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Effects of congruity on the state of user presence in virtual environments: Results from a breaching experiment

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The present study investigates how the user state of *presence* is affected by contingencies in the design of virtual environments. The theoretical framework of *congruity* is herein explicated, which builds upon the concept of plausibility illusion as one of the essential prerequisites for presence, and which systematically explains and predicts presence in terms of alignment between schemata in the user's memory and stimuli presented within the virtual environment. Three dimensions of congruity are explicated and discussed: *sensory*, *environmental*, and *thematic*. A series of breaching experiments were conducted in a virtual environment testing the effects of each dimension of incongruity on presence. These experiments were inconclusive regarding the effects of sensory and environmental congruity; however, the results strongly suggest that the state of presence is contingent upon thematic congruity in virtual environments. This finding has theoretical significance insofar as it points towards the necessity of considering genre and cultural context in predicting user states in virtual environments. The study also has practical relevance to designers and developers of content for virtual reality in that it identifies a critical psychological consideration for the user experience that is absent from existing models.

KEYWORDS
presence, congruity, plausibility illusion, mental models, genre, experiment

1 Introduction

Technological advances and decreases in production costs have made virtual reality (VR) accessible to consumers in recent years. However, the technology has remained in a transitional phase, mainly due to a dearth of compelling content (Ismail, 2017; Dickson, 2018). Despite significant market growth driven in part by lockdowns during the COVID-19 pandemic (O'Kane, 2020), analysts have remained skeptical of the potential for the widespread adoption and integration of VR into everyday life (Ovide, 2022). Despite financial losses, large technology companies, such as Google, Meta, Microsoft, Apple, and Sony, have invested heavily in developing mainstream VR platforms (Amenabar, 2022). Current projections estimate that the augmented and virtual reality market will continue to grow to $36 billion by 2025, with 50 million headsets shipped annually by 2026 (International Data Corporation, 2021; International Data Corporation, 2022).

The defining technological affordance of VR is the potential to generate in its users a sense of *presence*—that is, of being transported from the physical environment to a simulated environment (Bowman and McMahan, 2007). Spatial presence has been conceptualized as "a psychological [user] state in which virtual . . . physical objects are experienced as actual physical objects in either sensory or non-sensory ways" (Vorderer et al., 2004). Even before the successful commercialization of VR, there have been extensive empirical investigations of the effects on presence associated with various platform affordances, including degrees of freedom, latency, display resolution, and field of view (Cummings and Bailenson, 2016). However, hardware is only one component in the creation of compelling experiences: Careful attention must also be paid to software and content design, including interactive systems, user interface elements, and the construction of the simulated space to successfully generate a feeling of presence in users.

While it is often assumed that sensory fidelity is the primary factor in the immersion[1] afforded by VR systems—which in turn allows for feelings of presence—past research on the content of virtual environments (VEs) has demonstrated that this is not always the case: Affective narrative and visual cues embedded in the environment have been associated with higher self-reported levels of engagement, naturalism, believability, and reality compared to an affectively-neutral environment represented with the same level of fidelity (Baños et al., 2004). Riva et al. (2007) altered lighting and background sounds in a virtual park to induce emotions of relaxation and anxiety and found that even when presented with the same arrangement of virtual objects, participants reported a greater sense of presence in the affectively-valenced parks than in an affectively neutral control condition. These effects have also been related to the pre-existing psychological dispositions of the user, such that arachnophobes report higher levels of presence when exposed to a virtual spider, and ophidiophobes report higher levels of presence when deceived by an experimenter to believe that a VE contained unseen snakes (Renaud et al., 2002; Bouchard et al., 2008).

We propose that in addition to the influence of affective cues, feelings of presence are also partially determined by content features of the VE that affect cognitive processing. In this, we draw from Slater's (2009) concept of *plausibility illusion*, defined as the sense that "what is apparently happening is really happening" (3553). In contrast to *place illusion*, Slater relates plausibility illusion to the realistic behaviour of virtual objects and agents rather than the fidelity of their representation. Supporting this perspective, Slater (2009) found that not only was presence affected by the presence or absence of shadows but by the degree to which the movement of shadows tracked with the virtual objects that cast them.

This observation suggests that evaluations of plausibility in a VE are related to normative expectations regarding the behaviour of objects, and the interactions between objects and their environment. Such expectations are presumably drawn from past experiences outside of a VE; originating from the user's day-to-day existence in physical reality, these expectations may appear childishly obvious, even axiomatic (e.g., *when I move my hand, the shadow of my hand also moves*). Indeed, Piaget (1930) argued that associations between sensory cues were formed and internalized in childhood, as once-novel observations about the world crystallized into causal belief systems. The child thus forms mental models, or *schemata*, that associate physical objects perceived in reality with patterns of anticipated behaviour.

