Meta-affective behaviour within an intelligent tutoring system for mathematics

Genaro Rebolledo-Mendez[*] [*], N. Sofia Huerta-Pacheco[†], Ryan S. Baker[‡] and Benedict du Boulay[§]

g.rebolledo@tec.mx[*]; nshuerta@cienciaforense.facmed.unam.mx; rybaker@upenn.edu; b.du-boulay@sussex.ac.uk

[1] Tecnológico de Monterrey, Writing Lab, Institute for Future of Education, Monterrey, Nuevo León, 64849, México
https://orcid.org/0000-0002-3214-0935

[2]Consejo Nacional de Ciencia y Tecnología - Ciencia Forense, Facultad de Medicina, Universidad Nacional Autónoma de México, Ciudad de México, 04510, México
https://orcid.org/0000-0002-3642-4812

[3]Graduate School of Education, University of Pennsylvania, Philadelphia, PA 19104, United States of America

[4]Human-Centred Technology Research Group, Department of Informatics, University of Sussex, Brighton, BN1 9QJ UK

Abstract: Many previous studies have highlighted the influence of learners' affective states on learning with tutoring systems. However, the associations between learning and learners' meta-affective capability are still unclear. The goal of this paper is to analyse meta-affective capability and its influence on learning outcomes as well as the dynamics of affect over time. An exploratory study (n=54) was conducted in which students at the secondary level were asked to interact with an intelligent tutoring system for mathematics. Two criteria, awareness and self-regulation, were employed to define meta-affective capability, and students self-reported their affect during their interactions with the tutoring system. Pre-post learning outcomes were also measured. A post-hoc comparison of learning gains was made between more meta-affectively capable and less meta-affectively capable students. The results provide some empirical evidence to support the hypothesis that having meta-affective capability is positively associated with learning. Students not demonstrating meta-affective capability seemed to transition frequently from boredom to frustration (p=.0284) and from concentration to neutral (p=0.0017). However, only a small percentage of the sample were classified as having meta-affective capability, indicating that it is important to scaffold students who are not meta-affectively capable.

Keywords: Affect Dynamics, Meta-Affect, Educational Innovation, Educational Research, Affect, Intelligent Tutoring Systems, Mathematics.

1. Introduction

We all experience emotions, but some of us are more in touch with our own emotions and more able to control them than others. Emotion and affect (emotion in context) can have an important impact on learning (Craig, Graesser, Sullins, & Gholson, 2004; Lehman, et al., 2013; Shute, et al., 2015). For example, performance and end-of-year outcomes for students enrolled in secondary level mathematics are substantially affected by academic emotional experiences such as anxiety, anger, confusion, and boredom (Namkung, Peng, & Lin, 2019; Pardos, Baker, San Pedro, Gowda, & Gowda, 2014; Sutter-Brandenberger, Hagenauer, & Hascher, 2018). Negative emotions, a common experience during classroom learning (Sutter-Brandenberger, et al., 2018), have been highlighted as playing a role in reducing students' working memory (Ashcraft & Kirk, 2001) and, as a consequence, their performance. Positive emotions also appear to play an important role in secondary-level students' cognitive self-regulation in mathematics (Ahmed, Van der Werf, Kuyper, & Minnaert, 2013) and, for high-school and college students, in general (Ben-Eliyahu & Linnenbrink-Garcia, 2015). Furthermore, positive affect, along with personality factors and feelings of difficulty, can predict effort among primary mathematics students (Efklides et al., 2006). Dennis et al. (2015) present empirical evidence that emotionally charged feedback differentially impacts students with different

[*] Corresponding author.

types of personalities during learning. In aggregate, these findings highlight the importance of taking account of students' affect during the learning process.

In recent years, there has been considerable interest in developing intelligent tutoring systems that can recognize and respond to differences in student affect (D'Mello & Graesser, 2012; Harley, et al. 2017; DeFalco, et al., 2018) as effectively as they already respond to differences in student knowledge and cognition (Koedinger & Corbett, 2006).These systems attempt to identify negative affect (in particular) and to respond in ways that enhance both student affect and student learning. However, affect detection and responsiveness, can only, at best, enhance outcomes within the tutoring session and do not necessarily assist the learner in developing their own meta-affective capability. Ideally, these systems would develop learners' awareness of their own affect and improve their regulation of it (Richey, et al., 2019; Spann, Shute, Rahimi, & D'Mello, 2019), thus producing long-term learning benefits.

Goldin (2000) argues that learners, particularly in mathematics, should be helped to develop meta-affective insight, not just in recognizing their affective states in learning, such as frustration or pride, but also in recognizing and managing their meta-affective responses to these affective states. These meta-affective responses have both affective (e.g., wanting to escape frustration) and cognitive (e.g., being able to name both the original affect and its meta-affective reaction) components. He argues:

> "a curriculum in which affect is considered may include generating problems from the curiosity of students, in order to develop their sense that intense feelings are appropriate, and teaching them to apply heuristics when these feelings occur. Anxiety, fear, and despair (but not puzzlement, bewilderment, and frustration) maybe regarded as essentially undesirable affective states; yet we need to provide appropriate, domain-specific ways for students to handle the negative affect when it (inevitably) occurs.
>
> We also need to provide productive experiences with and uses of desirable affect, including the affect of frustration. Students should occasionally experience frustration--not too much, of course--and then be brought back from it, guided to make progress in the problem with processes suggested by the frustration, and feel subsequent pleasure, elation, and satisfaction that is heightened by the earlier experience of frustration. We give students too little experience with intensely positive affective states, rarely connecting them with their own, genuine mathematical achievements." (Goldin, 2000, page 217-8)

Goldin (2004) suggests that meta-affectivity is the process through which learners become aware of their emotions during learning and thereby create structures composed of both cognitive and affective elements that shape their reactions. In the case of learning mathematics, this process may occur maladaptively as follows: First, the student becomes aware of the difficulty of solving certain algebraic exercises. The student then becomes aware of the fact that she lacks the ability needed to solve this problem and becomes frustrated. The student becomes aware of her frustration and responds to this situation in the same way that she has responded to similar situations in the past. Believing that frustration only ever leads to boredom, the student does nothing to prevent herself becoming bored (Goldin, 2004). So the student becomes trapped in a cycle of frustration and boredom from which it is difficult to escape towards a more effective learning process (D'Mello & Graesser, 2012). DeBellis & Goldin (2006) propose that meta-affective mechanisms are of paramount importance during the process of learning mathematics. They suggest that the degree of learning depends on the learner's ability to recognize and regulate their potentially negative emotional reactions to the domain. D'Mello, Strain, Olney, and Graesser (2013) argued that:

> "Research is *conspicuously* absent on how the learners perceive the causes, consequences, and information value of each affect state [our emphasis]. The negative emotions are particularly in need of research. When a learner is frustrated from being stuck, the learner might attribute to either themselves ("I'm not at all good at physics") or to the tutor ("My tutor doesn't understand this either") or to the materials ("There are too many hyperlinks here to even begin to synthetize")." (D'Mello et al., 2013, p. 676).

The notion of "information value of each affect state" is based on the "Feelings-as-Information Theory" (Schwarz, 2012), which further explores the cognitive and affective aspects of meta-affect. Based on work by Gross (2008), D'Mello et al. (2013) develop Goldin's (2000) idea of a meta-affective curriculum by describing a number of emotion regulation strategies that learners can be taught to help them "avoid negative emotions and prolong positive emotions".

Some researchers have suggested that the development of these capabilities is related to cultural and environmental circumstances (DeBellis & Goldin, 2006; Moscucci, 2010). In their work, DeBellis & Goldin (2006) argue that the role of teachers in developing emotional awareness and regulation (meta-affect) is of particular importance for learning mathematics. Other researchers put the origin of meta-affective capability in the interplay between cognitive and affective capabilities (Hannula, 2001). There is compelling evidence of the effectiveness of emotional awareness and regulation (meta emotion) outside of mathematics, in association with elite athletes' performance. Some studies argue that the employment and purposeful increase of negative emotions leads to better performance (Lane, Beedie, Devonport, & Stanley, 2011). Along the same lines, further research suggests that not only do high performance athletes experience more negative emotions, but also explicitly regulating those negative emotions leads to decreased performance (Wagstaff, 2014). A different and more productive approach to emotional regulation in sport points to the positive effects of developing social situations and relationships to encourage emotional regulation (Friesen, et al., 2013). These findings merit further research to explore their replicability in educational settings mediated by technology.

