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Students' meaning-making of nonverbal communication as representational scaffolding in UK chemistry education: Chinese students' cross-cultural perspectives

Wing-Fu Lai [ab]

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Chemistry learning places distinctive multimodal demands on students, requiring coordination across symbolic, submicroscopic, and macroscopic representations. While nonverbal communication has been shown to support representational reasoning in chemistry, it is often treated as a stable instructional resource, with limited attention to how its meaning is interpreted across cultural and educational contexts. This study examines how nonverbal communication functions as a discipline-specific semiotic resource in internationalised chemistry classrooms, drawing on the experiences of fifteen Chinese international students engaged in chemistry learning in the UK. Guided by a sociocultural and interpretivist framework, in-depth semi-structured interviews were thematically analysed to explore how students notice, interpret, and respond to instructors' nonverbal cues. Findings show that visual and auditory nonverbal cues serve distinct roles in supporting translation across representational levels and engagement with spatial, mechanistic, and procedural aspects of chemical knowledge. Students' interpretations of these cues were strongly shaped by prior educational experiences and culturally grounded expectations, which in some cases led cues to be overlooked or misinterpreted as incidental rather than instructional. These findings highlight the importance of making nonverbal resources explicit to support inclusive engagement with chemical representations in internationalised classrooms.

1. Introduction

Learning chemistry poses unique cognitive and representational challenges. Students must navigate multiple levels of representation (including macroscopic phenomena, submicroscopic structures, and symbolic notation) (Taber, 2013). Constructing meaningful understanding of chemical concepts (such as reaction mechanisms, orbital hybridization, molecular geometry, and laboratory procedures) requires spatial reasoning, mechanistic thinking, and the ability to coordinate abstract, symbolic, and procedural knowledge (Stieff *et al.*, 2022). As in other scientific disciplines, there is growing recognition that linguistic competence plays a significant role in chemistry education (Markic *et al.*, 2013, Mönch and Markic, 2022), with factors such as insufficient language skills and limited familiarity with scientific discourse practices negatively affecting students' engagement and motivation (Lee and Fradd, 1998; Lee, 2005). While language plays a central role in mediating chemistry learning, verbal explanations alone are often insufficient to fully convey spatially and temporally evolving chemical phenomena (Irungu *et al.*, 2019; Deng and Flynn, 2023). For example, the motion of electrons in a reaction mechanism, the spatial orientation of functional groups, or the correct handling of laboratory apparatus are difficult to communicate through spoken language in isolation (Irungu *et al.*, 2019). Effective understanding therefore depends on the integration of multiple representational and communicative resources (Desutter and Stieff, 2017). Representational translation across symbolic, submicroscopic, and macroscopic levels remains a core cognitive demand in chemistry learning (Sim and Daniel, 2014), while mechanistic reasoning enables students to interpret reaction pathways and connect conceptual models to laboratory practice.

Over the last several decades, research has increasingly examined how nonverbal communication contributes to representational competence and mechanistic reasoning. Within this context, nonverbal communication can be understood as a discipline-relevant pedagogical resource that works in conjunction with verbal explanation rather than replacing it (Irungu *et al.*, 2019). Gestures, posture, and spatial positioning can help externalise otherwise abstract or procedural aspects of chemical knowledge and scaffold students' cognitive processing

[a] *School of Education, University of Bristol, Bristol BS8 ITS, UK*
[b] *School of Food Science and Nutrition, University of Leeds, Leeds LS2 9JT, UK. E-mail: rori0610@graduate.hku.hk*

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(Flood *et al.*, 2015; Stieff *et al.*, 2016a), while physical models can provide visual anchors for understanding bonding, stereochemistry, and reaction intermediates (Stieff *et al.*, 2016a, 2016b). Collectively, these multimodal cues can support students in coordinating relationships across symbolic, submicroscopic, and macroscopic representations while also promoting metacognitive engagement in chemistry learning (Rickey and Stacy, 2000). Despite growing recognition of their importance, much of the existing literature has predominantly conceptualised nonverbal cues as relatively stable and broadly generalisable instructional resources, with emphasis placed on their instructional effectiveness (Ping *et al.*, 2021; Mortimer and Pereira, 2024). Less attention has been paid to how such cues are interpreted by learners, or how their meaning may vary across different educational and cultural contexts. This limitation is significant because nonverbal communication does not carry fixed meanings (Cooperrider and Núñez, 2009; Calbris and Copple, 2011); rather, it is interpreted within socially and culturally situated frameworks of interaction, an idea consistent with interactional perspectives such as those developed by Goffman (1959, 1974). From this viewpoint, gestures, spatial positioning, and other nonverbal cues function as context-dependent resources whose meaning emerges through shared expectations and prior experience.

The role of nonverbal cues therefore becomes especially salient in internationalised classrooms, where students' prior educational experiences and culturally shaped interpretive frameworks may influence how such cues are perceived and acted upon. Students who have been socialised in educational environments that emphasise explicit verbal instruction and observational learning may encounter nonverbal cues in UK chemistry classrooms as unfamiliar or ambiguous, influencing how they experience and make sense of classroom interaction in chemistry learning contexts. This study examines how nonverbal communication shapes the chemistry learning experiences of international university students enrolled in food science programmes in the UK. These programmes provide a particularly relevant context because chemistry constitutes a core disciplinary component, yet students are typically non-chemistry majors. As a result, they are required to engage with complex chemical content despite having less established representational and symbolic fluency, which may increase cognitive load and heighten reliance on multimodal scaffolds (Chittleborough and Treagust, 2007). Chinese international students were selected as a model population due to their substantial presence in UK higher education and documented differences between Chinese and UK pedagogical environments (Mcmahon, 2011; Iannelli and Huang, 2014; Zhang, 2021), making them a useful group for examining how nonverbal communication is interpreted across educational contexts. It is the aim of this study to address the following research questions:

(1) How do Chinese international non-chemistry-major students perceive nonverbal communication as supporting the multimodal demands of chemistry education?

(2) How do these students perceive variations in the use of nonverbal communication to support the multimodal demands of chemistry learning across different instructional and cultural contexts?

(3) How do students' prior educational experiences and cultural backgrounds shape their interpretation and use of nonverbal communication in UK chemistry classrooms?

By exploring 15 recruited Chinese students' interpretations of nonverbal cues in UK chemistry classrooms through qualitative interviews, this research illuminates how culturally mediated expectations intersect with discipline-specific multimodal demands in chemistry learning. In particular, this study is expected to extend chemistry education research by examining how nonverbal communication functions as a tool for supporting representational translation across macroscopic, submicroscopic, and symbolic levels, and how students' prior educational experiences may shape interpretation of these cues. It is hoped that the context-specific account presented in this study can inform culturally responsive pedagogical practices by generating actionable insights for supporting the interpretive competence, engagement, and learning of students from diverse cultural backgrounds in chemistry classrooms.

2. Theoretical framework

This study is informed by a sociocultural perspective on learning, which emphasises the role of social interaction and culturally situated practices in shaping human cognition and behaviour (Kozulin, 2023; Lai, 2023). From a sociocultural standpoint, learning is not viewed as an individual or purely internal process, but as one that is fundamentally mediated through social relations, cultural norms, and shared meanings developed over time (Lai, 2023). Within this framework, nonverbal communication is understood as socially learned rather than biologically inherent. The meanings associated with nonverbal cues are acquired through participation in culturally specific social interactions and are sustained through social consensus (Guerrero and Floyd, 2006). As a result, individuals learn not only how to produce nonverbal behaviours, but also how to interpret them in ways that are considered appropriate and meaningful within the cultural context. This perspective helps explain why patterns of nonverbal communication vary across cultures, despite similarities in human biological makeup. Apart from this, sociocultural research suggests that the influence of societal norms on nonverbal cue interpretation often operates at an unconscious level (Philippot *et al.*, 1999). In another word, interpretive frameworks have likely been internalised through repeated social experience. Individuals may, therefore, find it difficult to articulate the underlying motivations or assumptions guiding their responses during nonverbal interactions (Bogdan, 2010; Zittoun and Gillespie, 2015). This has important implications for cross-cultural educational settings, where differences in socially constructed meanings among students may lead to misinterpretation of instructors' communicative intentions (Hayati and Sinha, 2024; Pang *et al.*, 2024). By foregrounding the socially constructed nature of nonverbal communication, this framework supports

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an analysis of how Chinese students' experiences of chemistry learning are shaped in UK higher education.