Individuals' understanding and expectation of the behaviour of objects in physical space has been theorized as fundamentally schematic: Judgements that might be considered common-sense, such as whether an object on the edge of a table might be expected to fall, rely on quasi-probabilistic, heuristic models of Newtonian physics under familiar conditions. Such models allow humans to make predictions about the physical world at an intuitive level (Battaglia et al., 2013). The necessity for happenings in a VE to "unfold according to the knowledge and prior expectations of the participant" has been recognized in past research as one of the prerequisites for maintaining the *credibility* of the simulated scenario, and thus, plausibility illusion (Rovira et al., 2009, 3).

One of the most exciting possibilities for the design of VEs is immersion in spaces unbound by physical constraints. However, the potential for the behaviour of the perceived environment to diverge from schematic expectations poses problems on both a theoretical and design level: One might expect any such breaches to critically undermine the plausibility illusion, resulting in a disruption of the user's sense of presence. Nevertheless, the fact that immersive VEs are possible *at all*, despite operating under a variety of physical and technological constraints (e.g., bounded space for movement, the absence of olfactory sensation, limited range of haptic feedback) illustrates that there is some psychological tolerance for differences in the processing of physical and virtual realities.

Congruity describes the alignment of two sets of sensory cues in a VE with a schema prescribing their interaction (Cahill, 2018). In this theoretical framework, schemata are internalized, normative, organizing heuristics that articulate expectations for how objects in the world should behave based on past observations. The present study explores the extent to which various types of schematic understandings govern the cognitive processing of VEs. Cahill proposes three dimensions of congruity as potentially influential for the experience of presence in VEs: *sensory*, *environmental*, and *thematic*. Each dimension is briefly explicated below, and relevant hypotheses are proposed for each (see also Figure 1).

In physical reality, objects are perceived simultaneously through different sensory modalities, and the relationships between these various sensory cues are generally stable. While there may be limitations on the modalities of sensation that may come into play in a given circumstance—we cannot feel all of the objects that we can see, for instance—in those cases where multimodal cues for a single object are available, there is likely to be a schematic association between them. For example, if one sees a waterfall in the distance, one does not necessarily expect to be able to perceive it through their other senses. However, moving closer, one has definite expectations regarding what the waterfall will sound like when it becomes audible and what it will feel like when it becomes tangible.

It is important to note that incongruity between sensory cues is very different from the absence of sensory cues in a VE. As observed above, there appears to be a certain level of tolerance for missing sensory information in mediated contexts, to the extent that participants have been observed to "fill in" haptic sensation in experimental contexts where suitable visual cues (e.g., a handle attached to a coiled spring) are given (Biocca et al., 2001). If

[1]Throughout this paper, we will use the term *immersive* to describe a mediated experience with the requisite affordances for a user to potentially experience *presence*, and presence to describe the sensation of "being there," itself.

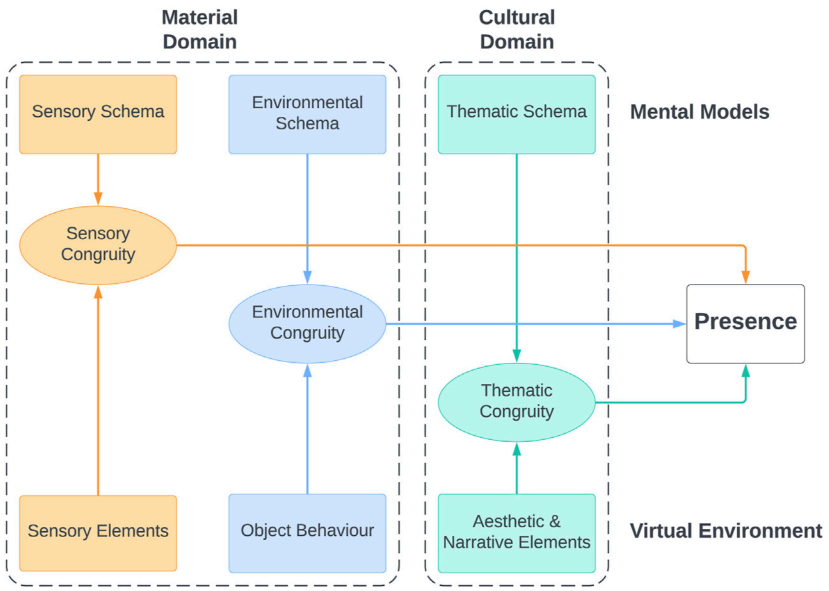

FIGURE 1
Conceptual diagram of the theoretical framework.

anything, this observation is consistent with the theory that certain sensory cues are associated in cognitive processing, yet it does not indicate how *contradictory* cues are processed.