Previous educational research provides evidence that both negative (i.e., boredom, frustration) and positive (i.e., confusion, engaged concentration/concentration/flow) affect relate to learning outcomes (Craig, et al., 2004; Pardos, et al., 2014). Confusion and frustration have had inconsistent relationships with learning outcomes across studies; some researchers have argued that these affective states may be associated with positive learning outcomes if they are brief and the cognitive difficulties that cause them are resolved, but they may be associated with negative learning outcomes if they are not eventually resolved (Lee, Rodrigo, Baker, Sugay, & Coronel, 2011; Liu, Pataranutaporn, Ocumpaugh, & Baker, 2013). Indeed, intentionally creating confusion through contradiction can, under specific conditions, improve learner outcomes (Lehman, D'Mello, & Graesser, 2012; Lehman, et al., 2013). Of the states mentioned, concentration can be considered positive in terms of valence, whereas frustration and boredom can be considered negative (Baker, D'Mello, Rodrigo, & Graesser, 2010). Confusion is somewhat more difficult to classify: It is thought to be mildly negative in terms of valence (Baker, et al., 2010), but it is also thought to be generally necessary for learning (D'Mello, Lehman, Pekrun, & Graesser, 2014; Lehman, et al., 2013). In that sense, it can be considered a positive affective state for learners to welcome, even if it is not always enjoyable. Despite these important findings, there is not yet empirical evidence of the extent to which meta-affect influences learning outcomes.

The current study presents an exploratory investigation into the role of meta-affect in learning with a tutoring system for mathematics. The overarching goal was to understand how meta-affectivity (i.e., awareness of and regulation of one's emotions) influences learning. The research questions guiding this investigation are:

RQ 1. To what extent does meta-affective capability enhance learning?

RQ 2. What are the affective dynamics associated with meta- and non-meta-affectively capable students?

RQ 3. How do different affective dynamics relate to learning?

These questions aim to help us understand the potential benefits of promoting meta-affective capability within educational technology. Evidence on the association between meta-affective capability and learning may have implications for re-designing purely cognitive-centred pedagogical models to include a broader context in which meta-affective capabilities are also recognized and scaffolded during learning.

Recognition of emotions during learning with tutoring systems remains an active research area. Conati & Gutica (2016) present some insights on when emotions are recognized by judges, and Harley et al. (2013) show that self-reports and video-based emotion detection have a 75% agreement rate. Our methodology for analyzing affective dynamics involves considering affective trajectories (i.e., individual series of self-reported affective states) as sequences. Sequence Analysis enables studying affective states based on the times in the learning process when they were expressed. By aggregating the affective dynamics seen across a cohort of students, we can better understand how an individual affect, such as frustration, emerges and changes. Sequence analysis complements prior work involving the L calculation, which has become a frequent methodology in this area and which requires calculating the normalized average transition probability between each pair of emotions in the data. The L metric (D'Mello & Graesser, 2012), however, only considers two-step shifts between affective states (i.e., from affective state A to affective state B), and recent work has raised concerns about its validity (see, e.g., Karumbaiah, Baker, et al. 2019). An alternate approach is to treat affect dynamics as sequences of arbitrary length. Work by Liu et al. (2013) analyzing three-step sequences associated with confusion and frustration finds statistically significant associations between sequences containing frustration and post-test scores but not between sequences containing frustration and learning gains. In a similar fashion, Andres et al. (2019) find a negative association between learning and sequences of affective states containing boredom. The sequences considered in this work were mostly binary, although two specific, theoretically-justified four-step sequences were also considered.

To deal with the negative issue of pre-determining sequence length, we utilize TraMineR (Gabadinho, Ritschard, Mueller, & Studer, 2011), a tool which enables us to consider a broader range of possible sequences using permutation formulas, based on the actual occurrence of sequences in the data.

The paper is organized as follows: In Section 2 we present the methodology for this study, Section 3 presents the results of the analyses, and Section 4 discusses the findings and offers conclusions.

2. Methodology

To understand the role of meta-affect during the use of an intelligent tutoring system, we collected data on learning, affect, affective awareness, and regulation in an exploratory study. Post-hoc, the students were divided into two groups on the basis of their meta-affective capability, and their learning gains were compared. We considered a set of four affective states in this study: boredom (BO), frustration (FR), confusion (CO) and concentration (CN), plus a neutral state (NE). These states have been reported as relevant during learning (Craig, Graesser, A., Sullins, J., & Gholson, B., 2004), and, consequently, much other work with intelligent tutoring systems has worked with this set (see discussion in Karumbaiah, Baker, & Ocumpaugh, 2019). While the ***L*** calculation (D'Mello & Graesser, 2012) is the most widely used formula to analyze affective dynamics, there has been recent argument that this approach may overestimate the probability of a transition under commonly occurring conditions (Karumbaiah, Baker, & Ocumpaugh, 2019). This overestimation produces apparent evidence that transitions occurring at chance frequency are statistically significantly more likely than chance, explaining the unexpected and confusing pattern reported by (Botelho et al., 2018), in which all transitions were simultaneously more likely than chance. This approach also can only consider single transitions between two affective states and is unable to detect more complex patterns.
Due to these limitations, we employed sequence analyses (Gabadinho, et al., 2011), using the TraMineR tool in specific, to analyse the affective dynamics. This tool calculates the possible number of permutations with repetition of n states, in sequences of length up to m, and provides statistics about the sequences identified in the data set.

2.1 Materials

The material resources used for carrying out the study comprised a technological tool (Intelligent Tutoring System), learning tests, a student preferences questionnaire, and a self-report sheet on affect.

2.1.1 Intelligent Tutoring System

The Intelligent Tutoring System (ITS) employed during the study was the scatter plot lesson of the Middle School Cognitive Tutor (Baker, Corbett, Koedinger, & Wagner, 2004), which was previously translated into Spanish for international comparative research (Ogan, et al., 2012). As with all Cognitive Tutors (Koedinger & Corbett, 2006), a student using this tutor completes multi-step mathematics problems where the problem-solving process is made visible, step by step. At each step, context-sensitive help is available on demand, and key errors that represent misconceptions receive “bug message” feedback that explains why the student was wrong. Other incorrect answers turn red. The student’s knowledge is tracked using an algorithm that infers a student’s knowledge of specific skills from their degree of correct usage on related mathematics problem-solving steps. This assessment of the student’s knowledge is communicated to the student and their teacher through “skill bars” in the interface. The scatter plot lesson takes the student through the process of creating and interpreting a scatter plot, including selecting variables, placing them on the correct axes, labeling the axes with values, plotting points, and answering questions about the relationships shown on each plot (Baker, Corbett, Koedinger, & Schneider, 2004). Each multi-step problem in the tutor is similar in complexity, enabling the system to track improvement in specific cognitive skills. This lesson has been found to be effective at promoting learning in studies in the USA (Baker, Corbett, Koedinger, & Schneider, 2004) and in Costa Rica and Mexico (Ogan, et al., 2012).

2.1.2 Learning Tests

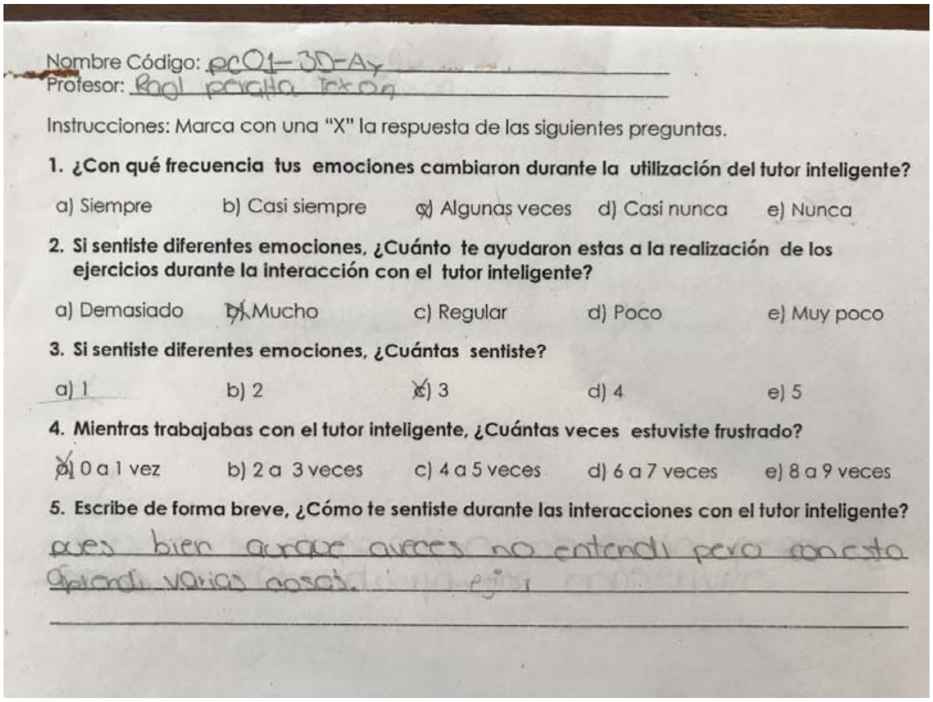
We employed learning tests used in previous evaluations of the same tutoring system (Baker, Corbett, Koedinger, & Schneider, 2004; Ogan, et al., 2012) although a formal evaluation of these tests has not been made. The test suite consists of two isomorphic tests (tests A and B), using the same questions with different cover stories. These tests were designed to assess the student’s ability to create a scatter plot and use it to interpret data. In addition to testing students’ learning regarding scatter plots, we obtained data on course grades given at the end of the academic year by their mathematics teacher (teacher’s mark on a 1-10 scale) and the students’ grades for mathematics on Mexico’s standardized learning ENLACE[**] test (on a 1–1000 scale), which is taken by all secondary school students in the country. Both grades were obtained at the end of the academic year in which the study took place.