In addition, and in alignment with the sociocultural framework outlined above, this study is situated within an interpretivist paradigm, which treats participants' accounts as situated constructions shaped by culture, context, and prior experience (Pervin and Mokhtar, 2022). Within this paradigm, social phenomena are understood as dynamic and context-dependent rather than fixed or universal (Ikram and Kenayathulla, 2022); accordingly, the aim of this study is to generate nuanced understandings of students' interpretations of instructors' nonverbal behaviours rather than to derive generalisable laws or to produce objective measurements of classroom behaviour. Guided by this epistemological stance, this study adopts a qualitative approach to explore how international students of Chinese origin perceive nonverbal communication within chemistry learning environments in the UK. Participants' accounts are treated as meaningful expressions of how nonverbal cues are understood and negotiated within specific chemistry learning contexts.

3. Methodology

3.1. Research setting and participant recruitment

Participants were eligible for interview recruitment if they met the following criteria: (1) self-identified as being of Chinese origin, (2) were currently enrolled in, or had previously completed, food science programmes within UK higher education, and (3) had completed at least one chemistry-related taught learning activity (*e.g.,* taught modules, training sessions, or laboratory classes) within their programme. Participants were recruited through convenience sampling. Following initial recruitment, purposive sampling was employed to recruit additional participants who met the study criteria (Ahmad and Wilkins, 2025). Participants were also invited to provide voluntary direct or indirect referrals to others who met the inclusion criteria. A total of 15 students were recruited. Among them, 40% (n = 6) self-identified as male and 60% (n = 9) self-identified as female. Of these, 46.7% (n = 7) were undergraduates and 53.3% (n = 8) were postgraduates. Among the undergraduates, 42.9% (n = 3) self-identified as male and 57.1% (n = 4) self-identified as female. Among the postgraduates, 37.5% (n = 3) self-identified as male and 62.5% (n = 5) self-identified as female. All participants self-identified as being of Chinese origin. The programme of study, length of stay in the UK, and subject areas engaged in chemistry-related taught learning activities were presented in Table 1.

3.2. Data collection

Data were collected through in-depth, semi-structured interviews lasting approximately 60 minutes, guided by an interview guide (Table 2) that was refined following three pilot interviews to ensure clarity, relevance, and alignment with the research aim. Interviews were conducted in English and audio-recorded with participants' consent. Demographic information, including gender and programme level, was collected to contextualize participants' experiences and provide insight into the diversity within the sample. Participants were recruited and interviewed until data saturation was reached, defined as the point at which

Table 1 Characteristics of the research participants

ID	Gender	Place of origin	Programme of study	Programme length	Year of study	Length of stay[a]	Subject areas engaged[b]
P01	Male	Mainland China	PhD	3 years	1	1 year	Food chemistry; organic chemistry; materials characterisation
P02	Male	Mainland China	PhD	3 years	1	2 years	Food safety; food structure and function; physical chemistry; biochemistry; chemical engineering
P03	Male	Hong Kong	BSc	3 years	3	3 years	Biochemistry; food structure and function; food safety and preservation; food chemistry; food analysis
P04	Female	Mainland China	PhD	3 years	2	2 years	Biochemistry; organic chemistry; analytical chemistry
P05	Male	Mainland China	BSc	3 years	2	2 years	Food processing; food structure and function; biochemistry; food chemistry
P06	Male	Hong Kong	BSc	3 years	3	4 years	Food structure and function; biochemistry; food chemistry
P07	Female	Mainland China	MSc	1 year	1	1 year	Food chemistry; food safety and preservation
P08	Female	Mainland China	BSc	3 years	1	1 year	Biochemistry; food chemistry
P09	Female	Mainland China	BSc	3 years	1	1 year	Biochemistry; food chemistry
P10	Male	Mainland China	PhD	3 years	3	3 years	Organic chemistry; analytical chemistry; physical chemistry
P11	Female	Mainland China	MSc	1 year	1	1 year	Food chemistry; food safety and preservation; food analysis
P12	Female	Mainland China	BSc	3 years	2	2 years	Food processing; food structure and function; biochemistry; food chemistry
P13	Female	Mainland China	MSc	1 year	1	1 year	Organic chemistry; physical chemistry; biochemistry
P14	Female	Mainland China	MSc	1 year	1	1 year	Organic chemistry; inorganic chemistry; biochemistry
P15	Female	Mainland China	BSc	3 years	2	2 years	Food processing; biochemistry; food chemistry

[a] Length of stay refers to the total duration of participants' residence in the UK at the time of data collection. [b] Subject areas engaged refer to the chemistry content areas in which the participant engaged in taught learning activities.

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Table 2 Question guide for in-depth interviews

Question type	Question
Opening	Could you share which country you consider to be your home country? Could you share how you describe your gender and ethnicity? How would you like me to address you during the interview? Which chemistry or chemistry-related taught learning activities have you undertaken in your programme?
Introduction	How would you personally define nonverbal communication in a classroom setting?
Transition	Thinking of "nonverbal communication" in a chemistry-related class, what comes to your mind? What do you think is the role, if any, of nonverbal communication in supporting teaching and learning in your subject?
Key	Why and how, if any, do you think your teacher has used any nonverbal communication cues purposely in his/her teaching? Have your teachers used any nonverbal communication cues shown by you to understand your learning and participation in their class? Why and how? Can you think of anything that might affect how your teacher understands your nonverbal behaviour? Can you think of anything that might affect how you use nonverbal cues? Thinking back on different factors you just said, which of those things has had the biggest impact on how nonverbal communication works in the classroom?
Ending	Can you give us some advice on how to enhance the use of nonverbal communication in a class related to chemistry or related subjects? Do you have any remarks, suggestions, additions to what have been discussed so far?
Additional unplanned/floating prompts	What do you think is behind that? How did that make you feel? Why do you think that happens?

no new themes or concepts emerged from additional interviews (Saunders *et al.*, 2018). To validate this judgement, two additional interviews were conducted once data saturation was judged to have been reached, in order to confirm that no further unique perspectives were identified. Data collection and analysis occurred iteratively, allowing emerging insights to inform subsequent interviews.

Following initial analysis, a subset of participants (n = 6) was purposefully selected for follow-up interviews to elaborate on emergent themes. This approach provided deeper contextual detail and supported an interpretivist aim of understanding participants' meaning-making processes in chemistry classrooms. Selection of participants for follow-up interviews was based on the richness of their initial accounts and their ability to provide illustrative, chemistry-specific examples of nonverbal behaviours experienced in chemistry classrooms. Prior to each follow-up interview, the interviewer reviewed the participant's initial transcript and prepared brief prompts and notes relating to previously discussed experiences, examples, or emerging themes. Follow-up interviews were flexible and participant-specific, allowing participants to expand on previous responses and highlight experiences or perceptions most relevant to key themes. Each follow-up interview lasted approximately 30–40 minutes and was audio-recorded and transcribed using the same procedures previously applied to the initial interviews.

3.3. Data analysis

Data analysis in this study involved coding, thematic analysis, and cross-case comparison, with thematic analysis conducted following Braun and Clarke's framework (2006). Interview transcripts were first analysed line-by-line to generate data-driven codes summarizing participants' experiences and perceptions of nonverbal communication in chemistry classes. These codes included descriptive elements (*e.g.*, "gesture", "facial expression", "tone of voice"), interpretive elements (*e.g.*, "sense of being encouraged", "increased anxiety", "seeking teacher approval"), contextual factors (*e.g.*, "lecture", "laboratory", "class size pressure") and identity-related elements (*e.g.*, "personal culture", "cultural expectations", "rapport building"). These codes were grounded in participants' narratives and reflected the content of discussion rather than any behaviours observed during the interviews themselves. They reflected the presence of discussion around a topic rather than uniform agreement among participants. This approach enabled the full range of participants' experiences and interpretations to be captured, even when perspectives differed. Initial codes were iteratively reviewed, refined, or merged. Less frequent codes were retained to ensure that all perspectives were represented.

