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Younger children engage more while adolescents feel more excluded in social interaction in VR: evidence from two controlled experiments

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Introduction: Recent advances in virtual reality (VR) have positioned immersive technologies as powerful tools in educational psychology, offering controllable and engaging environments for studying social and cognitive processes. The youth population is frequently at the center of this research domain; however, how developmental stage shapes children's and adolescents' experiences within VR remains insufficiently explored. Therefore, this study investigated the relationships between age and key experiential factors in VR, including perceptual engagement (immersion, perceived realism, involvement, and presence), usability, simulator sickness, and subjective feelings of social exclusion.
Method: Based on the renowned Cyberball ostracism framework, we designed and developed custom VR conversational scenarios to simulate social exclusion with appropriately interactive mechanisms. Two controlled experiments with Italian school students (total N = 313; ages 8–16) were conducted with proper consents and ethical approvals. The VR application was refined based on feedback collected from the first study. During the experimental sessions, participants interacted with virtual peers in a virtual classroom and subsequently completed questionnaires assessing the target constructs. The acquired data were analyzed using group comparisons, correlation analyses, and multiple regression models.
Results: Across both studies, younger participants (age <13) consistently reported higher levels of perceptual engagement as well as higher usability ratings. In contrast, older participants experienced significantly greater subjective social exclusion within the VR scenario. Simulator sickness scores did not differ significantly by age and showed no systematic developmental trend. Regression analyses confirmed that age negatively predicted perceptual measures and usability, and positively predicted exclusion, while perceptual realism and presence strongly contributed to usability judgments.
Discussion: Findings demonstrate that developmental stage substantially influences how youth experience VR. In particular, younger children responded more positively to perceptual and usability aspects, whereas adolescents showed heightened sensitivity to social dynamics. Based on our

empirical insights and established developmental theories, we propose a conceptual framework outlining the interplay among these factors and key design considerations for effective research in youth-centered VR applications.

KEYWORDS
age-related user experience, Cyberball paradigm, social exclusion, virtual reality, youth-centered design

1 Introduction

There has been a growing interest in developing virtual reality (VR) applications and experiments for young students within the field of educational psychology. Research in this area has shown that providing learning materials via VR elicits and amplifies positive emotions in students, owing to the enhanced active participation and engagement it engenders, thereby fostering a favorable attitude toward the learning materials. Specifically learners in VR environments reported significantly higher engagement and positive affect compared to those using traditional textbooks or video, which correlated with improved performance (Allcoat and Von Muhlenen, 2018) and an empirical study indicates that VR holds strong potential for simulations and other e-learning applications, as immersive VR is more effective than desktop VR in stimulating, engaging, and motivating students (Makransky and Lilleholt, 2018). In addition, meta-analytic and experimental findings show that VR interventions can enhance motivation and social–emotional learning outcomes in children and adolescents (Parong and Mayer, 2018; Zhang et al., 2023). Beyond instructional purposes, VR also offers researchers a powerful experimental context to examine developmental processes related to social cognition, empathy, and inclusion within controlled yet ecologically valid settings. These affordances position VR as both a pedagogical medium and a psychological laboratory for studying how young users perceive and engage with complex social environments.

Social interaction is central to educational psychology because belonging, collaboration, and peer acceptance are key determinators of learning and motivation in school-aged children (Wentzel, 2005). Experiences of social exclusion or neglect—being ignored, left out, or overlooked—can impair attention, self-esteem, and academic engagement (Baumeister and Leary, 1995; Williams et al., 2000). One widely used experimental method for inducing inclusion or ostracism is the *Cyberball paradigm* (Williams and Jarvis, 2006). In its classic form, the task involves three players tossing a ball among themselves, and the participant's sense of inclusion depends on how often they receive the ball. Exclusion is manipulated by controlling the distribution of throws, typically through computer-controlled confederates unknown to the participant. In the original computerized version, participants believe they are playing an online ball-tossing game with other real players, while the program's logic determines whether they are included or ignored. Research has consistently shown that even brief episodes of exclusion in Cyberball reliably threaten fundamental psychological needs, including belonging, self-esteem, control, and meaningful existence (Hartgerink et al., 2015). Translating this paradigm into immersive virtual environments enables researchers to reproduce realistic, interactive peer scenarios while maintaining experimental precision. Studies confirm that exclusion in VR elicits affective and physiological responses comparable to, or stronger than, those observed in real-life settings (Parsons et al., 2017; Kothgassner et al., 2021) Such findings underscore VR's potential as a platform for investigating the psychological mechanisms of inclusion and ostracism in contexts that mirror classroom or peer-group interactions.

The traditional Cyberball paradigm has been instrumental in studying peer exclusion, yet literature highlights clear limitations that justify the development of a VR-based scenario. Cyberball's minimalistic 2D interface, absence of authentic social cues, and abstract ball-tossing activity offer low ecological validity, making it difficult for children and adolescents to experience interactions that resemble real peer dynamics (Parsons, 2015; Tuijnman et al., 2021). The simplicity of the task and limited opportunities for naturalistic behavioral responses may also lead to boredom or disengagement, especially among younger participants accustomed to rich digital environments (Prendergast and Schubert, 2020). Moreover, Cyberball's restricted manipulation of variables reduces experimental control over social behaviors central to real-life exclusion, such as conversational turn-taking or subtle interpersonal neglect. Crucially, it fails to capture the complex, embodied dynamics of modern youth interaction. For these reasons, we stress the need for a 3D VR paradigm that provides immersive realism, enhanced social presence, and naturalistic peer interactions—qualities that align emotional and cognitive responses more closely with everyday exclusion experiences (Triberti et al., 2018; Villena-Taranilla et al., 2022).

Despite these theoretical and empirical insights, important research gaps persist. First, few studies have simultaneously examined perceptual (immersion, experienced realism, involvement, and presence), practical (usability and simulator sickness), and social-affective (exclusion) components of VR experience across developmental stages. Second, while ostracism has been studied through Cyberball games in over 600 studies since the program was developed in 2006, little is known about how children and adolescents experience conversational, peer-group interactions in immersive VR settings that more closely resemble real social and educational contexts. Third, the interrelations among experiential factors—how perceptual realism relates to usability, comfort, and social affect—remain poorly understood, limiting the derivation of evidence-based design principles for youth-appropriate educational VR.

To address these gaps, we conducted two sequential studies with 313 Italian schoolchildren and adolescents (ages 8–16), using a custom VR environment that adapted the Cyberball paradigm into a short conversational exclusion task designed to simulate classroom-like peer interaction. Rather than treating these as isolated outcomes, we investigate how they co-vary and jointly contribute to engagement, comfort, and social-emotional response, depending on the specific age group. To achieve this, we designed and employed a controlled "interactive social VR scenario" in which participants engaged in a conversational interaction with virtual peers. This scenario included a specific phase designed to elicit feelings of social exclusion. Consequently, this research is developed around these five research questions:

- RQ1: How does age influence perceptual dimensions of VR experience (immersion, experienced realism, involvement, presence) during an interactive social VR scenario?
- RQ2: To what extent does age relate to practical aspects such as system usability rating and simulator sickness in an interactive social VR scenario?
- RQ3: What relationships exist among perceptual experiences, usability, and simulator sickness across age groups in the context of an interactive social VR?
- RQ4: Does age modulate affective responses to social exclusion in VR, as elicited through an interactive social VR scenario?
- RQ5: Does the feeling of being excluded in an interactive social VR scenario affect the rating of perceptual intensity, usability, and simulator sickness?

2 Related work

In the broader context, recent literature emphasizes that, for youth, social reality is becoming increasingly immersive. Large-scale surveys of adolescents indicate that a substantial proportion of teen VR users have already experienced exclusion or harassment in "metaverse" environments, suggesting that VR-induced social pain is not only feasible to recreate experimentally, but is also already a prevalent real-world phenomenon within this demographic (Hinduja and Patchin, 2024). Conversely, systematic reviews have found that immersive VR can function as an effective intervention tool for improving social skills in children and adolescents with autism spectrum disorder, with particularly strong effects observed in the enhancement of complex social skills among individuals with high-functioning autism (Yang et al., 2025). Returning to the social interaction aspect, existing work on simulating controlled social interactions in VR provides an important foundation for the present conversational paradigm. Prendergast and Schubert (Prendergast and Schubert, 2020) successfully employed a VR group-discussion task to induce social exclusion in adults, demonstrating that conversational neglect can elicit need-threat responses similar to Cyberball, but with improved ecological validity due to richer behavioral and social cues. Other studies emphasize VR's capacity to recreate naturalistic interpersonal dynamics in educational or collaborative contexts, showing that immersive environments enhance realism, social presence, and emotional salience (Riva and Eck, 2016; Slater and Sanchez-Vives, 2016; Silseth et al., 2024; Marinucci and Riva, 2025). Together, these findings support the use of a VR conversational scenario for young populations, as VR can integrate behavioral realism, contextual relevance, and controlled manipulation of peer interactions—elements essential for capturing developmental differences in social exclusion responses.

In addition, understanding how young users perceive and emotionally respond to social VR experiences is essential. Well-established cognitive development theories could provide a useful framework for understanding how young people engage with VR. For example, *Piaget's Theory of Cognitive Development* (Piaget, 1964) framework highlights how children in the concrete operational stage (approximately 7–11 years) think logically but remain grounded in tangible and observable experiences, while adolescents entering the formal operational stage (beginning around age 12) develop advanced abilities in abstract thought, hypothetical reasoning, and metacognition. This cognitive shift renders adolescents more reflective and critical of virtual environments, potentially reducing pure perceptual immersion but increasing sensitivity to inconsistencies in realism or narrative coherence. Hence, while children might report stronger presence and involvement, adolescents probably tend to experience VR more evaluatively, filtering their perceptions through heightened reasoning capabilities.

Erikson's Stages of Development (Orenstein and Lewis, 2025) complements this cognitive perspective by emphasizing the social and emotional tasks specific to each developmental stage. Children in middle to late childhood face the psychosocial crisis of Industry vs. Inferiority, where mastery of skills and peer approval are central. In VR contexts, this may lead to heightened enthusiasm for achievement-oriented or gamified elements and strong responsiveness to interactive feedback. In contrast, adolescents navigate the crisis of Identity vs. Role Confusion, making identity formation and social belonging paramount. Consequently, adolescents may be especially sensitive to social dynamics in VR, such as simulated inclusion or exclusion, and may react more intensely when confronted with negative social experiences, even if their immersive engagement is comparatively lower. Taken together, these developmental theories underscore that VR experiences are shaped not simply by technological features but by age-related cognitive and psychosocial transitions, and they emphasize the necessity of understanding how age interacts with various VR experience factors when designing VR applications for young participants.

