How Do Students Listen to Each Other When Solving Complex Problems?

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Student ability to succeed in collaborative problem solving (CPS) is increasingly important. However, identifying aspects of CPS that individuals can act on to improve it remains a challenge. This study explores listening behaviour as a lever for effective CPS, given that listening is at once cognitive and social, and that individuals can enact it. Despite its importance in communication, listening is rarely systematically examined in CPS. To address this gap, we propose a framework for identifying listening behaviours in the text of student exchanges, and apply it to analyse patterns of listening behaviours of 34 K-12 students aged 11-14, working in nine groups on CPS activities. By combining content analysis, k-means cluster analysis, and correlation-based coupling network analysis, we identify ten distinct patterns of listening behaviours and their coupling over time, across groups with different success outcomes. We found that listening patterns varied by performance, under the assumption of moderate temporal dependence among interaction segments. Higher performing groups engaged in more counterarguments and constructive listening. Groups with lower CPS successes exhibited two ineffective patterns: questioning with instrumental listening, and counterarguments and questioning without encouraging listening. These findings pose questions about the relationship between listening and learning processes and have implications for multimodal research in learning analytics.

CCS Concepts: • **Human-centered computing → Social interaction**; • **Applied computing → Learning analytics**.

Additional Key Words and Phrases: Collaborative Problem Solving, Listening, K–12 Education, Learning Analytics, Group Communication, Social skills, Cognitive skills

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1 Introduction

Real-world challenges can rarely be addressed by a single individual in any domain. Solutions to open-ended complex problems require collaborative effort with multiple perspectives and areas of expertise [15, 21]. Collaborative problem solving (CPS) has therefore been identified as a set of skills to help solve open-ended complex problems collaboratively

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[39, 45]. Equipping students with CPS is no longer optional. It is a core educational imperative that demands explicit opportunities to practice, feedback grounded in group processes, and learning environments that foster interdependence.

CPS is a complex process where individual and group cognition are tangled with meta-cognitive and social processes. These processes take place via interpersonal interactions of socio-cognitive and socio-emotional nature exchanged by the group members working together towards a desired solution [18]. Because of its multifaceted nature, identifying how to best support CPS is not trivial. Literature has clearly identified that cognitive and meta-cognitive aspects of CPS competence matter for the group's success [6, 55]. Social processes have received less attention. Still, it is well-known that unequal participation [29] and suppression of expression [6] characterise unproductive groups. Studies also agree that positive social processes are associated with high-quality cognitive engagement [42], and if social processes fail, groups lack coordination and shared understanding [2, 50], undermining their group performance [5].

Although interpersonal interactions and positive social processes are fundamental to CPS, limited attention has been paid to interpersonal and social aspects that could be supported by *actionable* feedback. First, it is unclear *what* indicators of social interactions should become a target of such feedback. Thus far, many have been singled out, including participation, perspective taking, social regulation, and positive socio-emotional interactions [4, 22, 24]. It is unrealistic to expect that technologies that record CPS interactions would provide feedback on all of these aspects. A further expectation that students would act on all of them is equally unrealistic. Second, existing feedback scaffolds for CPS mostly focus on group-level indicators, through interventions such as group awareness tools [46]. Group awareness tools offer students visual feedback about how many ideas the group shared or how argumentative the group was [41, 48, 51]. Feedback based on group awareness does not differentiate between individual and group behaviour easily, whereas each group member needs clarity on what individual behaviour to focus on to improve the CPS process.

This study explores the role of listening behaviour in CPS as an actionable individual-level behaviour that could potentially improve CPS processes. Surprisingly, although seminal studies (e.g. [5]) found that effective collaborative groups engage in micro-level behaviour related to listening, i.e., clarification questions and building on ideas, this behaviour has rarely been examined directly in learning environments. Listening is a peculiar behaviour because it is an act of showing attentiveness to others, manifested through three interrelated components: behaviour, cognition, and emotion [11, 19]. Managing attention in collaborative groups is a fundamental piece of interaction and communication [5]. Thus far, there has not been a systematic examination of the presence of listening in CPS.

To address this gap, we propose a framework for identifying listening behaviour in the text of student CPS exchanges and apply it to analyse patterns of listening behaviour of K-12 students (N=34), working in nine groups on CPS activities. By combining content analysis, k-means cluster analysis, and correlation-based coupling network analysis, we identify ten distinct patterns of listening behaviour and their coupling over time, across CPS groups with different performance.

Our study makes several contributions. First, we develop an analytical, theoretically underpinned framework for listening behaviour. Second, we further offer evidence of the patterns of listening in CPS groups with different performance outcomes. Third, we analyse whether aggregates of listening patterns couple into distinct states that define how groups listen, and whether these states differ between group performances. Since we observe differences across these patterns and group performance, our work poses questions about the relationship between listening and learning processes, for further investigation in future research. Beyond these empirical contributions, our work has important implications for the learning analytics (LA) community. In particular, feedback provided at the individual level to support communication in CPS aligns with the need to identify individual behaviours that learners can more easily implement [36]. Although our study focuses specifically on identifying listening behaviours in text, the proposed framework and findings highlight opportunities for multimodal learning analytics. In particular, combining analytics of listening with other physiological, audio and video data could provide a more comprehensive understanding of CPS and guide the design of adaptive support.