Codes were grouped into themes, which in turn were further organized into domains to reflect higher-order patterns across participants' accounts. Themes reflected recurring patterns in the data, while domains represented higher-level organisational structures that integrated related themes. Cross-case comparison highlighted similarities and differences in how participants perceived instructors' nonverbal behaviours in relation to teaching effectiveness, engagement, and comprehension. Data from follow-up interviews were integrated into this analytic process to refine and elaborate themes, providing richer examples and clarifying participants' interpretations of nonverbal communication in chemistry classes in the UK.

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The resulting coding framework was provided in the supporting information (SI). It was used as an analytic aid underpinning the overall analytic process, with all codes informing the findings reported in the Results and Discussion section. Throughout the analysis, the focus remained firmly on participants' experiences, interpretations, and meaning-making. No direct observation, recording or analysis of participants' nonverbal behaviour during the interviews was conducted, as such behaviour was not relevant to the study's interpretivist aims. The analysis sought to represent how participants perceive and interpret nonverbal communication in chemistry classrooms, rather than to document or analyse their behaviours.

3.4. Trustworthiness

The trustworthiness of the study was enhanced by addressing credibility, dependability, and confirmability. Credibility was strengthened through the use of open-ended interview questions designed to elicit rich, detailed accounts of participants' experiences. During interviews, the researcher paraphrased participants' responses, invited clarification and sought elaboration, providing real-time member checking to ensure interpretations accurately reflected participants' intended meanings. Dependability was supported by maintaining a detailed audit trail that documented methodological decisions throughout data collection and analysis. Coding and thematic analysis were conducted through an iterative and reflexive process, in which codes were continuously reviewed, refined, and compared across transcripts to ensure they accurately represented participants' accounts. To enhance confirmability, emerging codes and themes were discussed with a peer researcher, who provided feedback on the interpretation and organisation of the data. This process of peer debriefing supported critical reflection and helped ensure that interpretations remained grounded in the data. Additionally, reflexive notes maintained by the researcher documented assumptions, decisions, and analytic reflections throughout the study.

3.5. Ethical considerations

All procedures conducted in this study adhered to the Declaration of Helsinki and received approval from the School of Education Research Ethics Committee at the University of Bristol (approval code 25224). Before data collection, participants were asked to provide informed consent and were fully briefed on their rights, including voluntary participation and withdrawal at any stage. To protect confidentiality, each participant was assigned a research code.

4. Results and discussion

This section presents findings from an interpretivist analysis of how Chinese students' prior educational experiences shape their noticing, interpretation, and use of nonverbal communication in UK chemistry classrooms. Analysis of fifteen interview transcripts identified the overarching domains: (i) forms of nonverbal communication; (ii) factors shaping it; (iii) experiences of it; (iv) its application; and (v) cognizance of it.

4.1. Participants' understanding of nonverbal communication

Twelve of the fifteen participants associated eye contact, gestures, and body movements with nonverbal communication, describing it broadly as communication without words. For example, P14 defined nonverbal communication as "communication between teachers and students, or among students, without spoken or written language, using facial expressions, eye contact, or gestures to convey information", whereas P17 noted it allows teachers to "convey information, emotions, or attitudes without using spoken language – through eye contact, facial expressions, gestures like nodding or shaking your head, and other physical reactions." Three participants reported limited prior familiarity with the concept. P07 admitted, "I'm not exactly sure what nonverbal communication means," and P15 had never thought explicitly about nonverbal cues. P09 even misinterpreted the term as "communication that's not in your native language." Several participants who could articulate definitions of nonverbal communication also acknowledged that they were not consistently aware of such cues in chemistry classrooms, as P05 stated: "I think I didn't notice any nonverbal communication used in class."

Participants linked their limited awareness to prior educational experiences in China, where chemistry instruction was described as teacher-centred and verbally focused (P02, P09). This instructional style was attributed to curriculum intensity and lesson pacing. They reported that heavy content loads and dense schedules in chemistry-related classes limited their ability to attend to interactional details in class, while also constraining teachers' capacity to incorporate non-verbal cues as part of instruction. This teacher-centred and verbally focused environment in chemistry classrooms in China was further linked to an assessment-driven teaching approach. As P02 explained, "In China, exams often account for a larger proportion of the final grade in chemistry-related modules. Therefore, if lecturers want their students to achieve better results, they may compress the teaching schedule to leave time at the end for exam-focused revision and Q&A sessions…Consequently, both lecturers and students may become more focused on covering knowledge points in the chemistry curriculum and on preparing for exams, rather than attending to non-verbal communication in the classroom. In contrast, in the UK, chemistry classes often cover a smaller amount of content per lesson and…most modules are assessed by coursework. This allows lecturers greater flexibility in deciding what to teach and therefore more scope to use non-verbal communication to support their teaching." This may help to account for why participants tended to describe themselves as having been socialised to attend primarily to spoken explanations and written instructions, rather than to nonverbal cues. From a sociocultural perspective, this suggests that attentional practices in chemistry classrooms are not neutral but are institutionally shaped, with assessment structures and curricular

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pacing mediating what counts as relevant communicative information (Black and Wiliam, 1998; Gibbs and Simpson, 2005). In this context, when UK instructors used non-verbal cues to scaffold representational translation, some students initially appeared not to recognise these as intentional chemistry-specific teaching strategies, but rather as peripheral or incidental actions. This highlights a misalignment between the semiotic resources emphasised in different educational contexts and students' expectations of how chemical meaning is communicated.

Few participants (P01, P02, P04) suggested that, beyond curriculum demands and an assessment-driven teaching approach, the structure of classroom practices and learning resources may socialise Chinese students into attentional patterns that reduce sensitivity to non-verbal cues in chemistry learning. They described chemistry teaching in China as heavily reliant on board-writing, printed textbooks, and unreleased lecture slides, requiring sustained attention to copying content, following explanations, and coordinating multiple information sources simultaneously. Handwritten note-taking was described as demanding continuous cognitive effort, leaving limited attentional capacity for gestures, facial expressions, or other non-verbal cues. This suggests that students' cognitive resources during chemistry instruction in China are largely directed toward symbolic and textual representations. By contrast, participants noted that in the UK, where slides are often provided in advance and teaching is more digitally supported, reduced transcription demands allow greater attention to teachers' explanations and accompanying non-verbal communication. This shift was interpreted as a redistribution of attentional labour, enabling increased engagement with multimodal representations of chemical phenomena and shaping students' attentional habits across contexts. As a result of these socialised attentional patterns, participants reported occasionally overlooking subtle non-verbal cues in chemistry instruction in the UK. This is illustrated by P09: "I was attending a lecture in the UK on a fairly complex redox reaction… I was focused on copying the equation and did not really notice his hand gesture… I ended up reversing the direction of electron transfer… later the teacher repeated the gesture, and I realised it indicated electron flow". This misinterpretation reflects prior participation in educational contexts where embodied cues were not foregrounded as instructional signals (Kress, 2009; Calbris and Copple, 2011; Müller *et al.*, 2013; Bezemer and Kress, 2015). It highlights how attentional habits shaped through prior schooling influence the extent to which non-verbal cues are noticed and incorporated into chemistry understanding (Wertsch, 1991a, 1991b; Hutchins, 1995), although participants also emphasised that such cues can function as important scaffolds when successfully perceived.