2.1.3 Measuring meta-affect

For our study, the participants reported their affective states by selecting one from the four (plus the neutral state) pictorial representations of affective states of interest (Figure 1a). The participants also reported the influence of their emotions during learning with the tutoring system (Figure 1b). The presentation order for the affective states was randomized across pages (with eight pages in total, as the instrument was administered eight times during the study – see below) to facilitate reflection. Please note that the expression for Bored (BO) is a standard way of representing boredom in Mexico. It signifies a yawn.

FIGURE 1a. Booklet to self-report affective states

[**] http://www.enlace.sep.gob.mx/


Nombre Código:
Profesor:

Instrucciones: Marca con una "X" la respuesta de las siguientes preguntas.

1. ¿Con qué frecuencia tus emociones cambiaron durante la utilización del tutor inteligente?

a) Siempre b) Casi siempre c) Algunas veces d) Casi nunca e) Nunca

2. Si sentiste diferentes emociones, ¿Cuánto te ayudaron estas a la realización de los ejercicios durante la interacción con el tutor inteligente?

a) Demasiado b) Mucho c) Regular d) Poco e) Muy poco

3. Si sentiste diferentes emociones, ¿Cuántas sentiste?

a) 1 b) 2 c) 3 d) 4 e) 5

4. Mientras trabajabas con el tutor inteligente, ¿Cuántas veces estuviste frustrado?

a) 0 a 1 vez b) 2 a 3 veces c) 4 a 5 veces d) 6 a 7 veces e) 8 a 9 veces

5. Escribe de forma breve, ¿Cómo te sentiste durante las interacciones con el tutor inteligente?

pues bien aunque aveces no entendi pero con esto aprendi varias cosas.

FIGURE 1b. Learner retrospective self-report used to calculate meta-affective awareness

Our intention for this research was to measure not general affect, but rather students' meta-affective capabilities in context – that is, were they aware of their affect, and did they show regulation from negative to positive affect? To measure meta-affective capability, we measured students' awareness and self-regulation of their emotions.

To assess awareness, we employed a two-fold measurement. Question 3 in Figure 1b asked the student to report the number of different emotions she felt during the interaction. This answer was compared to the actual number of emotions they selected from the pictorial representations in Figure 1a. Similarly, question 4 asked the student to report the number of times she felt frustrated; this answer was compared to the actual number of frustration instances in the booklet. The student was considered "aware" if and only if both answers correctly (exactly) matched the actual instances from the booklet. Frustration was chosen because of this state's importance for student outcomes and overall affective experience (Goldin, 2004; D'Mello & Graesser, 2012; DeFalco et al., 2018). It is worth noting that when answering this question, students no longer had the booklet in which they had recorded their affective states and could not simply look up their self-recorded affective states to answer it.

The degree of affective regulation was measured by considering whether students self-reported boredom (BO) or frustration (FR) followed by confusion (CO), concentration (CN), or neutral (NE) affect, at least once. While this measure may have captured some natural variation in affect that could be more properly considered noise, on aggregate, students who made any negative to positive transition were more likely to have been using regulatory strategies compared to students who never made such a transition. Of course, a student who did not experience negative affect at any point would not be able to demonstrate affective regulation, so this proxy for self-regulation may have potentially undercounted the number of students who used other forms of affective self-regulation.

Note that we operationalized meta-affective capability as requiring both awareness and self-regulation of negative affect into positive affect. To support this claim, we postulate that meta-affect, much like meta-cognition (Flavell, 1979; Brown, 1978), can be defined as the knowledge about and regulation of one's affect during learning.

2.2 Participants

Sixty-four students in the ninth year at a secondary school in a suburban area of Mexico took part in the study. This sample consisted of students who spoke Spanish as a first language and had an Amerindian-Spanish background. Students attending this secondary school are from low- to middle-income families. The secondary school ranked approximately average in mathematics in Mexico's ENLACE standardized test for the year when the study took place, suggesting that the school is reasonably representative of students within this demographic in Mexico. The participants belonged to two classes (class D and class F) randomly selected from the ninth-year population of the secondary school and taught mathematics by the same teachers. Ten students were not included in the analyses because they did not have complete data. The average age of the participants was approximately 14 years old. IRB approval for this research was provided by the University of Veracruz and consent was given by the school's head teacher, as minimal risk was associated in conducting this research and the results are presented in the form of anonymized aggregates.

2.3 Procedure

The study comprised four sessions, each lasting 50 minutes and occurring at the same time as students would normally have mathematics class. In session one, the students were presented with an introductory lesson to the topic lasting 20 minutes. After the introductory lesson, the students had 30 minutes to complete the learning pre-test. Students were assigned pre-test form A if they had an odd number in the class register and test form B if they had an even number. At post-test, the participants completed test B if they completed test A at pre-test, and vice-versa. During sessions two and three, the participants interacted individually with the tutoring system; each interaction with the system lasted 40 minutes. This activity did not take place in the students' usual classroom but in the school's library, where computers were available. Students self-reported their affective state at the beginning of the first interaction and at different times during the two interactions. They received a prompt to "answer the booklet" described above every 10 minutes, for a total of eight affective self-assessments for each student. This relatively high duration between self-reports was chosen to avoid interrupting students so frequently that it would degrade their task performance or cause them to feel negative emotions. Given the possibility of affect changing multiple times between self-reports (cf. D'Mello & Graesser, 2011), students were asked in each self-report to report their *current* affective state ("Cómo me siento"/"How do I feel?"), as shown in Figure 1. At the end of the second interaction in session three, students returned their booklets and were given a new questionnaire (see Figure 1b) which they had 20 minutes to complete. During session four, the students answered one questionnaire in relation to the use of computers at home for 20 minutes and for the remaining 30 minutes, they were asked to solve the post-test. During the interactions, students were asked to work individually and keep silent, but they could ask questions of their mathematics teacher.

3. Results

RQ 1: To what extent does meta-affective capability enhance learning?

To assist answering this research question, we first computed different learning measurements (see Table 1 for descriptive statistics for mathematics performance). The data for the first four variables in Table 1 were obtained as explained in the procedure section. To calculate learning gains (LG), we normalized the measures; for students who performed worse on the post-test than the pre-test, or for whom a learning gain could not be calculated due to division by 0 (i.e., pre-test = 1.0), the LG was set to 0 to denote an absence of learning. We used the following formula:

$$LG = \frac{\text{Posttest} - \text{Pretest}}{1 - \text{Pretest}}$$

TABLE 1a: Descriptive statistics for mathematics performance

	n	Minimum	Maximum	Mean	Std. Deviation
Pre-test	54	0.00	1.00	0.1837	0.2202
Post-test	54	0.00	0.83	0.4415	0.2995
Teachers' marks	54	5.40	10.00	7.7070	1.6431
ENLACE	54	291.00	760.00	569.40	118.3862
Learning gains	54	0.00	0.83	0.3250	0.3142

TABLE 1b Correlation Matrix for learning variables

		Pre-test	Post-test	Teachers' marks	ENLACE	Learning gains
Pre-test	Pearson Correlation	1	.363**	.171	.099	-.196
	Sig. (2-tailed)		.007	.218	.477	.159
	N	54	54	54	54	53
Post-test	Pearson Correlation	.363**	1	.468**	.543**	.763**
	Sig. (2-tailed)	.007		.000	.000	.000
	N	54	54	54	54	53
Teachers' marks	Pearson Correlation	.171	.468**	1	.739**	.316*
	Sig. (2-tailed)	.218	.000		.000	.021
	N	54	54	54	54	53
ENLACE	Pearson Correlation	.099	.543**	.739**	1	.420**
	Sig. (2-tailed)	.477	.000	.000		.002
	N	54	54	54	54	53
Learning gains	Pearson Correlation	-.196	.763**	.316*	.420**	1
	Sig. (2-tailed)	.159	.000	.021	.002	
	N	53	53	53	53	53

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Overall, the three measures of learning were associated, in terms of Spearman's correlation: post-test and ENLACE *($r_s(52)= 0.53$, $p < .0001$),* LG and ENLACE *($r_s(52)= 0.52$, $p < .0001$)*, teachers' mark and ENLACE *($r_s(52)= 0.78$, $p < .0001$).* Please refer to table 1b for the correlation matrix for all learning variables.

