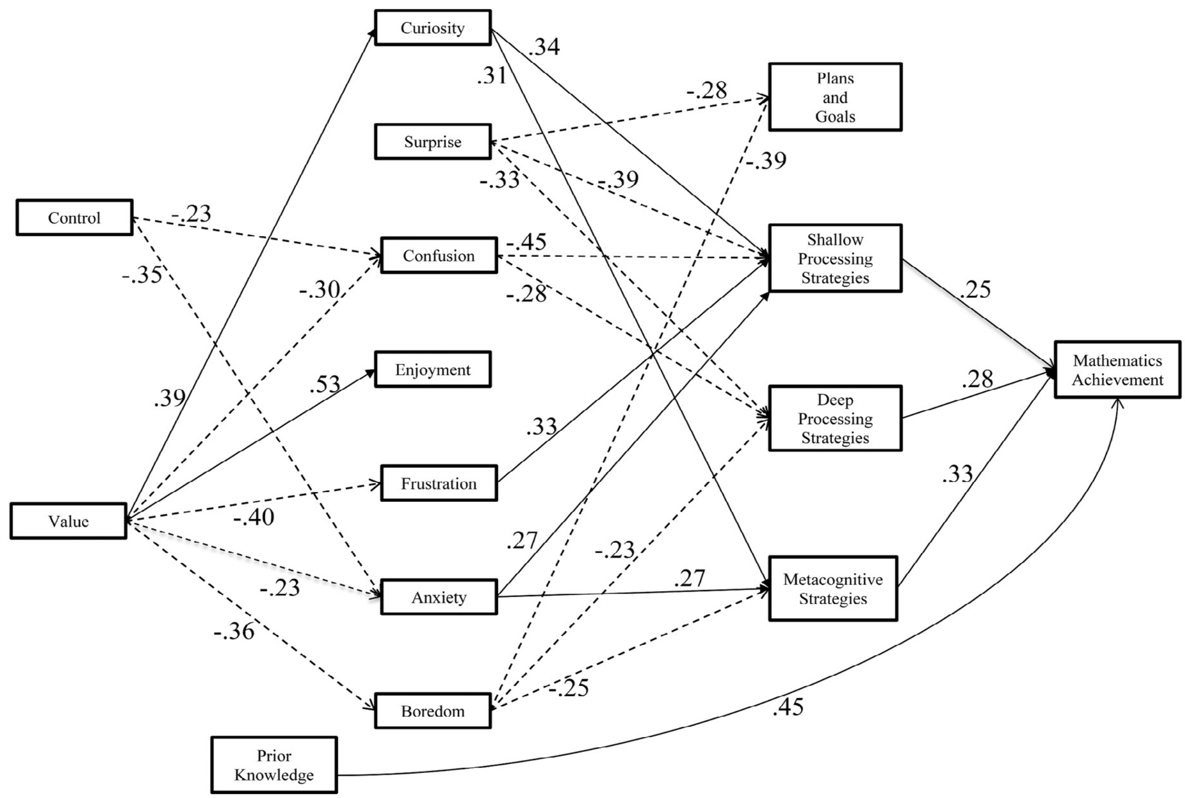

Fig. 2. Final path model.

2014; Buff, Reusser, Rakoczy, & Pauli, 2011; Pekrun, 2000), frustration, anxiety and boredom in mathematics (Dettmers et al., 2011; Frenzel, Pekrun, & Goetz, 2007). More importantly, our results provide initial empirical evidence with regard to plausible antecedents to the epistemic emotions that individuals experience during complex learning. Although philosophers have contemplated the role that importance (value) has on driving curiosity, our research provides evidence that value is a noteworthy antecedent. If students view mathematics as an important educational endeavor, they will more likely be curious about deriving a correct solution to a complex mathematics problem. As we elaborate below, this has important implications for learning when difficulties arise during problem solving. Interestingly, perceived control was a negative predictor of confusion and anxiety such that the more students felt they were in control of their learning and learning outcomes in mathematics, the less likely they were to experience confusion and anxiety during problem solving, which is consistent with previous research on anxiety and its antecedents (Frenzel et al., 2007).

