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A Multimodal Study of Emotion Regulation in Student Dyads During Computational Model Building

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Abstract: Collaborative problem solving (CPS) requires coordination of cognition and affect in complex, open-ended tasks. This study examines how pairs of high school students regulate learner-centered emotions (engagement, confusion, frustration, boredom, and delight) while constructing computational models in a STEM+C context. Extending Gross's (2015) process model to the group level, we analyze temporal dynamics of synchronized and unsynchronized emotional states during CPS. Multimodal data from six dyads (video, audio, system logs) were coded for CPS activities (e.g., information sharing, consensus building) and emotion transitions. Emotional alignment predominated, yet brief misalignments (especially between engagement and confusion) were frequent and often precipitated interpersonal regulation. Temporal analysis identified two dominant pathways: (1) transitions from misalignment to alignment that restore shared engagement, and (2) transitions between aligned states that shift partners from shared confusion to engagement. These pathways primarily occurred during information pooling and integration phases. Quantitative results show that effective regulation predicts higher model-building performance, with sustained engagement emerging as the stable endpoint of productive collaboration. The findings provide a temporal, group-level account of how students collectively manage emotion to sustain effective problem solving.

Introduction

Collaborative problem solving (CPS) in computational STEM integrates conceptual reasoning, coding, and social coordination. As students develop and test models, they share information, negotiate decisions, and experience emotions that shape collaboration quality (Cohn et al., 2025; Altaras et al., 2024). Learning-centered emotions (engagement, confusion, frustration, boredom, delight) fluctuate as groups construct solutions, face challenges, test hypotheses, and receive feedback. Managing these dynamics is crucial: positive emotions can strengthen persistence and cohesion, whereas negative emotions can disrupt communication and hinder joint reasoning. How groups handle emotion often determines whether collaboration remains productive (D'Mello et al., 2010; Haataja et al., 2022; Fonteles et al., 2024a; Ashwin et al., 2024; Akpanoko et al., 2024a; Fonteles et al., 2024b).

Emotion regulation research offers extensive insight into managing affect during learning. Gross's (2015) model distinguishes intrapersonal strategies for regulating one's own emotions from interpersonal strategies that influence others. Despite social contexts, much work in psychology and the learning sciences remains individual-focused. In socially shared and co-regulated learning (Järvelä et al., 2010; Hadwin et al., 2017), emotion is often treated as a background condition rather than a jointly managed process. Consequently, collective emotion regulation within CPS is not well understood. This gap is pronounced in computational modeling, where cognitive and emotional coordination are tightly coupled. Integrating science and computing concepts for model building depends on pooling information, negotiating understanding, and reaching consensus (Snyder et al., 2025). Emotions influence each activity: confusion can spark inquiry, frustration can motivate or impede progress, and delight can reinforce engagement. Yet prior work rarely examines group-level regulation—how partners detect emotional misalignments and co-regulate toward shared emotions that sustain collaboration (Chai et al., 2024; Altaras et al., 2024; Lönngren et al., 2024; Ashwin et al., 2025).

We address this gap by analyzing collaborative emotion regulation through emotional alignment and misalignment. We examine how pairs regulate emotions while solving computational modeling problems in a STEM+C environment. Using multimodal data—video, audio, and interaction logs—we track how partners' emotions align or diverge over time, how these shifts relate to CPS activities (information pooling, consensus building), and how regulation contributes to performance. We focus on two forms of collaborative regulation: (1) transitions from mismatched emotions to a shared state (misalignment-to-alignment) and (2) transitions from one shared emotion to another (aligned-to-aligned).

This study addresses three research questions:

- **RQ1:** Which emotional states are most frequently shared and misaligned during CPS?

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- **RQ2:** How do groups transition between aligned and misaligned states over time (frequency, typical paths, durations)?
- **RQ3:** How do aligned and misaligned intervals relate to CPS activities and subsequent performance?

Building on Gross (2015), we extend emotion regulation to group-level dynamics with a 2×2 framework distinguishing parallel and joint regulation within aligned and misaligned states. We map emotion trajectories onto CPS activities and performance, offering a temporally grounded account of collaborative emotion regulation in computational STEM learning. Together, the analyses show how emotions are collectively managed to sustain effective problem solving.