4.2. Varieties of nonverbal communicative modes in chemistry classrooms

After inviting participants to share their own definitions of "nonverbal communication," we defined the term as the process of conveying messages without using words and provided illustrative examples (*e.g.*, smiling to signal friendliness or using tone of voice to express frustration) to ensure a shared understanding for the remainder of the interview. Diverse nonverbal modes were reported in chemistry instruction, with several being discipline-specific. Through iterative coding and comparison of the interview transcripts, two broad categories of nonverbal modes emerged: visual and auditory.

4.2.1. Body-based visual modes. Participants consistently identified visual modes as an important component of nonverbal communication in UK chemistry classrooms. Visual modes were described in two main categories: body-based and non-body-based modes. Body-based modes included gestures, facial expressions, eye contact, posture, and teacher movement, while non-body-based modes encompassed physical models, props, and visual representations such as slides. This distinction reflects how meaning in chemistry classrooms is distributed across multiple semiotic resources, including embodied action and material artefacts, which together support access to disciplinary knowledge, consistent with embodied cognition and social semiotic perspectives on meaning-making in learning (Zuckerman *et al.*, 1981). Among body-based modes, gestures were the most frequently highlighted, with twelve of fifteen participants noting their perceived importance. Participants described gestures as particularly helpful for following explanations of abstract or spatially complex chemical concepts, supporting literature that identifies gestures as supportive or compensatory resources for verbal expression (Goldin-Meadow, 2014; Müller *et al.*, 2014; Müller, 2018), particularly in chemistry classrooms where technical language may not yet be sufficiently developed to support emerging concepts. P12 explained, "…gestures can sometimes explain concepts more clearly than words, so they use nonverbal cues to make lessons easier to understand." P01 also shared, "…gestures were used in a food chemistry session to explain structural changes in proteins during processing, such as the setting of egg whites, the firming of yogurt, and the transformation of meat from soft to firm…The teacher interlaced his fingers and squeezed them into a tight ball, representing the native protein in its folded structure. He then simulated the addition of heat and gradually released his hands until fully extended, representing denaturation…when I observe the process of folding, unfolding, and cross-linking undergone by proteins, as illustrated through his gestures, it becomes easier to understand their irreversibility. This is a concept that is difficult to convey using words alone". These accounts highlight how gesture functions as a representational tool (Cooperrider, 2019), making dynamic submicroscopic processes perceptible through embodied movement. In P01's example, gestures also support translation across Johnstone's three representational levels (Johnstone, 2000): submicroscopic processes (*e.g.*, structural rearrangement of proteins), macroscopic phenomena (*e.g.*, tangible changes in food texture and structure), and symbolic representations (*e.g.*, diagrams of protein folding/unfolding on slides). Beyond protein structural changes, participants (P01, P02, P03, P10) also reported that instructors used gestures to explain nucleophilic attack trajectories and three-dimensional molecular orientation. From a cognitive load perspective, gestures reduced extraneous load and supported intrinsic load management by externalising

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spatial and mechanistic reasoning (Chandler and Sweller, 1991; Milenković *et al.*, 2014). They also facilitated translation between representational levels, consistent with representational competence frameworks in which learners coordinate macroscopic, submicroscopic, and symbolic representations (Johnstone, 2000). In addition, within the Gesture as Simulated Action (GSA) framework (Hostetter and Alibali, 2019), such gestures can be understood as reflecting embodied simulation processes underlying mechanistic reasoning (Mcneill (2019)), potentially making aspects of the teacher's representational chemical reasoning publicly observable during explanation.

Gestures were also described as central in laboratory learning. P01 stated, "The teacher stands next to a spray dryer, and points to atomiser, drying chamber, and cyclone separator, explaining how each part works and how to set it up…In this kind of teaching, they rely more on hand gestures than on long verbal explanations." In this context, gestures appeared to scaffold understanding of equipment setup and operation, complementing verbal instruction (Wakefield and Goldin-Meadow, 2021). From a sociocultural perspective, this suggests that gestures function as mediational means in the development of procedural understanding, potentially supporting learners' engagement with laboratory practices *in situ*. Gestures were further reported to signal key conceptual points, as P04 noted: "When the teacher is explaining something important, they might use hand gestures to make sure students are paying attention." Participants described gestures as directing attention to epistemically significant aspects of explanation, particularly in dynamic processes such as rheological change. This was illustrated by P01: "When the teacher is explaining non-Newtonian fluids, such as ketchup and yogurt… they use the speed of their hand to show what's going on… That's ketchup at a low shear rate… Then the teacher speeds up the hand… That's a high shear rate… The degree and speed of the waving really land with us." Here, gesture functions as an embodied means of highlighting variation in process parameters in real time, shaping what students attend to within unfolding explanations (Müller *et al.*, 2014). In addition, while prior work categorises gestures into non-imagistic and imagistic types (Asbels 2016), the present data suggest that these functions frequently overlap in chemistry teaching contexts. As illustrated in P01's account of rheological explanation, a single gesture may simultaneously structure students' attention, support conceptual understanding, and represent non-observable processes.

Facial expressions were the second most prominent body-based cue. Participants described them as shaping the emotional climate of chemistry classrooms and influencing engagement with challenging content. P08 noted, "If the teacher looks happy and enthusiastic, it boosts my desire to learn", while P09 explained, "Smiling helps encourage me to answer questions… during a lecture on the redox cycle of polyphenol oxidase… the lecturer looked at me in a supportive way, which made me feel more at ease and gave me the confidence to speak up." This highlights how affective dimensions of classroom interaction are mediated through nonverbal cues that shape participation in disciplinary discourse. Positive expressions were perceived as particularly helpful when students engaged with abstract chemical reasoning or complex laboratory procedures. Similar findings have been reported in primary education by Marici *et al.* (2025), where teachers' positive emotional expressions fostered stronger student–teacher relationships and enhanced classroom engagement. Our interview data suggest that such effects may also extend to chemistry education in higher education contexts. This indicates that engagement with chemical content is co-constructed through cognitive and affective dynamics (Flaherty, 2020). Participants' perceptions of the impact of teacher enthusiasm on their chemistry learning also align with previous findings by Qian *et al.* (2022), reinforcing the role of nonverbal affective cues in regulating attention and cognitive load during complex learning tasks.

Apart from gestures and facial expressions, posture and teacher movement were perceived by participants as meaningful in chemistry classes. Seven participants indicated that stance, orientation, or positional changes could signal transitions in chemical reasoning. P02 stated, "Sometimes lecturers change their physical position in the classroom… that movement signals to us that something is changing, for example, from qualitative explanation to quantitative analysis or from conceptual overview to stepwise mechanistic reasoning". Teacher movement was described as helping students recognise shifts in explanatory mode and reasoning, structuring complex content into more cognitively manageable segments and reducing split-attention effects while supporting multimodal integration (Ayres and Sweller, 2005). From a sociocultural perspective, it structures participation frameworks in chemistry instruction (Goffman, 1981) and signals shifts in expected epistemic activity (Goffman, 1981, Kendon, 1990; Wertsch, 1991b; Goodwin, 2000; Berland and Hammer, 2012). Eye contact was also described as an additional feedback and attention-regulation mechanism. Eight participants highlighted its role in gauging comprehension or maintaining focus during procedural tasks. P04 explained, "If I'm thinking about something or the teacher is explaining something important, eye contact may occur between the teacher and me as a mutual signal of whether we are on the same page". P06 noted that a glance could serve as a subtle behavioural cue: "My lecturer doesn't scold me. Instead, they might just glance at me… like a silent reminder". Eye contact was therefore experienced as an interactional resource for coordinating attention and monitoring understanding without disrupting instructional flow (Kendon, 1990). This reflects how meaning-making is mediated through gaze as part of instructional interaction, enabling alignment of attention and interpretation during chemistry learning.

