Expected Comfort in Embodied Learning: A Framework of Design Considerations and a Validated Measurement Scale

Xiaoxuan Li
xiaoxuan.li@gess.ethz.ch
ETH Zurich
Switzerland

Manu Kapur
manukapur@ethz.ch
ETH Zurich
Switzerland

Julia Chatain
julia.chatain@unidistance.ch
UniDistance Suisse
Switzerland

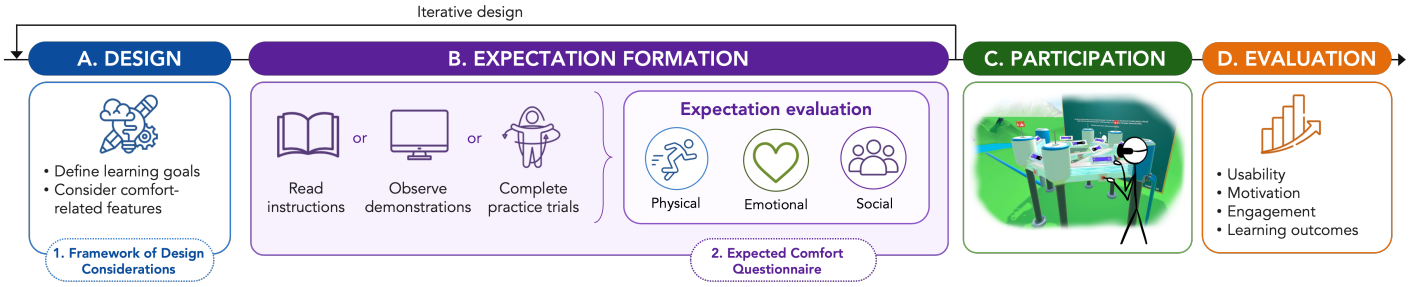


Figure 1: Overview of the proposed workflow, including our two contributions: (1) a framework of design considerations to support reflection on the design of embodied learning activities, and (2) the Scale of Expected Comfort in Embodied Learning (SECEL), assessing learners' expected physical, emotional, and social comfort after an activity has been introduced and before learners begin participating.

Abstract

Embodied learning activities vary widely in the types of movements, technologies, and social contexts they involve. After being introduced to an embodied learning activity, learners form expectations about what participating will feel like, even before their first move. These pre-participation expectations may influence their willingness to participate, and if they do, their engagement and learning outcomes. We conceptualize these expectations as ***Expected Comfort***: learners' expected physical, emotional, and social comfort before participation, extending existing evaluations that primarily assess experienced comfort after interaction. To translate this conceptualization into design practice, we first synthesize the literature to develop a framework identifying interaction design characteristics that may shape expected comfort. We then develop and psychometrically validate the Scale of Expected Comfort in Embodied Learning (SECEL). Together, the framework and scale enable designers to anticipate, assess, and design for learners' comfort before participation, positioning expected comfort as a key consideration in embodied learning design.

CCS Concepts

• **Human-centered computing** → **Interaction design theory, concepts and paradigms**; **Empirical studies in interaction design**.



This work is licensed under a Creative Commons Attribution 4.0 International License.
TEI '27, Lisbon, Portugal
© 2027 Copyright held by the owner/author(s).
ACM ISBN 979-8-4007-2848-8/2027/01
https://doi.org/10.1145/3830006.3864392

Keywords

Embodied Learning, Embodied Interaction, Expected Comfort, Movement-Based Learning, Scale Development, Psychometric Validation

ACM Reference Format:
Xiaoxuan Li, Manu Kapur, and Julia Chatain. 2027. Expected Comfort in Embodied Learning: A Framework of Design Considerations and a Validated Measurement Scale. In *Twenty-first International Conference on Tangible, Embedded, and Embodied Interaction (TEI '27), January 24–27, 2027, Lisbon, Portugal.* ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3830006.3864392

1 Introduction

Grounded in embodied cognition [7, 87], embodied learning refers to learning activities in which learners use bodily movement as an integral part of interacting with learning content [2, 45]. Advances in virtual and augmented reality, motion tracking, and other interactive technologies have broadened the range of embodied learning experiences that can be designed and studied, contributing to increased research attention within tangible, embedded, and embodied interaction [73, 92]. Designers now shape not only what learners learn but also how they move, when they move, where they move, with whom they move, and how their bodies become part of the interaction. Consequently, designing embodied learning is not only an educational challenge but also an interaction design challenge.

Every embodied learning activity asks learners to engage their bodies in particular ways. Some interactions require hand movements [84], whereas others involve whole-body movement [70], collaboration [1], or the use of wearable technologies [24]. These interaction design choices influence learning performance and shape the bodily experience of participation. Movement requirements

that are physically demanding, highly visible, or socially evaluative may create participation barriers for some learners, even when the instructional design is pedagogically effective. Consequently, two embodied learning activities may produce similar learning gains while differing substantially in whether learners perceive participation as enjoyable, manageable, or demanding. As embodied learning increasingly emphasizes accessibility and inclusion [75, 78], we argue that the effectiveness of an embodied learning activity depends not only on its instructional value but also on whether learners feel able and willing to participate. Designing embodied learning interactions, therefore, requires considering not only which movements support learning but also how those movements are likely to be experienced by diverse learners.

Despite the growing focus on learners' experiences and perceptions of embodied learning activities, existing evaluations primarily capture learners' experiences during or after interaction, for example, through the evaluation of cognitive load [53, 72], usability [12], engagement [64], motivation [69], etc. While these measures provide valuable insights into learners' experiences during participation, they reveal little about how learners anticipate an activity before it begins. This distinction is important because decisions about participation often precede the first movement [6, 36, 37]. Because embodied learning requires learners not only to complete a task but also to engage their bodies in particular ways specified by the interaction design, learners may already anticipate whether the required movements will be physically manageable, emotionally comfortable, or socially exposing before participation begins. These anticipatory judgments, in turn, may shape learners' willingness to participate and the quality of their engagement. Yet, such pre-participation expectations have received little attention in existing approaches to the design and evaluation of embodied interactions for learning.

We argue that existing work lacks an explicit construct to measure pre-participation barriers in embodied learning. Therefore, we introduce ***Expected Comfort***, defined as learners' anticipatory judgments formed after they have been introduced to an embodied learning activity (e.g., through instructions, demonstrations) but before participation begins. Unlike experienced comfort, which reflects learners' perceptions during or after participation [9], expected comfort captures barriers that learners anticipate before they engage. These expectations may influence whether and how they participate; yet, they do not necessarily match subsequent experiences. An activity that initially appears uncomfortable may ultimately be experienced positively, whereas one that appears approachable may prove physically, emotionally, or socially challenging during participation. We therefore conceptualize expected comfort as a design-sensitive construct that enables researchers and designers to identify potential barriers before learners engage with an embodied learning activity. Rather than reflecting stable learner characteristics alone, expected comfort is anticipated to be influenced by interaction design choices that shape how learners perceive and anticipate the embodied learning experience.

Figure 1 provides an overview of the proposed workflow. We make two complementary contributions that support different stages of the design process. First, we present a framework of design considerations that helps designers develop embodied learning activities by identifying interaction design considerations that may influence learners' expected comfort before participation. Once an activity has been designed and introduced to learners, our second contribution, the Scale of Expected Comfort in Embodied Learning (SECEL), is administered after activity introduction but before participation to assess learners' anticipated physical, emotional, and social comfort. The resulting expected comfort scores can be used to identify anticipated participation barriers, compare alternative interaction designs, and guide iterative refinement before implementation. After participation, measures of usability, motivation, engagement, and learning outcomes can be collected to evaluate the learning experience.

This paper addresses the following research questions:

- RQ1 What interaction design characteristics can be considered to identify potential barriers to learners' expected comfort before participation in embodied learning activities?
- RQ2 What is the underlying factor structure of expected comfort, and can it be measured reliably and validly as a multidimensional construct comprising physical, emotional, and social comfort?

2 Related Work

2.1 Embodied Learning as a Diverse Design Space

Embodied cognition proposes that cognition comes from ongoing interactions between the body and the environment rather than through abstract mental processes alone [7, 87]. This view is further reflected in the 4E framework, which conceptualizes cognition as embodied, embedded, enactive, and extended, emphasizing the roles of bodily capacities, environmental contexts, active engagement, and external resources in cognitive processes [60]. Applied to education, bodily action is not simply an output of learning but can play an integral role in how knowledge is constructed. Building on these theoretical foundations, embodied learning intentionally incorporates bodily action into educational experiences to support reasoning, problem solving, and conceptual understanding [2].

Johnson-Glenberg et al. [46] conceptualize embodiment as varying along multiple dimensions, including the amount of bodily engagement, the congruency between movement and learning content, and the level of immersion within an interactive environment. Consequently, embodied learning is better understood as a broad design space than as a single instructional approach. Learners may explore mathematical concepts through bodily interaction [1, 16], practice procedural skills through embodied simulations [18, 71], or learn language and arts through gesture [67] and collaborative movement [24]. This diversity gives designers considerable flexibility in how bodily participation is incorporated into learning. As embodied learning technologies continue to evolve, designers increasingly make decisions about how learners move, interact, and collaborate, as well as how bodily participation is experienced throughout the learning process.

2.2 Designing Bodies: Challenges of Bodily Participation

Although embodied learning offers many opportunities to enrich educational interaction, different interaction designs require learners to perform different forms of bodily engagement, ranging from simple hand gestures to full-body movement and collaborative physical interaction. These design choices shape not only how learners interact with educational systems but also the demands those interactions place on learners [15, 85].

Importantly, these design choices are not neutral. Spiel [75] argues that embodied interaction is inherently normative because every interaction design carries assumptions about the kinds of bodies it is designed for and the ways those bodies are expected to move, interact, and participate. These assumptions are often left unmarked, producing an implicit "ideal body" that is typically able-bodied, white, slim, young, and free from visible disability, while other bodies are treated as deviations from this norm. Rather than reflecting universal characteristics of human bodies, these assumptions arise from the social, cultural, and material contexts in which technologies are designed. As a result, interaction designs may unintentionally privilege some learners while creating barriers for others.

Building on this perspective, recent work has begun to examine how interaction design influences learners' experiences of participation in embodied educational settings. Vickery et al. [82] argue that embodied learning activities may unintentionally pressure students or even risk retraumatization when bodily participation is highly exposed, compulsory, or lacks meaningful alternatives. Rather than viewing participation as a simple binary of participating or not participating, they advocate designing for flexible participation, allowing learners to adjust their level of engagement over time and choose alternatives that align with their individual needs and comfort. Similarly, Tancredi et al. [78] argue that although embodied approaches can create valuable learning opportunities, they may also marginalize learners when interaction designs implicitly privilege particular bodies, identities, or ways of moving. Together, these perspectives highlight how the organization of bodily participation can create different opportunities and barriers for learners.

Inclusive educational design frameworks provide complementary perspectives to address these challenges. *Universal Design for Learning* (UDL) emphasizes learner variability by advocating multiple means of engagement, representation, action and expression, thereby encouraging flexibility in how learners access and participate in educational activities [14]. *Special Education Embodied Design* (SpEED) further challenges the assumption that learning experiences can be made equally accessible by translating the same content across sensory modalities [77]. Instead, SpEED recognizes that different sensorimotor experiences may shape how learners construct knowledge, highlighting the importance of designing embodied learning activities for diverse bodily and sensory resources. Overall, these approaches underscore the importance of accommodating learner diversity when designing embodied learning activities.