5.2. Consequences

Our second research question addressed the consequences of epistemic and activity emotions during complex problem solving, and whether emotions were predictive of multiple phases of self-regulated learning. Results from our research suggest that emotions do predict processes carried out across multiple phases of self-regulated learning, including planning and goal setting, enactment, and evaluation. As such, our work extends theoretical considerations of the role that emotions play in self-regulated learning. Specifically, previous research on emotions focused solely on the enactment phase of self-regulated learning and did not take into consideration how emotions might relate to the plans and goals that individuals set for learning. Given that planning and goal setting is a key phase of self-regulated learning, particularly for mathematics problem solving (Muis, 2008; Schoenfeld, 1985), results from our study suggest this relationship cannot be ignored. Interventions designed to foster positive emotional experiences should consider the emotions that students initially experience during the task definition phase, and any changes made to task definitions as individuals progress on a task.

Additionally, results from our study also suggest that interventions need to be developed to foster curiosity and to equip students with the necessary skills to address impasses when they occur during complex learning. Specifically, with regard to the role that confusion plays in learning, although previous research with adult populations has shown that confusion can be beneficial for learning when appropriate learning strategies are adopted to resolve that confusion (D'Mello et al., 2014), we questioned whether this was also the case for younger populations who may not have the learning skills necessary to resolve that confusion (Butler & Winne, 1995; Zimmerman & Martinez-Pons, 1990). As such, we explored relations between epistemic/activity emotions and use of shallow cognitive strategies and deep cognitive and metacognitive strategies.

For confusion, results from our study support the concern that elementary students (at least our sample) do not have the necessary skills to resolve confusion when it arises during complex problem solving. Counter to previous research with adult samples (Craig et al., 2004; D'Mello & Graesser, 2011; D'Mello et al., 2014; Graesser et al., 2007; Muis et al., accepted), confusion negatively predicted use of shallow and deep cognitive strategies, and was unrelated to deep metacognitive strategies. Accordingly, when confusion did arise students did not increase their use of metacognitive strategies to reduce confusion. Rather, it appears that confusion in this context behaved more like boredom in that students reduced processing strategies altogether. This is consistent with D'Mello and

Graesser's (2012) results. They found that when confusion persisted and resolution was not achieved after a few attempts, students disengaged, and frustration and boredom ensued. Similarly, VanLehn et al. (2003) found that learners in their study acquired a physics principle in only half of the challenges. They argued that students failed to learn the other principles because they were not able to resolve the impasses. As D'Mello et al. (2014) suggest, it may be worthwhile to distinguish productive confusion from unproductive confusion.

However, drawing from the mathematics education literature, it could very well be that students who experienced confusion during this complex and ill-structured problem may have benefitted from that struggle when given a subsequent well-structured mathematics problem (see Kapur, 2008). That is, as research on productive struggle has found, when students struggle with an ill-structured problem initially, but then are provided support to help solve the problem or are given a subsequent well-structured problem, students outperform others who are not provided scaffolding or given an initial ill-structured problem. As such, future research should explore whether confusion during one complex problem-solving episode has implications for subsequent well-structured problem-solving episodes.

In contrast to confusion, consistent with our predictions and previous research (Muis et al., accepted), curiosity was a positive predictor of metacognitive strategies, but also predicted use of shallow cognitive strategies. We interpret these results to suggest that, in the face of a challenging task, curious individuals will more likely engage in monitoring and evaluation of their approaches to solving the problem, and change courses of action when resolutions to issues are not immediately achieved. That is, curiosity fosters better self-regulated learning. Counter to our predictions, however, curiosity also predicted shallow cognitive strategies. To explain this result, shallow cognitive strategies included behaviors such as rereading the problem statement, calculating distances, or coloring the spectator seating areas. Perhaps because of the complexity of the problem, curious students, who are concerned about acquiring the correct answer, wanted to be meticulous and ensure all aspects of the problem were addressed (Morton, 2010). As such, shallow cognitive strategies may have also been beneficial to achieve this, particularly in the context of mathematics problem solving, which requires these kinds of processing strategies like basic calculations (Schoenfeld, 1985).