To address our central research question, we identified meta-affectively capable students using two criteria: 1) "awareness of their affect", which we defined as correctly remembering the exact number of different emotions and also instances of frustration they had reported, and 2) "self-regulation of their affect", demonstrated by at least one instance of an affective transition from a negative (BO, FR) to a positive (CO, CN) or neutral (NE) state.

Table 2a presents the number of students, regardless of their designation as meta-affectively capable or not, in relation to different aspects of affective recall and change. Only 18.88% of students (n=10) had both awareness and regulation, and 33.33% (n=18) had neither. Students who were aware but not regulated accounted for 40.74% (n=22) of the sample, whereas students who were regulated but not aware accounted for 44.44% (n=24) of students. Students who were aware but not regulated (n=12) accounted for 22.22% of the sample and students who were regulated but not aware (n=14) accounted for 25.93% of students.

TABLE 2a: Number of students in relation to different aspects of affective recall and change

A. Number of students who experienced only negative affective states	0
B. Number of students who experienced only positive affective states	27
C. Number of students who experienced at least one negative state but no subsequent positive state (neutrals as subsequent are included in this count)	16
D. Number of students who experienced at least one negative state followed by a positive state	12
E. Number of students who correctly recalled the number of different affective states	26
F. Number of students who incorrectly recalled the number of different affective states	28
G. Number of students who correctly recalled how many instances of frustration they had experienced	39
H. Number of students who incorrectly recalled how many instances of frustration they had experienced	15

I. Number of meta-affective capable students: experienced at least one negative state followed by a neutral or positive state), correctly recalled the number of different affective state, and correctly recalled how many instances of frustration they had experienced	10

Row A of Table 2a indicates that no students went through the learning without experiencing any positive affective states. Row B shows that 27 students experienced only positive affective states and thus could not be considered meta-affectively capable by our definition, though one might argue that remaining positive throughout suggested some degree of meta-affective capability. Row F shows that nearly half of the students were unable to recall correctly the number of different affective states that they had experienced. Row H shows that roughly a quarter of the students were unable to recall correctly the number of instances of frustration that they had experienced. Row I shows the number of students who fell within our strict definition of meta-affectively capable.

Table 2b presents descriptive statistics for each of the two groups in terms of meta-affective capability. We found that 18.52% of students (*n*=10) met the criteria to be considered meta-affectively capable, whereas 81.48% did not (*n*=44).

TABLE 2b: Means and standard deviations by meta-affective capability

	Meta-affectively Capable	
	No (*n*=44)	Yes (*n*=10)
Pre-test	0.17 ± 0.20	0.23 ± 0.27
Post-test	0.39 ± 0.30	0.64 ± 0.19
Teachers' marks	7.72 ± 1.70	7.62 ± 1.43
ENLACE	558.20 ± 120.67	618.40 ± 98.38
Learning gains	0.27 ± 0.31	0.52 ± 0.20

A paired-samples Wilcoxon test showed that both groups of students (meta-affectively capable and not) had learning gains from using the tutoring system ($Z = 666$, $p < .00001$). There was a significant difference in learning gains between meta-affectively capable and non-meta-affectively capable learners *(U*=117.5, *p*=0.0189*)*, according to a Mann-Whitney test, *,* indicating that meta-affectively capable students had greater learning gains. This provides some empirical evidence that meta-affective capability does play an important role in learning. However, it is possible that only one of the two components of meta-affective capability was sufficient to produce better learning outcomes. For instance, the awareness component could be understood as having a generally better memory, and this component could be sufficient in itself to produce better learning outcomes. It might also have been harder for students who experienced a lot of frustration to remember the exact number of times this emotion occurred, compared to students who only experienced frustration infrequently. While we cannot discount memory as a factor, we note that memory may simply be a prerequisite to meta-affective awareness. It would be difficult for a student to be aware of their affect and to reason about it if they could not remember it.

Table 3 shows the descriptive statistics for the learning variables in relation to the two components of meta-affective capability. The results of analyses using the separate components of meta-affective capability show that students with awareness of which affective states they had experienced (but not self-regulation) earned significantly higher scores than other students on both the post-test *(U*=215.5, *p*=0.014*)* and ENLACE *(U*=171.5, *p*=0.001*)*, but earned equivalent marks from their teacher. By contrast, students who demonstrated self-regulation alone did not have higher performance on any measure than other students. Students who demonstrated ***both*** awareness and self-regulation had significantly better learning gains than students who demonstrated only awareness (*U*=29, *p*<0.044), from a two-tailed test comparing the two groups' learning gains directly. Please note that having both components was rare: Students who were meta-affectively capable (*n*=10) accounted for less than half of the 22 students in the Awareness group and of the 24 in the Self-regulation group. In other words, the results show that having both traits is related to increased learning gains.

TABLE 3: Descriptive statistics for variables of interest. Cells report n, mean and SD values

	Awareness only		Self-Regulation only	
	No (n=32)	Yes (n=22)	No (n=30)	Yes (n=24)
Pre -test	0.12 ± 0.09	0.27 ± 0.30	0.20 ± 0.24	0.16 ± 0.19
Post-test	0.36 ± 0.30	0.56 ± 0.24	0.43 ± 0.30	0.45 ± 0.29
Marks from teacher	7.37 ± 1.66	8.19 ± 1.51	7.95 ± 1.75	7.40 ± 1.47
ENLACE	528.69 ± 116.86	628.50 ± 95.01	581.43 ± 118.58	554.25 ± 118.90
Learning gains	0.27 ± 0.33	0.39 ± 0.26	0.30 ± 0.31	0.34 ± 0.32

RQ 2: What are the affective dynamics associated with meta- and non-meta-affectively capable students?

As discussed above, we considered individual affective trajectories as sequences and used TraMineR (Gabadinho et al., 2011) to analyze the affective dynamics. The total number of permutations possible for our data set, consisting of 5 affective states and 7 transitions (for 8 self-reports), is 78,125. Please note there are 7 transitions and not 8 because the first state is not preceded by any other state. TraMineR accounts for self-transitions by merging them into a single state; that is, the sequence CN-CN-CN-CN-FR is treated as CN-FR, identical to a sequence that is originally CN-CN-FR-FR. The results of our sequence analyses are presented as follows: 1) descriptive statistics about the sequences identified in the data set 2) identification of statistically significant sequences in our data set (testing for associations of states in time) for both meta and non-meta-affectively capable students and 3) typologies of sequences (groups of patterns that tend to co-occur within specific students) for meta-affectively and non-meta-affectively capable students' affective sequences.

We first examine how frequent each affective state was for each group of students during the 80 minutes of interaction (see Table 4). Frustration was statistically significantly more common among the meta-affectively capable students (U=115, p=0.02). No other affective state was statistically significantly more common for one group than the other.

Another way of presenting this information was provided by TraMineR in Figures 2 and 3, which show descriptive statistics for the affective sequences, separated by meta- and non-meta-affectively capable students.

TABLE 4: Percentage of affective states instances per Meta-affective class

	BO % (counts)	FR %(counts)	NE % (counts)	CO % (counts)	CN% (counts)
Non-meta-affectively capable	4.26 (15)	**5.40 (19)**	25.57 (90)	19.32 (68)	45.45 (160)
Meta-affectively capable	16.25 (13)	**16.25 (13)**	25.00 (20)	12.50 (10)	30.00 (24)
Total by affective State	6.48 (28)	**7.41 (32)**	25.46 (110)	18.05 (78)	42.60 (184)

Note: Affective states that are statistically significantly more common for one group than the other are marked in bold. The numbers in brackets are the total instances for that affective state.