Background

Learning sciences research has established that emotion influences motivation, attention, and cognitive processing, impacting individual and group performance (Pekrun et al., 2017; Mänty et al., 2020; Ashwin and Guddeti, 2020; Desai et al., 2025; Yadannavar et al., 2024). In CPS, emotions arise both as internal reactions to cognitive demands and as socially situated responses to peers, group dynamics, and task progress. Positive emotions (e.g., engagement, delight) align with persistence, elaboration, and constructive dialogue, whereas frustration and boredom often co-occur with off-task behavior or disengagement (Bakhtiar et al., 2018; Ashwin et al., 2025). Certain negative emotions—particularly confusion—can be productive when regulated, prompting deeper reasoning or clarification (Isohätälä et al., 2020; Akpanoko et al., 2024b). Emotions thus fluctuate dynamically and continuously shape collaborative cognition.

Emotion regulation, notably Gross's process model (Gross, 2015), explains how individuals regulate and express emotions. Work in the learning sciences extends this framework to interpersonal and socially shared regulation, recognizing that learning often involves others. Research on co-regulation and socially shared regulation of learning (SSRL) (Järvelä et al., 2010; Hadwin et al., 2017) shows learners monitoring and managing their own and peers' cognitive and emotional states to maintain joint engagement, using reassurance, humor, and strategic reframing to sustain collaboration through affective challenges.

Despite progress, regulation is commonly treated as an individual phenomenon, with emotion peripheral to analysis and secondary to cognition. Studies typically rely on self-report or retrospective methods, capturing perceptions but not moment-to-moment evolution. Consequently, little is known about how regulation unfolds in real time within collaborative learning, especially when emotions are distributed and interdependent across partners. An underexplored area concerns learning-centered emotions—arising from cognitive demands—including engagement, confusion, frustration, boredom, and delight (D'Mello, 2012; D'Mello & Kory, 2015). These emotions shape epistemic processes, yet their collective regulation remains largely unexamined. While socio-emotional regulation studies identify strategies for managing climate and motivation, few investigate regulation of learning-centered emotions that fluctuates with conceptual understanding and task complexity during authentic collaboration. This gap is pronounced in computational STEM learning, where students coordinate conceptual science reasoning and computational thinking to build models. Such tasks demand ongoing negotiation of shared understanding, and resulting emotional dynamics directly influence collaboration.

Emotional misalignment (e.g., one partner frustrated, the other engaged) often requires regulation to restore balance; shared confusion, if effectively co-regulated, can transform into engagement and conceptual progress. Empirical analyses of how these configurations evolve during CPS—and how groups manage them—are scarce. Capturing these dynamics requires viewing regulation as both intrapersonal and as a temporal, relational process. Prior work frequently treats emotional states as discrete or aggregated measures, limiting insight into transitions—especially between aligned and misaligned configurations—and their links to regulation and performance. Moreover, most studies lack multimodal evidence synchronizing speech, action, and affect, obscuring the interplay among expression, regulation, and collaborative activity.

These limitations motivate a temporal, group-level perspective on emotion regulation. By examining how partners' emotions *align* or *diverge*—and how they regulate these dynamics in real time—research can move beyond individualistic models toward a comprehensive account of collective emotion regulation in learning. This study analyzes *collaborative emotion regulation* in authentic CPS tasks, using synchronized multimodal data to link emotional alignment and misalignment to activity patterns and performance. These dynamics point to two interrelated trajectories: resolution of misalignment and joint transformation of shared emotions. The next section formalizes these processes within a collaborative framework.

Conceptual framework

Social interactions during collaborative learning are complex and multi-dimensional, shaped by attention, discourse, emotional expression, and interpersonal coordination (e.g., Nasir et al., 2021; Vrzakova et al., 2020).

In collaborative problem solving (CPS), emotions are integral to how partners think, communicate, and sustain joint engagement. Emotional experiences can either support or disrupt collaboration (Mänty et al., 2020; Pekrun et al., 2017; Bakhtiar et al., 2018; Snyder et al., 2025). These emotional fluctuations are not random—they emerge in response to cognitive challenges, feedback, and social interaction within the group (Isohätälä et al., 2020). Thus, effective emotion regulation becomes essential to maintaining productive collaboration.