2 Background and Related Work

2.1 Collaborative Problem Solving Processes and Listening Behaviour

Research focused on CPS communication processes studies the relationships between moment-by-moment CPS behaviours that learners engage in, with CPS skills and outcomes [39, 50]. To this end, researchers evaluate main CPS competencies, such as establishing shared understanding, taking appropriate action, and maintaining team organization via observable behavioural indicators, to identify their relationship with group performances [22, 39, 50, 52]. This led to some insights differentiating between high- and low-performing groups (e.g. [20, 57]). However, effective use of CPS skills does not necessarily add up to an effective CPS process or outcome [50]. Teams may still fail if they lack sufficient knowledge or pursue ineffective strategies [50], or if they do not coordinate the cognitive and social aspects of the CPS process [50]. Since CPS processes arise from complex, non-linear mutual influences in moment-by-moment interactions and represent cognitive and social processes at individual and group levels [27], it is difficult to provide targeted feedback to improve CPS. The gap remains as to what meaningful aspect of CPS can be used as a lever for feedback that can help adapt micro-level, moment-by-moment interactions to improve CPS group outcomes.

We propose that listening behaviour can be a potential target of feedback to improve CPS. Listening is a behaviour that is at once cognitive, social, and serves the interactive needs of interpersonal communication [9, 56]. It is an individual-level behaviour that may potentially influence multi-faceted CPS processes. It, however, has been overlooked in the context of CPS. Current research on listening shows that it facilitates shared understanding [10] and is the mechanism that accomplishes the coordination in communication [32]. Listening can function as moment-by-moment feedback to others during communication. Naykki et al. [38] found that listening to the ideas of others offers opportunities for students to monitor and calibrate their understanding [3]. Additionally, listening unfolds in temporal alignment with interaction, signaling attentiveness to others [56]. Managing attention is fundamental for effective communication [56]. Hence, listening could be an individual moment-by-moment behaviour with upwards implications for the emergent group-level processes and effectiveness.

Empirical work allows to link listening with the group performance in CPS. Members of high-performing groups often acknowledge others, affirm and expand others' ideas [25, 47], inquire about others' goals and perspectives [49], and adjust one's position in response to teammates' arguments [16]. These specific behaviours can be embedded within a broader umbrella of listening, i.e. paying attention to what others say or do, and responding to it in an observable fashion. However, the components of listening defined in existing models are highly abstract, making them difficult to operationalize into observable behavioural indicators. Additionally, despite the presence of diverse behaviours related to listening in CPS, no study has systematically described patterns of listening as observable behaviours or examined their relationship to group effectiveness in CPS. To advance research in CPS, there is a need for an analytical framework of listening behaviour that captures observable indicators at the individual level. Using this framework can support an inquiry about how individual listening behaviour is related to patterns at the group level in CPS activities.

2.2 Conceptual Framework of Listening

Listening is an essential skill for mutual understanding and effective communication [28, 35, 40]. It fulfills broader cognitive, emotional, and social needs by sustaining interpersonal interaction [12]. Early work in therapy [43] emphasized the importance of active listening, i.e. paying attention, providing feedback, deferring judgment, and responding appropriately, for effective communication and relationships. Hoppe [23] expanded earlier models to incorporate reflecting, clarifying, summarizing, and sharing. These models exemplify a skills-focused approach, framing listening primarily in terms of trainable skills for interpersonal communication [54]. Few empirical studies have mapped specific, observable listener behaviours onto broader models of listening skills [11, 31, 44]. Commonly used behavioural indicators, derived from interpersonal communication research, include paraphrasing, back-channeling, asking clarifying questions, and demonstrating empathy. They are frequently treated as signals of active listening [8, 9, 31, 44]. Yet, many of them from the existing listening models cannot be easily converted into observable behavioural indicators.

To ground our framework in the literature and ensure its applicability to moment-by-moment interactions in CPS, we synthesized insights from three main sources: (1) models of listening, (2) empirical research on interpersonal communication, and (3) behavioural indicators identified in studies of small-group collaboration, including CPS and collaborative learning. When certain listening behaviours were already described in models of listening and measured in empirical research on interpersonal communication, we directly included these indicators. By comparing theoretical frameworks with behaviours observed in CPS exchanges, we synthesized overlapping dimensions and refined them into categories that capture both cognitive and emotional aspects of listening while differentiating levels of attentiveness. These categories and their indicators are summarized in Table 1 (See Section 3.2).

As shown in Table 1, eight behaviours were categorized, reflecting varying degrees of attentiveness across socio-cognitive and socio-emotional aspects of communication. **Encouraging listening** captures the *socio-emotional aspects of interaction*, which is important given that previous studies suggest high-performing groups display more socio-emotional interactions [17]. The *cognitive dimension* distinguishes between surface-level (**instrumental listening, paraphrasing**) and high-level attentiveness to the cognition of others (**construction**, **questioning**). Two behaviours at the surface-level level consist of brief responses to questions or requests and simple summarizations of others' ideas, without activating deeper cognitive engagement. Higher-level listening behaviours in the cognitive dimension involve asking questions to check shared understanding or elaborating on others' ideas, requiring more advanced cognitive processing. The *affirming dimension* is reflected in **back-channeling** and **confirmation**, which indicates agreement to others' ideas. **Counterargument** involves expressing an opposing view and captures interaction around conflict.

2.3 Research Gap and Research Questions

To the best of our knowledge, this is the first study in authentic CPS contexts to examine individual moment-by-moment listening behaviours in relation to group outcomes. Listening behaviours reflect group members' attention to each other, which supports CPS progress. Prior work on listening has limited applicability to CPS for two main reasons. First, most models of listening conceptualize listening as a skill in dyadic communication rather than as an observable, feedback-relevant behaviour. Second, their validation typically relies on self-reported measures designed for interpersonal communication, which remain either at a conceptual level or restricted to dyadic interactions.