4.2.2. Non-body-based visual modes. Non-body-based visual modes were similarly noted by participants as important. Physical models were described as aiding visualization and supporting the development of mental models of bonding, polarity, and molecular interactions, helping students anchor abstract submicroscopic concepts (Justi and Gilbert, 2002; Coll *et al.*, 2005; Coll, 2006; Dayal and Ali-Chand, 2022). Eight participants emphasised that such models made otherwise

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invisible structures more accessible for reasoning about chemical phenomena. PowerPoint slides and props mediated chemical understanding by highlighting key processes across representational levels, complementing and structuring verbal explanations (Gilbert, 2005). Three participants described them as helping to organise and visualise abstract chemical concepts, particularly when engaging with otherwise intangible phenomena. These accounts align with findings from Olympiou and Zacharia (2012), which show that students' understanding of science concepts can be enhanced through engagement with multiple representational modalities, such as physical and virtual models, which together support integration across different forms of representation. Beyond instructional artefacts, P13 also highlighted how instructors' clothing influenced perceived approachability, which she associated with her willingness to engage with challenging chemical material. This perception was not explicitly framed as specific to either UK or Chinese classroom contexts, suggesting that peripheral visual cues may operate beyond a single geographical setting in shaping participation through their role in signalling interpersonal accessibility and influencing students' engagement with complex chemistry content.

A few participants (P01, P02) also highlighted board work as an embodied form of meaning-making in chemistry classrooms. Writing, erasing, and redrawing chemical structures were described as nonverbal forms of modelling scientific reasoning, externalising the iterative and revisable nature of mechanistic thinking (Oatley and Djikic, 2008). Participants mentioned that they initially did not interpret these actions as instructional cues, instead they focused on copying final written content and missing epistemic signals such as hesitation or correction. P01 explained: "When I attended chemistry or related classes in China… teachers rarely scribbled things out… In the UK… they would stop, erase something, redraw it… They are showing students how a scientist actually thinks and self-corrects in real time… we could miss the key signal in those erasing moments." This suggests that nonverbal communication in chemistry extends beyond interpersonal cues such as gesture or gaze to include embodied inscription practices that structure how scientific knowledge can be communicated temporally and visually (Pantidos *et al.*, 2022; Kindfield and Singer-Gabella, 2010; Tanis Ozcelik and Mcdonald, 2013). When uncertainty and revision are made visible in real time through these practices, a mismatch may arise between prior classroom norms and UK instructional practices, posing interpretive challenges for students socialised to view written content as finalised and authoritative.

4.2.3. Nonverbal auditory modes. In addition to visual forms of nonverbal communication, participants emphasised the discipline-specific role of auditory modes in chemistry classrooms. Because chemistry teaching frequently involves transitions between conceptual and practical tasks (Holme *et al.*, 2015; Dayal and Ali-Chand, 2022), auditory modes were described by students as supporting attention management, cognitive processing, and task sequencing. This reflects the inherently temporal and process-oriented nature of chemical knowledge, where learners must follow ordered sequences of actions and representations (Taber, 2024). One example was the deliberate production of controlled sounds by instructors, such as tapping the blackboard, laboratory bench, or apparatus to signal activity shifts or capture attention (P02, P04, P07, P13). Participants reported interpreting these nonverbal communicative modes as regulatory signals within chemistry-specific workflows: a tap on a beaker could indicate readiness to begin a titration, highlight a critical procedural step, or mark the start of a mechanism discussion. This supports the idea that sound functions as a semiotic resource for structuring participation in laboratory and classroom practices (Mody, 2005; Weaver *et al.*, 2023), guiding students' engagement without reliance on explicit verbal instruction and aligning with attention-guiding principles in multimedia learning (Kozma and Russell, 2005a). Participants contrasted their chemistry classrooms in the UK with those in China, where verbal directives (*e.g.*, "start heating now" and "add the reagent carefully") predominate and nonverbal auditory cues are rare. As a result, they described needing to recalibrate their attention and meaning-making strategies when engaging with UK instructors' auditory signals. From a sociocultural perspective, this reflects a process of re-socialisation into new communicative norms (Henslin, 2018), where students must learn to recognise auditory cues as meaningful components of disciplinary practice rather than peripheral background signals.

Intentional silence was another auditory mode perceived as meaningful, particularly during explanations of the Maillard reaction mechanisms (P03), discussions of the mathematical steps involved in the Young-Laplace equation when explaining emulsion and foam breakdown (P10), and laboratory operations (P01, P03, P06, P07). Participants described silence as providing cognitive space to process multi-representational content, while also carrying culturally mediated meanings. P01 observed, "Silence is a powerful form of communication… staying silent shows that you're thinking, or it can express agreement, disagreement, or even tension." P06 similarly noted that teachers would remain quiet in ways that guided attention without verbal reprimand. These accounts suggest that silence operates not merely as the absence of sound but as an interactional and epistemic resource that regulates pacing, supports reflection, and signals expectations for independent reasoning (Su *et al.*, 2023; Alsoweed, 2025). In chemistry learning contexts, such pauses may further support students in integrating symbolic, visual, and conceptual representations when engaging with complex mechanisms or mathematical formulations, as suggested in earlier studies (Bachhel and Thaman, 2014, Liu *et al.*, 2022), and are consistent with segmentation principles in cognitive load theory (Mayer and Moreno, 1998; Mayer, 2005). From a sociocultural perspective, interpretations of silence are shaped by prior communicative norms (Yang and Kung, 2024; Wu *et al.*, 2025), influencing whether silence is perceived as an invitation to think, a signal of evaluation, or a source of uncertainty. In these accounts, silence was generally experienced as supporting reasoning and procedural awareness while interacting with participants' culturally shaped interpretive

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frameworks. Several participants contrasted these experiences with prior classroom practices in China, where silence was described more as a functional pause allowing students to copy notes or complete in-class tasks rather than as a communicative or pedagogical resource. Such comparisons suggest that students perceived silence in UK chemistry classrooms as carrying pedagogical and communicative meanings that differed from the more procedural forms of silence experienced in prior educational contexts.

Tonal variation was the third auditory mode mentioned by participants and was reported as supporting representational transitions and conceptual emphasis. P03 explained, "The teacher would respond with a stronger tone or deeper voice to emphasize the point…like highlighting something important", while P10 noted, "If their tone suddenly changes, that signals a shift. When I notice the change, I know something important is being introduced." Participants described tonal changes as especially useful for following multi-step processes, such as tracing reaction mechanisms or navigating instrument-based laboratory procedures. This indicates that tonal variation functions as an auditory marker of epistemic significance (Nurchintyawati, 2023; Paulmann and Weinstein, 2023), helping students prioritise information within complex sequences of chemical reasoning. Tone was also perceived as signalling urgency or safety relevance (Nurchintyawati, 2023), helping students discriminate between routine steps and higher-stakes actions in laboratory sessions. In this sense, tonal variation contributes to the regulation of both cognitive and practical activity (Nurchintyawati, 2023), supporting safe and effective participation in laboratory work. The tone of voice of the teacher in chemistry class was further reported to shape emotional engagement and classroom comfort, particularly when chemistry content was abstract or challenging. P08 highlighted that a lively, encouraging tone increased motivation when engaging with conceptually demanding topics such as molecular bonding and orbital concepts. Conversely, participants socialised in high-power-distance educational contexts reported heightened sensitivity to perceived negative tonal cues (P11, P14), sometimes interpreting subtle shifts as critique or disapproval. This suggests that prior educational socialisation and hierarchical classroom relations may shape how affective cues are interpreted (Bernstein, 1975; Mercer and Littleton, 2007; Clément, 2026), influencing students' willingness to participate and take intellectual risks. These experiences were linked to prior Chinese chemistry instruction, where mistakes (either conceptual or procedural) carry both cognitive and social consequences (Wu, 2009), influencing how students attended to auditory cues in UK classrooms. This suggests that auditory nonverbal communication is not interpreted uniformly but is filtered through culturally shaped expectations about authority, evaluation, and error (Wu, 2009), with implications for engagement in chemistry learning.