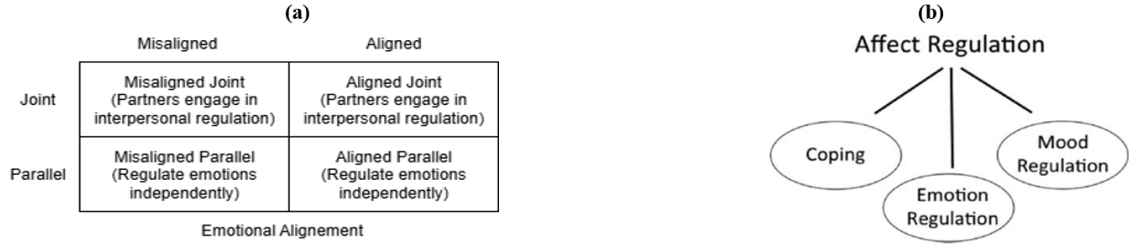
Gross's (2015) process model on emotion regulation conceptualizes regulation as the ways in which individuals influence which emotions they experience, when they experience them, and how these emotions are expressed. This model distinguishes between intrapersonal regulation, where an individual manages their own emotions, and interpersonal regulation, where one person intentionally influences another's emotions. Within collaborative learning, these processes are interwoven; learners must regulate both themselves and their partners while managing a shared cognitive and social space. Prior work on co-regulation and socially shared regulation of learning (SSRL) (Järvelä et al., 2010; Hadwin et al., 2017) has shown that such regulation is often negotiated collectively, particularly when groups encounter cognitive impasses or social tensions.

Building on this foundation, research on collaborative emotion regulation extends Gross's model, which describes the temporal stages of individual regulation (situation selection, attention deployment, cognitive change, and response modulation), to collaborative settings. In these more complex settings regulation must account for *emotional alignment* between partners. Alignment occurs when both group members experience similar emotional states (e.g., both engaged or both confused), whereas *misalignment* occurs when partners experience different emotions (e.g., one frustrated, one engaged). Collaborative regulation thus involves managing not only the intensity or valence of emotion, but also its distribution across individuals. To capture this relational nature of emotion regulation, we conceptualize dyadic emotional configurations within a 2×2 grid (Figure 1a). The x-axis represents emotional alignment, ranging from misaligned to aligned states, while the y-axis represents the regulatory focus, ranging from parallel to joint regulation.

This framework distinguishes four interactional configurations: (1) *Misaligned–Parallel*: Each student regulates emotions independently without explicitly engaging the partner's affect (e.g., one continues working while the other expresses frustration); (2) *Misaligned–Joint*: Partners recognize the emotional difference and engage in interpersonal regulation (e.g., one supports or reassures the other, restoring alignment); (3) *Aligned–Parallel*: Both students experience the same emotion but regulate independently (e.g., both quietly engaged or both confused without verbal coordination); and (4) *Aligned–Joint*: Both experience and regulate emotions together (e.g., jointly acknowledging confusion and co-regulating toward engagement). This grid highlights that emotional alignment alone does not guarantee effective regulation; rather, the quality of coordination—whether partners regulate in parallel or jointly—determines how successfully groups sustain or restore productive affective states. Transitions across these configurations capture the dynamic process of collaborative emotion regulation during CPS.

Figure 1

A 2×2 Framework and Hierarchical Model of Collaborative Emotion Regulation



(a): A 2×2 framework of collaborative emotion regulation during CPS. The horizontal axis represents emotional alignment (misaligned → aligned), and the vertical axis represents regulatory focus (parallel → joint), illustrating four possible dyadic configurations; **(b):** Hierarchical structure of affect regulation, adapted from Gross (2015).