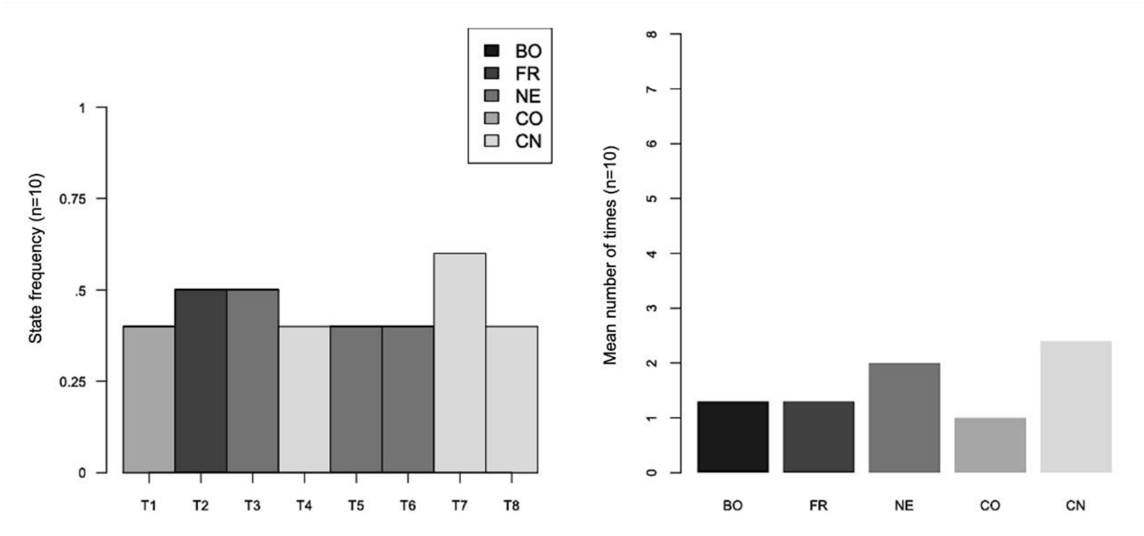


FIGURE 2: Frequencies of affective states for meta-affectively capable students

On the left-hand side of Figure 2, the results show the most frequent self-reports per time of measurement (T) for meta-affectively capable students (*n*=10). At times T3, T5, and T6, the neutral state is predominant, while at time T2, FR was the most common state, reported by half of these students. Towards the end of the interaction (T7 and T8), students had more instances of CN. On the right-hand side of Figure 2, we report the average number of times affective states are reported in the eight self-reports (T1... T8) issued by all students. The results show that, overall, meta-affectively capable students spent more time in neutral and positive affective states than in negative affective states, suggesting a more affectively balanced interaction as shown in Figure 2 and Table 4.

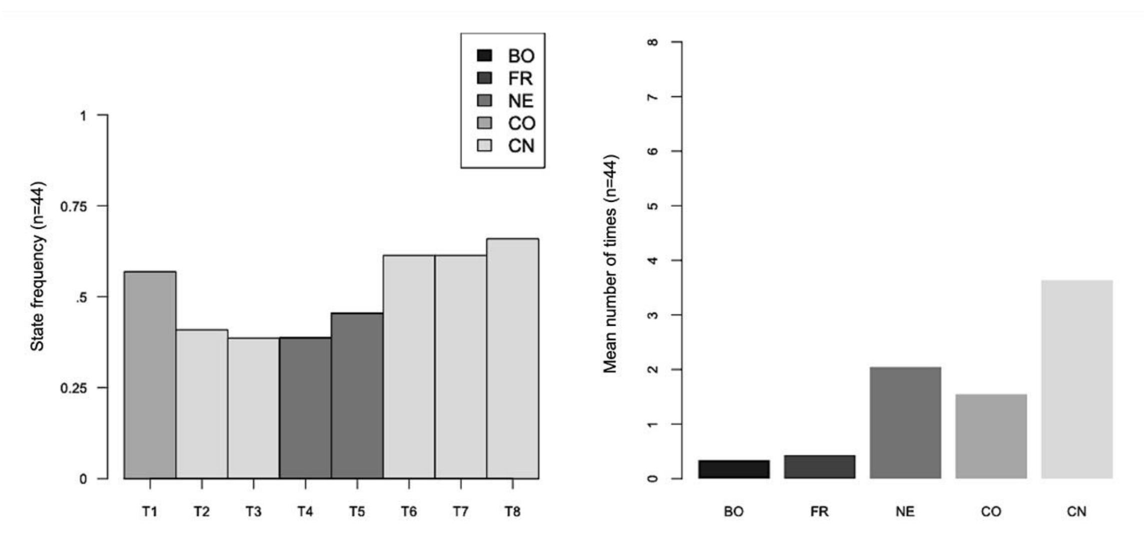


FIGURE 3: Frequencies of affective states for non-meta-affectively capable students

The left-hand side of Figure 3 shows the most frequent affective self-reports over time. Please note that non-meta-affectively capable students (*n*=44) had predominantly more self-reports of positive affect stemming from CO and CN, accounting for 60 minutes out of 80 (T1, T2, T3, T6, T7 and T8). CO is the most frequent at the beginning of the interaction, while CN and NE became predominant for the rest of the interaction. Across the eight self-reports, students show a clear tendency to report positive and neutral affect and not negative affective states (see the right-hand side of Figure 3).

We next consider frequencies of *sequences* of affect using TraMineR. This R package makes it possible to identify the most frequent sequences in the data set. This information is useful to understand which were the most representative transitions for meta-affectively and non-meta-affectively capable students. Please remember TraMineR does not only consider transitions from one state to one other state but all possible transitions following the permutation formula. No transitions occured significantly more than chance for meta-affectively capable students. It is surprising that the frequency of transitions from negative to positive affective states was not significantly higher than chance for this group, given that a student needed to have at least one transition from a negative to a positive state (self-regulation of affect) to be classified as meta-affectively capable.

RQ 3: How do different affective dynamics relate to learning?

Another possibility for understanding the dynamics of affect is to generate typologies, that is, patterns that tend to reoccur in the same student. Because non-meta-affectively capable students had tendencies in their behavior (Figure 3), we used unsupervised clustering (optimal matching distances by the Ward method) to discover typologies that could be used to discriminate patterns of affect. The results for the non-meta-affectively capable group are presented below. Because meta-affectively capable students were a small cohort (*n*=10), we chose to examine behaviours across only the non-meta-affectively capable students, to highlight differences in affective behaviour within that group. These analyses provide information regarding our third research question. We begin by showing that there were three typologies that represented different patterns of affective behaviour in non-meta-affectively capable students. Figure 4 shows the frequency of affective states (Y axis) over time (X axis), considering each self-report.

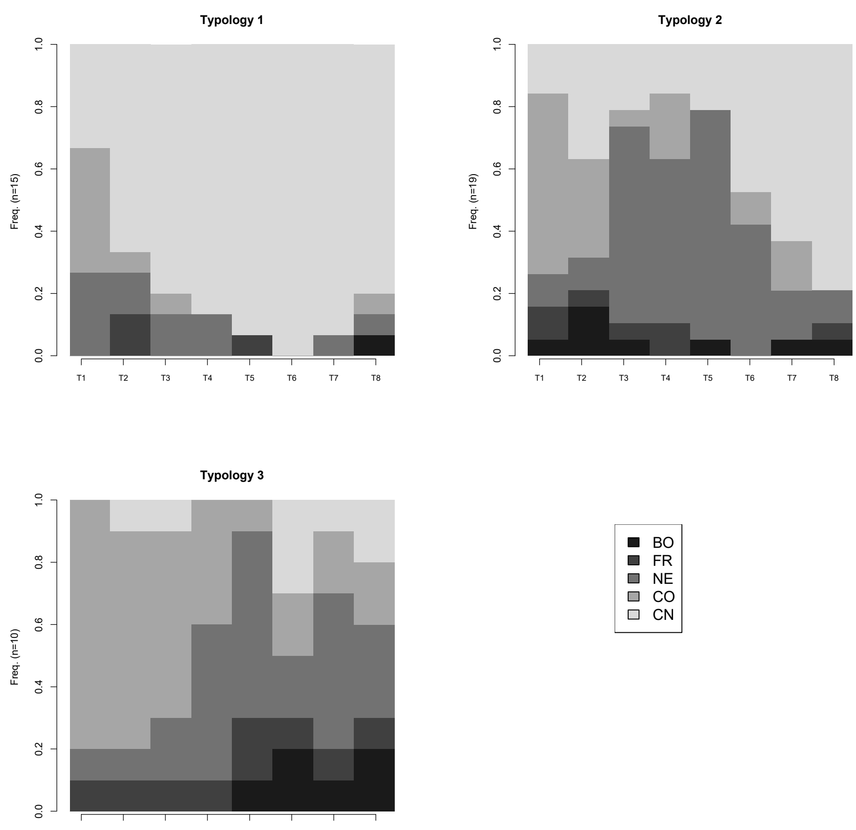


FIGURE 4: Frequencies of affective states for each typology of non-meta affective aware students.