To address the above-mentioned limitations, the present study examined listening behaviours among 34 students (ages 11-14) across nine groups in classroom CPS tasks. Drawing on prior work on listening, we developed an analytical framework and applied it to CPS discussion transcripts. Since the appropriate unit of analysis of listening in this context is unknown, it is necessary to examine three nested levels: (1) micro-level moment-by-moment observable listening behaviours, (2) their aggregates, and (3) recurrent patterns among the aggregates. We examine all three across CPS groups of varying performance, focusing on the following research questions:

- **RQ1.** What are the patterns of listening behaviours during CPS?
- **RQ2.** What is the relationship between the patterns of listening behaviours and group-level effectiveness of solving complex tasks?
- **RQ3.** How does the coupling between patterns of listening behaviours differ between groups with different effectiveness in solving complex tasks?

3 Methodology

3.1 The Study Context and Data

The data were collected in two separate sessions in a private school in South Australia. Data were collected from nine groups comprising 34 students aged 11-14 who were randomly assigned to groups. During the session in March 2023, 16 students participated in groups of four. During the second session, in May 2024, data were collected from 18 students arranged into three groups of four and two groups of three.

Both sessions used a Lego Mindstorms task where students had to assemble and program a robot that would be able to navigate six terrains of increasing difficulty. The goal was to drive the robot across each terrain for a 30-seconds. The terrains were constructed on large boards with progressively irregular surfaces, representing increasing levels of difficulty. Groups could advance to the next board after successfully completing the previous one. For the second session of data collection, each terrain was further divided into 3–4 subgoals and scores were assigned (2–4 points per board, 21 points in total) to provide a more fine-grained measure of group performance. To compare group performance in the CPS activity across the groups, we standardised the scores of all groups to a 10-point scale based on the number of boards completed and partial progress within boards.

Using these standardised scores, we classified the groups into four performance categories: Excellent, High, Low, and Zero. Group 1, which completed all six boards, was placed in the Excellent performance category (score = 10), representing a clear outlier in terms of achievement. At the other extreme, Groups 2 and 9 did not complete any boards and were therefore assigned to the Zero category (score = 0). The performance of the other groups was labelled as High (Groups 3 and 8, scores of 5 and 5.24) and Low (Groups 4, 6, 7, and 10, scores of 1.67, 1.9, 1.9, and 2.38) based on their relative progress. We deliberately retained Excellent and Zero as separate categories rather than merging them with adjacent groups because these extremes represent very different process outcomes: completing all tasks and failing to build a rover that can cross even the simplest terrain, respectively.

Each group's activity during the CPS task was recorded using analog audio devices and video cameras. Student exchanges were professionally transcribed. Utterances were segmented based on speaker changes, with a new line starting at each speaker's new turn. Each line in the transcript represented a semantically complete utterance and was treated as a unit of analysis. After cleaning the transcripts, a total of 540 minutes of data (60 minutes per group) were analysed, comprising 5,179 utterances. The average number of utterances per group was M = 575 (SD = 272). Across CPS groups, listening behaviours accounted for roughly 60–70%.

3.2 The Listening Coding Framework for CPS

We developed a listening framework (Table 1) to identify listening behaviours within CPS transcripts. By using content analysis, the coding framework is in line with suggestions [30], resulting in a dataset that is manually labelled following strict rules. Given the focus on text in the transcripts, the framework focuses exclusively on verbal aspects of listening. Based on the literature, a preliminary set of listening behaviours was generated by reading the transcripts. Next, using the eight listening categories outlined in Table 1, two coders independently coded the first 139 segments of one transcript. Through this process, the coders jointly reviewed the coded segments and refined the framework to improve clarity and consistency.

The unit of analysis was defined at the level of each speaker's utterance. Each utterance was restricted to a single code. If no listening behaviour was present, a segment was coded as a non-listening behaviour ("N"). Coders read a few surrounding utterances to ensure accurate contextual understanding before assigning a code to each target utterance. In cases of uncertainty about the label to assign, or if multiple listening behaviours could be assigned to the same segment, the utterance was set aside for further discussion, after the inter-rater reliability (IRR) was computed.

The overall IRR using Cohen's Kappa in the first round of coding was below 0.7. Kappa values were calculated for each individual listening category to identify sources of disagreement. In the initial round, question, counterargument, and back-channeling showed high agreement, while paraphrasing and construction showed low agreement. Their definitions were therefore refined, and explicit rules were developed to distinguish frequently confused categories. Four further rounds of iterative coding were subsequently conducted on a subset of the data, with coders reviewing disagreements and refining the coding rules after each round. By the fourth round, the overall IRR Kappa score reached 0.69, and by the fifth round Kappa reached 0.71.In the final coding round, the Cohen's Kappa values for all categories exceeded 0.59. Specifically, the coefficients were as follows: paraphrase (0.59), instrumental (0.67), construction (0.69), encouraging listening (0.87), question (0.83), back-channeling (0.78), counterargument (0.66), and confirmation (0.59). Given that 0.7 Kappa signals a good agreement, the remainder data were independently coded by the first author. Refined coding definitions used by the coders are reported in Table 1.

The coding framework contained eight categories (see Table 1). Back-channeling (8.16%) and confirmation (3.80%) originated from different strands of the listening and CPS literature. Both categories functioned similarly in our dataset as expressions of agreement and were therefore merged for analysis. Paraphrase (2.35%), which reflected shallow information-oriented engagement (i.e., restating or summarizing another utterance), accounted for a small proportion of the data and was merged into the instrumental listening category (18.1%). The remaining four categories included encouraging listening (6.77%), counterargument (13.16%), question (27.16%), and construction (20.48%). After these adjustments, six categories were used for the quantitative analysis.