We argue that understanding participation requires attention not only to how activities are designed to accommodate diverse learners, but also to how individual learners perceive the bodily demands of a particular activity. Even when an activity provides flexible and inclusive participation opportunities, learners may differ in how they anticipate experiencing its demands. Importantly, these judgments may form before participation begins, as learners interpret information about the activity and anticipate what engaging in it might feel like. This motivates a closer examination of how pre-participation expectations are conceptualized in existing research.

2.3 Anticipatory Judgements Before Participation

Before engaging in an educational activity, learners form judgments about what participation may require and what they can expect from it. Research on motivation, behavioral intention, and technology acceptance has examined these anticipatory judgments from different but overlapping theoretical perspectives. Rather than treating these perspectives as a unified model, we draw on them to distinguish several aspects of how learners evaluate activities before participation.

One aspect concerns anticipated capability, success, and task value. *Self-efficacy theory* emphasizes individuals' beliefs in their capacity to organize and perform the actions required to achieve a particular outcome [6], while *Expectancy-Value Theory* explains achievement-related choices through expectations of success and the subjective value of a task [27, 86]. A second aspect of research examines how anticipatory evaluations shape behavioral intentions and technology acceptance. The *Theory of Planned Behavior* proposes that intentions are shaped by attitudes, subjective norms, and perceived behavioral control [3]. Similarly, technology acceptance models, including the *Technology Acceptance Model* and the *Unified Theory of Acceptance and Use of Technology*, examine how perceived usefulness, ease of use, performance and effort expectations, and social influences relate to intentions to use a system [23, 80]. Although these theories differ in their explanatory focus, they collectively highlight how pre-participation judgments relate to subsequent intentions and behaviors, offering complementary perspectives on anticipatory evaluation.

From a 4E perspective, cognition is understood as embodied, embedded, enactive, and extended, emphasizing the roles of bodily capacities, situated activity, and environmental resources in cognition. This broadens the consideration of pre-participation judgments beyond what learners expect to achieve or whether they intend to participate, drawing attention to the bodily and situated nature of participation itself. Although existing theories address beliefs about capability, value, effort, and social evaluation, the subjective experience of bodily participation is not their primary explanatory focus. To develop this experiential dimension of pre-participation expectations, we turn to phenomenological and somaesthetic perspectives on lived bodily experience.

2.4 Beyond Observable Movement: Lived Bodily Experience

To understand what learners may anticipate about bodily participation, it is important to distinguish the physical performance of movement from its subjective experience. Drawing on phenomenology, Mueller et al. [59] distinguish between the body as Körper–the

measurable physical body–and the body as Leib–the lived body through which people perceive, feel, and make sense of interaction. This distinction highlights that observable bodily performance does not fully capture the subjective experience of participation. Two learners may perform the same movement while experiencing it differently. For one learner, the movement may feel natural and effortless, whereas another may experience it as physically demanding or unfamiliar. Thus, what learners do through bodily movement cannot necessarily tell us how they experience performing it.

Somaesthetic design similarly foregrounds the experiential qualities of bodily interaction [41, 42]. Rather than treating bodies merely as instruments for accomplishing tasks, somaesthetic approaches emphasize bodily sensations, proprioception, affective responses, and comfort as integral components of interaction. From this perspective, the quality of an embodied interaction depends not only on whether learners can perform the required movements but also on how those movements are experienced from the perspective of the moving body. Designers are therefore encouraged to consider how interaction designs shape bodily awareness, emotional responses, and feelings of comfort throughout the interaction.

Together, phenomenological and somaesthetic perspectives highlight the importance of understanding embodied interaction through learners' subjective bodily experiences, rather than observable movements alone. Bringing this experiential perspective together with the theories of anticipatory judgment reviewed in Section 2.3 provides a conceptual basis for examining learners' expectations about how bodily participation will feel.

2.5 Conceptualizing Expected Comfort in Embodied Learning

We conceptualize expected comfort as learners' anticipated comfort with the bodily participation required by an embodied learning activity. Phenomenological and somaesthetic perspectives foreground the lived and sensory experience of bodily movement [56, 91], while research on affect and learning highlights the emotional experiences associated with participation [65]. Critical and inclusive perspectives on embodied interaction further emphasize that bodily participation is socially situated and shaped by visibility, evaluation, and social norms [20, 75]. These perspectives inform our conceptualization of expected comfort along three distinct dimensions: *physical comfort* concerning the anticipated bodily experience of movement, *emotional comfort* concerning the anticipated affective experience of participation, and *social comfort* concerning the anticipated experience of performing bodily actions in social contexts.

Physical comfort distinguishes the anticipated ease of performing bodily movements from the ability to effectively execute them. Even when learners are capable of executing the required actions, they may anticipate differences in bodily ease, movement manageability, coordination, and control. *Emotional comfort* differentiates the anticipated psychological ease of participating in an activity from the ability to perform said activity. Learners may anticipate anxiety, stress, or emotional vulnerability even when the physical demands of an activity are manageable. *Social comfort* further acknowledges that bodily participation is anticipated differently depending on its social context. Learners who feel comfortable performing an action individually may nevertheless anticipate discomfort when their movements are visible to others or subject to observation, comparison, or evaluation. Together, these dimensions capture different aspects of learners' anticipated comfort with bodily participation, distinguishing the physical experience of movement, the emotional experience of participation, and the social experience of performing actions in the presence of others.

Finally, we conceptualize expected comfort as a context-specific anticipatory state rather than a stable individual trait. It reflects how comfortable learners expect to feel when participating in a particular embodied learning activity, based on the information available to them before participation. Although expected comfort may be influenced by relatively stable individual characteristics and prior experiences, it is situated in the anticipated interaction and may vary across activities and contexts. This context-specific nature makes expected comfort potentially sensitive to interaction design. Design decisions provide cues that may shape learners' anticipated comfort. Expected comfort thus offers a learner-centered perspective through which designers can consider and potentially address comfort-related concerns before participation begins.

2.6 Research Gap and Current Study

Conceptualizing expected comfort as a design-sensitive construct has important implications for embodied learning design and evaluation. If expected comfort can be influenced through interaction design, researchers and designers require methods to design for and assess it before implementation. However, current research provides limited support for either objective.

First, there is a lack of a systematic framework for identifying the design characteristics that are most likely to influence learners' expected comfort. Existing literature highlights a range of relevant considerations, including bodily norms and inclusivity [75, 78], flexibility and alternatives in participation [82], lived bodily experience [41, 59], and movement-related affordances and demands [15, 85]. However, these insights are dispersed across different theoretical perspectives and have not been integrated into a coherent framework. Second, there is no validated instrument for measuring learners' expected comfort. Existing evaluation methods primarily assess learners' experiences after interaction, such as cognitive load [53, 76], engagement [64], usability [12], and presence [88]. Consequently, researchers and designers lack a practical means of evaluating how alternative interaction designs influence learners' anticipated experiences before an embodied learning activity begins.

To address these gaps, this paper makes two complementary contributions. First, we develop a framework of design considerations that identifies aspects of embodied learning activities relevant to learners' expected comfort and supports designers in reflecting on these aspects during activity design (RQ1). Second, we develop and psychometrically validate the Scale of Expected Comfort in Embodied Learning (SECEL), a multidimensional instrument that measures learners' anticipated physical, emotional, and social comfort before participation (RQ2). Together, the framework and the SECEL provide complementary tools for designing, assessing, and evaluating expected comfort as a key consideration in embodied learning.

3 Methods

Although the project initially focused on questionnaire development, early item generation revealed an important methodological challenge. The initial items were embedded within concrete embodied learning scenarios that varied in educational context, movement type, collaboration, and technology use. While these scenarios demonstrated ecological validity, they also combined multiple interaction design features, making it difficult to determine whether participants' responses reflected their underlying expected comfort or their reactions to particular aspects of the activity.

To address this challenge, we distinguished two complementary levels of analysis, reflected in our two contributions. The framework of design considerations captures interaction design features that may influence expected comfort, whereas the SECEL measures learners' expected physical, emotional, and social comfort as a learner-level psychological construct. Separating these levels clarified both the conceptual model and the methodological approach adopted in this study.

To support both components of this study, we used a VR-based graph theory learning activity as a common reference scenario throughout the paper [17] (Figure 2). The activity was developed through an iterative design process involving a design study (N = 26) and a learning study (N = 89). The scenario serves two complementary purposes. First, it serves as an illustrative case for demonstrating the application of the proposed framework of design considerations. The framework is applied to analyze the interaction design characteristics of this activity in Section 4.2. Second, it provides a standardized context for validating the SECEL. All participants were presented with the same description of the activity and its key design features (Appendix C) before completing the questionnaire, ensuring that differences in expected comfort reflected participants' evaluations rather than differences between learning scenarios.

3.1 Development of the Framework of Design Considerations

The framework was developed through a narrative review and iterative design knowledge synthesis. A narrative review was considered appropriate [32, 33] because the objective was not to estimate intervention effectiveness but to synthesize conceptual and design knowledge from multiple disciplines into a practical framework for interaction design.

The review began from the observation that embodied learning represents a broad interaction design space in which learning activities differ substantially in how bodily participation is organized. We used Vickery's [83] deconstruction of embodied learning activities as the initial point of orientation because it provides a systematic description of design characteristics, including forms of movements, proximity between participants, visibility of movement, participation structures, and technology presence. We used these elements as an analytical lens for examining how embodied learning activities differ in the organization of bodily participation. Table 1 summarizes these activity elements together with the design questions that guided the subsequent literature synthesis.

Building on this foundation, we conducted an iterative review of literature spanning complementary research traditions, including embodied and tangible interaction [26, 43, 44, 47], embodied cognition and embodied learning [15, 45], somaesthetic design, movement-based interaction design [41, 59], and critical or inclusive perspectives on bodily participation [75, 82].The review began with key publications in these areas and was iteratively expanded through backward and forward citation searching to identify conceptually relevant literature. Rather than extracting design principles from a single theoretical perspective, we synthesized complementary insights across these traditions to identify interaction design considerations that may influence learners' expected physical, emotional, and social comfort.

Throughout the synthesis, the first author identified, compared, and iteratively refined recurring design concepts across the reviewed literature. A design consideration was included in the framework when it satisfied two criteria: (1) it represented a specific characteristic of an embodied learning activity that designers could intentionally manipulate, and (2) theoretical or empirical literature suggested that it could plausibly influence learners' expected comfort. The emerging framework was refined through repeated comparison between the literature, candidate design considerations, and representative embodied learning activities to ensure that each consideration was conceptually coherent, practically meaningful, and sufficiently distinct from the others.

The resulting framework was intentionally developed at an intermediate level of abstraction. Rather than prescribing specific design solutions, it identifies modifiable interaction design considerations that may shape learners' expected physical, emotional, and social comfort across a wide range of embodied learning activities. This level of abstraction allows the framework to support both analysis of existing activities and the design of new embodied learning experiences.