Empirical and developmental evidence further clarifies why children and adolescents experience VR environments differently. Children tend to focus on concrete and perceptually salient features of the virtual environment, which enhances immersion, presence, and perceived realism (Villena-Taranilla et al., 2022). Their reliance on tangible cues makes them more responsive to visual and environmental aspects, leading them to interpret virtual interactions as more "real." In contrast, adolescents show heightened emotional attunement to social cues: developmental research describes adolescence as a period of increased sensitivity to peer evaluation, social approval, and rejection (Sebastian et al., 2010; Somerville, 2013). This heightened social orientation could intensify adolescents' affective and motivational responses during VR-based exclusion. Thus, children's perceptual engagement and adolescents' socio-emotional sensitivity represent distinct developmental pathways that VR can uniquely capture—highlighting the value of immersive environments for age-comparative research on social exclusion.

Building upon the insights gleaned from existing literature and well-known cognitive development theories, our work aims to clarify how the aforementioned factors interrelate in shaping overall VR experience among children and adolescents. Our study specifically focuses on the following factors:

- ***Perception*** in VR refers to how users interpret and make sense of virtual environments, including how real, immersive, and believable they feel. This approach aligns with Slater's distinction (Slater, 2009) between system-driven immersion and perceptual states such as presence and plausibility, which together determine users' subjective experience of the virtual world. Similarly, we explored four contributing subsections, including:
  - *Immersion* is the ability to draw people in (commonly in gaming experience) by "providing appealing distractions so that the users do not notice things in the real world such as the amount of time has passed, or another person calling them" (Jennett et al., 2008).
  - *Experienced realism* is the user's judgment of how believable or plausible the virtual environment feels (Weber et al., 2021).
  - *Involvement* relates to the user's engagement, attention, and participation within the virtual environment (Witmer and Singer, 1998).
  - *Presence* is the psychological sensation of "being there" in the virtual world, rather than merely observing it on a screen (Witmer and Singer, 1998; Triberti et al., 2025). This quality is often misunderstood or conflated with immersion; however, Jennett et al. (Jennett et al., 2008) stated the distinction such that Presence is conceptualized as a psychological state, whereas Immersion is understood as a temporally unfolding experiential process. These experiences can occur independently of one another such as a game with simple graphics like Tetris may not evoke a strong sense of presence (the players unlikely feel they are in a world of falling blocks), yet it can still induce a deep sense of immersion, as players may lose track of time during gameplay.
- ***Usability*** is defined by ISO 9241-11 (International Organization for Standardization, 2018) as "the effectiveness, efficiency and satisfaction of specific users who achieve goals in a specific context of use"; hence, it plays a crucial role in the success of software product. In our research, we focus on how comfortably users feel while performing actions, interacting and achieving their goals within immersive 3D environments.
- ***Simulator Sickness*** is a syndrome characterized by discomfort, nausea, dizziness, and other symptoms experienced during or after exposure to virtually immersive environments (Qamar et al., 2023). While similar to traditional motion sickness, simulator sickness does not require physical movement—visually induced perception of self-motion in a stationary state is often sufficient to trigger symptoms (Pöhlmann et al., 2022).
- ***Social Exclusion*** often termed as ostracism, refers to the experience of being deliberately kept apart from others—either physically (such as being left alone) or emotionally (such as being ignored, shunned, or told one is unwanted). It is a study object from the renowned Cyberball paradigm (Williams and Jarvis, 2006). This experience is a deeply aversive emotional state arising from perceived or actual social rejection, with significant implications for mental health and wellbeing (Kawamoto et al., 2015).

Younger users may be particularly sensitive to discomfort in immersive environments, including symptoms of simulator sickness such as nausea, dizziness, or disorientation (Villena-Taranilla et al., 2022; Qamar et al., 2023). Because children engage more intensely and focus more strongly on concrete environmental features (Prendergast and Schubert, 2020; Villena-Taranilla et al., 2022), they may experience heightened perceptual load, making it essential to monitor any adverse physical reactions. At the same time, assessing usability remains important even in a low-interaction VR paradigm: usability contributes to users' comfort, satisfaction, and ability to engage naturally within the environment, especially given that VR headsets and spatial rendering can pose cognitive or sensory challenges for younger populations. Even without complex interaction mechanics, measuring usability helps ensure that the paradigm is accessible, age-appropriate, and capable of eliciting reliable emotional responses without technical barriers that could confound exclusion effects (Parsons, 2015; International Organization for Standardization, 2018).

Based on established theoretical and empirical work, we initially hypothesized (1) that younger children would report higher perceptual intensity than adolescents; (2) that adolescents would experience stronger feelings of social exclusion in the ostracism condition; and (3) that greater perceptual authenticity would be associated with higher usability and lower simulator-sickness symptoms. Collectively, these analyses aim to clarify the developmental contours of social VR experience and to provide empirically grounded guidance for the design of inclusive, educationally meaningful VR environments for young people.

3 Materials and methods

3.1 Research design

Our research adopted an intentional two-stage approach aligning with Pantelidis' (2010) guidelines for developing and validating VR tools in educational contexts. Study 1 served as an exploratory phase in which brief heuristic items and student feedback were used to evaluate core perceptual dimensions and identify areas for improvement in the scenario. Building on these insights, the VR application was refined to enhance clarity, usability, and ecological relevance, reflecting Pantelidis' recommendation to iteratively adjust formative versions of an immersive environment before confirmatory testing. Study 2 consequently implemented validated psychometric measures and a more polished VR design to confirm the relationships among perceptual, usability, and affective variables. This sequential exploratory-confirmatory structure ensured that the paradigm was developmentally appropriate, aligned with educational VR design principles, and prepared for future applications in research and school-based interventions aimed at improving peer interactions and social skills. Therefore, we view Study 1 as exploratory and Study 2 as confirmatory. This iterative approach allowed us to efficiently develop and evaluate a novel VR application for a young population and then verify the relationships among targeted variables using validated measures. Both studies were conducted in Italian schools, involving Italian-speaking students. Therefore, all materials and application content were developed in Italian.

3.2 Participants

The recruitment strategy involved collaboration with schools, whose headmasters had previously been engaged in our past research projects. Students with intellectual, physical, or emotional disabilities (according to International Classification of Diseases (World Health Organization, 2019)) were excluded due to potential difficulties in understanding instructions, limitations in motor/visual skills, or risk of harm from exclusion scenarios—particularly for those with anxiety. This sampling plan aims to ensure scientific rigor and ethical integrity to the study. Upon completion of the recruitment plan, we obtained 313 participants in total. Participants were distributed across age groups, genders, and socioeconomic backgrounds, as detailed below:

- Study 1: 150 participants aged 8–16 years (M = 12.54, SD = 2.14), including 76 children (8–12 years; 50.7%) and 74 adolescents (13–16 years; 49.3%). The sample comprised 79 males (52.7%) and 71 females (47.3%), with 147 participants (98%) born in Italy. Based on the Economic, Social and Cultural Status (ESCS) indicator (Campodifiori et al., 2010), 88 participants (58.7%) were classified as high socioeconomic status (SES), 60 (40%) as medium SES, and 2 (1.3%) as low SES.
- Study 2: 163 participants aged 10–16 years (M = 13.19, SD = 2.02, including 79 children (10–12 years; 48.5%) and 84 adolescents (13–16 years; 51.5%). The sample comprised 84 males (51.5%) and 79 females (48.5%), with 156 participants (95,7%) born in Italy. Based on the ESCS indicator 96 participants (58.9%) were classified as high SES, 62 (38%) as medium SES, and 5 (3.1%) as low SES.

3.3 Ethical approval

The research was conducted in accordance with all relevant ethical regulations established with the protocol numbers 0001227 and 0151020. The sample comprised exclusively underage Italian children and adolescents. Consequently, the researchers obtained informed consent from the parents and legal guardians of all participants, and subsequently, informed assent was obtained from the participants themselves.

3.4 Application

We designed and developed a custom Unity application (Unity Technologies, San Francisco, CA, United States of America) deployed on Meta Quest 2 (Meta Platforms, Inc., Menlo Park, CA, United States of America) to precisely simulate our desired social behaviors while ensuring ecological relevance for school-aged participants. This approach allowed us to tailor agent appearance, virtual surroundings and scripted audio to the targeted age group; implement a novel interactive mechanism; and ensure safety and data privacy when experimenting with minors. Existing off-the-shelf applications rarely permit the fine-grained timing and behavioral control required for an ostracism manipulation that must appear natural yet remain experimentally controllable.

3.4.1 Scenario

Building on the core principles of the Cyberball paradigm, our experiment preserves the same logic but replaces the traditional ball-tossing mechanic with scripted conversational turns. In the experiment, the participants were invited to join a group conversation with two virtual "students" (perceived agents) and were encouraged to express their opinions and participate in the discussion. It is important that the participants are convinced that they would interact with virtual avatars controlled by real human peers via the Internet rather than computer-programmed agents because perceived agency determines the level of social presence (Blascovich et al., 2002), which in turn affects the ecological validity of the experiment.

Ostracism is induced when the agents subtly ignore or dismiss the participant's attempts to contribute, which is equivalent to the experience of not receiving the ball in the original Cyberball experiment. This conversational approach maintains the experimental rigor of the Cyberball framework while leveraging more naturalistic and socially relevant interaction cues.

3.4.2 Virtual environment and agents

The virtual environment depicts a typical school classroom, chosen to evoke a sense of familiarity and comfort among participants. This setting includes standard classroom elements such as desks, chairs, a blackboard, and ambient lighting, all optimized for spatial clarity in VR (Figure 1).

Agents' appearances were designed and selected to reflect the age of each participant group; each scenario includes one male and one female to eliminate gender bias. The agents are positioned in a seated posture, with upper-body expressiveness conveyed through animations (Figure 2). We also had participants remain seated throughout the experiment to prevent discomfort from prolonged standing.

3.4.3 Audio dialogues

The core interactive element was driven by two pairs of scripted conversation sets. Each pair was tailored to a specific participant age group, and within each pair, one set was designed for the inclusion condition and the other for the exclusion condition. Each participant was assigned to the set according to their age. The scripts revolved around school-related themes such as classroom discussions, extracurricular activities, and peer relationships to ensure thematic relevance.

Each script involves two agents engaged in a conversation, with pre-recorded audio files used to deliver the conversation lines. At predefined points, one agent poses a direct question to the participant, then pauses to wait for their vocal response. In exclusion conditions, these conversational turns were designed to include the participant just enough to simulate inclusion. In contrast, they kept overall engagement minimal to induce a controlled sense of exclusion.

Voice recordings were obtained from gender- and age-matched volunteers to ensure audio authenticity and alignment with the agents' appearance.

FIGURE 1
A screenshot of the virtual classroom environment.

FIGURE 2
Virtual agents (male and female): top row—children, bottom row—adolescents.