Interestingly, students' experiences of surprise lead to a reduction in planning and goal setting, as well as shallow and deep cognitive strategies. Given these results, which are consistent with previous research (Muis et al., accepted), it is likely the case that surprise more often led to confusion rather than curiosity for our sample of students. The decrease in these strategies when surprise occurred paralleled relations between confusion and processing strategies. However, like confusion, it may be beneficial for future research to distinguish between surprise that leads to curiosity versus surprise that leads to confusion. Unfortunately, we did not measure emotions dynamically (e.g., as they occurred). As such, we recommend that future research explore dynamic relations between emotions and learning strategies. If surprise occurs, what emotion is likely to arise in the sequence? Do perceptions of value and control predict the likelihood of one emotion over another in these dynamic sequences? We also recommend that future research explore under what context these sequences of emotions occur. For example, what role does prior knowledge play in the activation of these various emotions? Are more knowledgeable students more likely to experience curiosity and less confusion compared to less knowledgeable students? Additionally, we did not measure reciprocal relations between emotions and self-regulatory processes. It may be the case that lack of planning and goal setting predicted higher levels of surprise, rather than the other way around. As such, future work is needed that explores possible reciprocal relations between emotions and self-regulatory strategies.

To our own surprise, enjoyment was not a significant predictor of any of the processing strategies, despite being the most reported emotion (followed by curiosity). We have no theoretical explanation for the lack of a relationship between enjoyment and any of the processing strategies. We speculate that perhaps the enjoyment that students experienced was a function of the novelty of being part of a research study. Although students reported enjoyment during the activity itself, the object of that emotion may not have been targeted at the process of problem solving but rather because of the researchers circulating the room and providing additional attention that they normally would not experience with only one teacher. Future research is necessary to clarify this lack of relationship.

Consistent with predictions, frustration was a positive predictor of shallow cognitive strategies. For frustration, its positive relationship to shallow cognitive strategies is consistent with Pekrun's (2006) control-value theory and research that supports it (see Pekrun & Stephens, 2012). Similarly, anxiety was a positive predictor of shallow cognitive strategies, but also of metacognitive strategies. As Pekrun et al. (2011) suggest, anxiety can undermine intrinsic motivation but can induce strong extrinsic motivation to invest effort to avoid failure. That is, students may be driven by the fear of failure given the high value they place on the activity and, when this occurs, implement strategies that will help them to succeed in problem solving. As such, students may have invested more effort in metacognitive strategies to ensure they correctly solved the problem, especially given the authentic nature of the task.

Additionally, consistent with our predictions, previous research (Acee & Weinstein, 2010; Pekrun et al., 2010, 2011) and Pekrun's (2006) control-value theory, boredom was a negative predictor of planning and goal setting, deep processing strategies as well as metacognitive strategies. As a negative deactivating emotion, boredom is clearly detrimental to learning, particularly when the learning activity is complex. If the complexity of the task drives students to boredom, they will less likely succeed in solving the problem. Given that deep cognitive and metacognitive strategies were positive predictors of students' problem solving achievement, it is imperative to design learning environments that reduce boredom or that can provide scaffolds for students when boredom arises to shift their learning strategies or regulate that boredom. As previous research in mathematics problem solving has shown, central to successful problem solving is employment of these kinds of deep cognitive and metacognitive strategies (Jacobse & Harskamp, 2012; Muis, 2008; Schoenfeld, 1985). Our results provide support for this.

5.3. Educational implications

Results from our study have important educational implications. First, given relations between control and value and the various epistemic and activity emotions, we recommend that teachers relay messages to students about the importance (value) of mathematics, and establish learning environments wherein students' perceived control is heightened. When students perceive mathematics as an important and useful endeavor, they are more likely to experience positive activating emotions and less likely to experience negative ones. Explicit messages that teachers convey can have powerful effects on students' beliefs (Muis & Foy, 2010). Additionally, students should be given meaningful and authentic problems to solve (Windschitl, 2002). By linking what they are learning to why it is important in the real-world context, students' beliefs about the value of mathematics may increase (Muis, 2004).