3.2 Development of the SECEL

Following the development of the framework of design considerations, we developed the SECEL to measure learners' expected comfort independently of any specific embodied learning activity. Because expected comfort concerns anticipated experiences, self-report was considered the most appropriate measurement approach [39]. Although multimodal learning analytics can provide valuable evidence regarding attention, workload, engagement, and physiological responses during interaction [63, 79], these methods capture real-time bodily and learning experiences and not anticipated ones.

3.2.1 Item Generation. Following Hinkin's [39] deductive approach to scale development, we generated an initial pool of 18 items representing the proposed dimensions of physical comfort, emotional comfort, and social comfort. Item generation was informed by both the theoretical conceptualization of expected comfort and the interaction design considerations identified in the framework. Six items were initially developed for each dimension to reflect anticipated bodily manageability (physical comfort), anticipated emotional responses to participation (emotional comfort), and anticipated comfort with performing bodily actions in social contexts (social comfort). Items were written to be activity-specific, concise, and to capture a single construct.

Content validity was assessed through expert review involving seven experts with expertise in embodied learning, embodied

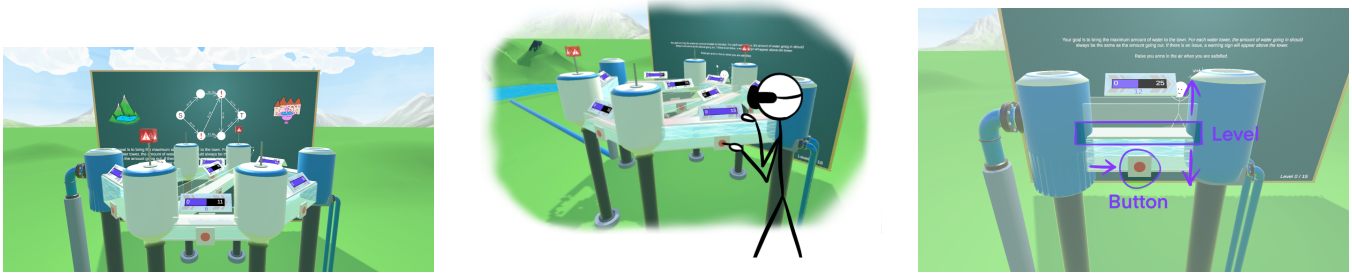


Figure 2: The embodied graph theory learning task in VR. (a) The graph is represented using a water pipeline metaphor, where nodes and edges correspond to water towers and connecting pipes. (b) The learner's position relative to the virtual pipeline environment. (c) The learner adjusts the water level by moving their hand up or down, enabling embodied interaction with the graph representation.

Table 1: Summary of embodied activity elements

Activity element	Guiding design question	Description
Forms of movement	What kind, intensity, and duration of bodily action is required?	Embodied learning activities range from small hand gestures and object manipulation to sustained postures, repeated actions, and whole-body movement. These forms of movement differ in their physical effort, fatigue, and perceived manageability.
Proximity	How close are learners to others, shared objects, or physical contact?	The physical distance between learners, shared materials, and opportunities for bodily contact may influence personal space, social awareness, and interaction with others.
Visibility	Who can see the learner's body, movement, or attempt?	Movement may be visible only to the learner, an instructor, peers, or a wider audience. Different levels of visibility can influence social exposure and perceived evaluation.
Participation structures	Can learners adapt the movement, choose another role, reduce visibility, or use an alternative?	Participation may be mandatory or flexible. Allowing learners to modify movements, adopt different roles, or choose alternative forms of participation can support autonomy and accommodate diverse needs.
Technology presence	What technologies are present, and how do they shape participation?	Technologies such as cameras, motion sensors, VR headsets, controllers, projectors, and wearable devices can influence how movements are performed, captured, interpreted, and experienced.

interaction design, inclusive education, and questionnaire development, each with at least four years of relevant research experience (Table 2). Experts E1–E3 provided qualitative feedback on the conceptual relevance, comprehensiveness, and wording of the proposed items, identifying ambiguous or overlapping statements and suggesting refinements to improve conceptual clarity. Experts E4–E7 then completed a structured evaluation form, rating each item's relevance, clarity, and appropriateness on a four-point scale while also providing qualitative comments and recommendations. Their feedback informed revisions to improve conceptual alignment, eliminate ambiguity, and simplify item wording. The revised questionnaire was subsequently pilot-tested with three doctoral researchers experienced in embodied learning, who evaluated its readability, comprehensibility, and overall coherence. Minor wording revisions were made based on their feedback before proceeding to large-scale validation.

3.2.2 Ethics. Before beginning the study, participants were presented with an electronic information sheet and provided informed consent digitally. Participation was voluntary, and participants could withdraw from the study at any time. All data were collected anonymously through the online survey platform, stored securely, and analyzed only in aggregate to protect participant confidentiality. The study was approved by the ETH Zurich Ethics Commission (25 ETHICS-375).

3.2.3 Participants. Two independent samples were recruited through Prolific [66] to support the psychometric evaluation of SECEL. The first sample (Set A; n = 120) was used for exploratory factor analysis (EFA) and item reduction. The second independent sample (Set B; n = 170) was used for confirmatory factor analysis (CFA) and evaluation of construct validity. Participants were required to be at least 18 years old, native speakers of English, and without any long-term health concerns.

Prior to CFA, we screened the validation sample for potential response-quality issues related to reverse-coded items. Participants were flagged if they provided high ratings to both positively worded comfort items and negatively worded reverse-coded items before reverse scoring, or if they straightlined across all 12 raw items. This procedure identified 12 of 170 participants (7.1%), who were removed from the CFA validation sample. The final sample for CFA included 158 participants. Participant characteristics are summarized in Table 2.

Table 2: Overview of samples used for each phase of scale development and validation.

Phase	Method	Sample Used
Content validity	Expert consultation	Subject matter experts (n = 7) and doctoral students (n = 3)
Item reduction	Exploratory factor analysis	Participant Set A (n = 120; Age: M = 38.70, SD = 11.97)
Construct validity	Confirmatory factor analysis	Participant Set B (n = 158; Age: M = 38.71, SD = 11.71)

3.2.4 Measures and Procedures. Participants completed the study online via Qualtrics. They first read the standardized instructions used in an embodied graph theory learning activity (Figure 2), followed by SECEL and a measure of willingness to participate (Appendix A). Items were rated on a 7-point Likert scale (1 = *Strongly disagree*, 7 = *Strongly agree*). The questionnaire took approximately 8 minutes to complete. They did not perform the VR activity as part of the questionnaire study.

3.2.5 Data Analysis. Internal consistency was assessed using Cronbach's alpha [21] and McDonald's omega [58] for each subscale. EFA was conducted to examine the underlying factor structure of the questionnaire and identify poorly performing items [28]. The suitability of the data for factor analysis was evaluated using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy [48] and Bartlett's test of sphericity [8]. Factor extraction was based on eigenvalues, scree plot inspection, factor interpretability, and theoretical consistency. Items with low factor loadings (<0.30), substantial cross-loadings, or conceptual redundancy were considered for removal [28]. The retained factor structure was evaluated using CFA in an independent sample to test whether the model accurately represents the data [13]. Following Hair Jnr et al. [34, 35], model fit was evaluated using recommended criteria.

- Chi-square/degree of freedom (χ^2/df): A ratio of less than 3 indicates a satisfactory fit between the hypothesised model and the observed data.
- Root mean square error of approximation (RMSEA): Values less than 0.05 suggest a good match, and values less than 0.08 are considered appropriate.
- Standardised root mean square residual (SRMR): Values less than 0.05 suggest a good match, and values less than 0.08 are considered appropriate.
- Tucker-Lewis Index (TLI): Values greater than 0.9 indicate an acceptable fit, and values above 0.95 are considered good.
- Comparative fit index (CFI): Values greater than 0.9 indicate an acceptable fit, and values above 0.95 are considered good.

Convergent validity was assessed using composite reliability (CR) and average variance extracted (AVE). CR indicates the internal consistency of the latent construct based on standardized factor loadings, with values above .70 generally considered acceptable [4]. AVE indicates the proportion of variance in the items explained by the latent construct, with values above .50 suggesting adequate convergent validity [29].

4 Results

4.1 Framework of Design Considerations (RQ1)

The review identified eight interaction design considerations that characterize how embodied learning activities are designed and, consequently, how learners may anticipate experiencing bodily participation. Rather than prescribing specific interface features or design solutions, the framework identifies broader design dimensions that designers can intentionally manipulate when developing embodied learning activities (Table 3).

Recoverability refers to the extent to which learners are able to recover from unsuccessful bodily actions during interaction. Rather than referring to conceptual misunderstandings or learning errors, movement recoverability concerns whether incorrect gestures, misaligned movements, or tracking failures can be corrected without disrupting participation. Because embodied learning inevitably involves exploration and occasional movement errors [68], expected comfort may increase when learners know they can pause, retry, undo, recalibrate, or continue without social embarrassment or learning penalties. Consistent with established usability principles, interaction designs that support user control and error recovery help learners perceive bodily errors as a normal part of interaction rather than visible failures [61, 62], reducing the perceived risk of participation and fostering greater expected comfort before participation.

Scaffolding concerns the extent to which learners receive support to understand and perform the required bodily actions. Unlike movement recoverability, which focuses on recovering from unsuccessful movements after they occur, movement scaffolding aims to reduce uncertainty before movement-related difficulties arise. Support may be provided by instructors or the system through movement demonstrations, guided practice, rehearsal opportunities, real-time feedback, or adaptive prompts [19, 44]. Knowing that movement-specific support will be available may increase learners' confidence in performing the required movements while reducing apprehension about making mistakes [40], thereby fostering greater expected comfort before participation.

Evaluation pressure concerns the extent to which learners' bodily actions will be assessed, compared, or judged by peers, instructors, or the system. Unlike visibility, which concerns whether movements are observable, evaluation pressure concerns the perceived consequences of those movements being evaluated. Anticipating that one's bodily performance will be evaluated may increase anxiety and reduce confidence before participation begins [20, 25, 65]. Expected comfort may therefore decrease when activities involve public performance, peer comparison, movement accuracy scoring, or high-stakes feedback.

Perceived congruency concerns the extent to which required movements meaningfully represent or support the intended learning content. Embodied learning evidence suggests that bodily actions support learning when they are conceptually related to the knowledge being acquired rather than serving as arbitrary movements [2, 45, 54, 55]. When learners can anticipate a meaningful connection between the required movements and the learning objective, participation may feel more natural and purposeful. In contrast, movements that appear arbitrary or disconnected from

Table 3: Design considerations that may influence learners' expected comfort in embodied learning activities.