3.4.4 Agent animations

To increase behavioral realism, the agents were animated with a focus on upper-body movements, particularly in response to the seated configuration of the interaction. The animations are divided into two categories:

- **Idle animations**: this provides a continuous baseline of natural body behavior during the conversation, including movements such as subtle breathing, posture adjustments, and minor hand or arm gestures. This animation is played on loop as default animation to simulate the physical presence of a person naturally engaged in listening, maintaining visual interest and a sense of liveliness.
- **Emotion animations**: a library of 26 emotion-specific animations was developed to reflect a range of interpersonal expressions, such as excitement, satisfaction and agreement, observed in natural conversations. These were contextually triggered to align with dialogue content, ensuring emotional synchrony between audio delivery and agent behavior.

3.4.5 Engagement mechanisms

Two real-time engagement strategies were designed to replicate natural social cues:

- **Dynamic question-response attention**: when the script reaches a moment where one agent asks a question directed at the participant, both agents dynamically shift their attention toward the participant. This is visually represented through head and upper-body orientation, simulating attentive body language. Simultaneously, a listening module is activated, which records and monitors the participant's vocal response in real time. Rather than using a predetermined silence period, the agents remain in this attentive posture until the system detects that the participant has stopped speaking (based on real-time audio amplitude analysis). This design ensures natural pacing and responsiveness, avoiding the artificial feel of fixed-timed pauses and supporting a smoother turn-taking experience.
- **Noise-reactive attention**: to enhance environmental reactivity, the system continuously monitors ambient sound levels generated by the participant. Upon detecting a sound that exceeds a predefined threshold (e.g., a cough, sigh, or vocal utterance), the agents briefly turn their heads toward the participant. This momentary reaction simulates the social behavior of individuals responding to unexpected noises in shared spaces, enhancing the perceived awareness and responsiveness of the agents. The mechanism is designed to be subtle yet noticeable, reinforcing the illusion that agents are attuned to the participant's presence even outside of direct conversational turns; thus, improving the belief of the participants on the realism of the agents.

Together, these features create a virtual experience that balances realism while maintaining experimental control. By combining naturalistic visual design, contextual audio delivery, expressive animations, and dynamic engagement strategies, the system supports the study of social presence, exclusion, and interpersonal responsiveness in VR environments.

3.5 Procedure

Participants in both studies followed the same five-step procedure (pre-experiment, exclusion condition, post-experiment, inclusion condition, and debriefing), with an additional feedback collection step in Study 1, as depicted in Figure 3.

1. ***Pre-experiment***: participants began with a brief, 2-min orientation period to familiarize themselves with the virtual environment. During this phase, they navigated a virtual classroom without any agents present to avoid distraction and to become accustomed to the controls and spatial layout. This phase was identical for all participants across both studies.
2. ***Exclusion condition*** (main experiment): following the orientation, participants entered the social exclusion condition. They were instructed that they would take part in an online virtual conversation with two peers from other schools in the same region. In the same classroom environment used during the pre-experiment phase, two agents appeared and interacted with each other while ignoring the participant's attempts to engage. The appearance of the agents and the scripted conversation content were selected based on the participants' age group.
3. ***Post-experiment***: immediately after the exclusion phase, participants completed a series of self-report questionnaires assessing their subjective experiences. The specific instruments are described in the following subsection. Participants within the same study completed the same questionnaires, regardless of age group. All personally identifiable information was pseudonymized using participant codes.
4. ***Inclusion condition***: participants then re-entered the same virtual classroom scenario with the same agents they encountered in the exclusion condition. In this phase, however, the agents actively engaged with the participant and responded positively to their contributions. This phase was designed to provide a restorative social interaction in which participants felt accepted and integrated into the conversation. This step was crucial for mitigating and neutralizing the negative emotional effects induced by the social exclusion experience.
5. ***Debriefing***: at the end of the experiment, participants were fully debriefed and informed that the avatars were computer-controlled agents. All participants across both studies followed an identical debriefing procedure.
6. ***Feedback collection*** (Study 1 only): after debriefing, participants in Study 1 were asked to provide open-ended feedback regarding what they liked and disliked about the experience. These responses were collected in free-text format and used to inform further development of the VR system.

3.6 Materials

3.6.1 Study 1

In our first study, we utilized the following questionnaires:

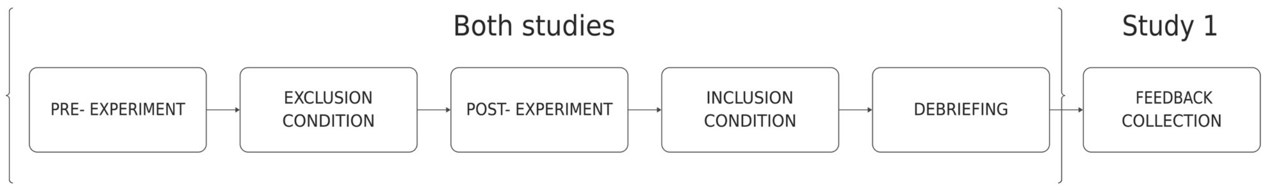

FIGURE 3
Study procedure's flowchart.

1. **Heuristic questionnaire for Perception's rating:** a 4-item questionnaire to assess 4 perceptual qualities using one 5-point Likert-scale item per subsection.
2. **Heuristic questionnaire for social exclusion**: comprised two 5-point Likert-scale items evaluating how effectively the VR application elicited feelings of social exclusion.

Our heuristic questionnaire items were developed based on a validated measure for ostracism according to the study from Williams and colleagues (Williams et al., 2000). The full list of questions is provided in *Appendix A, Heuristic Questionnaire Items*.

Additionally, after the debrief, participants were asked about their opinion on the VR and Cyberball paradigm with a single open-ended question "What did you like and what did you dislike within the VR environment?". Full comments are provided in *Appendix B, First study feedback*.

3.6.2 Study 2

In the second study, data was collected using the following questionnaires:

1. **IGroup Presence Questionnaire (IPQ)** (Regenbrecht and Schubert, 2002)**:** a14-item, 7-point Likert-scale tool with four subscales—Experienced Realism, Involvement, Spatial Presence, and General Presence. Nevertheless, Spatial and General Presence were combined into a single Presence category, as our experiment did not emphasize motion or spatial navigation.
2. **System Usability Scale (SUS)** (Brooke, 1996): a 10-item, 5-point Likert-scale questionnaire measuring overall usability, with total scores ranging from 0 to 100 (higher scores indicating better usability).
3. **Simulator Sickness Questionnaire (SSQ)** (Kennedy et al., 1993): comprised 16 symptoms rated on a 4-point scale. However, we excluded two symptoms—Stomach Awareness and Burping—because in factor-analytic studies of cybersickness, stomach awareness and burping consistently load on a gastrointestinal symptom cluster that is prominent during motion-based simulator exposure but much less so under purely visual stimulation–our case (Nesbitt et al., 2017; Saredakis et al., 2020). By contrast, when developing the Visually Induced Motion Sickness Susceptibility Questionnaire, Keshavarz and colleagues (Keshavarz et al., 2023) included only five symptoms—nausea, headache, dizziness, fatigue, and eyestrain—and deliberately omitted stomach awareness and burping. Additionally, we focused solely on the Total SSQ score rather than analyzing each subscale individually, as our goal was to assess simulator sickness as a comprehensive experience rather than isolate specific symptom clusters. *Because we did not follow precisely the standard SSQ, from here, we define our simulator sickness as* ***adapted SSQ.***
4. **Heuristic questionnaire for social exclusion**: used in Study 1 was also employed in this study. The decision to keep these short heuristic questions is mainly to minimize response time and cognitive load for younger participants on their subjective exclusion feeling.

3.7 Data analysis

Following data collection, data were cleaned, and subsection and total scores were calculated according to standard scoring procedures. Mean scores were then compared between the Children and Adolescent groups. Data normality was assessed using the *Shapiro–Wilk Test* (Shapiro and Wilk, 1965). Normally distributed data were analyzed with the *Independent Samples t-test* (Ross and Willson, 2017); otherwise, the *Mann–Whitney U Test* (Mann and Whitney, 1947). Was applied to identify group differences.

To examine relationships between variables, pairwise correlation analyses were conducted. Depending on data normality, either *Pearson's* (Pearson's Correlation Coefficient, 2008) or *Spearman's* (Spearman Rank Correlation Coefficient, n.d.) correlation was applied. Furthermore, *multiple regression analyses* based on the *Ordinary Least Squares (OLS)* method (Kotsakis, 2023) explored interdependencies and the unique contribution of each variable. *Multicollinearity* was assessed using the *Variance Inflation Factor (VIF)* (Belsley et al., 1980) to ensure model robustness.

The data analysis process was performed in a Jupyter Notebook implementing SciPy (Virtanen et al., 2020) and statsmodels libraries (Seabold and Perktold, 2010). The full analysis script is provided in *Appendix C: Data analysis script*. Statistical significance was set at $p < 0.05$ for all tests, supporting rigorous interpretation of the findings.

4 Results

4.1 Perceptions

Children consistently rated their VR experiences more intensely than adolescents in all categories of Perceptions across both studies

TABLE 1 Comparison of perception between two groups in study 1 (n = 150).

Variable	Children (n = 76)		Adolescents (n = 74)		Effect size	Statistical power	Statistical method	Statistic	p-value
	Mean	SD	Mean	SD					
Immersion	3.39	1.42	2.31	1.22	0.36	99.86%	Mann-Whitney U	4001	4.82e-6
Experienced realism	3.29	1.40	2.18	1.20	0.38	99.90%	Mann-Whitney U	4035.5	2.47e-6
Involvement	2.39	1.37	1.80	1.00	0.21	78.40%	Mann-Whitney U	3490	7.18e-3
Presence	3.72	1.33	2.51	1.32	0.41	99.98%	Mann-Whitney U	4134.5	3.80e-7

TABLE 2 Comparison of perception between two groups in study 2 (n = 163).