3.3 Data Analysis

Data analysis process is summarised in Fig. 1. Using content analysis [30], we have generated a description of moment-by-moment listening behaviours for each transcript utterance (Fig. 1). After that, to address RQ1, cluster analysis was applied to segments of listening behaviour, separated by non-listening behaviour. This allowed to examine patterns of these moment-by-moment behaviours across the CPS activities. To investigate if these patterns differ across group performances (RQ2), a chi-square test was used. Because listening segments arise from continuous interaction and may exhibit contextual or temporal dependence, as well as may be independent, we conducted sensitivity analyses under alternative dependence assumptions. Finally, to understand if these patterns recur over time forming particular listening states, we constructed a correlation-based coupling network (RQ3). The pairwise correlations between timeseries of patterns reflected how listening patterns rose and fell together over time.

RQ1 addressed the presence of listening patterns in CPS through the use of cluster analysis. After labeling each utterance at the individual level defined in the listening coding framework (Table 1), we segmented the discussions by using instances of non-listening as boundaries. Each segment thus consists of a “continuous” sequence of listening behaviours, represented as a string of labels (e.g., [instrumental, question, question, construction, counterargument]).

To calculate the similarity between listening descriptions for each of the segments, a computation which is needed for clustering, we assigned a numerical value to each listening behaviour (confirmation = 0, encouraging listening = 0, instrumental listening = 1, construction = 1, counterargument = 1, question = 2). However, to better capture and emphasize the patterns for specific listening segments, these counts were subsequently transformed into percentages. This method ensures that the percentages computed are not influenced by the length of the listening segments, allowing us to capture the dominant listening behaviours in each of the segments regardless of the segment length.

We then applied k-means clustering to all listening segments to identify aggregates of listening patterns. K-means clustering adopts an iterative approach to optimize the position of cluster centroids and assigns each sample to the nearest centroid. To determine the appropriate number of clusters to explore, average silhouette widths (ASW) were computed. We selected the 10 listening clusters solution by AWS and report their composition. The ASW was 0.47, indicating a moderate overall structure: clusters are present but with non-negligible boundary overlap.

The within-cluster sum of squares (WCSS) elbow reached the lowest value (889,917.5) at k=10. Another method for determining the best number of clusters was implemented: the gap statistic method [53]. We additionally applied the Gap Statistic to determine the number of clusters, which suggested ten as the optimal cluster solution.

To address RQ2, we examined whether the distribution of listening clusters differed across the four performance groups. We constructed a contingency table (performance group × listening cluster) and conducted a chi-square test of independence [1]. When the test was significant, follow-up pairwise chi-square tests were conducted to examine whether the distribution of listening clusters differed between each pair of performance groups.

To address RQ3, we built correlation-based coupling networks for each performance group, in which the nodes represent the six states. Coupling refers to the simultaneous occurrence of multiple listening patterns, which may characterize specific states formed by the group. These states capture how aggregates of listening behaviours unfold over time. We time-aligned each 60-minute CPS group activity by partitioning it into six equal-progress windows (10 minutes each). For every window, there are several listening clusters (identified in RQ1), we computed the mean percentage of each listening state from these aggregated patterns. Within each performance group, to examine how listening states were correlated, we then treated all these window observations within each performance group as data points and calculated Pearson correlations for a set of state pairs.

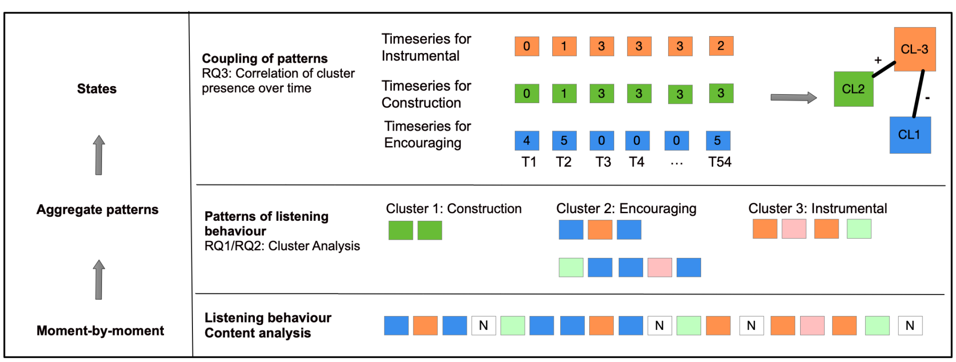

Fig. 1. Overview of methodology: content analysis of moment-by-moment listening behaviours, cluster analysis of aggregate listening behaviours, and coupling network analysis of temporal interdependencies between listening patterns.