Design consideration	Guiding question	Description
Recoverability	Can learners pause, retry, undo, recalibrate, or recover their movements without embarrassment?	Expected comfort may increase when movement mistakes can be corrected privately without penalty or public embarrassment (e.g., repeating a misperformed gesture after tracking loss).
Evaluation pressure	Are learners' bodily actions scored, compared, or judged by instructors, peers, or the system?	Expected comfort may decrease when learners anticipate that their bodily performance will be judged, compared, or evaluated (e.g., demonstrating gestures individually in front of classmates).
Scaffolding	What guidance is available when learners struggle to complete the action?	Expected comfort may increase when demonstrations, rehearsal opportunities, and prompts are available to support bodily participation (e.g., practising simple gestures before more complex movements).
Perceived congruency	Is the relationship between the bodily action and the learning goal meaningful and clear?	Expected comfort may increase when learners perceive the required movements as meaningful and relevant to the learning goal (e.g., tracing water flow to represent network flow).
Representation of the body	How are learners' bodies represented or visualized in the activity?	Expected comfort may be influenced by how learners' bodies are represented during interaction (e.g., virtual hands, a full-body avatar, or motion traces).
Movement tolerance	How much variation in learners' movements does the activity or system allow?	Expected comfort may decrease when successful participation depends on tightly constrained movements (e.g., reproducing a gesture with a specific trajectory or timing).
Material contact	What objects, tools, or devices must learners touch, hold, or wear?	Expected comfort may be influenced by the physical characteristics of interaction materials (e.g., wearing a VR headset, holding controllers, or manipulating tangible objects).
Accessibility	Can learners participate through adapted movements, assistive technologies, or alternative input methods?	Expected comfort may increase when activities provide flexible and inclusive ways of participating (e.g., allowing seated interaction or alternative ways of participation).

the intended learning content may reduce expected comfort by making bodily participation seem less meaningful or justified.

Representation of the body concerns how learners' bodies are represented during interaction. Depending on the interaction design, learners may interact through their physical bodies [52], virtual hands [57], full-body avatars [70], or other digital representations [15]. Research in embodied interaction and virtual reality suggests that different forms of bodily representation influence body ownership, sense of agency, self-perception [51, 74, 90], and even cognitive performance [5]. For example, older adult participants embodied in a virtual Einstein avatar improved their performance on a cognitive task while simultaneously reducing age-related stereotyping [5]. These findings suggest that body representation shapes how learners expect to perceive and experience themselves during interactions. Consequently, anticipating a particular form of body representation may influence learners' expected comfort before participation.

Movement tolerance concerns the degree of variation in movement execution that an embodied learning activity permits while still supporting successful participation. Some activities allow learners to perform movements in multiple acceptable ways, whereas others require specific gestures, trajectories, or postures to be reproduced with high precision. Karam and Schraefel [50] argue that gesture systems should account for natural variation and imperfect recognition rather than assuming that users will perform gestures in a perfectly consistent way. Likewise, learners naturally differ in how they perform movements, with experts often using more economical actions than novices, who tend to reproduce movements more literally [30]. In embodied learning, this distinction is reflected in directed bodily actions, which prescribe specific movements, and spontaneous bodily actions, allowing greater freedom [16]. Expected comfort may decrease when learners anticipate that successful participation depends on tightly constrained movements with little tolerance for variation.

Material contact concerns the physical interaction between learners' bodies and the objects, tools, or devices used in an embodied learning activity. Learners may touch, hold, or wear physical artifacts such as tangible interfaces, controllers, wearable sensors, or everyday objects [31, 43, 47]. The physical properties of these materials, including their weight, fit, texture, and the degree of bodily contact they require, may influence learners' expected comfort. Designers should therefore consider not only the functionality of physical artifacts, but also how they feel to wear, hold, and use during learning activities.

Accessibility concerns the extent to which an embodied learning activity accommodates diverse bodies, abilities, and ways of participating. Embodied learning often assumes that learners can perform particular movements, use specific technologies, or interact within a prescribed physical environment [75]. In practice, however, learners differ substantially in their physical capabilities, sensory abilities, prior experiences, and interaction needs. When these differences are not considered, some learners may anticipate

Table 4: Illustrative application of the framework to the embodied graph theory activity [17].

Design consideration	Example from the graph theory activity	Anticipated level of expected comfort and rationale
Forms of movement	Learners manipulated parts of a virtual pipe system using two-handed movements, object manipulation, and spatial interaction. They also walked around the virtual environment to interact with different pipes and obtain an overview of the system.	**Moderate.** The activity involved moderate upper-body movements and sustained standing, but did not require strenuous physical exertion or complex whole-body actions.
Proximity	The VR setup required learners to occupy an individual interaction space measuring 4 m × 4.5 m while using the equipment.	**High.** Individual participation minimized concerns about personal space. A VR tutorial also familiarized learners with the controls and interaction area.
Visibility	Learners' movements were visible only to the experimenter present in the room.	**Moderate.** Observation by the experimenter may increase self-consciousness for some learners, but the activity did not involve public performance.
Participation structures	Learners could not select an alternative role or participate through a non-bodily form of interaction.	**Low.** Limited flexibility may reduce comfort for learners who prefer alternative ways of participating.
Technology presence	Learners completed the activity while standing and wearing a VR headset for approximately 30 minutes.	**Moderate.** Wearing a VR headset for an extended period may cause discomfort for some learners.
Recoverability	Learners could immediately repeat or adjust their hand movements to revise unsuccessful solutions.	**High.** Opportunities to retry and refine solutions may reduce anxiety about making mistakes.
Scaffolding	No explicit movement guidance or hints were provided during the interaction.	**Low.** Limited support may increase uncertainty for learners who are unfamiliar with the task or the VR environment.
Evaluation pressure	The activity was completed individually. Bodily actions functioned as input for interacting with the system rather than as movements to be evaluated.	**High.** The absence of public performance or explicit movement evaluation reduces concerns about being judged.
Perceived congruency	Raising and lowering the water level with hands directly represented flow values within the graph, creating a meaningful correspondence between bodily action and the mathematical concept.	**High.** A meaningful action-concept mapping is likely to make participation feel purposeful and natural.
Representation of the body	Learners' bodies were represented through virtual hands rather than their entire bodies. The skin tone of the virtual hands matched that of the participant.	**Moderate.** Representing learners only through virtual hands may reduce appearance-related self-consciousness, but the absence of a fuller body representation may also feel unfamiliar or disembodied.
Movement tolerance	Learners adjusted the water level using controlled hand movements, although multiple movement trajectories could achieve the same outcome.	**Moderate.** Controlled movement was required, but the motor demands were not highly complex.
Material contact	Learners continuously interacted with the VR headset throughout the activity.	**Moderate.** Wearing a VR headset for an extended period may reduce comfort because of physical fatigue or simulator sickness.
Accessibility	The activity required compatibility with headset use, visual displays, sustained standing, and changes in body orientation to interact with the learning materials.	**Low.** Although height calibration was performed before the activity, participation required standing and headset use, with no alternatives.

Note. For illustrative purposes, the qualitative ratings (low, moderate, and high) indicate the anticipated level of expected comfort associated with each design consideration, rather than the degree to which the design consideration is present. Higher ratings indicate more favorable implications for expected comfort. These ratings are interpretive rather than empirically measured and are not prescribed by the framework.

that participation will be physically demanding, uncomfortable, or even impossible before the activity begins. Conversely, expected comfort may increase when activities provide flexible and inclusive ways of participating, such as offering alternative movement options, adaptable interaction modalities, adjustable levels of physical demand, or multiple pathways for completing the same learning task [14, 78, 81, 89]. By reducing unnecessary barriers and accommodating diverse learners, accessible interaction designs are more likely to foster positive expectations about participation before engagement begins.

4.2 Case Illustration

To demonstrate how the framework can be applied in practice, we retrospectively analyzed the embodied graph theory activity [17] (Table 4). In this study, learners explored the graph theory concept of maximum flow through an immersive virtual reality activity.

Instead of learning from diagrams or equations alone, learners interacted with a virtual pipe network in which water flowed from a lake to a city. By manipulating the flow of water through the pipes, they developed an embodied understanding of how flow moves through a network and how bottlenecks determine the maximum amount of flow (Figure 2). The example illustrates how researchers and designers may identify activity features and consider their possible implications for learners' expected comfort.

4.3 SECEL Validation (RQ2)

4.3.1 Item Reduction. Exploratory factor analysis (EFA) was conducted on the initial pool of 18 items to examine the underlying factor structure and identify items for refinement, using Participant Set A. The three-factor solution was consistent with the proposed conceptualization of expected comfort.

To improve both the psychometric quality and practical usability of the scale, item reduction was guided by two criteria: (1) statistical performance and (2) conceptual redundancy. Specifically, items with substantial cross-loadings across multiple factors were considered for removal because they did not clearly represent a single latent construct. In addition, conceptually overlapping items were removed to produce a shorter and more practical instrument while maintaining adequate coverage of each dimension.

Six items were removed during this process (Appendix B). Four items were excluded because they demonstrated substantial cross-loadings, suggesting that they simultaneously reflected multiple dimensions of expected comfort. For example, "It would be hard to focus on learning because my body would feel tense" and "I would feel confident while performing the required movements" loaded on both the Physical and Emotional Comfort factors, whereas "I would hesitate to participate if other participants seemed more experienced than I was" and "I would feel comfortable collaborating with another participant in the activity" loaded on both the Social and Emotional Comfort factors. These cross-loadings reduced conceptual distinctiveness between factors.

Two additional items were removed because they were conceptually redundant with retained items. Specifically, "Performing the required movements would feel physically tiring for me" overlapped substantially with the broader construct of physical comfort, while "I would worry about making mistakes when performing the movements to learn" captured a similar aspect of evaluative concern as the retained social comfort items. Removing these items increased the practicality of the questionnaire without compromising representation of the three proposed dimensions.

Although two emotional items exhibited relatively modest primary loadings and some cross-loadings in the EFA, they were retained because they represent theoretically important aspects of expected emotional comfort and demonstrated satisfactory loadings in the subsequent CFA. Similar overlap between physical and emotional responses is conceptually expected in embodied learning contexts, where emotional reactions are often elicited through bodily engagement.

The final 12-item expected comfort scale showed good sampling adequacy, KMO = .819, and Bartlett's test of sphericity was significant, $\chi^2(66) = 1129.66$, p < .001. The identified three factors explained 68.56% of the variance (Table 5).

4.3.2 Measurement model. We conducted a CFA using participant Set B. The 12-item three-factor CFA model showed an acceptable-to-good fit, $\chi^2(49) = 84.57$, $p = .001$, CFI = .955, TLI = .940, RMSEA = .068, SRMR = .061. Standardized loadings were moderate to strong: physical comfort .799-.852, emotional comfort .594-.928, and social comfort .787-.870.

4.3.3 Descriptive statistics and reliability. Descriptive statistics and internal consistency estimates were calculated among the three expected comfort dimensions and overall expected comfort. The three expected comfort dimensions demonstrated good internal consistency (α = .850–.899; McDonald's ω = .840–.901), while the overall expected comfort scale also showed high consistency (α = .907; ω = .896). Physical and emotional comfort received relatively high mean ratings (M = 5.84, SD = 1.18; M = 5.61, SD = 1.42), whereas social comfort was rated comparatively lower (M = 4.36, SD = 1.82, see Figure **??**).

4.3.4 Convergent validity. All three factors showed good CR and AVE values: physical comfort (CR = .895, AVE = .680), emotional comfort (CR = .863, AVE = .617), and social comfort (CR = .900, AVE = .692). These results indicate adequate convergent validity for the three expected comfort dimensions.

4.3.5 Discriminant validity. Discriminant validity was examined using HTMT ratios [38]. HTMT values were below the recommended .85 threshold (Physical-Emotional: .796, Physical-Social: .495, Emotional-Social: .614). The results suggest that the three comfort dimensions are empirically distinguishable.