4.3. Determinants of nonverbal communication in chemistry classrooms

4.3.1. Sociocultural, demographic, and individual factors. Sociocultural background, particularly prior chemistry education in China, was frequently identified by participants as shaping how they perceived and responded to nonverbal communication in chemistry classrooms. As outlined in previous sections, participants linked their expectations of classroom interaction to earlier teacher-centred and verbally focused chemistry instruction, which influenced how nonverbal cues were interpreted in UK settings. As P01 reflected: "I think it's harder for teachers to pick up on non-verbal cues from Chinese students…". Even participants without explicit examples acknowledged cultural influence. For example, P08 commented, "I can't think of any examples or experiences, but I think cultural backgrounds could make a difference in nonverbal communication". This suggests that both explicit experience and tacit cultural schemas shape participants' assumptions about nonverbal communication in chemistry classrooms. Beyond sociocultural background, various individual differences (including emotional state, social anxiety, and interpersonal familiarity) were mentioned by participants as shaping the use of chemistry-related nonverbal cues in class. Moreover, P10 recalled an incident from his prior educational experience: "My professor in a general chemistry module once got really angry when he found out someone had used generative AI in an assignment on thermodynamics. He slammed the table with a pile of handouts, and his face went red… Some people might think he overreacted or was too harsh, while others might see it as a warning not to rely on generative AI". This suggests that the same nonverbal emotional display can be interpreted in multiple ways depending on students' prior experiences and relational positioning within the classroom (Gendron, 2017).

Some participants highlighted demographic characteristics as shaping nonverbal interactions in chemistry instruction, too. Younger teachers were generally described by participants as more energetic, expressive, and gesturally active, which participants associated with more dynamic and visually engaging explanations of chemical concepts (P09–P14). P11 observed: "Older chemistry teachers tend to have a more stable tone, use smaller gestures, rely more on facial expressions, and show more subtle movements when teaching chemistry. Younger ones are livelier, smile more, and use larger gestures in chemistry teaching". This suggests that age-related generalisations may shape participants' beliefs about teaching styles in chemistry instruction, influencing their perception of embodied teaching behaviours. Gender and perceived ethnic background were also occasionally noted, with female instructors sometimes described as displaying more expressive and relationally oriented nonverbal behaviours, and instructors perceived as Chinese as relying more on verbal explanation and fewer illustrative gestures. Overall, these accounts suggest that interpretations of nonverbal communication in chemistry classrooms may be influenced by prior educational and sociocultural experiences, consistent with Goffman's notion that social interaction is interpreted through learned frames of experience (Goffman, 1974).

4.3.2. Educational stage, disciplinary context, and classroom environment. Stage of education was described by participants as a factor shaping nonverbal communication, with differences reported between secondary school chemistry

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classes and university-level chemistry education (P03, P04, P06, P08–P15), reflecting shifts in pedagogical expectations. P08 explained: "In secondary school, teachers try to help us understand chemistry in a more intuitive way. For example, when teaching about compounds, they might use modelling clay to help us visualize the structure…In university, teachers mostly present their ideas over PowerPoint slides and we just take notes". For Chinese international students, this transition required adapting to reduced use of concrete demonstrations while maintaining comprehension of spatially and symbolically complex chemical content. This suggests that participants perceive progression to higher education as involving a shift in the semiotic environment of chemistry learning (Mcpherson *et al.*, 2017), moving from more guided, concrete demonstrations to more abstract, representation-heavy instruction.

Variation across chemistry sub-disciplines in the use of nonverbal communication was also noted by participants. Food chemistry and biochemistry were perceived by two participants (P01, P09) as involving more nonverbal cues than other areas, whereas analytical chemistry was described by three participants (P02, P06, P10) as being characterised by more gestural cues related to equipment use and experimental procedures. These differences were attributed to variations in content and teaching practices across sub-disciplines. For example, participants described gestures used to trace protein folding in biochemistry or to guide titration procedures in analytical chemistry, illustrating how nonverbal communication is experienced as supporting different forms of chemical understanding. Classroom infrastructure was reported by participants to further shape both the perception and enactment of nonverbal cues. Large lecture halls and physical distance were said to reduce the visibility and transmission of nonverbal feedback (P01–P03, P07–P11, P14). P02 observed, "In my undergraduate chemistry modules, classes were usually in large lecture halls because there were so many students. It was hard to see the teacher's face clearly, and I didn't really notice things like eye contact or facial expressions. But in my postgraduate studies, the chemistry classes are in smaller seminar rooms or classrooms because there are fewer students. The teacher is physically closer to us, so it's easier to notice things like gestures and facial expressions". This suggests that spatial organisation may influence the visibility and accessibility of nonverbal communicative resources in chemistry education (Kroczek *et al.*, 2020; Wang *et al.*, 2022). Chemistry learning may therefore be shaped not only by disciplinary content, but also by how sub-disciplinary practices and physical learning environments structure access to representational resources in instruction.

4.4. Experiences and perception of nonverbal communication in chemistry classrooms

Participants indicated that the interpretation of nonverbal cues was context-dependent. One example was provided by P01: "In chemistry classes in China, teachers usually talk pretty much non-stop... In the UK lab sessions...some teachers go quiet for a few seconds and sweep their eyes across the whole class with a serious look…at first, I totally misread that pause". Teacher movement and posture were similarly described by P01 as initially being interpreted as procedural or incidental rather than as interactional invitations within chemistry learning environments, leading to missed opportunities for engagement. These accounts indicate that the recognisability of nonverbal cues as pedagogical resources in chemistry instruction is shaped by students' prior educational experience, which structures what counts as meaningful instructional behaviour. Beyond interpretive alignment, participants also described affective and relational dimensions of nonverbal communication in chemistry learning environments. P04 explained, "Eye contact can make me feel nervous… sometimes I worry that I've done something wrong in the experiment." P01 similarly noted discomfort with sustained eye contact during a teaching session on food chemistry due to unfamiliarity with direct individual attention from instructors, while P06 described a casual touch from a teacher as "a bit odd" and "a little awkward." Such accounts suggest that nonverbal communication is not only cognitively interpreted but also emotionally and relationally negotiated (Goffman, 1959; Goffman, 1974; Vygotsky and Cole, 1978; Kress, 2009). In these cases, cues such as gaze and touch were not read as pedagogical support in chemistry instruction but were instead filtered through expectations about appropriate conduct, where interactions are often structured by formal teacher-student boundaries.

Participants' accounts also highlighted the evaluative role of nonverbal communication within chemistry learning, particularly in relation to assessment and epistemic judgement. P11 and P14 described instances in which tone, gaze, and facial expressions following errors in problem-solving or laboratory procedures were interpreted as signals of judgement regarding scientific understanding or experimental competence, affecting confidence and willingness to participate in subsequent chemistry tasks. Such interpretations illustrate how nonverbal cues are embedded within the evaluative structures of chemistry education, where student performance is continuously monitored through both explicit assessment and implicit behavioural feedback during chemistry instruction (Murphy *et al.*, 2024; Van Der Eijk *et al.*, 2024). Across these accounts, nonverbal communication in chemistry classrooms operates as a multimodal mediational system that functions as a resource for chemical conceptual and procedural understanding (Taber, 2013; Irungu *et al.*, 2019), but also operates as an affective and evaluative medium through which participation is regulated (Bambaeeroo and Shokrpour, 2017; Abekah Keelson *et al.*, 2024). Despite these evaluative and affective complexities, participants' overall experiences of nonverbal communication were positive. Participants generally perceived nonverbal communication as playing a discipline-specific role in supporting chemistry learning by making chemical concepts more accessible beyond verbal explanation alone. They reported that gestures and models supported comprehension of abstract, spatially complex, and procedurally structured chemical content, including electron movement in reaction mechanisms, molecular geometry and three-dimensional orientation, laboratory techniques, and experimental workflows (P01, P05). Some participants also

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mentioned that facial expressions, eye contact, and gestural cues enhanced engagement and classroom interaction (P02, P03, P12). Teachers' nonverbal enthusiasm was also perceived as motivating interest in chemistry content (P12, P15). Overall, nonverbal communication was experienced as both a cognitive scaffold for chemical understanding and an affective resource shaping participation and engagement.