Variable	Children (n = 79)		Adolescents (n = 84)		Effect size	Statistical power	Statistical method	Statistic	p-value
	Mean	SD	Mean	SD					
Experienced realism	18.67	5.41	16.40	3.83	0.49	71.50%	Mann-Whitney U	4070.5	1.23e-2
Involvement	17.89	4.32	16.23	3.41	0.43	65.64%	Mann-Whitney U	4020.5	1.93e-2
Presence	22.67	4.41	22.01	4.12	0.15	16.38%	Independent samples t-test	0.9778	3.33e-1

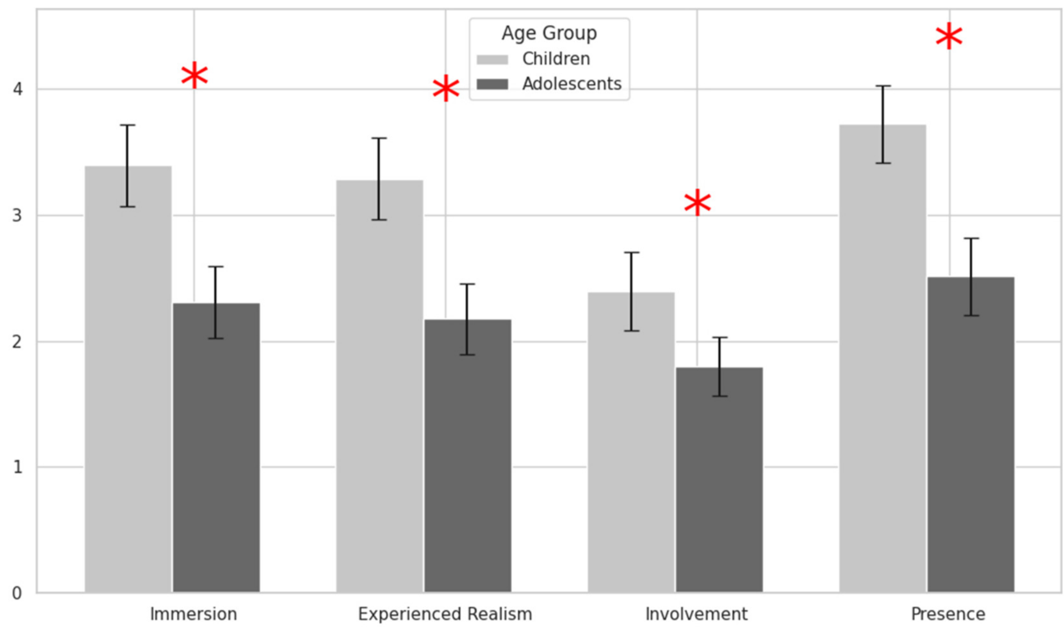

FIGURE 4
Age group Differences in Dimensions of Perceptions in Study 1 (p < 0.05, n = 150, * indicates statistical significance).

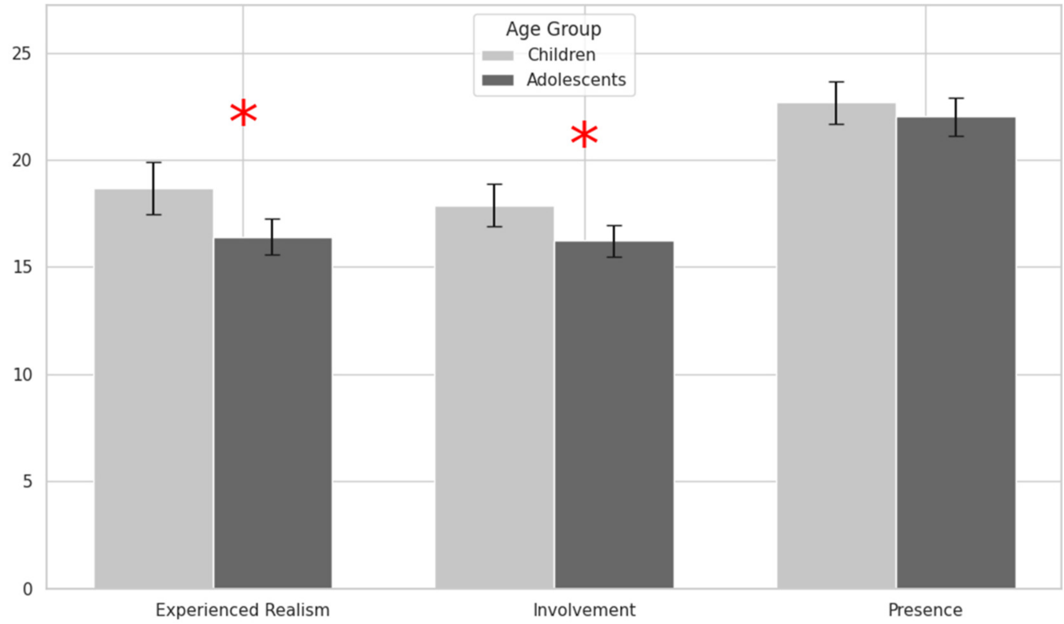

FIGURE 5
Age group Differences in Dimensions of Perceptions in Study 2 ($p < 0.05$, $n = 163$, * indicates statistical significance).

(detailed results are provided at Tables 1, 2). These differences were statistically significant in every instance, except for the *Presence* measure in Study 2, where the children's mean rating was still higher (Figures 4, 5).

In Study 1, which used heuristic single-item scales, the between-group differences were particularly pronounced, for example, in Immersion: Children $M = 3.39$ and Adolescents $M = 2.31$ with $p < 0.001$. In Study 2, employing validated IPQ subscales, effect sizes were smaller but directionally identical such as in Experienced Realism: Children $M = 18.67$ and Adolescents $M = 16.40$ with $p = 0.012$. Although these instruments differ in scale range, both converge on a robust developmental gradient in perceptual intensity.

Correlation analyses (Figure 6) further revealed significant negative relationships between Age and almost all perceptual dimensions ($p < 0.05$). The downward-sloping regression lines illustrate that as participants grow older, their reported sense of "being there," realism, and involvement declines.

4.2 Usability and simulator sickness

In terms of the practical aspects of VR, children reported significantly higher in System Usability ($M = 53.45$) than adolescents ($M = 49.43$), with this difference being statistically significant ($p = 0.009$). On the other hand, Adolescents' report on Simulator Sickness is higher than their counterpart, even though the result is not statistically significant (Figure 7). The absence of an age-related effect is further reflected in the large standard deviations observed in both groups, indicating highly heterogeneous responses (Table 3).

A negative correlation between Age and SUS (Figure 8) with $r = -0.19$ indicates that older users evaluate the interface more critically—potentially reflecting higher expectations shaped by broader digital experience. No significant correlation emerged between Age and SSQ, implying that susceptibility to cybersickness is not developmentally determined under a stationary, conversational VR task.

Since both Perception and Usability have negative correlation with Age, we then assumed that higher Perception could result in higher satisfaction in the virtual environment; therefore, higher Usability score. To check our assumption, we then analyzed the relationship between SUS and perception. The result (Figure 9) partially confirms our prediction by indicating that both Experienced Realism and Presence have a positive correlation with SUS ($r = 0.38$ and $r = 0.26$ respectively).

On the other hand, we were surprised that the only dimension of Perception - Involvement, which does not correlate with System Usability, shows a slightly negative correlation with Simulator Sickness ($r = -0.17$, Figure 10).

We also analyzed the relationship between SUS and SSQ, which results in a statistically insignificant result of $r = 0.03$ with $p = 0.71 > 0.05$, confirming that practical satisfaction and physiological comfort represent independent experiential dimensions.

4.3 Social exclusion

Lastly, we examined the impact of the virtual environment on our desired psychological effect - Social exclusion (Table 4). In general, the Adolescent group reported to feel more excluded in both studies. Their mean values were 6.88 and 8.14 compared to 6.1 and 6.71 of the Children group respectively with statistical significance (Figure 11).

Figure 12 shows further relationship between Exclusion score and Age. In Study 1, a positive correlation ($r = 0.29$) is observed between age and exclusion ratings, indicated by an upward-sloping regression line. This suggests that older participants tend to report higher exclusion scores. However, in Study 2,

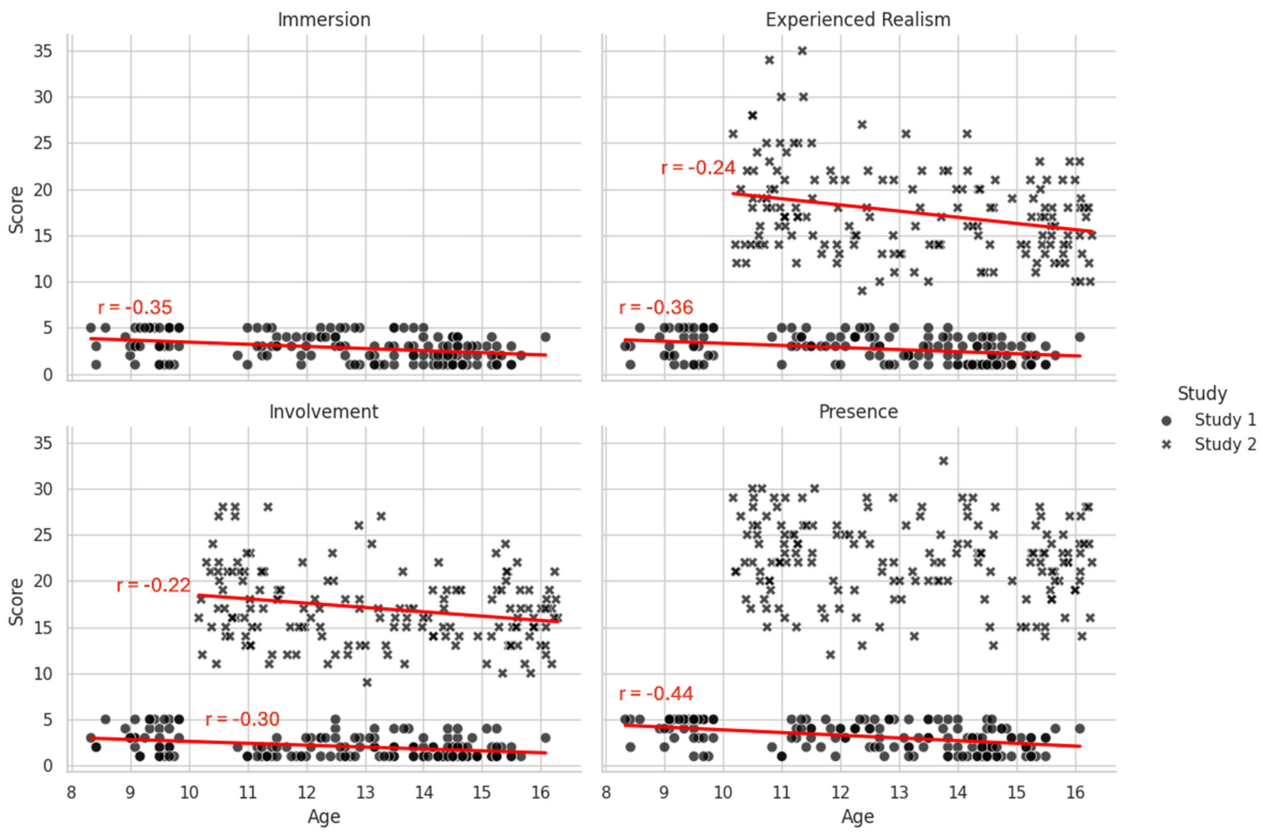

FIGURE 6
Correlation between Age and Dimensions of Perceptions across two studies ($p < 0.05$, n1 = 150, n2 = 163, Regression lines indicate significant associations).