4.3.6 Criterion Validity. Concurrent criterion validity was examined through the association between expected comfort and willingness to participate in embodied learning activities. The four-item willingness-to-participate measure demonstrated good internal consistency (α =.851, ω = .863). Overall expected comfort was strongly and positively correlated with willingness, $r = .685$, $p < .001$. When the three comfort dimensions were entered simultaneously in a multiple regression model, they explained 50.6% of the variance in willingness. Social comfort ($\beta = .500$) and physical comfort ($\beta = .367$) showed significant positive associations with willingness, whereas emotional comfort did not make a significant unique contribution after accounting for the other dimensions ($\beta = -.043$, $p = .612$, Figure 3). These findings provide initial evidence of criterion-related validity and indicate that willingness to participate was particularly associated with social and physical comfort.

5 Discussion

5.1 Expected Comfort as a Pre-participation Evaluation

This work argues that learners' experiences of embodied learning begin before participation. Existing evaluations have predominantly focused on experiences during or after interaction, providing valuable insights into how learners respond to embodied learning activities but revealing little about how they anticipate participation. Before engaging, learners interpret instructions, observe demonstrations, and form expectations about the physical, emotional, and social demands of an activity. By introducing expected comfort, this

Table 5: Exploratory factor loadings for the final 12-item SECEL

Item wording	Physical ($M = 5.84$, $SD = 1.18$)	Emotional ($M = 5.61$, $SD = 1.42$)	Social ($M = 4.36$, $SD = 1.82$)
P1. I would feel physically comfortable performing the movements required in this activity.	**0.548**	0.223	0.275
P2. The required movements would feel manageable for me.	**0.786**	0.298	0.021
P3. I would feel in control of my body when performing the required movements.	**0.863**	0.337	0.123
P4. I would be able to coordinate my movements comfortably while solving the task.	**0.840**	0.230	0.226
E1. I would feel psychologically safe performing the required movements.	0.287	**0.842**	0.196
E2. I would feel emotionally comfortable performing the required movements.	0.298	**0.934**	0.155
E3. I would feel anxious while performing the required movements. [R]	0.316	**0.459**	0.388
E4. I would find the required movements emotionally stressful. [R]	0.436	**0.499**	0.241
S1. I would feel comfortable participating in this activity when other people could see me.	0.181	0.220	**0.696**
S2. I would feel comfortable if my movements looked different from those of other participants.	0.139	0.256	**0.658**
S3. I would worry about being judged while performing the required movements. [R]	0.161	0.152	**0.807**
S4. I would feel uncomfortable performing the required movements around people I did not know. [R]	0.097	0.135	**0.910**

Note. $N = 120$ (Set A). Exploratory factor analysis was conducted using principal axis factoring with varimax, which served as the basis for item-reduction decisions. A Direct Oblimin sensitivity analysis allowing correlated factors supported the same broad three-factor structure. Bold values indicate the primary factor loading. [R] indicates reverse-coded items.

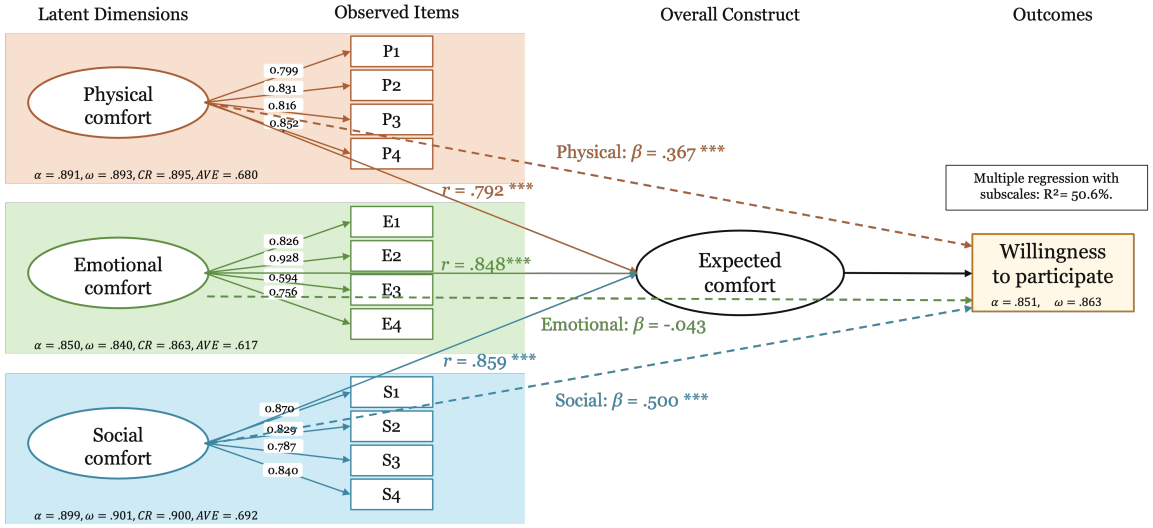


Figure 3: Measurement model of the SECEL and criterion-related multiple regression

Note. Ovals represent latent constructs, and rectangles represent observed items. Solid arrows indicate standardized factor loadings or regression paths. Curved dashed arrows represent correlations between latent factors, and horizontal dashed arrows indicate standardized regression coefficients from the multiple regression analysis predicting willingness to participate. β denotes standardized regression coefficients. *** indicates $p < .001$.

work extends the evaluation of embodied learning to this anticipatory stage, enabling researchers and designers to consider learners' experiences before interaction begins.

Importantly, expected comfort should not be interpreted as a direct indicator of interaction quality or educational effectiveness. Rather, it reflects learners' anticipatory experiences, which arise

from the interaction between the design of an embodied learning activity and the characteristics of the learner. Consequently, the same activity may elicit different SECEL scores across learners, even when it has been carefully designed. Lower expected comfort may indicate interaction design decisions that introduce unnecessary physical, emotional, or social demands, but it may also reflect individual differences, such as movement preferences, physical abilities, body confidence, cultural norms, personality, or temporary personal states. Appendix D presents a set of supplementary questions that can help researchers distinguish between different potential sources of discomfort. These questions are intended solely to support the interpretation of SECEL; they are not part of the validated questionnaire and are not included in score calculation.

Distinguishing between these potential sources is important because each suggests a different response. When lower expected comfort appears to arise from interaction design, it highlights opportunities for redesign, such as reducing unnecessary visibility, increasing learner autonomy, simplifying movement requirements, or providing alternative ways to participate. When anticipated discomfort primarily reflects relatively stable learner characteristics, the goal is not to eliminate individual differences but to accommodate a broader range of learners through flexibility and choice. Similarly, when expectations are influenced by temporary personal states, researchers should interpret SECEL scores with caution rather than attributing anticipated discomfort solely to the interaction design.

5.2 Interpreting the Regression Results

The observed association supports the premise that anticipated participation barriers can be identified before learners engage in bodily interaction. Overall expected comfort was strongly associated with self-reported willingness to participate, explaining 50.6% of its variance in this VR learning scenario. These findings suggest that learners' anticipated comfort is closely related to their stated willingness to engage.

When the three comfort dimensions were examined simultaneously, social comfort emerged as the strongest unique predictor of willingness, followed by physical comfort. Emotional comfort was not a significant predictor after physical and social comfort were controlled. This pattern suggests that willingness to participate may depend especially on whether participants feel socially comfortable being seen, judged, or moving around unfamiliar people. Physical comfort also showed a significant association, while social-evaluative concerns appeared to be particularly relevant to participants' stated willingness to participate in this context. The prominence of social comfort reinforces the idea that embodied learning is not simply about performing movements but about performing them in the presence of others. Unlike many conventional learning activities, embodied learning often makes learners' bodies visible to peers or instructors, increasing the potential for self-consciousness, evaluation apprehension, or concerns about appearing different from others. These findings are therefore consistent with recent work emphasizing that embodied interaction is inherently social and that participation is shaped not only by cognitive demands but also by how learners anticipate their bodies will be perceived within a learning environment [22]. Expected social comfort may therefore be an important factor to consider when examining how interaction design relates to learners' willingness to participate.

The non-significant association between emotional expected comfort and willingness to participate should not be interpreted as evidence that emotional comfort is unimportant. One possible explanation is that its relevance varies across embodied learning activities. For example, emotional comfort may be particularly salient in activities involving public performance, evaluation pressure, or unfamiliar bodily interactions, whereas it may play a less prominent role in the individual VR-based task examined in this study. Moreover, because the SECEL measures anticipated experiences before participation, emotional responses may become more salient during interaction itself, once learners directly experience success, failure, enjoyment, or frustration. Future studies should examine whether task characteristics influence the relationship between emotional expected comfort and willingness to participate across different embodied learning contexts.

6 Implications

6.1 Implications for Interaction Design

The proposed framework of design considerations contributes to embodied learning by shifting attention from movement solely as an instructional strategy to movement as an interaction design decision. Rather than asking only whether embodied activities improve learning, the framework encourages designers to consider how specific interaction characteristics may shape learners' anticipated experiences before participation occurs. In doing so, it provides a structured vocabulary for discussing expected comfort during the design process and supports more systematic reflection on the physical, emotional, and social consequences of interaction design decisions.

The framework is not intended as a checklist or a prescriptive set of design rules. Instead, it identifies interaction characteristics that are likely to influence expected comfort while recognizing that their effects depend on the educational context, learning objectives, and learner characteristics. Consequently, the same design feature may increase or decrease expected comfort depending on how it is implemented and why it is included.

Importantly, designing for expected comfort does not imply eliminating all forms of challenge. Many embodied learning activities intentionally incorporate uncertainty, collaboration, public performance, or precise bodily control because these experiences support important educational objectives. For example, instructional approaches such as productive failure [49] and desirable difficulties [10] deliberately introduce manageable challenges that may temporarily reduce expected comfort while promoting deeper learning. The purpose of the framework is therefore not to maximize comfort, but to help designers distinguish between discomfort that serves a pedagogical purpose and unnecessary barriers that discourage participation without contributing to learning. By making these trade-offs explicit, the framework supports more intentional and transparent interaction design decisions.

6.2 Implications for Measurement

From a design perspective, aggregated SECEL responses can provide formative feedback about aspects of an embodied learning activity that may create anticipated barriers to participation, supporting iterative refinement before implementation. To complement the scale, the supplementary questions provided in Appendix D can help researchers and designers explore learners' perceived sources of anticipated discomfort. Designers can administer the scale while evaluating sketches, storyboards, prototypes, or pilot activities to compare alternative interaction designs before implementation. Rather than waiting until learners complete an embodied activity, designers can identify anticipated participation barriers early and refine interaction designs before they are deployed in educational settings. From a research perspective, the SECEL operationalizes expected comfort as a measurable psychological construct. While the present study provides initial evidence of its association with self-reported willingness to participate, future research can examine whether expected comfort predicts actual engagement, participation behaviors, and learning outcomes.

The SECEL also enables researchers to investigate how learners' expectations evolve through interaction when used alongside measures of experienced comfort. Prior ergonomic research has distinguished comfort expected before product use from comfort experienced during use and shown that the two may diverge [11]. Extending this perspective to embodied learning, comparing expected and experienced comfort can reveal both expectation-experience alignment and expectation-experience mismatches, where learners' anticipated comfort either corresponds to or differs from their subsequent experiences. Examining these relationships may provide additional insights into how interaction design shapes learners' experiences beyond what expected or experienced comfort alone can reveal.