Table 1. Description of coding categories for listening behaviours

Listening Behaviour	Definition in Literature	Indicators in CPS	Examples
Encouraging listening (Roos et al., 2023; Clark and Lemay 2024) [13, 44]	Motivating the speaker to continue participating, by offering support, expressing empathy for others' feelings, fostering connection, recognition, and acceptance	Supporting emotion or recognizing group members' emotional issues	I think our team's doing pretty good.
		Encouraging action when group feels uncertain	Just try without it first.
		The utterance conveys positive socio-emotional elements	Yeah, it's about right down there. Perfect
Paraphrase (Weger et al., 2014; Bodie, 2017) [9, 56]	Repeating or summarizing the speaker's utterance without adding personal evaluation or judgment.	Repetition of others' utterances	*Spk A:* It's a pushy thingy. *Spk B*: Pushy thing, yo, yo, yo
		Summarizing meaning, no further extensions of the meaning	*Spk A*: We went backwards. *Spk B*: We went back a page.
Instrumental listening (Bavelas et al., 2017; Kuhn et al., 2018) [7, 34]	Responding to requests with brief, direct answers that meet the immediate need or expected response without adding extra opinions or information.	Responding to request or giving a hand to others but not making own argument.	*Spk A*: Can I have two black things? *Spk B*: I already got them for you.
		Short response not adding content information, just a shallow/superficial reaction	*Spk A*: Did you guys already do this? *Spk B*: That one, we haven't done that.
Construction (Barron, 2003) [5]	Involving building on the previous speaker's ideas by elaborating, adding details, and bringing out or recognizing others' thinking.	Building on others' ideas. Same words between the utterances, with expansion of the ideas could be one salient indicator.	*Spk A*: Yeah. I mean it should work... *Spk B*: I think Sam should drive...
Confirmation (Molenaar & Chiu, 2014) [37]	Demonstrating agreement or understanding.	Showing agreement (if short acknowledgment, label as back-channeling)	*Spk A*: We have to detach the little ball. *Spk B*: We do have to detach the ball.
Back-channeling (Weger et al., 2014) [56]	Brief acknowledgments to encourage continued disclosure, indicating attention to the speaker's thought	Brief/simple acknowledgments	Yeah
Counterargument (Molenaar & Chiu, 2014) [37]	Involving resistance, rebuttal or denial to the other's utterance.	Rejecting/disagreeing others' proposals for task execution	*Spk A*: You didn't need this bit at all. *Spk B*: Oh no, you need that to hold the thing together.
Question (Bodie, 2017) [9]	Involving an active effort to seek information, request clarification, and check understanding.	Seeking clarification/Checking back for understanding	The motor, I don't know what this means?
		Seeking information	It's not moving. Why?
		Checking for shared understanding	Okay. And do I start at number one?

4 Results

4.1 Cluster Analysis for Listening and Descriptions

The total number of listening segments was $N = 1317$. The longest segment had a length of 35 individual utterances, although such cases were rare. 95% of segments between the non-listening behaviour were no longer than 11 utterances, while 75% fell within 5 utterances. Segments were typically short to medium in length (*Mdn* = 3, *IQR* = 4), with 48% classified as short (fewer than 3 steps) and 18.75% as long (7 or more steps).

The centroids for the ten-cluster k-means solution are presented in Figure 2 based on the percentage of listening behaviours within the segments. These centroids illustrate the behavioural composition of each cluster. Figure 3 further displays the standardised segment proportions of each listening cluster across performance groups. For each cluster, proportions were computed within groups and then z-scored across the four groups to highlight relative over- or under-representation. The identified clusters are described below.

Cluster 1: Instrumental Listening-dominant (*N* = 98, 7.4%). The cluster consisted of 95.6% instrumental listening behaviours. In terms of group performance, the performance group that completed zero levels exhibited such behaviours more frequently, whereas the other three performance groups engaged in them less often.

Cluster 2: Mix of Question and Instrumental (*N* = 231, 17.5%). With 41.7% of question behaviours and 41.3% of instrumental listening behaviours, this cluster reflects a procedural question–answer cycle. It was the most prevalent in the zero-output group, where it appeared to sustain collaboration but contributed little to the generation of new ideas for task progression.

Cluster 3: Counterargument-dominant (*N* = 85, 6.5%). This cluster is dominated by counterarguments (96.9%), reflecting conflicts of opinion among members. It was relatively frequent in the Low and Excellent performance groups, but less so in the High and Zero groups. This distribution suggests that conflicting exchanges alone are not sufficient to account for performance differences.

Cluster 4: Question-dominant (*N* = 140, 10.6%). This cluster is dominated by questions (96.4%), reflecting members' attempts at clarification and exploration. It shows considerable potential for initiating inquiry. The behaviour was more common in the Low, High, and Excellent groups, but relatively infrequent in the Zero group.

Cluster 5: Mix of Confirmation and Question (*N* = 127, 9.6%). With 35.6% confirmation and 33.9% question behaviours, this cluster represents a mixed pattern of acknowledging other group members' contributions and seeking subsequent CPS actions. Such questions often appear as simple confirmation checks.

Cluster 6: Confirmation-dominant (*N* = 65, 4.9%). This cluster is dominated by confirmation behaviours (96.0%), characterized by acknowledging others' ideas and agreeing on task directions. It reflects smooth interaction with limited cognitive depth. It is less frequent in the High and Low groups but more prevalent in the Zero and Excellent groups.

Cluster 7: Construction-focused (*N* = 229, 17.4%). This cluster is characterized by 45.5% construction behaviours, alongside a mix of listening behaviours. It is more frequent in higher-performing groups, increasing from 11.1% in the Zero group and 16.2% in the Low group to approximately 21% in the High (21.2%) and Excellent (21.5%) groups.

Cluster 8: Encouraging Listening-dominant (*N* = 88, 6.7%). Comprising 70.9% encouraging behaviours, this cluster reflects socio-emotional support that helps maintain a positive atmosphere and participation. Its higher prevalence in the Zero and Excellent groups indicates that, while beneficial for group climate, this behaviour may not directly translate into improved performance or productivity.

Cluster 9: Construction-dominant (*N* = 105, 8.0%). This cluster is dominated by construction behaviours (98.0%), characterized by sustained expansion and integration around a single solution with little interruption from other behaviours. Similar to the Construction-focused cluster (Cluster 7), it is more frequently observed in the High (9.7%) and Excellent (11.5%) groups than in the Zero (1.7%) and Low groups (8.3%).