Figure 1b illustrates Gross's (2015) hierarchical framework of affect regulation, showing how coping, mood regulation, and emotion regulation relate conceptually. In this paper, we focus specifically on emotion regulation—and more precisely, on the regulation of *learning-centered emotions* (engagement, confusion, frustration, boredom, and delight) within collaborative problem solving. By mapping emotional alignment, misalignment, and transitions across time, we extend prior models of emotion regulation to collaborative contexts, offering a temporally grounded perspective on how emotions evolve and are collectively managed in group learning. In this paper, we analyze how transitions across these configurations—particularly from misaligned to aligned and from aligned to aligned—capture the dynamic processes of collaborative emotion regulation that emerge during CPS.

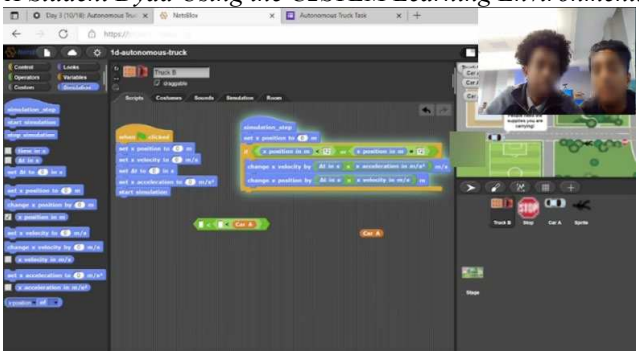
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Learning environment and data

We conducted a two-month University Institutional Review Board (IRB) approved study with 10th-grade students at a public high school in the Southeastern United States. Weekly classroom sessions lasted two hours. Twenty-seven students participated, organized into 13 groups (12 dyads, one triad), each using a shared laptop for formative assessment and model-building in the Collaborative, Computational STEM (C2STEM) learning environment (Figure 2), where students built models to solve one-dimensional (1D) and two-dimensional (2D) challenges (Snyder et al., 2025). Students were free to collaborate without prior instruction and were encouraged to discuss and explore solution strategies together. All activity occurred on the shared laptop in class. We collected (a) pre- and post-test scores (summative assessments), (b) logs of computational model building from C2STEM, and (c) audio-video recordings captured with OBS on each group's laptop. Conversations were transcribed with Otter.ai and edited for accuracy by two researchers. Pre- and post-tests comprised four physics items (17 points) and three computing items (16 points). Scores were rubric-graded and reported as proportions of points earned over points possible. Groups lacking complete audio-video for both CPS tasks were removed, yielding a final analytic sample of six dyads with full recordings across both tasks.

Figure 2

A Student Dyad Using the C2STEM Learning Environment.



Method

Information pooling and consensus building

We analyzed group interactions via verbal exchanges on information pooling and consensus building. Each utterance was coded using Weinberger's (2006) framework for: (1) *Information Pooling (IP)* – eliciting and sharing relevant task information (a) *Elicitation:* one student asks the partner for task-related information (b) *Externalization:* a student articulates facts, observations, or describes actions within the environment; and (2) *Consensus Building* (CB) – jointly evaluating and integrating information (a) *Conflict-oriented*: disagreement or debate over interpretations or next steps; (b) *Integration-oriented*: building upon or integrating a partner's contribution; and (c) *Quick*: a proposal is accepted immediately without further discussion (Ashwin et al., 2025). An additional off-task label identified dialogue unrelated to the modeling activity. Two researchers independently coded all transcripts, achieving strong inter-rater reliability (Cohen's $\kappa = 0.77$). For each group, we computed the proportion of utterances per code relative to total utterances. These measures quantified information exchange and consensus processes and served as temporal references for segmenting episodes in later emotion analyses.

Affect analysis

We examined students' emotions during CPS using manual, time-aligned multimodal annotation. Data comprised synchronized screen recordings, webcam video (facial expressions, posture), audio, transcripts, and interaction logs. We focused on five learning-centered emotions—*confusion, frustration, delight, boredom*, and *engagement* (D'Mello, 2012; Pekrun et al., 2017; D'Mello & Graesser, 2012). Modalities provided complementary cues: facial and bodily signals indicated visible affect, while dialogue and tone validated context. When cues conflicted, the predominant signal guided labeling; explicit statements (e.g., "*this is frustrating*") overrode neutral expressions. Laughter or smiling after task success was coded as delight. Engagement was annotated as a neutral, task-focused state. Many students displayed steady gaze, neutral expressions, and consistent participation—behaviors aligned with epistemic emotions that support learning without strong positive or negative valence (D'Mello & Baker, 2010; Pekrun, 2012). This aligns with the notion of flow (Csikszentmihalyi, 1990), where learners exhibit deep immersion but limited external affect. Two trained annotators independently reviewed all sessions, recording for each episode the emotion label, start and end timestamps, and brief contextual justification. After iterative

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calibration, inter-rater reliability reached Cohen's $\kappa = 0.91$. Emotion timelines were synchronized across dyad members to identify aligned and misaligned intervals and subsequent regulation transitions.