4.5. Use of nonverbal communication in chemistry classrooms

As presented in preceding sections, participants described multiple ways in which teachers used non-verbal cues that they perceived as enhancing chemistry learning, ranging from visual modes (such as physical models and gestures) used to convey three-dimensional spatial relationships in chemical phenomena to auditory cues (including tone modulation or tapping) used to refocus attention during lectures and laboratory activities. Beyond their role in teacher-to-student communication, participants also indicated that non-verbal communication operates bidirectionally in chemistry classrooms. Participants described using nonverbal cues to seek approval (P03), demonstrate engagement (P01, P02, P03, P06), withdraw from participation (P07, P08, P11), offer silent acknowledgement (P11), or even convey perceived understanding or uncertainty to instructors (P01, P04, P05, P06, P08, P10, P12). P04 explained, "When I'm confused, I pause my writing and make eye contact with the teacher. If the teacher notices, they usually slow down, repeat, or rephrase the explanation." In chemistry contexts, articulating confusion verbally can be challenging due to the need to coordinate macroscopic, submicroscopic, and symbolic representations in real time (Kozma, 2003; Permatasari *et al.*, 2022), particularly for Chinese international students navigating interlanguage spaces (Lee *et al.*, 2023). This multi-representational demand increases cognitive load, limiting opportunities for immediate verbal expression of misunderstanding (Taber, 2009). P04's account shows that nonverbal signalling was adopted by students as a means of negotiating understanding during fast-paced teaching sessions. In laboratory settings, participants described using eye contact, gestures, and other subtle cues to signal hesitation or uncertainty, which instructors could interpret and respond to during ongoing experimental activity. Such interactional alignment was perceived as supporting both procedural accuracy and laboratory safety, particularly where timely adjustments were required to prevent errors during equipment handling or chemical procedures. Overall, nonverbal communication functioned as a coordination mechanism for aligning instructional pacing with student understanding in real time through shared attention and embodied interaction.

Peers introduced an additional layer of nonverbal mediation that extended coordination beyond instructor-student interaction into distributed self-organisation of learning activity. Rather than functioning primarily as responses to teacher-led pacing, peer cues operated as locally negotiated micro-signals for sustaining shared understanding during cognitively demanding chemistry tasks. P04 described using eye contact with other students in the class to verify alignment in conceptual understanding, noting, "Eye contact doesn't just happen between teachers and students. It also happens between students. For example, if I'm in class with a friend, we might make eye contact to check if we both understand something". Such exchanges indicate that peer-to-peer nonverbal communication functions as a mechanism for mutual epistemic checking during the interpretation of symbolic and mechanistic representations in classrooms, supporting alignment in conceptual reasoning and limiting the propagation of interpretive misalignments into subsequent in-class activities. In laboratory contexts, however, coordination shifts from epistemic alignment to procedural synchronisation within material and temporal constraints of experimental work. As P01 described: "when we needed to conduct a flame test... he would just point to the reagent bottle with a slight chin tilt, and I'd pass it to him". Here, gesture functions as an efficient coordination device embedded within the spatial, temporal, and safety conditions of laboratory practice (Kang and Tversky, 2016), enabling continuity of action without disrupting experimental flow. Unlike coordination in non-laboratory teaching spaces, which centre on aligning conceptual interpretation, laboratory-based nonverbal communication is oriented towards the orchestration of shared physical action where timing and precision directly affect the accuracy of observational data (*e.g.*, transient flame colour changes) and experimental outcomes.

4.6. Improvement of nonverbal communication in chemistry instruction

Participants identified several strategies perceived as enhancing nonverbal communication in chemistry classrooms. A primary recommendation was targeted teacher training to support the intentional use of nonverbal cues in conveying chemistry-specific content. P02 stated, "Chemistry teachers should be trained in how to use non-verbal communication effectively as part of their teaching skills... and to better interpret students' cues in chemistry lessons". Participants further recommended that teachers make more deliberate and varied use of nonverbal strategies, such as gestural tracing of key processes, positional shifts to signal conceptual transitions, or strategic silence to allow reflection. This reflects participants' awareness of nonverbal communication as a meaningful component of chemistry teaching and learning. Building teacher-student rapport was another key recommendation, with participants suggesting that closer interpersonal relationships may enhance teachers' sensitivity to students' silence, hesitation, and other subdued nonverbal responses in class. P01 further noted that chemistry teachers' awareness of students' culturally shaped communicative expectations (such as preferences for explicit instruction and reluctance to interrupt) may help prevent misinterpretation of nonverbal signs of reticence as disengagement in chemistry classrooms. Participants also emphasised that chemistry teachers should be aware of their own nonverbal behaviours (such as approachable facial expressions, attentive gestures, and responsive body language), as these may influence student participation in engaging with complex chemistry content.

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Class size and physical layout were also perceived as important for supporting nonverbal communication. Smaller class sizes and closer proximity between instructors and students were reported by some participants to enhance the visibility of gestures and eye contact, thereby supporting communication of chemistry content in teaching contexts. P10 remarked, "Classes should be smaller... when teachers and students are physically closer, they can pick up on each other's emotions and gestures more easily." This echoes the perception of participants in preceding sections that spatial organisation influences the visibility and accessibility of nonverbal communicative resources in chemistry education (Kroczek *et al.*, 2020; Wang *et al.*, 2022). Finally, few participants highlighted the role of students in enhancing nonverbal communication in chemistry learning environments. They reported that students may need to develop confidence in using nonverbal cues to support understanding of chemical representations, through interaction with teachers or peers in chemistry classrooms. This underscores that participants recognize that they are active agents in shaping communicative practices, not passive recipients of instructional cues. Such student agency is an essential complement to teachers' practices, reinforcing the bidirectional and co-constructed nature of nonverbal communication in chemistry learning across culturally diverse contexts.

5. Interpretation and implications

Nonverbal communication plays a central role in chemistry learning, particularly where abstract, spatial, and procedural knowledge must be coordinated across multiple representational levels (Kozma and Russell, 2005b; Fisher, 2017; Ping *et al.*, 2022). Findings from this study indicate that students' interpretations of nonverbal cues are strongly shaped by prior educational experiences and culturally grounded expectations. For participants socialised in teacher-centred chemistry classrooms characterised by predominantly verbal instruction, embodied cues in UK settings (such as body movement, posture, and gaze) were sometimes interpreted as procedural or incidental rather than as pedagogical resources. When recognised as meaningful, however, these cues supported mechanistic reasoning and the integration of symbolic notation, submicroscopic structures, and macroscopic phenomena (Kozma *et al.*, 2000). These findings indicate that nonverbal communication in chemistry functions not only as a cognitive scaffold for mechanistic and spatial reasoning, but also as a culturally mediated resource shaping students' representational competence across macroscopic, submicroscopic, and symbolic domains (Treagust *et al.*, 2003; Reid, 2021). This aligns with Goffman's interactional framework (Goffman, 1959), in which nonverbal cues acquire meaning through shared definitions of the situation and socially learned interpretive norms that guide interaction. From this perspective, nonverbal signals are not inherently transparent but are contingently understood within culturally situated expectations of classroom communication (Manusov, 2017). Taken together, these findings highlight the importance of extending institutional support for international students beyond language proficiency to include awareness of nonverbal and interactional norms specific to chemistry education. Induction programmes may therefore incorporate examples of how nonverbal cues function within established interactional norms in higher education settings, including laboratory-based and other practical learning environments.

Professional development for teaching staff may enhance awareness of how students' interpretive frameworks influence engagement with nonverbal communication in chemistry learning. Teachers may benefit from making implicit communicative practices explicit in internationalised chemistry classrooms, for example by stating that a hand movement represents electron flow when using gestures in reaction mechanism explanations, or by saying "let's pause before we move on to the next stage" when pauses mark transitions between safety-critical stages in laboratory procedures. Explicitly addressing how such cues may be interpreted differently across cultural backgrounds may help reduce assumption-driven misinterpretation and support more accurate engagement with chemistry learning activities. For nonverbal resources such as physical models and props, their use need not be limited to teacher demonstration. Teachers may allow students to actively engage with these resources, as this can promote learning by offloading the cognitive demands of mentally simulating chemical structures and processes onto external objects and embodied actions, thereby reducing cognitive load and supporting generative processing (Stull *et al.*, 2018). Teacher training that develops sensitivity to students' real-time attentional cues may also help regulate the pace of instruction and support participation in chemistry-specific reasoning and problem-solving, particularly in fast-paced, diagram-intensive lectures or procedurally demanding laboratory sessions.