Cluster 10: Counterargument-focused (*N* = 149, 11.3%). Characterized by 36.9% counterargument behaviours in combination with various other listening types, this cluster occurred more often in the Low (14.9%) and Excellent (12.0%) groups, less in the Zero group (10.4%), and least in the High group (4.7%). Although counterargument at moderate levels may facilitate clarification, its high frequency or dominance is negatively associated with performance, highlighting the importance of redirecting such exchanges toward constructive building.

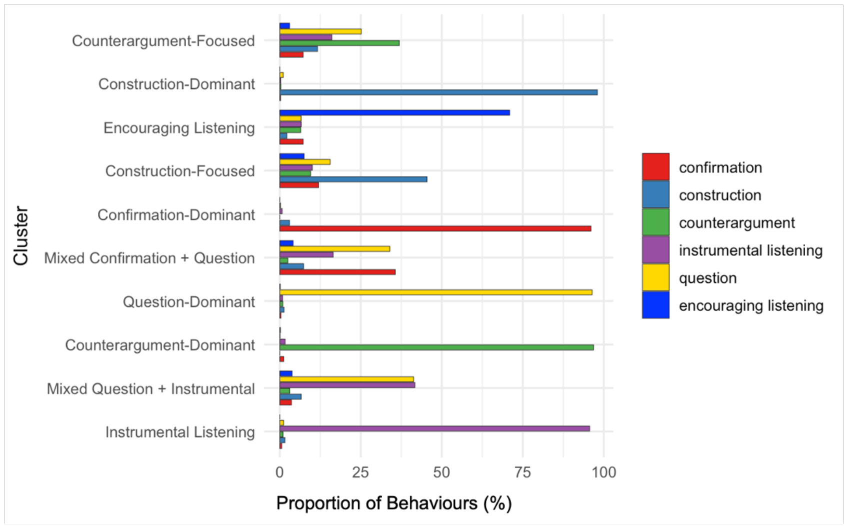

Fig. 2. Behaviour Proportions across Clusters

4.2 Listening Cluster Distribution across Group Performing Levels

To address *RQ2*, we conducted chi-square tests to examine whether the distribution of listening clusters differed across performance groups. The z-scored clusters are shown in Fig. 3. Results indicated an association between the four performance groups and cluster distribution. An omnibus chi-square test revealed a significant difference in the distribution of listening-behaviour clusters across the four performance groups ($\chi^2(27, N = 1317) = 105.16,\ p < .001,\ V = .163$). Cramér's V is an effect size measure used with chi-square tests of independence, describing the strength of association between categorical variables. Pairwise chi-square tests with Bonferroni correction identified group pairs differing in their cluster distributions. Differences ($p < .001$) in the distribution of the ten listening clusters were observed between the Zero group and each of the three performance groups: Zero vs. High ($V = .295$), Zero vs. Low ($V = .262$), and Zero vs. Excellent ($V = .346$). These results indicate that the listening behaviours of the group that failed the task differed substantially. The corresponding Cramér's V values suggest small to medium effect sizes. As a post hoc analysis, we examined observed–expected differences to identify which clusters were associated with each performance group [1]. We found that the pattern "Mixed Question + Instrumental" was significantly over-represented, whereas the pattern "Construction-Dominant" was under-represented in the Zero Group. In the Excellent group, the pattern "Mixed Question + Instrumental" was under-represented. In the High group, the pattern "Counterargument-Focused" was under-represented.

The analyses above treat listening segments as independent observations. Whether segments are dependent or independent is unknown a priori: nesting and temporal ordering could induce dependence, but segments are distinct interactional events. To examine this, we conducted sensitivity analyses across a range of assumptions.

Investigating potential group-level dependence, we conducted a group-block permutation test, in which performance labels were permuted across the nine groups ($p \approx .34$), and a Rao–Scott cluster-adjusted χ^2 using group as the clustering unit (F-based $p \approx .074$). Both procedures yielded substantially larger p-values than the original segment-level χ^2 ($p < .001$). Under the extreme assumption that all segments within a group are fully dependent, the omnibus association is therefore not supported.

Changing the assumption to local temporal dependence, we grouped consecutive segments into blocks of size k (with $k = 1$ corresponding to segment-level independence and $k = 250$ approaching group-level dependence). We applied two approaches: block permutation of block labels followed by chi-square analysis and Rao–Scott χ^2, which analytically corrects for intra-block correlation. The omnibus association remained significant ($p < .01$) for $k \leq 50$. At $k = 30$–50, both methods yielded closely comparable p-values ($p \approx .0004$ at $k = 30$; $p \approx .004$–$.006$ at $k = 50$), indicating that the result is not an artifact of how dependence is modeled. Beyond $k = 100$, block permutation p-values exceeded .05, approaching the group-level estimate.

For pairwise comparisons under block permutation, Zero vs. all other groups remained significant up to $k = 50$ (all $p \leq .013$). Among non-Zero groups, differentiation was weaker and emerged only at smaller block sizes: High vs. Excellent reached significance at $k = 10$ ($p \approx .03$) and was marginal at $k = 15$ ($p \approx .055$); High vs. Low was marginal at $k = 10$ ($p \approx .06$); Low vs. Excellent remained non-significant ($p \approx .27$ at $k = 10$).

The contrast between the Zero group and all other groups is supported across a wide range of temporal dependence assumptions. Differentiation among Excellent, High, and Low is weaker and sensitive to independence assumptions.