Operationalizing emotional alignment and misalignment

Combining Gross's (2015) process model and socially shared regulation (Järvelä et al., 2010; Hadwin et al., 2017), we examined intrapersonal and interpersonal regulation. Intrapersonal regulation concerns managing one's own emotions; interpersonal regulation involves responding to or influencing a partner's affect. We defined emotional alignment as both dyad members experiencing the same emotion simultaneously (e.g., both confused or engaged) and misalignment as partners experiencing different emotions (e.g., one engaged, the other frustrated). Synchronized emotion timelines identified aligned and misaligned intervals.

We traced transitions between states (aligned → misaligned; misaligned → aligned) to characterize the temporal flow of collaborative regulation. Dialogue excerpts and contextual behaviors indicated how partners recognized and responded to affective differences, revealing efforts to negotiate and restore shared emotional states during CPS. Our focus was peer-to-peer regulatory dynamics emerging naturally in collaboration. We examined two transition types: (1) *misalignment-to-alignment*, where partners regulated toward a shared state, and (2) *aligned-to-aligned*, where partners jointly shifted from one shared emotion to another (e.g., confusion to engagement). Each transition was analyzed with CPS activity codes and performance to determine when and how regulation occurred. CPS segments defined task-based episodes (e.g., IP, CB phases), while emotional intervals captured continuous periods of alignment or misalignment within those segments; transitions marked the shifts between intervals.

Performance evaluation

Group performance was evaluated via rubric-based assessment of computational models in the C2STEM learning environment, covering physics and computing constructs: *Physics*: correct initialization of motion variables (position, velocity, acceleration) and appropriate relationships among them. *Computing*: simulation control, variable updating, and logical sequencing. Each criterion was scored 1 (present/correct) or 0 (absent/incorrect), totaling 19 points (11 physics, 8 computing). Scores were normalized across groups and tasks. Performance was analyzed alongside emotional-alignment data to test whether regulation, especially transitions restoring or maintaining alignment—was associated with stronger CPS outcomes.

Results and discussion

We analyzed 910 CPS segments from six student dyads over six hours of collaborative modeling. Each was coded for CPS phase and emotion. Overall, 107 segments (11.8%) showed emotional misalignment, with the rest aligned. There were 114 misaligned intervals, 65 of which involved Engagement–Confusion, and 107 regulation transitions. These findings formed the basis for further analysis of frequency, patterns, and performance links.

RQ1. Frequency and distribution of aligned and misaligned emotional states

During collaborative problem solving (CPS), students showed fluctuations among five emotions—engagement, confusion, frustration, boredom, and delight. About 12% of segments indicated emotional misalignment, while 88% showed alignment, mostly with engagement (≈57%) and confusion (≈24%), meaning students were often either focused or uncertain together. *Misalignment* was most common during Information Pooling (IP), especially Externalization, when students verbalized reasoning or explained code, revealing differing understanding or confidence. Consensus Building (CB), particularly Integration, also caused misalignment as partners debated ideas or negotiated solutions. Fewer misaligned segments occurred during Quick and Conflict phases, which were shorter and more decisive.