Non meta-affectively capable students did have transitions that occurred more than would be predicted by chance, unlike meta-affectively capable students. Instead of analyzing transitions from one state to another, TraMineR can look into sequences of transitions or events and determine statistically significant events from all events in the sample. Table 5 shows the five most frequent events and transitions for the three typologies of non-meta affectively capable students, considering all possible events in the sample (n=1027). The second event in the table, for example, corresponds to a sequence of CO transitioning into a sequence of CO followed by NE. The third event in the table, boredom to frustration, is meaningful for non-meta affectively capable students. We hypothesize that the behaviour seen in this transition reflects the fact that students are not aware of their boredom and become frustrated, because they are unable to regulate the boredom and may instead blame the activity. By contrast, students who are more meta-affectively capable would understand that they are bored and either remain bored or transition to a positive affective state. By far, the most frequent event for these students was (NE>CN). How these behaviors relate to learning is given in Table 6, which shows pre- and post-test scores by each typology.

TABLE 5: Significant affective events for non-meta affectively aware students

Events	Counts	*p*	Typology
(CO>NE)	19	0.0017	3
(CO)-(CO>NE)	16	0.0043	3
(BO>FR)	2	0.0284	3
(CO>NE)-(NE>CN)	13	0.0356	2
(NE>CN)	28	0.0373	2

Note. Table showing counts (total events = 1027) and p-values less than 0.05

FIGURE 4: Typologies of affective behaviours for non-meta-affectively capable students

TABLE 6: Averages and standard deviations (M ± SD) achievement by typologies for non-meta-affectively capable students

	n	*Pre-test*	*Post-test*	*p*
Typology 1	15	0.21 ± 0.30	0.52 ± 0.25	0.0096 **
Typology 2	19	0.15 ± 0.16	0.35 ± 0.33	0.0090 **
Typology 3	10	0.15 ± 0.05	0.26 ± 0.22	0.0889

Note. *p < 0.05, ** p < 0.01, *** p < 0.001

Typology 1 students reported a greater proportion of concentration and were found to have a significant learning gain. Typology 2 students had significant affective transitions involving the neutral state, such as CO>NE and NE>CN, and spent more of their time in the concentrating and neutral affective states. They too had significant learning gains. Finally, Typology 3 students spent more time being confused and tended to transition from confused to neutral or from bored to frustrated. In this group, students did not demonstrate learning gains: Their pre-test and post-test scores were not significantly different, though there was the appearance of a positive trend.

The percentages of each affective state according to the typology of non-meta-affectively capable students are shown in Table 7, and the frequencies for the top five significant transitions associated with each typology are shown in Table 8.

TABLE 7: Percentage of affective states per non-meta-affectively capable typologies

	BO	FR	NE	CO	CN
Typology 1	0.83 (1)	2.50 (3)	10.00 (12)	7.50 (9)	**79.17 (95)**

Typology 2	5.26 (8)	4.61 (7)	**34.87 (53)**	17.76 (27)	**37.50 (57)**
Typology 3	7.50 (6)	11.25 (9)	**31.25 (25)**	**40.00 (32)**	10.00 (8)
Total by typology	4.25 (15)	5.40 (19)	25.57 (90)	19.32 (68)	45.45 (160)

Note. The highest values are marked in bold

TABLE 8: Significant affective transitions for non-meta-affectively capable students

Subsequence	*p*	Statistic	Typology 1 (Freq)	Typology 2 (Freq)	Typology 3 (Freq)
(CO>NE)	0.0016	12.75	0.06	0.57	**0.70**
(CO)-(CO>NE)	0.0043	10.87	0.06	0.42	**0.70**
(BO>FR)	0.0283	7.12	0.00	0.00	**0.20**
(CO>NE)-(NE>CN)	0.0355	6.67	0.06	**0.47**	0.30
(NE>CN)	0.0372	6.57	0.53	**0.84**	0.40

Note. Table showing p-values lesser than 0.05 and the highest frequencies were marked in bold

4. Discussion and Conclusions

In this paper, we study the relationship between meta-affect, students' knowledge about their affect, and their transitions in affect over time. In this research, meta-affective capability has been conceptualized as the student's ability to 1) be aware of their affective responses and 2) regulate their negative affect. To determine the degree of affective regulation, we looked for evidence of at least one affective transition from a negatively to a positively valenced affect. Awareness of affective responses was measured by comparing students' in-the-moment self-reports to their retrospective self-reports. Our strict definition of meta-affective capability excluded students who experienced positive affect throughout the experiment, as they were by definition unable to make an explicit transition from negative to positive. Future work might explore the value of studying a definition of meta-affective capability that includes such students. Our definition also excluded students who experienced only negative affective states; this seems broadly sensible, since a student who is consistently experiencing negative affect is probably not regulating their affect successfully. The fact that students did relatively poorly at recalling the number of different affective states that they had experienced as well as the number of instances of frustration suggests that there might be some leeway allowed in the *awareness* aspect of the definition of meta-affective capability.

There were limitations that it may be beneficial for future studies to address. The most important was sample size, as this exploratory study employed a relatively small convenience sample. Given the small sample size, the cultural expression of affect used, and the exploratory nature of this study, more research is needed to determine how broadly this result generalizes. Future studies should include bigger cohorts in order to validate the results. By broadening the samples to include students at different ages, at different schools with different demographic representation, and, eventually, in other cultural contexts, we can more fully understand the scope of the findings presented here.

Another limitation was the limited number of affective data points collected during the study and the time gap between self-reports. In our study, students only reflected on their affect when prompted to do so every 10 minutes. This time gap was imposed by our self-report methodology in order to avoid disrupting the learning task or annoying students and changing their affect, but it likely added noise to our estimates of affect and affective sequences. With current technologies, it would be feasible to use automatic detection of affect by training machine learning algorithms (i.e., Pardos et al., 2014; DeFalco et al., 2018; Andres et al., 2019; Richey et al., 2019) and increasing the granularity of the sample for studying affective sequences (e.g., Botelho et al., 2018). Systematically monitoring for affect using current technologies will provide a larger data set for doing similar studies and will avoid the limitations imposed using a real-time, self-report methodology. Finally, the use of automated detection of affect might also reduce the potential for bias inherent in self-report measures. Ideally, a study would incorporate both self-report and automated measures of affect to enable triangulation of findings. There is also a case to be made for adjustments to the method of determining the degree of meta-affective regulation, for example, weakening the constraint that students had to later recall the *exact number of reports of frustration* and strengthening the constraint that *only a single instance* of a transition for a negative to a positive affective state was needed. However, in both cases it may then become difficult to find a justifiable alternative cut-off.

While we acknowledge that the participant numbers were small, the principal finding of this research was that meta-affectively capable students tended to fluctuate between negative and positive states throughout the interaction, displaying more varied and balanced affective dynamics than non-meta-affectively capable students. Non-meta-affectively capable students, by contrast, had characteristic typologies and transitions between affective states associated with those typologies, including a typology with characteristic transitions from boredom to frustration, the opposite of the pattern hypothesized by D'Mello & Graesser (2012). Notably, none of the transitions hypothesized in that paper's prominent model were particularly common in any of the typologies or among the meta-affectively capable students (see discussion in Karumbaiah et al., 2019).

Meta-affectively capable students also had statistically significantly higher learning gains than non-meta-affectively capable students, gaining almost double as much, despite starting off with higher performance. However, we also found that even students who did not display meta-affective capability had statistically significant learning gains.