4.3 The Coupling Network Across Group Performing Levels

The coupling networks for each performance group are shown in Figure 4, in which the nodes represent the six listening states. The orange line represents a negative correlation, and the blue line represents a positive correlation. The nodes are linked based on Pearson's r. The thickness of the links reflects the strength of the relationship: thicker lines indicate stronger connections, corresponding to a higher co-occurrence of listening patterns. The four performance groups showed some similarity in the links between different listening states, with some notable differences. Overall, construction showed links to multiple other listening states, though the strength of these links varied across performance groups. Across all groups, instrumental listening and construction showed moderate to strong negative links, and only the Low group showed a significant correlation, $r = -.488, p < .005$.

In the Excellent group, construction showed strong negative associations with counterargument ($r = -.870, p < .05$) and question ($r = -.640$). Two weak positive associations were observed: between counterargument and encouraging listening ($r = .128$) and between construction and confirmation ($r = .214$), though neither reached statistical significance. The High-performance group showed negative associations across the entire network (e.g., instrumental and question: $r = -.530$). The links between encouraging listening and counterargument ($r = .334$) and between construction and encouraging listening ($r = .219$) showed weak to moderate positive relationships.

In the lower-performing groups, the links between construction and confirmation were negative (Zero: $r = -.324$; Low: $r = -.339$). Both performance groups showed weak positive associations between counterargument and construction (Low: $r = .296$; Zero: $r = .316$). Compared with the Zero group, the Low group additionally exhibited a weak positive relationship between construction and encouraging listening ($r = .107$).

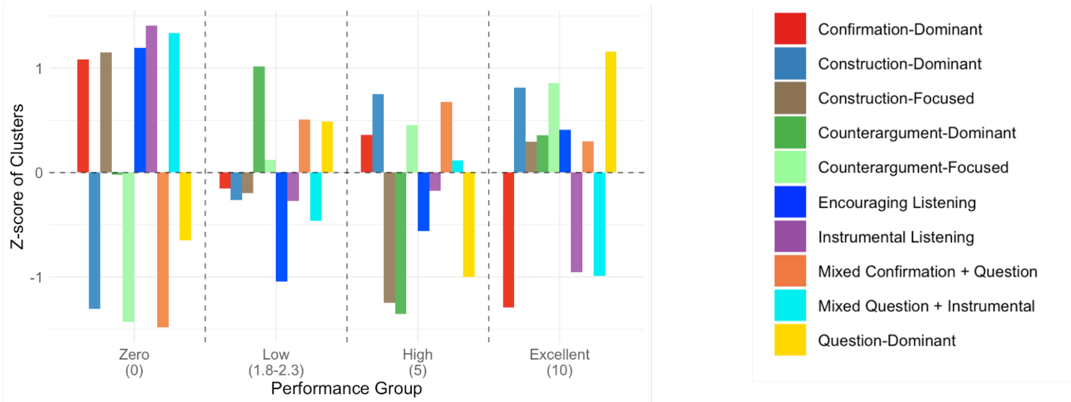

Fig. 3. Listening Clusters Across Performance Groups

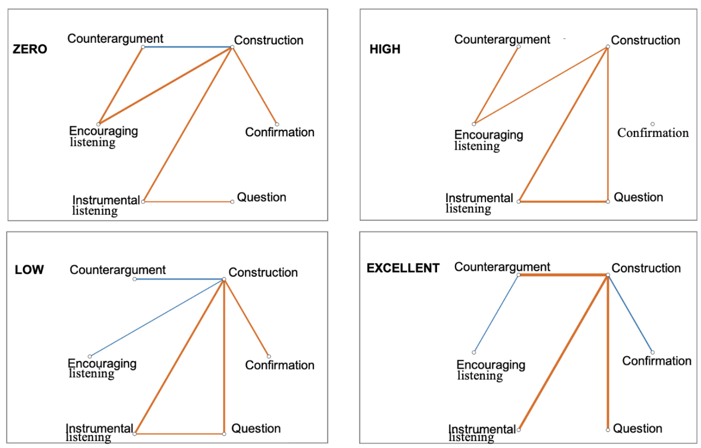

Fig. 4. The correlation-based coupling networks of the varying performance groups. The networks are based on co-occurrence links between listening behaviours during the CPS activity, with ***negative*** (orange) and ***positive*** (blue) correlations.

5 Discussion

Our study examined moment-by-moment listening behaviours in authentic CPS contexts and how they relate to group outcomes. Listening reflects how group members attend to one another, and effective CPS appears to build on such signals. Yet prior work has mainly examined listening in interpersonal communication, and existing models lack clear behavioural indicators applicable to CPS. To address this gap, we analysed listening behaviours as observable indicators of CPS processes, focusing on how these behaviours accumulated into patterns and how these patterns co-occurred into listening states over time. We found that effective and ineffective groups displayed distinct listening patterns that accumulated from moment-by-moment listening behaviours and they differ in listening states. Specifically, effective groups engaged in counterarguments with constructive listening, whereas less successful groups showed two ineffective patterns: questioning with instrumental listening and counterarguments or questioning without encouraging listening.

Table 2. Correlation coefficients by performance group.

State A	State B	Zero	Low	High	Excellent
Construction	Question		-0.469*	-0.333	-0.640
Counterargument	Encouraging listening	-0.449		-0.334	0.128
Instrumental listening	Question	-0.191	-0.220	-0.530	
Confirmation	Construction	-0.324	-0.339		0.241
Construction	Counterargument	0.316	0.296		-0.870*
Construction	Encouraging listening	-0.512	0.107	-0.219	
Instrumental listening	Construction	-0.398	-0.488*	-0.433	-0.640

Note. Correlation coefficients are shown only if $|r| > 0.1$.
Significance: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; no star = not significant.