Apart from this, as presented by the conceptual model of the interpretive cycle in nonverbal communication in chemistry classrooms as derived from the findings of this study (Fig. 1), interpretation of nonverbal cues is not solely experience-driven but also shaped by anticipatory assumptions about classroom communication. As illustrated by P08, students may invoke "cultural differences" as explanatory frameworks even when their direct experience of such differences remains limited. These interpretive lenses guide selective attention to particular cues and influence how meaning is assigned (Mercier, 2022), sometimes reinforcing initial assumptions through a recursive process of interpretation (Nickerson, 1998; Talluri *et al.*, 2018). This suggests that students' engagement with nonverbal communication in chemistry is shaped by the interpretive frameworks through which such practices are categorised. Such assumption-driven framing may influence students' participation and sense-making in chemistry learning. Initiatives aimed at challenging such assumptions through equality, diversity, and inclusion (EDI) in chemistry education may support students in developing more experience-grounded and context-sensitive interpretations of nonverbal communication in chemistry learning.

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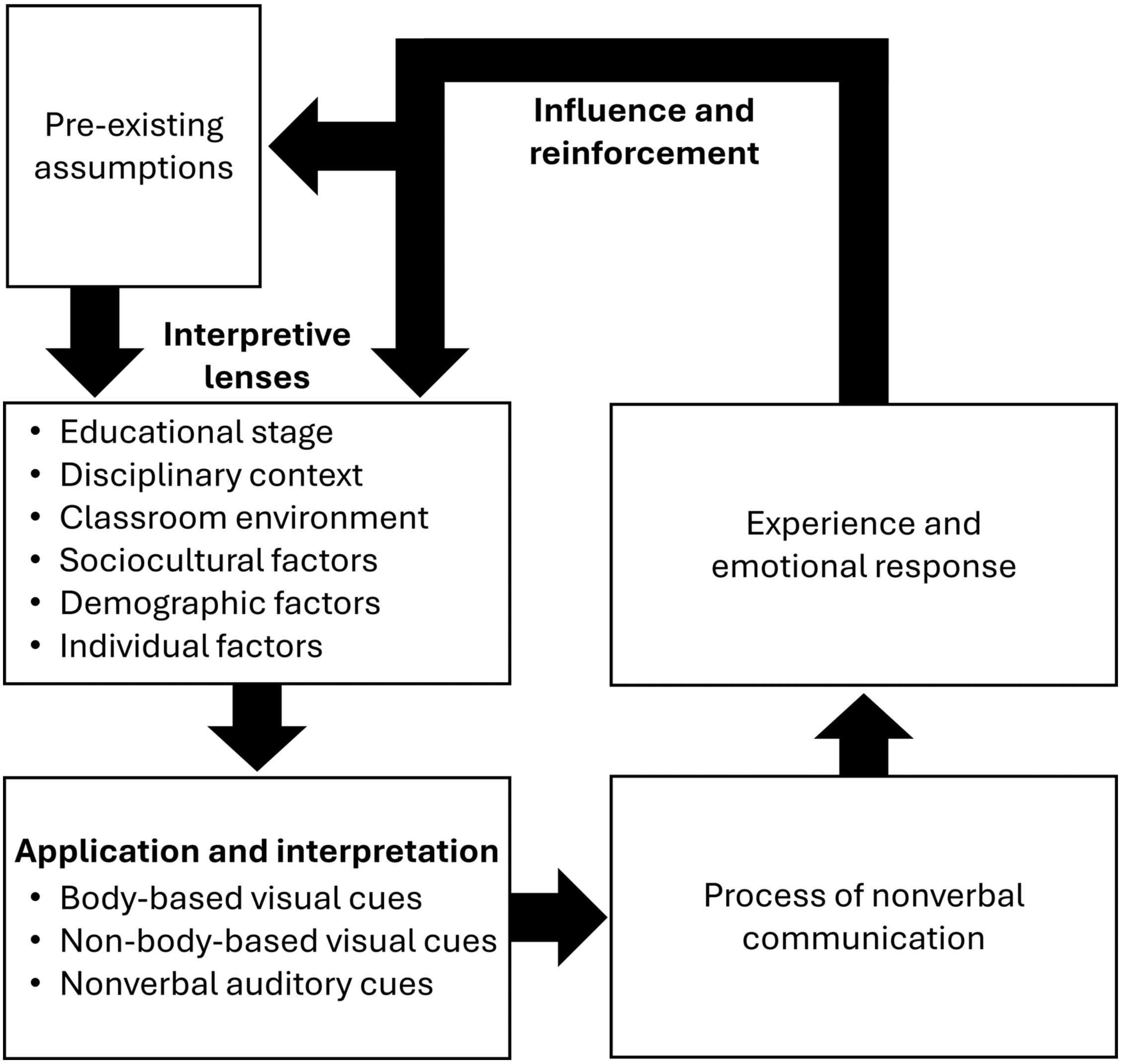

Fig. 1 The conceptual model illustrating the interpretive cycle in nonverbal communication in classroom settings.

6. Concluding remarks

Nonverbal communication, as shown in this study, is an integral component of chemistry pedagogy, structurally embedded within the teaching and learning of complex scientific concepts rather than being a peripheral classroom feature. It plays an important role in shaping international students' experiences of chemistry learning in UK higher education. Findings of this study further indicate that the interpretation and effectiveness of nonverbal cues are mediated by culturally shaped interpretive frameworks developed through prior chemistry education. Students' experiences in teacher-centred, verbally explicit classrooms influenced how they perceived and interpreted nonverbal communication in UK chemistry educational contexts, sometimes leading to misinterpretation of cues in chemistry learning environments. Several limitations should be acknowledged. First, reliance on self-reported data introduces potential recall and interpretive bias, particularly regarding salient or emotionally charged classroom experiences. Second, the sample is contextually specific to Chinese international students in UK food science programmes, which may shape the enactment and interpretation of nonverbal communication reported in this study. Third, individual differences such as prior knowledge and affective factors may also shape interpretation of nonverbal cues but were not systematically controlled, consistent with the interpretivist design of this study. Finally, retrospective accounts may conflate multiple classroom experiences, introducing variability in recall.

Despite these limitations, the study offers contextually grounded insights into how prior educational and cultural experiences may shape interpretation of nonverbal communication in chemistry classrooms. It highlights that the effectiveness of nonverbal communication depends on the interaction between disciplinary demands, cognitive load, and culturally mediated interpretive frameworks, underscoring the importance of deliberately designing for multimodal and inclusive chemistry instruction. Future research could build on these

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findings by incorporating classroom observation or video-based multimodal analysis to examine how gestures, mimicry, and embodied nonverbal interactions are enacted and interpreted in real time. Research could also be extended beyond student participants to include teaching staff, and conducted on students from other cultural backgrounds and educational settings beyond universities. Such approaches may complement the present interview-based focus on participants' retrospective meaning-making processes and provide additional insight into how nonverbal communication supports chemistry learning.

Author contributions

Conceptualization: Wing-Fu Lai. Methodology: Wing-Fu Lai. Data collection: Wing-Fu Lai. Formal analysis: Wing-Fu Lai. Writing – original draft: Wing-Fu Lai. Writing – review and editing: Wing-Fu Lai.

Conflicts of interest

The author declares no conflict of interest.

Data availability

The data are not publicly available as publicly releasing the data could potentially compromise the privacy of the research participants. Supplementary information (SI) includes the themes and codes identified through analysis of transcripts. See DOI: https://doi.org/10.1039/d6rp00243a.

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