The results of this paper are interesting for several reasons. First, we found empirical evidence that meta-affectively capable students are able to self-regulate affect, perhaps as a main strategy for overcoming negative affective states during the learning process, as theorized by DeBellis & Goldin (2006). This does not mean that meta-affectively capable students have more positive affect overall; in fact, if anything meta-affectively capable students appeared to experience more boredom and frustration than non-meta-affectively capable students. Instead, we found that meta-affectively capable students did not appear to have characteristic transitions between affective states, unlike the non-meta-affectively capable students. However, this may be an artifact of the small size of the meta-affectively capable group (n=10). It might be inferred, then, that meta-affectively capable students successfully employed emotional self-regulation without being prompted. Previous studies have highlighted the relationships between negative affect and learning, particularly for mathematics (Kim, Park, & Cozart, 2014; DeFalco et al., 2018); our results also suggest there is value in negative affect, particularly FR, as long as the student is self-regulating (as in our study). Similar benefits could potentially be obtained if the student is prompted to employ self-regulating techniques similar to those described in Spann, et al. (2019).

Second, by analyzing the affective dynamics using sequence analyses, we found evidence of the different ways that affect emerges among non-meta-affectively capable students, a counterpoint to the considerable amount of work assuming a single dynamic of affect (e.g., D'Mello & Graesser, 2012; Rodrigo et al., 2012; Karumbaiah et al., 2019). The learning results suggested that there are three distinctive affective patterns among non-meta-affectively capable students, resulting in different learning outcomes; however, again, caution is needed because of the small size of this group (n=44). Typology 1 students showed a greater proportion of concentration and learning gains. Typology 2 students showed transitions involving the neutral state and learning gains. Typology 3 students spent more time being confused and tended to transition from confused to neutral or from bored to frustrated (the opposite of the transition posited in D'Mello & Graesser, 2012). In this last group, students did not demonstrate learning gains. We suggest that scaffolding strategies, such as the use of erroneous examples or cognitive reappraisal, may be useful as self-regulation strategies for non-meta-affectively capable students, as previous evidence shows these strategies can be successful at mitigating the effects of negative affect (Richey et al., 2019; Spann, et al., 2019). For instance, the use of erroneous examples – such as attributing an incorrect response to another (fictional) student rather than the student themselves – gives students an opportunity to understand and self-explain their mistakes, while avoiding the threat associated with having to correct mistakes attributed to oneself. Such a strategy may help to avoid the negative affect that a non-meta-affectively capable student might experience. Another approach for avoiding negative affect that a student who is not meta-affectively capable may deal with is the use of cognitive reappraisal strategies. In using a cognitive reappraisal strategy, a student may be encouraged to think differently about difficulty, for instance, considering it a challenge that they can and will surpass rather than as evidence of their lack of ability (cf. Mrazek et al., 2018). Another possibility, presented by Tzohar-Rozen & Kramarski (2017), is to explicitly train students in affective self-regulation. By helping students to better understand and regulate their negative affect – knowing how they are feeling, why they feel that way, and when it is appropriate to attempt to improve their affect – we may produce benefits for students that are durable and general.

While negative affect is a natural part of learning and may even be important for successful learning (Lehman et al. 2013; Spann et al., 2019), we argue that meta-affective capabilities play a significant role in learning. In particular, our findings suggest that meta-affective capability may shape behaviours that prevent students from staying in negative sequences of affective states (i.e., BO>FR), even if meta-affective capability does not produce overwhelmingly positive affect either. The inclusion of measurement and scaffolding at the meta-affective level will provide a platform to study why some students possess meta-affective capabilities and how they disrupt negative cycles associated with negative affect – ultimately helping us to design AIED systems that help students better understand and regulate their affect and improve their learning.

Acknowledgements

The first author acknowledges the technical support of Writing Lab, TecLabs, Tecnologico de Monterrey, Mexico in the production of this work. The second author gratefully acknowledges financial support from the Mexican Council of Science and Technology (CONACYT). The first author thanks Dr. Mario Martinez for suggesting the TraMineR library applied in this paper.

References

Ahmed, W., van der Werf, G., Kuyper, H., & Minnaert, A. (2013). Emotions, self-regulated learning, and achievement in mathematics: A growth curve analysis. Journal of Educational Psychology, 10

Andres, J. M. A. L., Paquette, L., Ocumpaugh, J., Jiang, Y., Baker, R. S., Karumbaiah, S., et al. (2019). Affect sequences and learning in Betty's brain. In ACM International Conference Proceeding Series<

Ashcraft, M. H., & Kirk, E. P. (2001). The relationships among working memory, math anxiety, and performance. Journal of Experimental Psychology: General, 130(2), 224–237. https://doi.org/1

Baker, R. S., Corbett, A. T., Koedinger, K. R., & Schneider, M. P. (2003). A formative evaluation of a tutor for scatterplot generation: evidence on difficulty factors. Proceedings of the Conference on Artificial Intelligence in Education, 107–114.

Baker, R. S., Corbett, A. T., Koedinger, K. R., & Wagner, A. Z. (2004). Off-task behavior in the cognitive tutor classroom: When students "game the system." In Proceedings of the ACM Conference on Human Factors in Computing Systems (pp. 383–390). ACM Press. https://doi.org/10.1145/985692.985741

Baker, R. S., D'Mello, S. K., Rodrigo, M. M. T., & Graesser, A. C. (2010). Better to be frustrated than bored: The incidence, persistence, and impact of learners' cognitive-affective states during interactions with three different computer-based learning environments. International Journal of Human Computer Studies, 68(4), 223–241. https://doi.org/10.1016/j.ijhcs.2009.12.003

Ben-Eliyahu, A., & Linnenbrink-Garcia, L. (2015). Integrating the regulation of affect, behavior, and cognition into self-regulated learning paradigms among secondary and post-secondary students. Metacognition and Learning, 10(1), 15–42. https://doi.org/10.1007/s11409-014-9129-8

Botelho, A. F., Baker, R. S., Ocumpaugh, J., & Heffernan, N. T. (2018). Studying affect dynamics and chronometry using sensor-free detectors. In Proceedings of the 11th International Conference on Educational Data Mining, EDM 2018.

Brown, A. L. (1978). Knowing when, where, and how to remember: A problem of metacognition. Advances in Instructional Psychology. Volume 1, 225–253.

Conati, C., & Gutica, M. (2016). Interaction with an Edu-Game: A Detailed Analysis of Student Emotions and Judges' Perceptions. International Journal of Artificial Intelligence in Education, 26(4), 975–1010. https://doi.org/10.1007/s40593-015-0081-9

Craig, S., Graesser, A., Sullins, J., & Gholson, B. (2004). Affect and learning: An exploratory look into the role of affect in learning with AutoTutor. Journal of Educational Media, 29(3), 241–250. https://doi.org/10.1080/1358165042000283101

D'Mello, S., & Graesser, A. (2011). The half-life of cognitive-affective states during complex learning. Cognition & emotion, 25(7), 1299–1308. https://doi.org/10.1080/02699931.2011.613668

D'Mello, S., Lehman, B., Pekrun, R., & Graesser, A. (2014). Confusion can be beneficial for learning. Learning and Instruction, 29, 153–170. https://doi.org/10.1016/j.learninstruc.2012.05.003

D'Mello, S. K., Strain, A. C., Olney, A., & Graesser, A. (2013). Affect, Meta-affect, and Affect Regulation During Complex Learning BT - International Handbook of Metacognition and Learning Technologies. In R. Azevedo & V. Aleven (Eds.), (pp. 669–681). New York, NY: Springer New York. https://doi.org/10.1007/978-1-4419-5546-3_44

D'Mello, S., & Graesser, A. (2012). Dynamics of affective states during complex learning. Learning and Instruction, 22(2), 145–157. https://doi.org/https://doi.org/10.1016/j.learninstruc.2011.10.001

Debellis, V. A., & Goldin, G. A. (2006). Affect and meta-affect in mathematical problem solving: A representational perspective. Educational Studies in Mathematics, 63(2), 131–147. https://doi.org/10.1007/s10649-006-9026-4

DeFalco, J. A., Rowe, J. P., Paquette, L., Georgoulas-Sherry, V., Brawner, K., Mott, B. W., et al. (2018). Detecting and Addressing Frustration in a Serious Game for Military Training. International Journal of Artificial Intelligence in Education, 28(2), 152–193. https://doi.org/10.1007/s40593-017-0152-1

Dennis, M., Masthoff, J., & Mellish, C. (2016). Adapting Progress Feedback and Emotional Support to Learner Personality. International Journal of Artificial Intelligence in Education, 26(3), 877–931. https://doi.org/10.1007/s40593-015-0059-7

Efklides, A., Kourkoulou, A., Mitsiou, F., & Ziliaskopoulou, D. (2006). Metacognitive knowledge of effort, personality factors, and mood state: their relationships with effort-related metacognitive experiences. Metacognition and Learning, 1(1), 33–49. https://doi.org/10.1007/s11409-006-6581-0

Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive–developmental inquiry. American Psychologist, 34(10), 906–911. https://doi.org/10.1037/0003-066X.34.10.906

Friesen, A. P., Lane, A. M., Devonport, T. J., Sellars, C. N., Stanley, D. N., & Beedie, C. J. (2013). Emotion in sport: Considering interpersonal regulation strategies. International Review of Sport and Exercise Psychology. https://doi.org/10.1080/1750984X.2012.742921

Gabadinho, A., Ritschard, G., Müller, N. S., & Studer, M. (2011). Analyzing and visualizing state sequences in R with TraMineR. Journal of Statistical Software, 40(4), 1–37. https://doi.org/10.18637/jss.v040.i04

Goldin, G. A. (2004). Problem solving heuristics, affect, and discrete mathematics. ZDM, 36(2), 56–60. https://doi.org/10.1007/BF02655759

Goldin, G. A. (2000). Affective Pathways and Representation in Mathematical Problem Solving. Mathematical Thinking and Learning, 2(3), 209–219. https://doi.org/10.1207/S15327833MTL0203_3

Gross, J. J. (2008). Emotion regulation. In Handbook of emotions, 3rd ed. (pp. 497–512). New York, NY, US: The Guilford Press.