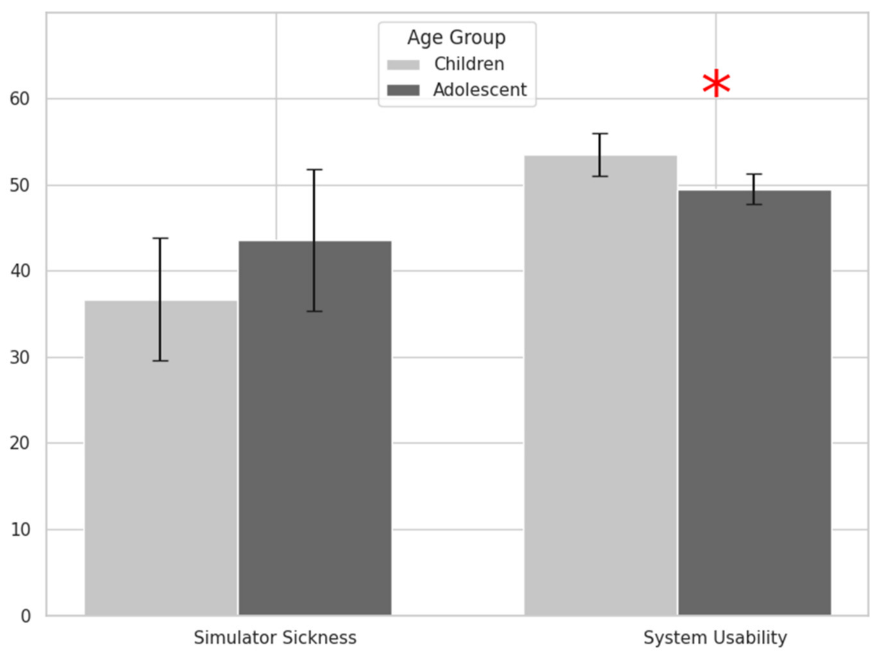

FIGURE 7
Age group Differences in Simulator Sickness and System Usability ($p < 0.05$, n = 163, * indicates statistical significance).

TABLE 3 Comparison of Usability and Simulator Sickness Between Two Groups in Study 2 ($p < 0.05$, $n = 163$).

Variable	Children (n = 79)		Adolescents (n = 84)		Effect size	Statistical power	Statistical method	Statistic	p-value
	Mean	SD	Mean	SD					
System usability	53.45	10.95	49.43	8.03	0.42	75.44%	Independent samples t-test	2.6398	9.22e-3
Simulator sickness	36.69	31.54	43.54	37.87	−0.07	14.82%	Mann-Whitney U	3048	3.70e-1

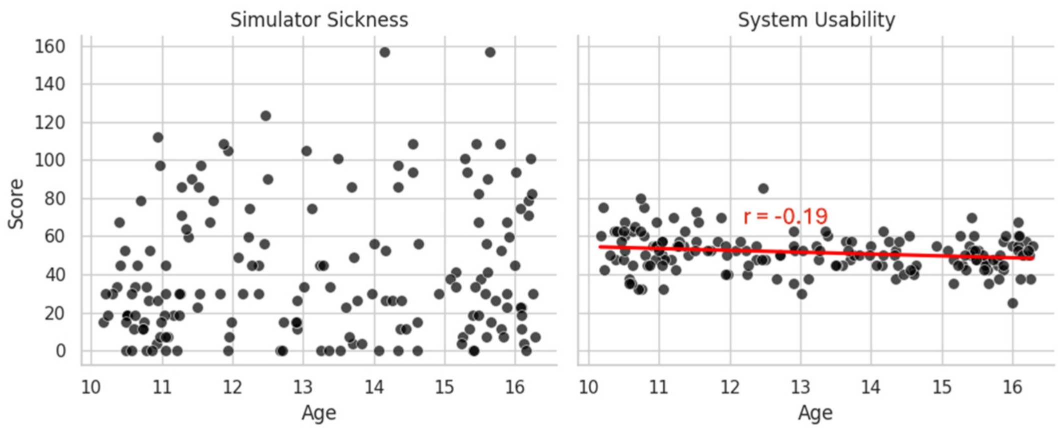

FIGURE 8
Correlation between Age and (Simulator Sickness and System Usability) ($p < 0.05$, $n = 163$, Regression lines indicate significant associations).

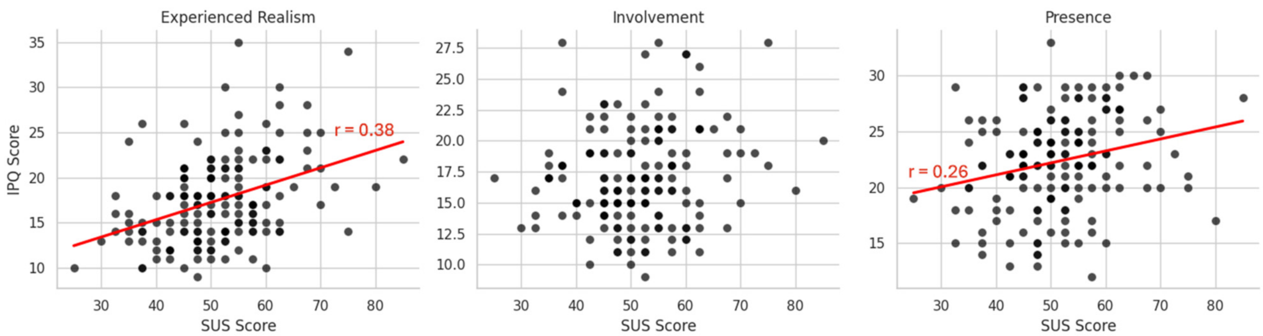

FIGURE 9
Correlation between System Usability and Dimensions of Perceptions ($p < 0.05$, $n = 163$, Regression lines indicate significant associations).

no clear linear correlation is evident, with the data points widely dispersed. The reduced linearity in Study 2 may reflect ceiling effects or increased affective variability when richer conversational cues were introduced.

We then investigated the relationship between social exclusion and perceptions. Overall, the results mostly show negative correlations in all categories of perceptions across both studies (Figure 13). Interestingly, only Involvement dimension in Study 1 shows a slight positive correlation ($r = 0.16$); however, the data for this dimension in Study 2 shows a strong negative correlation ($r = -0.64$).

Finally, the analysis shows no correlated relationship between Exclusion ratings and both Simulator Sickness and System Usability with the data points widely dispersed (Figure 14).

4.4 Interrelationships among variables

4.4.1 Correlation heatmaps

As a summary of the pairwise correlation analysis, Figures 15, 16 present correlation heatmaps displaying significant associations ($p < 0.05$) between all variables. Both heatmaps highlight consistent negative links between Age and perceptual dimensions and positive associations among the perceptual measures themselves.

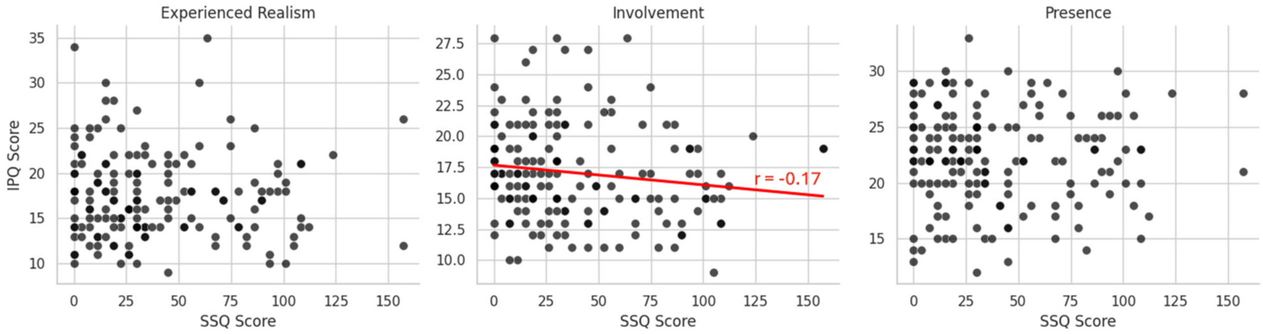

FIGURE 10
Correlation between Simulator Sickness and Dimensions of Perceptions ($p < 0.05$, $n = 163$, Regression lines indicate significant associations).

TABLE 4 **Comparison of Exclusion Ratings Between Two Groups in Both Studies ($p < 0.05$, $n1 = 150$, $n2 = 163$).**

Variable	Children		Adolescents		Effect size	Statistical power	Statistical method	Statistic	p-value
	Mean	SD	Mean	SD					
Exclusion study 1	6.71	3.03	8.14	2.17	−0.21	77.00%	Mann-Whitney U test	2116.5	7.36e-3
Exclusion study 2	6.10	2.51	6.88	2.03	−0.16	56.22%	Mann-Whitney U test	2686	3.45e-2

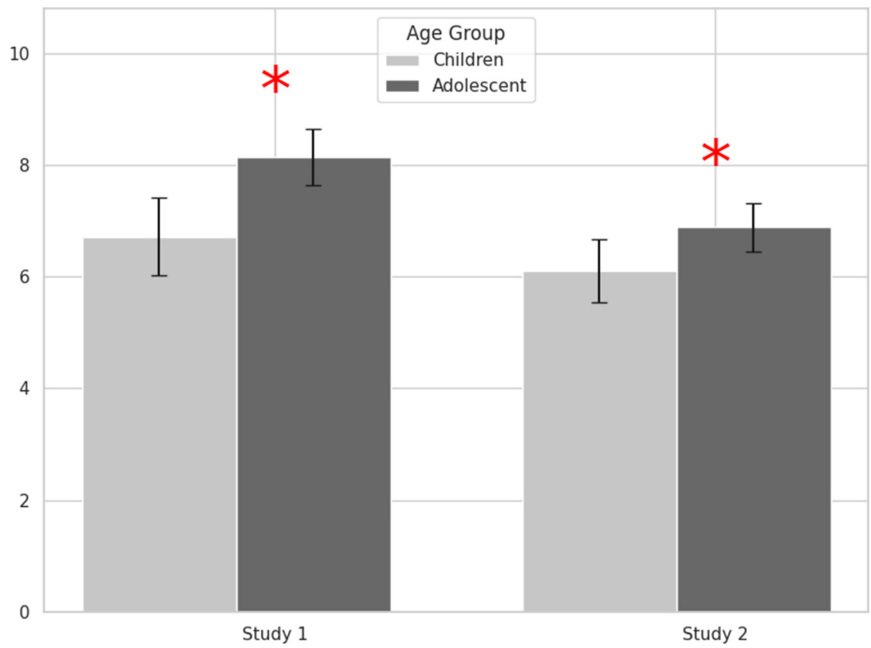

FIGURE 11
Age group Differences in Exclusion ratings in two studies ($p < 0.05$, $n1 = 150$, $n2 = 163$, * indicates statistical significance).