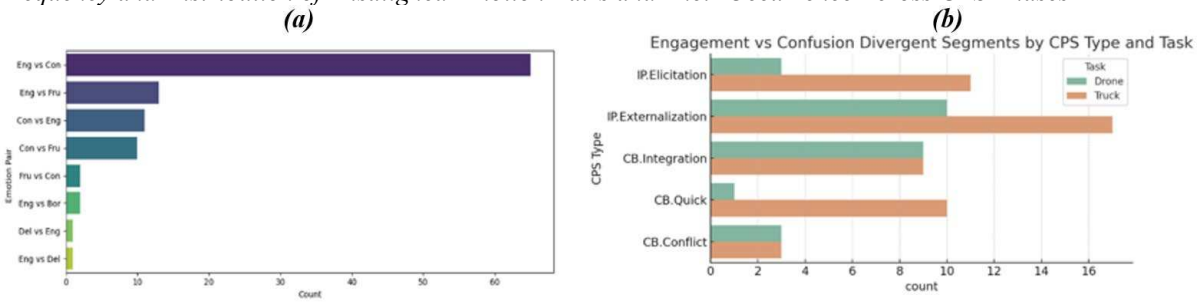
Dominant emotional pairings: Among misaligned intervals, Engagement ↔ Confusion was most common (≈ 65 instances; ~57%), followed by Engagement ↔ Frustration and Confusion ↔ Frustration (Figure 3a). These often reflected asymmetries—one partner focused, the other uncertain or challenged. Less common pairs (e.g., Engagement ↔ Boredom, Delight ↔ Engagement) occurred in under 2% of cases and are grouped as other low-frequency pairs. Since Engagement ↔ Confusion was most prevalent, we examined its distribution across CPS phases (Figure 3b). It appeared mostly during IP.Externalization and CB.Integration, indicating misalignments often coincided with elaboration or negotiation. When one partner scaffolded reasoning, misalignment frequently shifted to shared engagement, signaling successful regulation. Table 1 summarizes frequencies, durations, and CPS contexts. While aligned segments dominated total time, Engagement ↔ Confusion was a key misalignment often leading to regulation.

Statistical results: CPS phase significantly affected misalignment frequency ($F(4, 20) = 5.82$, $p = .003$, $\eta^2 = .54$), with IP.Externalization having more misalignments than CB.Conflict and CB.Quick. Segment durations varied across emotions, with Aligned–Confusion longer than Aligned–Engagement and Misaligned–Frustration.

Chi-square analysis indicated a highly uneven distribution of emotion pairs, mainly Engagement ↔ Confusion. Misalignment was a regular, meaningful part of CPS, indicating moments of one partner struggling while the other stayed focused, often leading to interpersonal regulation. Pooling highlighted differences; Integration helped repair alignment. Misalignment signals uneven understanding and triggers collaborative regulation to restore shared engagement.

Figure 3

Frequency and Distribution of Misaligned Emotion Pairs and Their Occurrence Across CPS Phases



(a): Frequency of misaligned emotion pairs. Engagement–Confusion dominated the dataset, followed by Engagement–Frustration and Confusion–Frustration; (b): Engagement-Confusion misalignment segments by CPS type and task

Table 1

Frequency and Duration of Aligned and Misaligned Emotional States across CPS Activities

Emotional Configuration	Frequency (%)	Duration (s)	Dominant Emotions	Typical CPS Phase	Example Regulatory Outcome
Aligned – Engagement	56.8	22 ± 5	Engagement	CB.Integration	Sustained joint focus
Aligned – Confusion	23.7	34 ± 7	Confusion	IP.Externalization	Shared uncertainty → clarification
Misaligned – Engagement ↔ Confusion	9.1	33 ± 9	Engagement / Confusion	IP.Elicitation → CB.Integration	Interpersonal repair → shared engagement
Misaligned – Engagement ↔ Frustration	2.7	28 ± 6	Engagement / Frustration	CB.Conflict	Brief tension, often resolved
Misaligned – Confusion ↔ Frustration	1.7	31 ± 8	Confusion / Frustration	IP.Externalization	Peer reassurance or withdrawal
Other Low-Frequency Pairs (a)	1.0	< 20	Eng ↔ Bored, Del ↔ Eng	Various	Transient misalignment

(a) "Other Low-Frequency Pairs" combine all misaligned configurations occurring < 2% each.