Finally, given the negative effects that confusion had in our study, it is imperative for teachers to relay the message to students that confusion is a normal emotion to experience. Students also need to be taught explicit strategies that help resolve confusion when it arises, and teacher support and modeling is critical to help foster these strategies (Zimmerman, 2000). In our study, few students engaged in help-seeking behaviors likely due to the exam-like nature of the task. Even though students were told to ask for help if needed, they rarely took the opportunity to seek guidance during problem solving. Future research is needed to delineate precisely what students were confused about. Perhaps scaffolding during these critical moments would result in productive confusion and students would persist in the face of challenge (Kapur & Bielaczyc, 2012). As such, students should be encouraged to seek help when needed, coupled with an important message that help seeking is not a sign of weakness. Although challenging for teachers, providing the right amount of scaffolding for students and fading that scaffolding over time is critical for the development of students' self-regulated learning (Zimmerman, 2000).

5.4. Conclusion

In conclusion, our research adds to the current literature on emotions and self-regulated learning. To our knowledge, our study is one of the first to explore both the antecedents and consequences of epistemic emotions during complex learning. Second, we broadened research on achievement emotions and their link to self-regulated learning by taking into consideration how emotions influence processes across three of the four phases of self-regulated learning. That is, as both Muis (2007) and Pekrun (2006) proposed, emotions are activated during the task definition phase of learning. Activation of these emotions may then influence planning and goal setting (the second phase of self-regulated learning), enactment of learning strategies (the third phase) as well as evaluative processes like monitoring, evaluation, and control of learning that occur during the fourth phase of self-regulated learning. Our results provide support for Muis's (2007) model, and have important implications for other models of self-regulated learning. Clearly, emotions are important to consider not only in terms of learning outcomes but also with regard to how they foster or hinder self-regulatory processes. Future research we plan will specifically target how to scaffold emotions in ways that foster better learning outcomes.

Our research is also unique in that it was carried out in an authentic classroom situation, and measured students' learning strategies as they occurred in real time. Given that much of the previous work in this area has relied on self-report measures of strategy use, our study also extends that work by incorporating trace data of students' actual learning strategies. To push the field forward, we recommend that future work measure emotions dynamically as they occur. Coupled with traces of learning strategies, researchers will be better equipped to assess whether certain emotions trigger specific strategies, how quickly students react to those emotions, and whether there are non-linear relations that need to be taken into consideration. We also recommend that future research take into consideration different contexts within which students could potentially solve these complex problems. For example, how might emotional experiences differ when students solve these problems in groups? What epistemic, activity, and social emotions might arise, and how might these emotions relate to co-regulated learning? We believe this will be a fruitful line of inquiry that we plan to explore in our future endeavors. Clearly, much more work is necessary before our curiosity is satisfied with regard to the nature of epistemic emotions and their role in complex learning tasks. Confusion may very well be a productive emotion, but students need to have the necessary skills to overcome that confusion in positive ways. Given that these skills can be modeled and taught to young students (MacArthur, 2011; Zimmerman & Labuhn, 2011), we believe there are promising avenues for future intervention research.

Appendix

	Your Mark	Total Mark
Racetrack design:		
7-sided polygon		**7**
perimeter between 4.5 km and 5 km		**4**
measures of each line segment (with ruler and label)		**4**
1 acute angle, 1 obtuse angle, and reflex (180°–360°) [have and label]		**6**
Identifies the starting line with an "S"		**1**
Spectator area:		
8 sections		**1**
letter identification for each section		**1**
15 squares per section		**1**
Starting line frieze pattern:		
rectangular design measuring 6 squares by 3 squares, reflected twice		**3**
1/3 white and 2/3 black		**3**
Starting line painting:		
costs 112.50 $		**1**
Calculations:		
50 cm represents **5000 m**		**3**
6 cm + 5 cm + 4 cm + 9 cm + 5 cm + 10 cm + 10 cm = **49 cm**		**3**
15 000 ÷ 1000 = **15** squares		**3**
120 000 ÷ 15 000 = **8** sections		**3**
(18 m × 3 m = 54 m^2) (1/3 × 54 m^2 = **18** m^2)		**3**
or 1/3 white squares, 6 squares white, 18 white squares total		
6.25 $/$m^2$ × 18 m^2 = **112.50 $**		**3**
Total:		**50**
Percent:		

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