6.3 Integrating Design Considerations and Measurement

Taken together, the framework of design considerations and the SECEL offer complementary resources for the iterative design and evaluation of embodied learning activities. While the framework supports designers in identifying and reflecting on interaction characteristics that may influence learners' expected comfort, the SECEL provides a learner-reported measure of anticipated physical, emotional, and social comfort before participation. Their combined use suggests a design–measurement–redesign workflow: designers can develop embodied learning activities informed by the framework, introduce the proposed activities to learners, assess their expected comfort using the SECEL, and refine the interaction design based on the findings. This workflow extends the evaluation of embodied learning beyond post-participation assessment by providing opportunities to identify and address potential comfort-related concerns before learners engage with an activity. In this way, expected comfort serves not only as an evaluation outcome but also as a design resource for developing more inclusive and learner-responsive embodied learning experiences.

7 Limitations and Future Work

This study has several limitations that suggest important directions for future research. Regarding the framework of design considerations, its development was primarily informed by a narrative literature review and theoretical synthesis. While the reviewed literature included empirical studies documenting learners' experiences, these studies served as secondary sources of evidence rather than direct stakeholder input during framework development. Consequently, the framework may not fully capture the diverse perspectives and context-specific concerns of learners, educators, and designers. Future research could address this limitation by directly engaging these stakeholders through interviews, participatory design, or co-design workshops to further validate and refine the framework across different embodied learning contexts.

Regarding the SECEL, although the scale was developed to be applicable across a broad range of embodied learning activities, its validation was conducted using a standardized VR-based graph theory learning scenario. While this approach reduced contextual variability during scale development, it may limit the generalizability of the findings. The relative importance of physical, emotional, and social comfort may also vary across activities, potentially influencing their associations with willingness to participate. Future research should therefore evaluate the SECEL across diverse embodied learning contexts and examine measurement invariance across educational settings and cultural contexts. Additionally, the SECEL was validated only with adults screened for the absence of long-term health concerns and disabilities. Although anticipated barriers to participation were evident even within this sample, the findings may not generalize to learners with different bodily capacities and accessibility needs. Further validation with more diverse populations is needed to establish the scale's applicability and measurement equivalence across learner groups.

The administration and predictive validity of the SECEL also require further investigation. Learners' expected comfort may depend on the information provided before completing the scale, such as task instructions, demonstrations, or opportunities for practice. Moreover, the present study examined willingness to participate but did not investigate actual engagement, participation behaviors, or learning outcomes. Future research could examine these issues and further establish the predictive validity of the scale.

Finally, although the present work focuses on embodied learning, the concept of expected comfort may have broader implications for human-computer interaction. Many interactive systems, including virtual and augmented reality applications, exergames, rehabilitation technologies, public interactive installations, and motion-based interfaces, require users to anticipate how participation will feel before engaging. Future research should therefore examine whether the proposed framework and the SECEL can be adapted to these broader contexts and investigate how anticipated bodily experiences influence engagement, accessibility, technology acceptance, and continued participation. Such work would help determine whether expected comfort is primarily a construct for embodied learning or a more general principle of movement-based interaction design.

8 Conclusion

This paper makes two complementary contributions to embodied interaction and embodied learning research. First, it proposes a framework of design considerations that identifies interaction design considerations that may shape learners' expected comfort before participation. Second, it develops and validates the SECEL, providing researchers and designers with a psychometrically sound instrument for assessing expected comfort prior to interaction. Together, the framework and the SECEL establish expected comfort as a design consideration that can be anticipated, assessed, and addressed before an embodied learning activity is implemented. This shifts the evaluation of embodied learning beyond learners' experiences during or after interaction to include the anticipatory stage, when learners form expectations about the physical, emotional, and social consequences of participation. As embodied interaction continues to expand across education, extended reality, rehabilitation, and public interactive systems, designing not only for how people move, but also for how they expect movement to feel, may become increasingly important for creating engaging, inclusive, and accessible interactive experiences.

Acknowledgments

This work was supported by the Joint ETH Zurich-EPFL Doctoral Program in the Learning Sciences (JDPLS), funded by the Jacobs Foundation. We would like to thank Megan Humburg, Charlotte Hannah Müller, Ronja Sowinski, Morgana Vickery, Fan Wang, and Fangli Xia for their valuable feedback and suggestions during the development and refinement of the questionnaire.

References

[1] Elham Abdelmaksoud, Alena Kessem, and Francesco Cafaro. 2026. Designing Tangible and Embodied Interaction for Montessori Elementary Mathematics Education. In *Proceedings of the Twentieth International Conference on Tangible, Embedded, and Embodied Interaction*. 1–7. doi:10.1145/3731459.3779337

[2] Dor Abrahamson, Mitchell J Nathan, Caro Williams-Pierce, Candace Walkington, Erin R Ottmar, Hortensia Soto, and Martha W Alibali. 2020. The Future of Embodied Design for Mathematics Teaching and Learning. In *Frontiers in Education*, Vol. 5. 147. doi:10.3389/feduc.2020.00147

[3] Icek Ajzen. 1991. The Theory of Planned Behavior. *Organizational Behavior and Human Decision Processes* 50, 2 (1991), 179–211. doi:10.1016/0749-5978(91)90020-T

[4] Donald R Bacon, Paul L Sauer, and Murray Young. 1995. Composite Reliability in Structural Equations Modeling. *Educational and Psychological Measurement* 55, 3 (1995), 394–406. doi:10.1177/0013164495055003003

[5] Domna Banakou, Sameer Kishore, and Mel Slater. 2018. Virtually Being Einstein Results in an Improvement in Cognitive Task Performance and a Decrease in Age Bias. *Frontiers in Psychology* 9 (2018), 917. doi:10.3389/fpsyg.2018.00917

[6] Albert Bandura. 1997. *Self-Efficacy: The Exercise of Control*. Macmillan.

[7] Lawrence W Barsalou. 2008. Grounded Cognition. *Annual Review of Psychology* 59, 1 (2008), 617–645. doi:10.1146/annurev.psych.59.103006.093639

[8] Maurice S Bartlett. 1950. Tests of Significance in Factor Analysis. *British Journal of Psychology* 3, 2 (1950), 77–85. doi:10.1111/j.2044-8317.1950.tb00285.x

[9] Steve Benford, Chris Greenhalgh, Gabriella Giannachi, Brendan Walker, Joe Marshall, and Tom Rodden. 2012. Uncomfortable Interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2005–2014. doi:10.1145/2207676.2208347

[10] Elizabeth Ligon Bjork and Robert A. Bjork. 2011. Making Things Hard on Yourself, but in a Good Way: Creating Desirable Difficulties to Enhance Learning. In *Psychology and the Real World: Essays Illustrating Fundamental Contributions to Society*. Vol. 2. Worth Publishers, 56–64.

[11] Joyce M. A. Bouwens, Udo W. Schultheis, Suzanne Hiemstra-van Mastrigt, and Peter Vink. 2018. Expected versus Experienced Neck Comfort. *Human Factors and Ergonomics in Manufacturing & Service Industries* 28, 1 (2018), 29–37. doi:10.1002/hfm.20721

[12] John Brooke et al. 1996. SUS-A Quick and Dirty Usability Scale. *Usability Evaluation in Industry* 189, 194 (1996), 4–7.

[13] Timothy A Brown, Michael T Moore, et al. 2012. Confirmatory Factor Analysis. *Handbook of Structural Equation Modeling* 361, 2012 (2012), 379.

[14] CAST. 2024. Universal Design for Learning Guidelines Version 3.0. https://udlguidelines.cast.org

[15] Julia Chatain, Manu Kapur, and Robert W Sumner. 2023. Three Perspectives on Embodied Learning in Virtual Reality: Opportunities for Interaction Design. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–8. doi:10.1145/3544549.3585805

[16] Julia Chatain, Virginia Ramp, Venera Gashaj, Violaine Fayolle, Manu Kapur, Robert W Sumner, and Stéphane Magnenat. 2022. Grasping Derivatives: Teaching Mathematics through Embodied Interactions Using Tablets and Virtual Reality. In *Proceedings of the 21st Annual ACM Interaction Design and Children Conference*. 98–108. doi:10.1145/3501712.3529748

[17] Julia Chatain, Rudolf Varga, Violaine Fayolle, Manu Kapur, and Robert W Sumner. 2023. Grounding Graph Theory in Embodied Concreteness with Virtual Reality. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction*. 1–13. doi:10.1145/3569009.3572733

[18] Zhenfang Chen, Tate Johnson, Andrew Knowles, Ann Li, Semina Yi, Yumeng Zhuang, Daragh Byrne, and Dina El-Zanfaly. 2024. Augmenting Embodied Learning in Welding Training: The Co-Design of an XR-and tinyML-Enabled Welding System for Creative Arts and Manufacturing Training. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 1–14. doi:10.1145/3623509.3633398

[19] Allan Collins, John Seely Brown, and Susan E Newman. 2018. Cognitive Apprenticeship: Teaching the Crafts of Reading, Writing, and Mathematics. In *Knowing, Learning, and Instruction*. Routledge, 453–494.

[20] Nickolas B Cottrell. 1972. Social Facilitation. In *Experimental Social Psychology*, C. G. McClintock (Ed.). Holt, Rinehart and Winston, New York, 185–236.

[21] Lee J Cronbach. 1951. Coefficient Alpha and the Internal Structure of Tests. *Psychometrika* 16, 3 (1951), 297–334. doi:10.1007/BF02310555

[22] Joshua A Danish, Noel Enyedy, Asmalina Saleh, and Megan Humburg. 2020. Learning in Embodied Activity Framework: A Sociocultural Framework for Embodied Cognition: Danish JA et al. *International Journal of Computer-Supported Collaborative Learning* 15, 1 (2020), 49–87. doi:10.1007/s11412-020-09317-3

[23] Fred D Davis. 1989. Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS Quarterly* 13, 3 (1989), 319–340. doi:10.2307/249008

[24] Kayla DesPortes, Kathleen McDermott, Yoav Bergner, Francisco Enrique Vicente Castro, Sauda Musharrat, and Aakruti Lunia. 2024. DanceBits' It Tells You to See Us': Supporting Dance Practices with an Educational Computing Kit. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 1–19. doi:10.1145/3623509.3633350

[25] Sally S Dickerson and Margaret E Kemeny. 2004. Acute Stressors and Cortisol Responses: A Theoretical Integration and Synthesis of Laboratory Research. *Psychological Bulletin* 130, 3 (2004), 355. doi:10.1037/0033-2909.130.3.355

[26] Paul Dourish. 2001. *Where the Action Is: The Foundations of Embodied Interaction*. MIT press Cambridge. doi:10.7551/mitpress/7221.001.0001

[27] Jacquelynne S Eccles and Allan Wigfield. 2002. Motivational Beliefs, Values, and Goals. *Annual Review of Psychology* 53, 1 (2002), 109–132. doi:10.1146/annurev.psych.53.100901.135153

[28] Leandre R Fabrigar, Duane T Wegener, Robert C MacCallum, and Erin J Strahan. 1999. Evaluating the Use of Exploratory Factor Analysis in Psychological Research. *Psychological Methods* 4, 3 (1999), 272. doi:10.1037/1082-989X.4.3.272

[29] Claes Fornell and David F Larcker. 1981. Evaluating Structural Equation Models with Unobservable Variables and Measurement Error. *Journal of Marketing Research* 18, 1 (1981), 39–50. doi:10.2307/3151312

[30] Susan Gerofsky. 2011. Seeing the Graph vs. Being the Graph: Gesture, engagement and awareness in school mathematics. *Integrating Gestures: The interdisciplinary nature of gesture* (2011), 245–256. doi:10.1075/gs.4.22ger

[31] Elisa Giaccardi and Elvin Karana. 2015. Foundations of Materials Experience: An Approach for HCI. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2447–2456. doi:10.1145/2702123.2702337

[32] Maria J Grant and Andrew Booth. 2009. A Typology of Reviews: An Analysis of 14 Review Types and Associated Methodologies. *Health Information & Libraries Journal* 26, 2 (2009), 91–108. doi:10.1111/j.1471-1842.2009.00848.x

[33] Bart N Green, Claire D Johnson, and Alan Adams. 2006. Writing Narrative Literature Reviews for Peer-Reviewed Journals: Secrets of the Trade. *Journal of Chiropractic Medicine* 5, 3 (2006), 101–117. doi:10.1016/S0899-3467(07)60142-6

[34] Joseph F Hair, Marcelo Gabriel, and Vijay Patel. 2014. AMOS Covariance-Based Structural Equation Modeling (CB-SEM): Guidelines on Its Application as a Marketing Research Tool. *Brazilian Journal of Marketing* 13, 2 (2014).