4.4.2 Multivariable regression analysis

To understand the interdependencies among variables and isolate unique effects, we conducted a series of multiple regression analyses, treating each key construct as a dependent variable in turn. In each model, Age and the remaining study variables were entered as predictors, allowing us to examine the unique contribution of each factor while controlling for others. This approach addresses potential confounding effects that pairwise correlations cannot reveal and clarifies whether relationships persist under multivariable conditions.

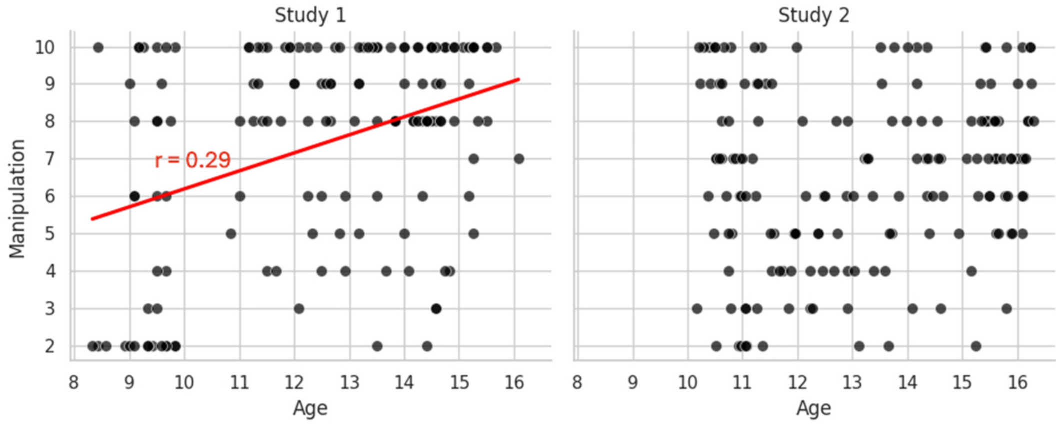

FIGURE 12
Correlation between Age and Exclusion ratings in two studies (p < 0.05, n1 = 150, n2 = 163, Regression lines indicate significant associations).

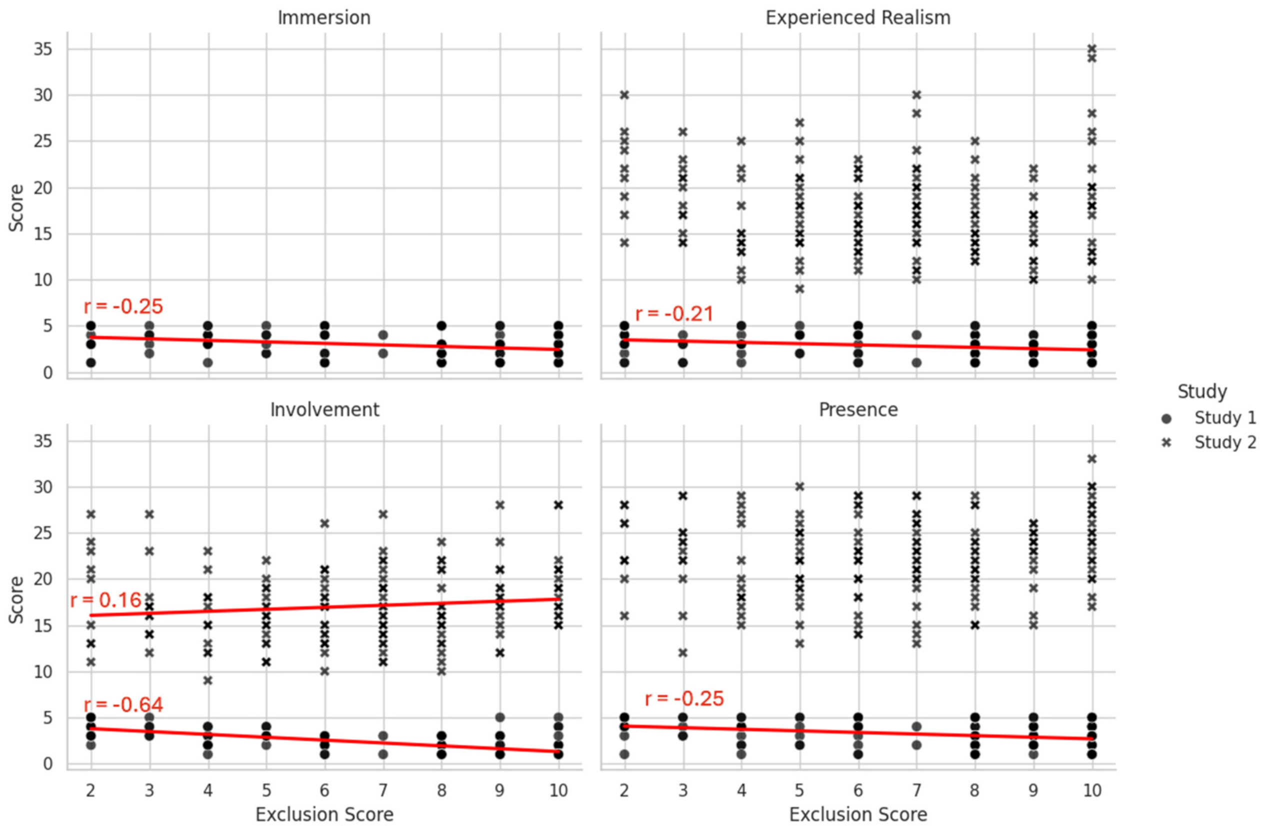

FIGURE 13
Correlation between Exclusion ratings and Dimensions of Perceptions across two studies (p < 0.05, n1 = 150, n2 = 163, Regression lines indicate significant associations).

The regression results confirm and deepen earlier findings. In Study 1 (Table 5), Age negatively predicted *Presence* ($\beta = -0.12$, $p < 0.05$) and positively predicted *Exclusion* ($\beta = 0.20$, $p < 0.05$), while *Involvement* strongly reduced Exclusion ($\beta = -1.41$, $p < 0.05$). These findings indicate that engagement mitigates ostracism effects even when age and other perceptual variables are controlled. High R^2 values (up to 0.69) confirm substantial shared variance among perceptual constructs, consistent with theoretical overlap between immersion, involvement, and presence.

In Study 2 (Table 6), Experienced Realism robustly predicted System Usability ($\beta = 0.69$, $p < 0.05$), affirming that realism—not simply immersion—drives evaluative judgments. No reliable

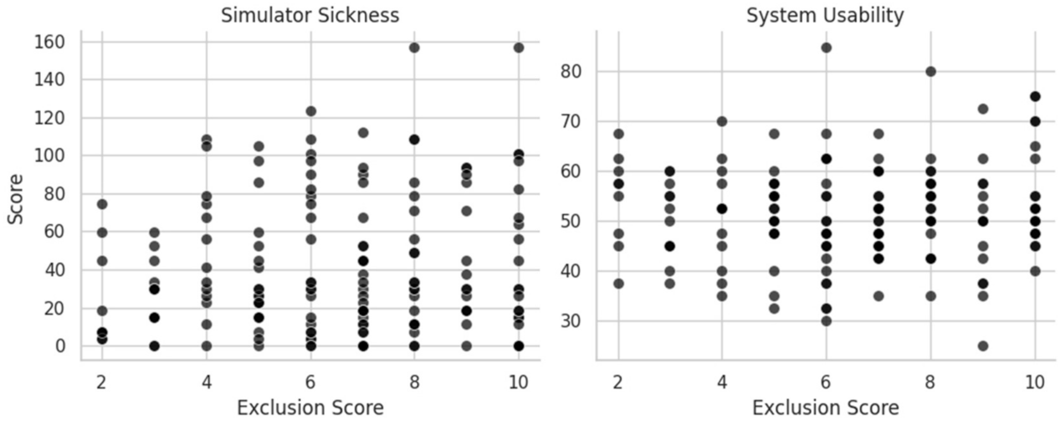

FIGURE 14
Correlation between Exclusion ratings and Dimensions of Perceptions across two studies (p < 0.05, n1 = 150, n2 = 163, Regression lines indicate significant associations).

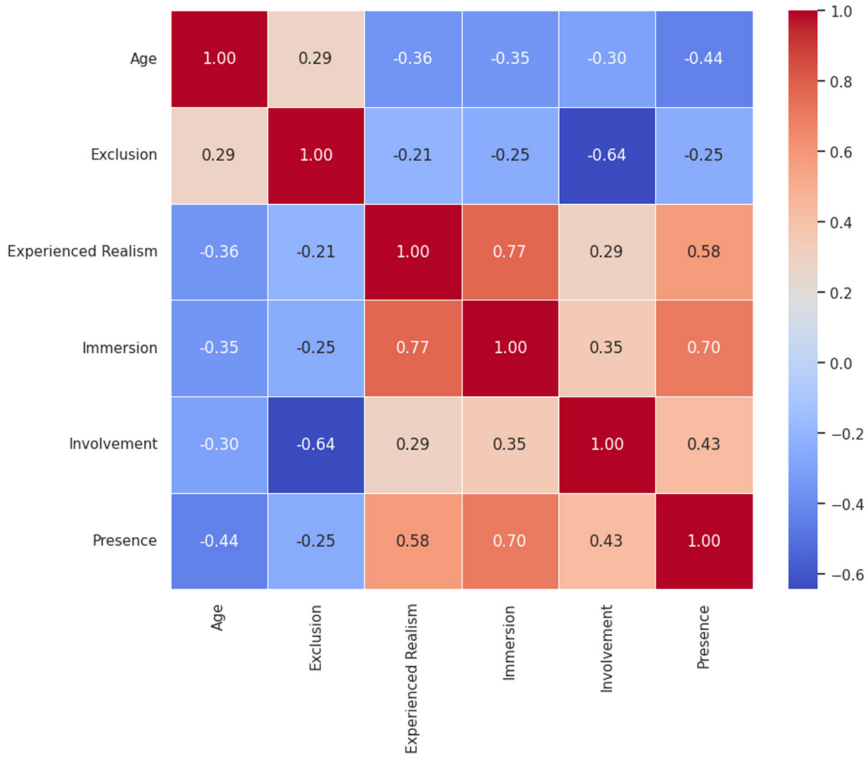

FIGURE 15
Correlation Heatmap in Study 1 (N = 150, only significant correlations with p < 0.05 are shown).

predictors emerged for Simulator Sickness, confirming its independence from cognitive or affective predictors. Interestingly, partial regression coefficients revealed small suppressor effects (e.g., Involvement switching from negative bivariate to positive partial relation with Exclusion), illustrating complex interdependencies among perceptual components. Overall, these models strengthen the cross-study interpretation that perceptual realism underlies usability and attenuates exclusion, while age operates primarily through perceptual mediation.