Hannula, M. S. (2001). The metalevel of cognition-emotion interaction . (M. Ahtee, O. Björkqvist, E. Pehkonen, & V. Vatanen, Eds.). University of Jyväskylä, Institute for educational research .

Harley, J. M., Bouchet, F., & Azevedo, R. (2013). Aligning and Comparing Data on Emotions Experienced during Learning with MetaTutor BT - Artificial Intelligence in Education. In H. C. Lane, K. Yacef, J. Mostow, & P. Pavlik (Eds.), (pp. 61–70). Berlin, Heidelberg: Springer Berlin Heidelberg.

Harley, J. M., Lajoie, S. P., Frasson, C., & Hall, N. C. (2017). Developing Emotion-Aware, Advanced Learning Technologies: A Taxonomy of Approaches and Features. International Journal of Artificial Intelligence in Education, 27(2), 268–297. https://doi.org/10.1007/s40593-016-0126-8

Karumbaiah, S., Baker, R. S., & Ocumpaugh, J. (2019). The case of self-transitions in affective dynamics. In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) (Vol. 11625 LNAI, pp. 172–181). https://doi.org/10.1007/978-3-030-23204-7_15

Kim, C., Park, S. W., & Cozart, J. (2014). Affective and motivational factors of learning in online mathematics courses. British Journal of Educational Technology, 45(1), 171–185. https://doi.org/https://doi.org/10.1111/j.1467-8535.2012.01382.x

Koedinger, K. R., & Corbett, A. (2006). Cognitive Tutors: Technology Bringing Learning Sciences to the Classroom. In The Cambridge handbook of: The learning sciences. (pp. 61–77): Cambridge University Press.

Lane, A. M., Beedie, C. J., Devonport, T. J., & Stanley, D. M. (2011). Instrumental emotion regulation in sport: relationships between beliefs about emotion and emotion regulation strategies used by athletes. Scandinavian Journal of Medicine and Science in Sports, 21(6), e445–e451. https://doi.org/10.1111/j.1600-0838.2011.01364.x

Lee, D. M. C., Rodrigo, M. M. T., Baker, R. S. J. d., Sugay, J. O., & Coronel, A. (2011). Exploring the Relationship between Novice Programmer Confusion and Achievement BT - Affective Computing and Intelligent Interaction. In S. D'Mello, A. Graesser, B. Schuller, & J.-C. Martin (Eds.), (pp. 175–184). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-24600-5_21

Lehman, B., D'Mello, S., & Graesser, A. (2012). Confusion and complex learning during interactions with computer learning environments. Internet and Higher Education, 15(3), 184–194. https://doi.org/10.1016/j.iheduc.2012.01.002

Lehman, B., D'Mello, S., Strain, A., Mills, C., Gross, M., Dobbins, A., et al. (2013). Inducing and Tracking Confusion with Contradictions during Complex Learning. In International Journal of Artificial Intelligence in Education (Vol. 22, pp. 85–105). https://doi.org/10.3233/JAI-130025

Liu, Z., Baker, R. S. J. D., Pataranutaporn, V., & Ocumpaugh, J. (2013). Sequences of frustration and confusion, and learning. In Proceedings of the 6th International Conference on Educational Data Mining, EDM 2013.

Moscucci, M. (2009). Why Is There Not Enough Fuss About Affect and Meta-affect Among Mathematics Teachers? In V. Durand-Guerrier, S. Soury-Lavergne, & F. Arzarello (Eds.), Proceedings of the Sixth Conference of European Research in Mathematics Education (pp. 1811–1820). Lyon, France. http://ife.ens-lyon.fr/editions/editions-electroniques/cerme6/

Mrazek, A. J., Ihm, E. D., Molden, D. C., Mrazek, M. D., Zedelius, C. M., & Schooler, J. W. (2018). Expanding minds: Growth mindsets of self-regulation and the influences on effort and perseverance. Journal of Experimental Social Psychology, 79, 164–180. https://doi.org/https://doi.org/10.1016/j.jesp.2018.07.003

Namkung, J. M., Peng, P., & Lin, X. (2019). The Relation Between Mathematics Anxiety and Mathematics Performance Among School-Aged Students: A Meta-Analysis. Review of Educational Research, 89(3), 459–496. https://doi.org/10.3102/0034654319843494

Ogan, A., Walker, E., Baker, R. S. J. D., Rebolledo-Mendez, G., Catro, M. Ji., Laurentino, T., & de Cavello, A. (2012). Collaboration in cognitive tutor use in latin America: field study and design recommendations. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 1381–1390). https://doi.org/10.1145/2207676.2208597

Pardos, Z. A., Baker, R. S. J. D., San Pedro, M., Gowda, S. M., & Gowda, S. M. (2014). Affective States and State Tests: Investigating How Affect and Engagement during the School Year Predict End-of-Year Learning Outcomes. Journal of Learning Analytics, 1(1 SE-), 107–128. https://doi.org/10.18608/jla.2014.11.6

Richey, J. E., Andres-Bray, J. M. L., Mogessie, M., Scruggs, R., Andres, J. M. A. L., Star, J. R., et al. (2019). More confusion and frustration, better learning: The impact of erroneous examples. Computers & Education, 139, 173–190. https://doi.org/https://doi.org/10.1016/j.compedu.2019.05.012

Rodrigo, M. M. T., Baker, R. S. J. d., Agapito, J., Nabos, J., Repalam, M. C., Reyes, S. S., & Pedro, M. O. C. Z. S. (2012). The Effects of an Interactive Software Agent on Student Affective Dynamics while Using ;an Intelligent Tutoring System. IEEE Transactions on Affective Computing, 3(2), 224–236. https://doi.org/10.1109/T-AFFC.2011.41

Schwarz, N. (2011). Feelings-as-information theory. In P. A. M. Van Lange, A. W. Kruglanski, & E. T. Higgins (Eds.), Handbook of theories of social psychology (Vol. 1, pp. 289–308). London, UK: SAGE Publications Ltd. https://doi.org/10.4135/9781446249215.n15

Shute, V. J., D'Mello, S., Baker, R., Cho, K., Bosch, N., Ocumpaugh, J., et al. (2015). Modeling how incoming knowledge, persistence, affective states, and in-game progress influence student learning from an educational game. Computers & Education, 86, 224–235. https://doi.org/https://doi.org/10.1016/j.compedu.2015.08.001

Spann, C. A., Shute, V. J., Rahimi, S., & D'Mello, S. K. (2019). The productive role of cognitive reappraisal in regulating affect during game-based learning. Computers in Human Behavior, 100, 358–369. https://doi.org/https://doi.org/10.1016/j.chb.2019.03.002

Sutter-Brandenberger, C. C., Hagenauer, G., & Hascher, T. (2018). Students' self-determined motivation and negative emotions in mathematics in lower secondary education—Investigating reciprocal relations. Contemporary Educational Psychology, 55, 166–175. https://doi.org/https://doi.org/10.1016/j.cedpsych.2018.10.002

Tzohar-Rozen, M., & Kramarski, B. (2017). Metacognition and meta-affect in young students: Does it make a difference in mathematical problem solving? Teachers College Record, 119(13).

Wagstaff, C. R. D. (2014). Emotion regulation and sport performance. Journal of sport & exercise psychology, 36(4), 401–412. https://doi.org/10.1123/jsep.2013-0257