RQ2. Temporal transitions between aligned and misaligned states

Temporal analysis revealed patterns in how groups shifted between aligned and misaligned emotional states during CPS. As discussed, two main transition types were observed: misalignment-to-alignment and aligned-to-aligned. About 90% of misaligned episodes transitioned into an aligned state within the same task segment, often through explanations or reassurance (average 3.8 min, SD = 1.2). Shorter (~2 min) transitions occurred during CB.Conflict when tension was reduced. Longer sequences occurred during IP.Elicitation and early CB.Integration, where partners elaborated reasoning before re-establishing alignment. A smaller subset (~10%) involved partners moving from the same emotion to another shared state, most commonly Confusion → Engagement during CB.Integration, lasting about 5.0 min (SD = 1.5). Brief Engagement → Delight transitions

(~1.2 min) happened after successful tasks. Overall, 91% of sequences ended in shared engagement, confirming it as a stable outcome of CPS. Only eight episodes ended in sustained confusion, and none persisted in frustration or boredom beyond five minutes. Confusion and frustration episodes took about 10 min to recover, indicating greater regulatory difficulty.

Statistical results: A Kruskal–Wallis test showed a significant effect of CPS phase on regulation duration, $H(4) = 15.67$, $p < .001$, with longer transitions in IP.Elicitation and CB.Integration than in CB.Conflict. Transitions were not uniformly distributed across emotion pairings, $\chi^2(5, N = 107) = 11.64$, $p = .049$: Engagement ↔ Confusion was most likely to resolve to Engagement. The association between CPS phase and the resolution emotion was also significant, $\chi^2(4, N = 107) = 29.43$, $p < .001$, with Integration most likely to culminate in shared engagement. Table 2 summarizes durations (in minutes), CPS contexts, and characteristic mechanisms for the observed transitions. Most misalignments were brief and resolved through interpersonal regulation, while aligned transitions showed socially shared regulation deepening understanding. Engagement was the stable endpoint, reinforcing its role as the emotional basis of productive CPS. Longer transition durations in Integration suggest sustained emotional alignment is linked to conceptual co-construction, not passive convergence.

Table 2
Temporal Characteristics of Emotional Transitions During CPS

Transition	Starting State	Duration	Resolution	CPS Phase	Mechanism
Misaligned → Aligned	Engaged ↔ Confused	3.8 ± 1.2	Engagement	IP.Elicitation → CB.Conflict	Clarification / reassurance
Misaligned → Aligned	Engaged ↔ Frustrated	2.1 ± 0.7	Engagement	CB.Conflict	Supportive feedback
Aligned → Aligned	Confused → Engaged	5.0 ± 1.5	Engagement	CB.Integration	Joint cognitive reappraisal
Aligned → Aligned	Engaged → Delight	1.2 ± 0.5	Delight	CB.Quick	Shared success / closure

RQ3. Linking emotion regulation to CPS activities and collaborative performance

To relate regulation to collaborative quality, we linked aligned–misaligned transitions to CPS activities and Model performance was evaluated with a 19-point rubric, focusing on whether transitions restoring or maintaining alignment related to improved scores. Regulation occurred across all CPS phases, most often in IP and CB, with misalignments mainly in Elicitation and Externalization, where partners questioned and explained. Successful regulation in these phases restored alignment, fostering collaboration. Longer, stable aligned states appeared in CB.Integration, where groups refined models. Conflict and Quick episodes were brief, involving rapid affective stabilization. Regulated intervals correlated with higher performance, with a +3.0 point average gain.

Table 3
Regulation Contexts and Associated Performance

CPS Phase	Dominant Regulation	Duration (min)	Resolution Emotion	Δ score*
IP Elicitation	Misaligned → Aligned	3.5	Engagement	+1.2
CB Conflict	Misaligned → Aligned	2.0	Engagement	+0.8
CB Integration	Aligned → Aligned	5.0	Engagement → Delight	+3.0
CB Quick	Aligned → Aligned	1.0	Delight	+0.5

*Δ score = mean performance improvement relative to non-regulated intervals.