4.4.3 Variance Inflation Factor analysis (VIF)

VIF scores for all variables (as shown in Tables 7, 8) in both studies were found to be well below the common threshold of 5, confirming that multicollinearity was not a concern (Hair et al., 2013). This diagnostic validates that the coefficients obtained from the regression models are reliable and that they accurately represent the unique, unconfounded effect of each predictor on the outcome variables. Consequently, the inferential conclusions drawn for

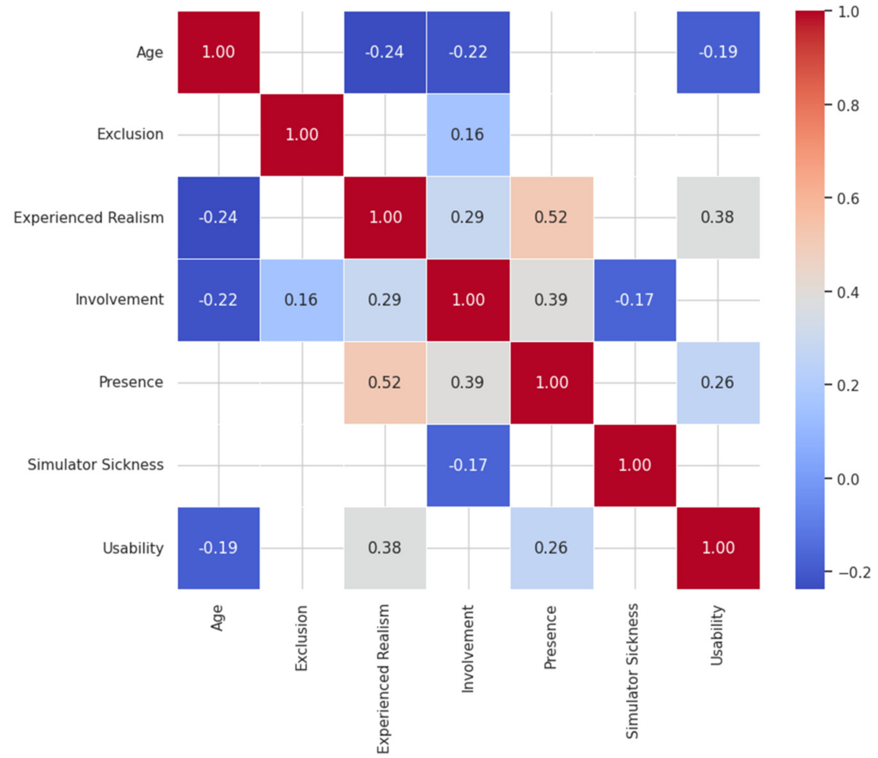

FIGURE 16
Correlation Heatmap in Study 2 (N = 163, only significant correlations with $p < 0.05$ are shown).

TABLE 5 Multivariable Regression on Study 1 (N = 150, $p < 0.05$, * indicate statistically significant).

Predicted variables	Dependent variables coefficient						Model fit	
	Age	Immersion	Experienced realism	Involvement	Presence	Exclusion	R^2	Adjusted R^2
Immersion	0.020	-	0.546*	0.034	0.371*	−0.022	0.698	0.687
Experienced realism	−0.051	0.704*	-	−0.044	0.06	−0.008	0.603	0.589
Involvement	−0.016	0.039	−0.04	-	0.198*	−0.270*	0.528	0.511
Presence	−0.120*	0.549*	0.069	0.252*	-	0.041	0.567	0.552
Exclusion	0.203*	−0.134	−0.037	−1.412*	0.169	-	0.495	0.478

RQ1–RQ5 are statistically stable and not artifacts of redundant predictors.

5 Discussion

5.1 Empirical findings

5.1.1 Perception

Perceptual ratings across both studies show significant differences between children and adolescents, with consistently higher scores observed in the younger group. This suggests that children may be more receptive to, or more strongly influenced by, immersive technologies. In addition, the significant downward trend between age and perceptual ratings indicates a negative correlation, meaning perceptual intensity decreases as age increases.

This effect likely reflects developmental cognitive shifts from concrete to more abstract representational reasoning. Younger children tend to focus more on vivid perceptual cues, whereas adolescents are more likely to critically evaluate realism and the credibility of interaction within the virtual environment.

Taken together, both datasets provide convergent evidence for addressing our ***RQ1*** (*How does age influence perceptual dimensions of VR experience* (*immersion, experienced realism, involvement, presence*) *during an interactive social VR scenario?*) and confirming our initial hypothesis that younger participants experience stronger immersion, involvement, and realism during

TABLE 6 Multivariable Regression on Study 2 (N = 163, $p < 0.05$, * indicate statistically significant).

Predicted variables	Dependent variables coefficient							Model fit	
	Age	Experienced realism	Involvement	Presence	System usability	Simulator sickness	Exclusion	R^2	Adjusted R^2
Experienced realism	−0.312	-	0.192*	0.408*	0.125*	0.002	−0.273*	0.380	0.356
Involvement	−0.317*	0.161*	-	0.235*	−0.006	−0.014	0.261*	0.238	0.209
Presence	0.091	0.363*	0.249*	-	0.023	0.003	0.184	0.305	0.278
System usability	−0.569	0.692*	−0.04	0.141	-	0.01	0.338	0.173	0.142
Simulator sickness	1.543	0.133	−1.424	0.272	0.154	-	1.728	0.046	0.010
Exclusion	0.170	−0.093*	0.106*	0.07	0.021	0.007	-	0.089	0.054

TABLE 7 Variance inflation factor scores for Study 1.

Feature	Age	Immersion	Experienced realism	Involvement	Presence	Exclusion
VIF	1.35	3.31	2.52	2.12	2.31	1.98

TABLE 8 Variance inflation factor scores for Study 2.

Feature	Age	Experienced realism	Involvement	Presence	System usability	Simulator sickness	Exclusion
VIF	1.17	1.61	1.31	1.44	1.21	1.05	1.10

social-VR engagement. The consistency across distinct measures strengthens the developmental interpretation rather than implying measurement artifact.

5.1.2 Usability and simulator sickness

Age appears to be a key factor influencing usability ratings. Across both studies, children reported significantly higher usability scores than adolescents, and usability ratings showed a significant negative correlation with age. In contrast, no age-related effects were found for simulator sickness: the difference between the two age groups was non-significant, and simulator sickness scores were not correlated with age. Notably, the large standard deviations observed in both groups indicate substantial inter-individual variability. This variability may be attributed to other factors such as prior VR experience, motion sensitivity, or individual tolerance to sensory mismatch. Therefore, age alone may not be a reliable predictor of susceptibility to simulator sickness.

These findings contribute to ***RQ2*** (*To what extent does age relate to practical aspects such as system usability rating and simulator sickness in an interactive social VR scenario*), indicating that while age negatively influences perceived usability, simulator sickness remains largely unaffected by developmental stage.

Furthermore, usability showed a positive correlation with experienced realism and presence. This suggests that user acceptance of a VR application is strongly influenced by how realistic the environment feels and the extent to which users experience a sense of "being there." Simulator sickness, however, exhibited a significant negative relationship with involvement indicating that those participants who were involved deeply in the virtual environment had less symptoms of simulator sickness.

Overall, these findings clarify ***RQ3*** (*What relationships exist among perceptual experiences, usability, and simulator sickness across age groups in the context of an interactive social VR?*) and partially verify our initial hypothesis: that not all perceptual qualities but Experienced Realism and Presence boost the acceptance of system usability; and that only Involvement supports reducing overall symptom of simulator sickness.

5.1.3 Social exclusion

Across both studies, adolescents reported significantly higher exclusion scores than children. This suggests that the designed virtual environment and scenario were more effective in eliciting ostracism-related affective responses in the adolescent group. These results support our hypothesis that adolescents demonstrate heightened social-affective sensitivity during peer interactions.

In addition, negative correlation between exclusion score and perceptual dimensions across studies suggest that participants, who have high perceptual intensity in the virtual environment, feel less excluded during the experiment. This suggests that high perceptual intensity may buffer the emotional impact of exclusion during the VR interaction.

Exclusion ratings were also independent of both usability and simulator sickness, implying that how psychologically excluded the participants felt during the experiment was not linked to their level of cybersickness and satisfaction with the system.

In summary, across both datasets ***RQ4*** (*Does age modulate affective responses to social exclusion in VR, as elicited through an interactive social VR scenario?*) and ***RQ5*** (*Does the feeling of being excluded in an interactive social VR scenario affect the rating of perceptual intensity, usability, and simulator sickness?*) are supported: adolescents are more sensitive to exclusion, while heightened perceptual involvement mitigates exclusion regardless of usability or sickness levels. These results align with developmental theories of socio-emotional maturation and indicate that perceptual realism may serve a protective role in emotionally challenging VR interactions.

5.2 Interpretations and comparison

Our findings show clear developmental differences in how children and adolescents experience social VR. Beyond simply addressing our five research questions, we interpreted them with the support of two established developmental theories. Together they reveal two partially independent developmental trajectories:

1. **Perceptual–cognitive pathway (age → realism/presence → usability)**: our statistical data have shown younger participants reported higher perceptual intensity and usability. This pattern can be understood through cognitive-developmental theory: children in Piaget's concrete-operational stage privilege sensory and contextual cues (Piaget, 1964) when constructing meaning. For them, realism and the feeling of "being there" are central to evaluating a system's quality, which explains the strong link between perceptual engagement and usability ratings observed in this group. Adolescents, by contrast, employ more abstract reasoning and self-monitoring, which can dampen immersion and realism ratings. The positive association between perceptual realism and usability thus reflects a perceptual-cognitive continuum—users who interpret the environment as authentic also find it more functional and satisfying.
2. **Social–affective pathway (age → exclusion ↔ perceptual realism)**: across our studies, adolescents consistently reported stronger feelings of social exclusion. Drawing on Erikson's psychosocial theory (Orenstein and Lewis, 2025), this aligns with the adolescent focus on identity formation and peer validation: exclusion—even simulated—threatens a salient social goal. For younger children, situated within industry vs. inferiority, mastery and task success overshadow subtle social feedback, reducing the subjective weight of ostracism cues. Importantly, higher perceptual realism and involvement mitigated exclusion across ages, suggesting that believable environments and sustained engagement can buffer negative effects. This supports the notion that perceptual and affective layers of VR jointly construct socio-emotional experience rather than operating independently.

Simulator sickness did not vary significantly with age, indicating that physical comfort in a conversational, low-motion VR context depends more on individual sensitivity than developmental stage. However, this pattern differs in adult populations, where the older group (mean age >35) reported significantly lower scores (Saredakis et al., 2020). Alternatively, the lack of age variance may be attributed to the low-motion nature of our conversational task.

On the other hand, simulator sickness showed a negative correlation with involvement across ages, even though the later result of multiple regression showed no significance. This finding aligns with Weech's review (Weech et al., 2019) which concluded that the balance of evidence favors a negative relationship between experience in VR and cybersickness, even though a serious lack of high-powered studies exists. Additionally, Yip and Saunders (Yip and Saunders, 2023) demonstrated that directing users' attention to the central visual field, thereby narrowing attentional focus, can reduce cybersickness during VR exposure. Although their work manipulated perceptual attention rather than task engagement, both sets of findings converge on the idea that users allocating attention can meaningfully influence the experience of discomfort in VR.