[35] Joseph F Hair Jnr, William C Black, Barry J Babin, and Rolph E Anderson. 2010. *Multivariate Data Analysis*. Prentice-Hall, Inc., USA.

[36] Marc Hassenzahl. 2010. *Experience Design: Technology for All the Right Reasons*. Vol. 8. Morgan & Claypool Publishers.

[37] Marc Hassenzahl and Noam Tractinsky. 2006. User Experience-A Research Agenda. *Behaviour & Information Technology* 25, 2 (2006), 91–97. doi:10.1080/01449290500330331

[38] Jörg Henseler, Christian M. Ringle, and Marko Sarstedt. 2015. A New Criterion for Assessing Discriminant Validity in Variance-Based Structural Equation Modeling. *Journal of the Academy of Marketing Science* 43, 1 (2015), 115–135. doi:10.1007/s11747-014-0403-8

[39] Timothy R Hinkin. 1998. A Brief Tutorial on the Development of Measures for Use in Survey Questionnaires. *Organizational Research Methods* 1, 1 (1998), 104–121. doi:10.1177/109442819800100106

[40] Cindy E Hmelo-Silver, Ravit Golan Duncan, and Clark A Chinn. 2007. Scaffolding and Achievement in Problem-Based and Inquiry Learning: A Response to Kirschner, Sweller, And Clark (2006). *Educational Psychologist* 42, 2 (2007), 99–107. doi:10.1080/00461520701263368

[41] Kristina Höök. 2018. *Designing with the Body: Somaesthetic Interaction Design.* MIT Press. doi:10.7551/mitpress/11481.001.0001

[42] Kristina Höök, Steve Benford, Paul Tennent, Vasiliki Tsaknaki, Miquel Alfaras, Juan Martinez Avila, Christine Li, Joseph Marshall, Claudia Daudén Roquet, Pedro Sanches, et al. 2021. Unpacking Non-Dualistic Design: The Soma Design Case. *ACM Transactions on Computer-Human Interaction (TOCHI)* 28, 6 (2021), 1–36. doi:10.1145/3462448

[43] Eva Hornecker and Jacob Buur. 2006. Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 437–446. doi:10.1145/1124772.1124838

[44] Caroline Hummels and Jelle Van Dijk. 2015. Seven Principles to Design for Embodied Sensemaking. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*. 21–28. doi:10.1145/2677199.2680577

[45] Mina C Johnson-Glenberg. 2018. Immersive VR and Education: Embodied Design Principles That Include Gesture and Hand Controls. *Frontiers in Robotics and AI* 5 (2018), 375272. doi:10.3389/frobt.2018.00081

[46] Mina C Johnson-Glenberg, David A Birchfield, Lisa Tolentino, and Tatyana Koziupa. 2014. Collaborative Embodied Learning in Mixed Reality Motion-Capture Environments: Two Science Studies. *Journal of Educational Psychology* 106, 1 (2014), 86–104. doi:10.1037/a0034008

[47] Ida Kathrine Hammeleff Jørgensen and Harun Kaygan. 2024. The Body in Play: Dimensions of Embodiment in Design for Play. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 1–12. doi:10.1145/3623509.3633379

[48] Henry F Kaiser. 1960. The Application of Electronic Computers to Factor Analysis. *Educational and Psychological Measurement* 20, 1 (1960), 141–151. doi:10.1177/001316446002000116

[49] Manu Kapur. 2008. Productive Failure. *Cognition and Instruction* 26, 3 (2008), 379–424. doi:10.1080/07370000802212669

[50] Maria Karam and MC Schraefel. 2006. Investigating User Tolerance for Errors in Vision-Enabled Gesture-Based Interactions. In *Proceedings of the Working Conference on Advanced Visual Interfaces*. 225–232. doi:10.1145/1133265.1133309

[51] Konstantina Kilteni, Raphaela Groten, and Mel Slater. 2012. The Sense of Embodiment in Virtual Reality. *Presence: Teleoperators and Virtual Environments* 21, 4 (2012), 373–387. doi:10.1162/PRES_a_00124

[52] Panagiotis Kosmas and Panayiotis Zaphiris. 2020. Words in Action: Investigating Students' Language Acquisition and Emotional Performance through Embodied Learning. *Innovation in Language Learning and Teaching* 14, 4 (2020), 317–332. doi:10.1080/17501229.2019.1607355

[53] Jimmie Leppink, Fred Paas, Cees PM Van der Vleuten, Tamara Van Gog, and Jeroen JG Van Merriënboer. 2013. Development of an Instrument for Measuring Different Types of Cognitive Load. *Behavior Research Methods* 45, 4 (2013), 1058–1072. doi:10.3758/s13428-013-0334-1

[54] Xiaoxuan Li, Julia Chatain, Fan Wang, and Manu Kapur. 2026. From Body to Word: A Three-Level Meta-Analysis of Embodied Vocabulary Learning. *Educational Psychology Review* 38, 1 (2026), 102. doi:10.1007/s10648-026-10194-9

[55] Robb Lindgren and Mina Johnson-Glenberg. 2013. Emboldened by Embodiment: Six Precepts for Research on Embodied Learning and Mixed Reality. *Educational Researcher* 42, 8 (2013), 445–452. doi:10.3102/0013189X13511661

[56] Leilah Lyons, Brian Slattery, Priscilla Jimenez, Brenda Lopez, and Tom Moher. 2012. Don't Forget About the Sweat: Effortful Embodied Interaction in Support of Learning. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*. 77–84. doi:10.1145/2148131.2148149

[57] Maria Ioanna Magkouta, Rudolf Varga, Julia Chatain, and Manu Kapur. 2026. Morphological Changes in Virtual Reality for Learning Mathematics. In *The Learning Confoederatio—Navigating (Digital) Change through Evidence: Book of Abstracts*, Juliette Désiron (Ed.). Institute of Education, University of Zurich, Zurich, Switzerland, 189–190.

[58] Roderick P McDonald. 2013. *Test Theory: A Unified Treatment.* psychology press. doi:10.4324/9781410601087

[59] Florian 'Floyd' Mueller, Richard Byrne, Josh Andres, and Rakesh Patibanda. 2018. Experiencing the Body as Play. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–13. doi:10.1145/3173574.3173784

[60] Albert Newen, Leon De Bruin, and Shaun Gallagher. 2018. *The Oxford Handbook of 4E Cognition.* Oxford University Press. doi:10.1093/oxfordhb/9780198735410.001.0001

[61] Jakob Nielsen. 1994. Enhancing the Explanatory Power of Usability Heuristics. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 152–158. doi:10.1145/191666.191729

[62] Don Norman. 2013. *The Design of Everyday Things: Revised and Expanded Edition.* Basic books.

[63] Xavier Ochoa, AWDG Charles Lang, and George Siemens. 2017. Multimodal Learning Analytics. *The Handbook of Learning Analytics* 1 (2017), 129–141. doi:10.18608/hla17

[64] Heather L O'Brien, Paul Cairns, and Mark Hall. 2018. A Practical Approach to Measuring User Engagement with the Refined User Engagement Scale (UES) and New UES Short Form. *International Journal of Human-Computer Studies* 112 (2018), 28–39. doi:10.1016/j.ijhcs.2018.01.004

[65] Reinhard Pekrun. 2006. The Control-Value Theory of Achievement Emotions: Assumptions, Corollaries, and Implications for Educational Research and Practice. *Educational Psychology Review* 18, 4 (2006), 315–341. doi:10.1007/s10648-006-9029-9

[66] Prolific. 2026. Prolific. https://www.prolific.com. Online participant recruitment platform.

[67] Jack Ratcliffe, Nick Ballou, and Laurissa Tokarchuk. 2021. Actions, Not Gestures: Contextualising Embodied Controller Interactions in Immersive Virtual Reality. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. 1–11. doi:10.1145/3489849.3489892

[68] James Reason. 2000. Human Error: Models and Management. *BMJ* 320, 7237 (2000), 768–770. doi:10.1136/bmj.320.7237.768

[69] Richard M Ryan, Valerie Mims, and Richard Koestner. 1983. Relation of Reward Contingency and Interpersonal Context to Intrinsic Motivation: A Review and Test Using Cognitive Evaluation Theory. *Journal of Personality and Social Psychology* 45, 4 (1983), 736. doi:10.1037/0022-3514.45.4.736

[70] Benjamin Lukas Schnitzer, Stefano Gampe, Arndt Bieberstein, Isabel Hoffmann, Daniel Görlich, and Oliver Korn. 2025. Language Learning in Virtual Reality: Enhancement of Long-Term Vocabulary Recognition and Understanding through Full-Body Avatars. In *Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*. 1–9. doi:10.1145/3706599.3720187

[71] Qinglan Shan, Manu Kapur, and Juergen Brugger. 2026. From Apprenticeship to Autonomy: Mixed Reality-Assisted Training in a Cleanroom by a Hybrid Authoring Workflow. In *Proceedings of the Extended Abstracts of the 2026 CHI Conference on Human Factors in Computing Systems*. 1–6. doi:10.1145/3772363.3798988

[72] Alexander Skulmowski and Günter Daniel Rey. 2017. Measuring Cognitive Load in Embodied Learning Settings. *Frontiers in Psychology* 8 (2017), 1191. doi:10.3389/fpsyg.2017.01191

[73] Alexander Skulmowski and Günter Daniel Rey. 2018. Embodied Learning: Introducing a Taxonomy Based on Bodily Engagement and Task Integration. *Cognitive Research: Principles and Implications* 3, 1 (2018), 6. doi:10.1186/s41235-018-0092-9

[74] Mel Slater. 2009. Place Illusion and Plausibility Can Lead to Realistic Behaviour in Immersive Virtual Environments. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364, 1535 (2009), 3549–3557. doi:10.1098/rstb.2009.0138