Regulation during Integration showed the strongest link, supported by a Spearman correlation of .63 ($p = .014$), especially in Integration ($r = .71$, $p < .01$) and Elicitation ($r = .52$, $p = .04$). No significant links were found for Conflict or Quick ($p > .10$). Episodes ending in shared engagement usually led to successful model iterations; those ending in shared confusion often stalled progress. A chi-square test showed that resolution

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emotions differed by performance tier ($\chi^2(3, N=107)= 12.76$, $p= .005$), with engagement-aligned intervals clustering in higher-rated teams. Table 3 details CPS phase, regulation types, durations, and their performance effects. Emotion regulation closely links to CPS activity. Extended regulation in Integration improved sustained engagement, reflection, and higher model scores. Brief or unresolved regulation in Elicitation or Conflict led to superficial alignment without deeper gains. Shared sustained engagement is key for productive collaboration and quality solutions.

Discussion

This study advances research on collaborative emotion regulation by situating it within learning-centered emotions during collaborative problem solving (CPS). We extend Gross's (2015) process model to collaborative regulation, showing alignment and misalignment as fluid configurations that evolve through cognitive and social coordination. Prior work on socially shared and co-regulated learning (e.g., Järvelä et al., 2010; Hadwin et al., 2017) links regulation to joint engagement but often treats affect as background to outcome. Our findings move beyond this view, offering fine-grained temporal evidence that emotions are dynamically regulated through interaction. Misalignments, especially engagement–confusion pairings were not failures but productive triggers for interpersonal regulation. Through talk, scaffolding, and reassurance, students restored shared engagement, positioning emotion regulation as a central mechanism for sustaining collaborative reasoning. These results bridge individual models of regulation and group-level coordination in CPS, showing how affective repair and progression underpin successful problem solving.

Beyond prior literature, our analyses yield several insights. First, emotion regulation in CPS operates through two complementary temporal pathways: emotional divergence inviting interpersonal repair (misalignment-to-alignment) and shared confusion evolving into collective engagement (aligned-to-aligned). Effective regulation thus depends not on constant positive affect, but on navigating emotional diversity. Second, the strong association between regulation during consensus-building phases and higher collaboration performance suggests sustained alignment supports deeper conceptual integration; alignment functions as a stabilizing force enabling cognitive progress. Third, our multimodal temporal approach—integrating emotion, discourse, and task phases—offers a methodological advance for capturing the microgenesis of regulation in situ, empirically validating emotion regulation as a collective, emergent phenomenon embedded in CPS. These results carry implications for emotion-aware learning in collaborative environments. They underscore the need to conceptualize emotion regulation as both social and epistemic, inseparable from joint meaning-making. For classroom and CSCL design, systems and instructors should attend to interpersonal affective configurations, i.e., moments of divergence or convergence, as key opportunities for scaffolding co-regulation. Automated detection of such transitions could inform adaptive prompts that foster emotional awareness and peer support. More broadly, the study supports a vision of collaboration in which emotional alignment is treated as a dynamic resource for maintaining shared focus, rather than a by-product of successful teamwork.

Limitations: Despite the paper's contributions, several limitations should be considered. The sample size, although adequate for microgenetic and qualitative temporal analysis, restricts our ability to generalize statistically. The setting—a single high school class working in a specific computational modeling environment—also limits the applicability of findings to other age groups or contexts. Furthermore, the emotion annotations, validated through multimodal evidence, depended on human interpretation, which introduces some subjectivity despite high inter-rater reliability.

Conclusions

This study provides empirical and theoretical insight into how students regulate their learning-centered emotions during collaborative problem solving. By analyzing temporal transitions between aligned and misaligned emotional states, we show that collaborative emotion regulation unfolds as an ongoing process of maintaining, repairing, and transforming shared affective engagement to advance shared understanding and problem-solving. Emotional misalignment especially *engagement–confusion pairings* emerged as a productive precursor to regulation, while sustained alignment during consensus-building phases predicted stronger collaboration performance. Together, these findings demonstrate that emotion regulation in CPS is not merely a reaction to affective disruption but a mechanism through which groups coordinate understanding and sustain joint inquiry. Extending Gross's (2015) model to the group level, this work positions emotional alignment as a fundamental dimension of collaboration dynamics, offering both conceptual grounding and methodological tools for studying emotion in learning. Future research should further investigate how emotion-aware designs can support students in recognizing and regulating these affective dynamics, enabling more resilient and productive forms of collaborative learning.

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