Interestingly, usability judgments remained independent of sickness levels, implying that practical evaluations of the system are not necessarily diminished by physical discomfort. This contrasts with a study suggesting that usability is more likely to be negatively impacted by simulator sickness (Voinescu et al., 2023). The difference might be due to the nature of the VR task; in the other study, participants engaged in a more attention-demanding task, which may have amplified the impact of simulator sickness.

Finally, the lack of correlation between exclusion ratings and measures of usability or simulator sickness suggests that the psychological impact of ostracism in VR operates independently of system practical qualities. This distinction underscores the importance of designing VR not only to be technically functional and comfortable, but also to account for developmental differences in how social experiences are processed.

5.3 Conceptual framework

To synthesize these relationships, Figure 17 presents a conceptual framework that models why and how age shapes the social VR experience.

Structure and rationale including:

- **Age** acts as the primary independent variable, representing developmental stage.
- **Perception** (immersion, realism, presence, involvement) mediates between age and downstream outcomes.
- **Usability** and **Exclusion** function as distinct evaluative outcomes—practical and affective, respectively.
- **Simulator Sickness** is retained as a control variable affecting comfort but not central to the developmental mechanisms.

Arrow semantics:

- Solid arrows denote empirically supported associations derived from significant regression or correlation results ($p < 0.05$).
- Dashed arrows indicate weak trends (non-significant or inferred) or indirect correlation introduced to capture plausible but untested links for future work.

This framework captures the essence of our research. First, age, as an independent variable, has a negative effect on perception. Given the inverse relationship between perception and usability, age indirectly

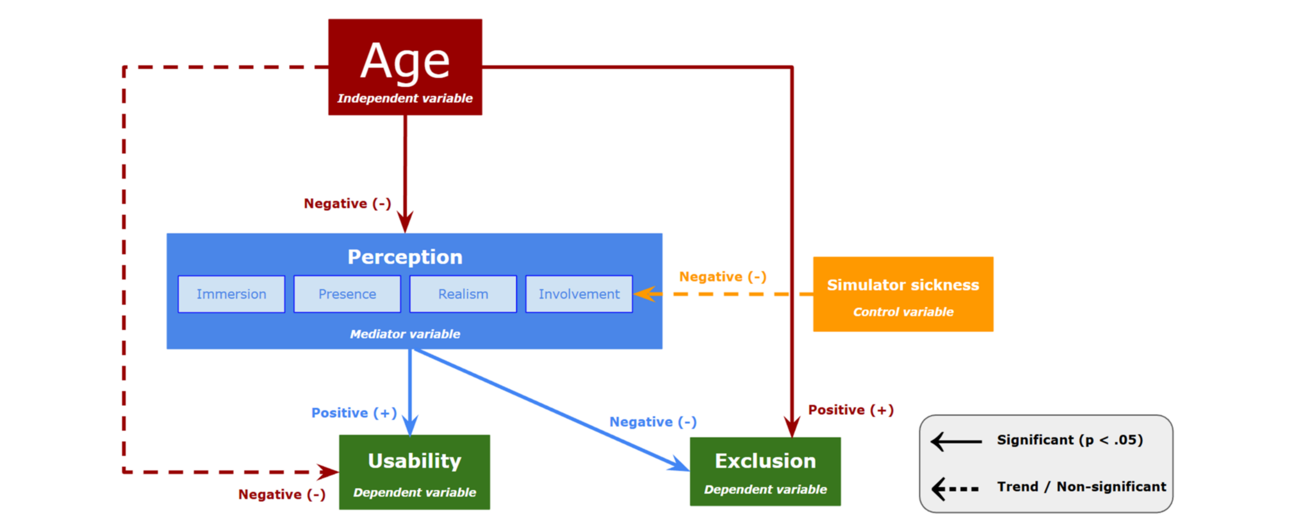

FIGURE 17
Conceptual framework.

influences the overall acceptance of the system. Secondly, subjective exclusion feeling increases significantly among older participants while higher levels of perceptual intensity can mitigate this effect. Finally, although in this research, we cannot statistically prove the regression relationship between simulator sickness, our findings showed a significantly negative correlation between participants' engagement levels and their reported discomfort in the virtual environment, hence the weak link in the framework.

5.4 Design suggestions

Drawing on our results, we outline the following evidence-based design principles explicitly linked to empirical results and relevant theory to guide the design of VR applications for social studies:

- **Leverage children's strong perceptual intensity** (*based on evidence of significant age differences in immersion/realism*): since young children naturally exhibit a strong perceptual sense, the design should avoid excessive visual stimulation or overly complex interactive elements. According to Coherence Principle (Mayer, 2009), reducing extraneous cognitive load by eliminating seductive but irrelevant visual details is critical for younger users with developing working memory capacities. Simple visuals and interactions can minimize unnecessary distractions and help maintain the intended experiential effects.
- **Design for adolescents' social sensitivity** (*based on evidence of higher exclusion ratings among adolescents*): adolescents are more emotionally affected by social exclusion despite experiencing lower presence, a finding consistent with developmental literature on rejection sensitivity (Sebastian et al., 2010) and the "imaginary audience" phenomenon (Elkind and Bowen, 1979). Therefore, if the VR experiment involves virtual agents, it is important to incorporate inclusive behaviors such as natural eye contact, friendly facial expressions, and varied dialogue pacing. These features can enhance social authenticity, improve participant engagement, and reduce feelings of detachment. Otherwise, the interaction may produce negative effects and ultimately weaken the intended psychological outcomes.
- **Enhance usability through perceptual realism** (*based on highly significant regression of experienced realism and usability, $\beta = 0.69$*): our results suggest that usability correlates strongly with perceived realism. This aligns with previous findings that Natural engagement, a key heuristic stating that ideally the user should be unaware that the environment is virtual (closely related to our realism attribute), is most useful for interpreting usability (Sutcliffe and Gault, 2004). Therefore, to achieve optimal usability in VR applications, designers should prioritize environmental coherence, ensuring that lighting, shadows, and spatial acoustics behave consistently with real-world physics. Furthermore, interactive elements should follow natural mapping principles; for example, objects should exhibit appropriate weight and friction in their physical responses, and graspable items should be indicated through naturalistic cues (e.g., subtle glints or textural distinctness) rather than abstract UI overlays.
- **Stable application flow to sustain involvement and reduce cybersickness** (*as this relationship only has correlational evidence, we marked this as speculative extension which can be explored in future studies*): a well-structured, logically paced flow of events can keep users engaged, which in turn is associated with lower levels of cybersickness. Additionally, sensory conflict theory suggests that motion sickness in VR can arise from a mismatch between visual input and vestibular (balance) sensations (Ng et al., 2020). Taken together, the VR design should avoid abrupt transitions, ensure smooth scene changes, and maintain a rhythm of interaction that matches the user's cognitive and physical comfort levels.

6 Limitation and future work

We acknowledge the following limitations of our study. Firstly, our measures, which used heuristic questionnaires, were self-developed for the purposes of this research and have not undergone formal psychometric validation. While they were informed by relevant literature and tailored to the study context, the absence of established reliability and validity testing limits the strength of inferences drawn from these instruments. Future research should refine and validate these measures through pilot studies, factor analysis, and reliability assessments. Secondly, the demographic scope of our participant sample was limited to Italian schoolchildren. This homogeneity may restrict the generalizability of our findings, as cultural and educational contexts could shape how different age groups experience and interpret VR. Broader, cross-cultural studies are needed to examine whether the observed patterns hold across diverse populations and settings. Finally, although this was not intentional, our sample was also skewed toward participants from higher SES backgrounds. This might introduce a sampling bias, as children from higher socioeconomic backgrounds may have greater prior exposure to digital technologies, more familiarity with gaming environments, and different levels of parental support or access to extracurricular activities. These factors could influence both their engagement with the VR intervention and their subjective responses, potentially inflating usability ratings or reducing perceived difficulty compared to lower-SES groups.

Building on findings and limitations, future work should focus on two primary directions. The first direction emphasizes two design suggestions regarding children's heightened perceptual sensitivity and adolescents' strong social awareness. Beyond applying these recommendations within individual VR applications, it may be valuable to investigate the development of dynamic VR content systems that adapt in real time based on the user's age, engagement level, and interaction patterns. Rather than offering static experiences, we envision VR environments that adapt and evolve alongside the user, supporting long-term comfort, engagement, and psychological wellbeing. Such adaptability is likely to improve user outcomes, for instance by enhancing learning performance and strengthening psychological benefits (Guy et al., 2025). The second is cross-cultural and cross-context validation of our framework and measures, involving participants from diverse cultural, educational, socioeconomic, and developmental backgrounds. This will help determine whether the observed patterns hold universally and refine our age-adaptive design principles. Together, these directions aim to move VR design toward more inclusive, adaptive, and evidence-based applications in social and educational research.

7 Conclusion

By experimenting on a large sample of targeted participants, this work highlights that VR design must account for age-related differences, especially among young users. In particular, young children heightened perceptual ratings suggest that they can benefit from highly engaging virtual environments for purposes such as education, training, or therapeutic interventions. For adolescents, who report greater sensitivity to social exclusion, careful framing of social dynamics is critical to prevent unintended negative effects. Additionally, our observation that greater user involvement is associated with reduced simulator sickness highlights an important direction for future research, particularly in exploring whether interactive, goal-oriented tasks can systematically reduce discomfort by sustaining engagement.

With the concise conceptual framework and design suggestions derived from practical findings, this study contributes to the growing body of research on age-adaptive VR design. It provides empirical evidence and actionable guidelines for tailoring virtual environments to developmental needs, thereby supporting both positive user experiences and ethical considerations in youth-oriented VR. We hope these insights will inform future VR applications in educational, clinical, and social contexts, and encourage further exploration of adaptive systems that dynamically respond to users' characteristics and engagement patterns.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The research was conducted in accordance with all relevant ethical regulations established with the protocol numbers 0001227 and 0151020. The sample comprised exclusively underage Italian children and adolescents. Consequently, the researchers obtained informed consent from the parents and legal guardians of all participants, and subsequently, informed assent was obtained from the participants themselves. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin. Written informed consent was obtained from the minor(s)' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

Author contributions

TK: Methodology, Investigation, Validation, Formal Analysis, Writing – original draft, Software, Conceptualization. GD: Writing – original draft, Conceptualization, Methodology, Investigation, Validation, Formal Analysis. MB: Supervision, Methodology, Conceptualization, Writing – review and editing. EM: Funding acquisition, Project administration, Supervision, Writing – review and editing. GM: Writing – review and editing, Funding acquisition, Supervision, Project administration.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2026.1789480/full#supplementary-material

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