[75] Katta Spiel. 2021. The Bodies of TEI–Investigating Norms and Assumptions in the Design of Embodied Interaction. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 1–19. doi:10.1145/3430524.3440651

[76] John Sweller. 2023. The development of cognitive load theory: Replication crises and incorporation of other theories can lead to theory expansion. *Educational Psychology Review* 35, 4 (2023), 95. doi:10.1007/s10648-023-09817-2

[77] Sofia Tancredi, Rachel SY Chen, Christina Krause, Dor Abrahamson, and Filippo Gomez Paloma. 2021. Getting Up to SpEED: Special Education Embodied Design for Sensorially Equitable Inclusion. *Education Sciences & Society-Open Access* 12, 1 (2021). doi:10.3280/ess1-2021oa11818

[78] Sofia Tancredi, Morgan Vickery, Christina Krause, Jessica Benally, Dionne Champion, Foloshadé Solomon, Farha Najah Hussain, Maisie L Gholson, Ananda Marin, Lindsay Lindberg, et al. 2024. Learning for Every Body: Intersectional Dimensions of Embodied Learning. In *Proceedings of the 18th International Conference of the Learning Sciences-ICLS 2024, pp. 2037-2044*. International Society of the Learning Sciences. doi:10.22318/icls2024.270203

[79] Jakob Carl Uhl, Georg Regal, Laura Koesten, Michael Oppermann, Markus Murtinger, and Manfred Tscheligi. 2025. Embodied Measurement: Tangible Interactions to Enhance the Validity of Self-Report Measures. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. 1–16. doi:10.1145/3706598.3714055

[80] Viswanath Venkatesh, Michael G Morris, Gordon B Davis, and Fred D Davis. 2003. User Acceptance of Information Technology: Toward a Unified View1. *MIS Quarterly* 27, 3 (2003), 425–478. doi:10.2307/30036540

[81] Morgan Vickery and Joshua Danish. 2025. Realizations & Re-Mediations: Enabling Expression and Interaction in Collective Embodied Activities for Children with Disabilities. *Learning, Culture and Social Interaction* 53 (2025), 100919. doi:10.1016/j.lcsi.2025.100919

[82] Morgan Vickery, Nitasha Mathayas, and Joshua Danish. 2024. Being Body-Conscious: A Trauma-Informed Inquiry into Elementary Students' Collective Embodied Learning Experiences. In *Proceedings of the 18th International Conference of the Learning Sciences-ICLS 2024, pp. 1846-1849*. International Society of the Learning Sciences. doi:handle/1/10826

[83] Morgan Ann Vickery. 2025. *Towards a Sociocritical Framework for Body-Inclusive Embodied Activity Design*. Ph. D. Dissertation. Indiana University. doi:pqdtglobal/docview/3241807544/CA5399A2E81F4326PQ/1

[84] Candace Walkington, Mitchell J Nathan, Min Wang, and Kelsey Schenck. 2022. The Effect of Cognitive Relevance of Directed Actions on Mathematical Reasoning. *Cognitive Science* 46, 9 (2022), e13180. doi:10.1111/cogs.13180

[85] Candace Walkington, Max Sherard, LeaAnne Daughrity, Prajakt Pande, Theodora Beauchamp, and Anthony Cuevas. 2025. The Affordances and Constraints of Mathematics Tutoring in Immersive, Collaborative, and Dynamic Virtual Reality Environments. *Virtual Reality* 29, 2 (2025), 60. doi:10.1007/s10055-025-01122-3

[86] Allan Wigfield and Jacquelynne S Eccles. 2000. Expectancy–Value Theory of Achievement Motivation. *Contemporary Educational Psychology* 25, 1 (2000), 68–81. doi:10.1007/BF02209024

[87] Margaret Wilson. 2002. Six Views of Embodied Cognition. *Psychonomic Bulletin & Review* 9, 4 (2002), 625–636. doi:10.3758/BF03196322

[88] Bob G Witmer and Michael J Singer. 1998. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence* 7, 3 (1998), 225–240. doi:10.1162/105474698565686

[89] Jacob O Wobbrock, Shaun K Kane, Krzysztof Z Gajos, Susumu Harada, and Jon Froehlich. 2011. Ability-Based Design: Concept, Principles and Examples. *ACM Transactions on Accessible Computing (TACCESS)* 3, 3 (2011), 1–27. doi:10.1145/1952383.1952384

[90] Nick Yee and Jeremy Bailenson. 2007. The Proteus Effect: The Effect of Transformed Self-Representation on Behavior. *Human Communication Research* 33, 3 (2007), 271–290. doi:10.1111/j.1468-2958.2007.00299.xDigitalObjectIdentifier(DOI)

[91] Luian Zhang, Martin G Helander, and Colin G Drury. 1996. Identifying Factors of Comfort and Discomfort in Sitting. *Human Factors* 38, 3 (1996), 377–389. doi:10.1518/001872096778701962

[92] Rong-Ling Zhang, Shu-yu Yu, Rui-feng Gao, Li-fei Wang, and Xiang-chun He. 2025. How Does Technology-Based Embodied Learning Affect Learning Effectiveness?–Based on a Systematic Literature Review and Meta-Analytic Approach. *Interactive Learning Environments* 33, 6 (2025), 4135–4158. doi:10.1080/10494820.2025.2479176

A Final Scale of Expected Comfort in Embodied Learning (SECEL)

Items 1-12 form the final SECEL, Items 13-16 assess willingness to participate for criterion validity.

You have just finished reading the instructions for a VR movement-based graph theory learning activity and are preparing to begin the activity. The following questions ask about how you expect you would feel while participating in the activity. Please base your responses only on the information provided in the instructions. You do not need any prior knowledge of graph theory to answer these questions. Please indicate the extent to which you agree with each statement. There are no right or wrong answers. Respond according to your first impression of the activity as described, rather than your general preferences for mathematics or learning. Responses were recorded on a seven-point Likert scale ranging from 1 (*Strongly disagree*) to 7 (*Strongly agree*).

A.1 Physical Comfort

(1) I would feel physically comfortable performing the movements required in this activity.
(2) The required movements would feel manageable for me.
(3) I would feel in control of my body when performing the required movements.
(4) I would be able to coordinate my movements comfortably while solving the task.

A.2 Emotional Comfort

(5) I would feel psychologically safe performing the required movements.
(6) I would feel emotionally comfortable performing the required movements.
(7) I would feel anxious while performing the required movements. (R)
(8) I would find the required movements emotionally stressful. (R)

A.3 Social Comfort

(9) I would feel comfortable participating in this activity when other people could see me.
(10) I would feel comfortable if my movements looked different from those of other participants.
(11) I would worry about being judged while performing the required movements. (R)
(12) I would feel uncomfortable performing the required movements around people I did not know. (R)

A.4 Willingness to participate

(13) I would actively participate in this activity if given the opportunity.
(14) I would be willing to participate in similar VR movement-based learning activities in the future.
(15) I would avoid participating in this activity. (R)
(16) I would prefer to learn the same content (graph theory) without using body movement. (R)

Note. (R) indicates reverse-coded items.

B Initial SECEL (18 items)

B.1 Physical Comfort

(1) I would feel physically comfortable performing the movements required in this activity.
(2) The required movements would feel manageable for me.
(3) I would feel in control of my body when performing the required movements.
(4) I would be able to coordinate my movements comfortably while solving the task.
(5) *Performing the required movements would feel physically tiring for me. (R)*
(6) *It would be hard to focus on learning because my body would feel tense. (R)*

B.2 Emotional Comfort

(1) I would feel psychologically safe performing the required movements.
(2) I would feel emotionally comfortable performing the required movements.
(3) *I would feel confident while performing the required movements.*
(4) I would feel anxious while performing the required movements. (R)
(5) I would find the required movements emotionally stressful. (R)
(6) *I would worry about making mistakes when performing the movements to learn. (R)*

B.3 Social Comfort

(1) I would feel comfortable participating in this activity when other people could see me.
(2) I would feel comfortable if my movements looked different from those of other participants.
(3) *I would feel comfortable collaborating with another participant in this activity.*
(4) *I would hesitate to participate if other participants seemed more experienced than I was. (R)*
(5) I would worry about being judged while performing the required movements. (R)
(6) I would feel uncomfortable performing the required movements around people I did not know. (R)

Note. (R) indicates reverse-coded items. Items removed during scale refinement are presented in italics.

C Scenario Presented to Participants

About the Activity

Graph theory is a branch of mathematics that studies how objects are connected. It uses points (called nodes) and lines (called edges) to represent relationships between objects. For example, graphs can be used to represent road networks, friendships between people, or transportation systems.

The activity takes place in virtual reality. Virtual reality is a technology that allows users to experience and interact with a

computer-generated three-dimensional environment using a head-mounted display (VR headset). Instead of viewing information on a computer screen, users can look around the virtual environment and interact with virtual objects using their hands and body movements.

In this activity, graph theory concepts are learned through body movement in the VR environment. Rather than studying diagrams on paper, you will use your hands to interact with virtual graph components.

Learning Task

Imagine that you are about to participate in the following learning activity. Your goal is to bring the maximum amount of water from the lake to the city by adjusting the flow through a network of connected pipes.

To complete the task:

- Each pipe has a maximum capacity that cannot be exceeded.
- Water towers cannot store water. Therefore, for every water tower, the amount of incoming water must equal the amount of outgoing water. If this constraint is violated, a warning sign will appear above the tower.
- Your objective is to satisfy all constraints while maximizing the amount of water delivered from the lake to the city.
- To adjust the water flow, you press a button on a pipe and move your hand upward or downward to increase or decrease the amount of water flowing through that pipe.
- Releasing the button confirms the selected flow. When you are satisfied with your solution, you raise both hands above your head to proceed to the next level.

D Supplementary Questions for Exploring Perceived Sources of Anticipated Discomfort

The following supplementary questions are provided to help researchers and designers identify potential sources of anticipated discomfort. These questions are **not part of the validated SECEL** and are intended solely to support design reflection and interpretation of expected comfort scores.

What, if anything, contributes to your anticipated discomfort?

(Select all that apply.)

A. Design of the activity.

- ☐ The movements seem too physically demanding.
- ☐ The movements seem too complex.
- ☐ The activity requires movements that are too visible.
- ☐ I would have little choice in how I participate.
- ☐ The activity requires close interaction with others.
- ☐ The technology or equipment seems uncomfortable to use or wear.
- ☐ The instructions or expectations seem unclear.
- ☐ Other design-related reason: _____

B1. Stable learner characteristics.

- ☐ I generally prefer less movement during learning.
- ☐ I have physical limitations or health concerns.
- ☐ I have had negative experiences with similar activities.
- ☐ I feel self-conscious about my body or movement.
- ☐ My cultural or personal values make this activity feel uncomfortable.

B2. Temporary personal state.

- ☐ I am feeling tired today.
- ☐ I am feeling stressed or anxious before the activity.
- ☐ I am not in a good mood before participating.
- ☐ I am feeling unwell today.
- ☐ Other temporary reason: _____

C. Depends on both me and the activity.

- ☐ I worry that other people may judge me.
- ☐ I worry about making mistakes in front of others.
- ☐ I would feel embarrassed performing the movements.
- ☐ I am unsure whether I could perform the movements successfully.
- ☐ It would depend on who else is participating.
- ☐ It would depend on the classroom environment.