Our findings from RQ1 highlight the patterns of listening behaviours in authentic CPS tasks. Cluster analysis revealed ten distinct patterns, including six dominated by a single listening behaviour (e.g., instrumental listening, counterargument, questioning, confirmation, encouragement, and construction) and four reflecting mixed patterns (e.g., combinations of question and instrumental listening, or confirmation and question). These patterns illustrate the diversity of listening patterns that emerge when groups engage in CPS.

In RQ2, we examined how listening patterns varied across performance groups, with the most robust distinction observed between the Zero group and the remaining groups, and weaker differentiation among the non-Zero categories.The Zero group exhibited a superficial pattern of listening that relied mainly on instrumental and confirmation behaviours. According to the coding framework (Table 1), instrumental listening reflects a procedural form of task-following. It supports task progression but primarily involves shallow cognitive engagement with limited potential for the construction of knowledge or ideas. The CPS processes of Zero group students have mainly focused on procedural aspects of moving the task forward (e.g., how to do it or what it is) through question and quick response exchanges. Although encouraging behaviours and some construction occurred in the group, these were not substantial enough to drive deeper cognitive engagement. This finding suggests that the Zero group tends to pay only superficial attention to others, rather than engaging in deeper cognitive exchanges. The low-performing group showed different patterns of extensive questioning and counterarguments but showed little encouraging behaviours, suggesting that their critical exchanges were not accompanied by emotional support, which might have influenced the low overall performance.

Among the non-Zero groups, the high-performing groups combined construction with confirmation, while the occurrence of questions and instrumental listening remained moderate. This pattern suggests that confirmation was used to coordinate and support constructive progress. By contrast, the Excellent group shows a different pattern. Unlike the zero-performing group, they rarely relied on the combination of questioning and instrumental listening, and instrumental listening itself was minimal. Instead, their interaction was strongly characterized by questioning and counterargument, rather than confirmation or instrumental listening. Confirmation occurred less frequently than in the other three performance groups, while construction was more prominent than in any of them. These contrasts among the non-Zero groups should be interpreted as suggestive rather than definitive, as their statistical support depends on assumptions of segment independence.

In RQ3, we further inquire into how the co-occurrence of listening patterns within each performance group unfolds over time. The Zero-performing group showed a heavy reliance on surface-level behaviours but lacked deeper constructive engagement. In the low-performing group, team resources were directed toward questioning and counterargument, which often came at the expense of construction. When counterargument and construction occurred together, they tended to create tension rather than coordinated progress, and the absence of confirmation or emotional support further limited collaborative advancement. By contrast, the Excellent group combined critical moves and construction with confirmatory and affective support, which helped sustain progress despite potential relational strain. High-performing groups also displayed relatively strong construction and confirmation, but these did not consistently co-occur as a pattern. This suggests that, similar to the Excellent group, they relied on a structure of critical moves plus construction, yet lacked the same level of confirmatory and emotional support to buffer against conflict.

Our findings highlight that patterns of moment-by-moment listening behaviours can have an accumulated effect, shaping different CPS listening patterns. Additionally, certain listening aggregates are more likely to couple in effective and ineffective groups. More productive groups were characterized by participants actively engaging with one another's thinking, actively and deeply listening and responding to their peers [33]. In contrast, the low-performing groups in our study exhibited conflicting positions, which often pulled interactions in competing directions and required constant negotiation of shared understanding. This aligns with [26], who emphasize that building shared understanding depends on ideas being clearly articulated, positively appraised, and recognized by the team before moving forward.

High-performing groups demonstrated that conflict or disagreement can lead to deeper constructive cognitive engagement among individuals. Our findings align with prior findings that disagreement, when verbalized and resolved, can foster deeper understanding [14]. At the same time, our results indicated that such constructive conflict requires emotional support and confirmation from peers in order to move forward. Encouraging emotions reflect members' supportive attitudes and help establish a climate of respect and trust that facilitates effective group work [4].

6 Limitation and Future Work

We acknowledge several limitations. First, the sample size of nine CPS groups is relatively small, which limits generalisability and calls for replication with a larger number of groups. Although the analysis includes 1,317 listening segments, the effective sample size depends on assumptions about temporal and contextual dependence among segments; we addressed this through permutation-based sensitivity analyses. Second, the analysis focused exclusively on verbal listening behaviours derived from group discussion transcripts. Incorporating multimodal data such as audio, video, gaze, or gesture could provide a richer account of listening processes in future work. Third, other individual and contextual variables may influence both listening behaviour and group performance. Because students were randomly assigned to groups and drawn from the same school, these factors were likely addressed, but cannot be fully ruled out.

Despite these limitations, this study makes several contributions. First, we developed an analytical framework of listening, which is suitable for CPS context. Second, we provide insights into a nested granularity of analysis, ranging from individual listening indicators to listening patterns and higher-level listening states, and show how these differ between different levels of group performance. Our findings suggest that listening is a practical lever for supporting individuals and has actionable implications for educational design, including feedback, scaffolds, and training in CPS.

Building on the insights of our study, future research should focus on automating the detection of listening behaviours in CPS and examining whether, and to what extent, such behaviours contribute to improving the effectiveness of CPS communication and CPS competence. We suggest future researchers to validate our analytical framework in other small group collaboration and learning contexts, such as Computer Supported Collaborative Learning (CSCL), and CPS in virtual environments. In addition, it would also be valuable to explore whether, and in what ways, individual listening behaviours change during the CPS process and whether they converge over time into group-level patterns or a shared listening culture. Finally, future research could consider multimodal analytics of listening behaviours in CPS. Enriching text data with other data channels, such as gaze, body posture, physiological signals, and vocal features can provide deeper insights into how individual listening behaviours have an accumulated effect on group interaction and how these relate to group performance.

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