Physical objects in physical reality are also governed by physical laws. Individuals develop heuristic understandings of these laws through experience, resulting in intuitive mental models that approximate principles of physics (Battaglia et al., 2013). The behaviour of virtual objects is expected to conform to these schematic models: This expectation is already implicitly acknowledged in the engineering of game engines and other software systems that underpin virtual reality, which typically include the ability to simulate the physics of virtual reality as a baseline affordance. *Environmental congruity* articulates this principle and the extent to which the behaviour of virtual objects aligns with the relevant schema for the behaviour of a comparable physical object. In most cases, environmental congruity is operationally relevant to virtual objects' motion or collision, since the simulation of other physical properties (e.g., temperature, viscosity, mass) requires sensory affordances that are less readily available with commercial VR hardware.

A notable caveat regarding environmental schemata is that they may be context-specific to some degree and that the relevant contexts may extend beyond those with which an individual has direct experience. A schema articulating the behaviour of physical objects in high orbit or on the Moon will no doubt differ from one articulating the behaviour of a comparable object on Earth and yet may be as deeply internalized through educational or mediated representations of those contexts. Thus, if a VE can maintain the plausibility illusion of being on the surface of the Moon, environmental congruity may be more readily maintained through simulation of low-gravity physics than through a recreation of familiar object behaviours.

The contextual associations of different environmental cues and the objects in those environments are addressed by the concept of *theme* or the understanding that certain classes of objects are schematically associated with one another and with particular environments. While the basis for thematic associations may originate in personal experience, the prevalence of *genre* as a formal feature of entertainment media suggests the possibility that thematic expectations are likely to be culturally determined and based on *other mediated experiences*. While genre is often thought of as inherent in texts, it can also be functionally conceptualized in terms of cognitive structures that the text invokes in the reader (Schmidt, 1987). This way of thinking is in line with Livingstone's dual conceptualizations of genre as both specifying a worldview common to the mediated and physical worlds and embodying a "contract" to be negotiated between the text and the reader (Livingstone, 1993; Livingstone, 2013). Arsenault (2009) has discussed the complications inherent in attempting to rigidly define genre typologies for interactive media objects such as video games. Rather than objectively defined categories, genres may be thought of as dynamic arrangements of narrative structures and aesthetic elements that arise from historical trends of cultural influence involving individuals as consumers, arrangers, and producers of media. The encoding of consumed media into mental models is thus implicated in the reproduction of genre on a cultural scale, as designers draw on their own memories of mediated experiences to shape the form and content of new VEs. From this perspective, an experience falls into a particular genre classification not because of any stable, deterministic traits but because of the agglomeration and interaction of sensory and narrative cues associated by the audience with a particular schema.

Elements that are strongly associated with particular genre classifications or thematic schemata are hypothesized to invoke thematic incongruity when they appear out of their familiar context, even where this appearance does not produce incongruity along the other two dimensions: As an example, the image of a stagecoach, pulled along by horses, and accompanied by the appropriate sounds of rattling and whinnying, may be sensorially and environmentally congruous, and will not arouse dissonance in an environment that is coded as "Western" (e.g., a dusty road or mountain pass). The same sensory cues, however, will become uncanny if placed in the environmental context of a modern-day city street or accompanied by the trappings of a futuristic science-fiction narrative.

The inclusion of thematic schemata, based on experience of culturally embedded narrative and aesthetic cues—alongside sensory and environmental schemata derived from the experience of physical reality—represents one of the primary theoretical contributions of the congruity framework proposed by Cahill (2018), as compared to models similarly oriented towards predicting the experience of presence by users of immersive technology. While this model is consistent with past empirical work (see Renaud et al., 2002; Baños et al., 2004; Riva et al., 2007; Bouchard et al., 2008; Slater. 2009; Skarbez et al., 2017), there have been no studies to date that take a confirmatory approach to congruity, and thus, there is a clear need for experimental research in this area.

As with other normative schemata (e.g., social norms), individuals' past experiences in the material and cultural domains are presumed to be *de facto* congruous, and thus, the operation and significance of congruity in VEs is most easily demonstrated through breaching experiments, with manipulations that create circumstances of incongruity for the participant. In testing the following hypotheses, derived from the theoretical framework of congruity, the present study addresses the need for empirical testing of the framework in general and of the effects of thematic congruity in particular:

H1a: Spatial presence will be lessened when spatial congruity is breached.

H1b: Spatial presence will be lessened when environmental congruity is breached.

H1c: Spatial presence will be lessened when thematic congruity is breached.

H2a: Symptoms of simulator sickness will be intensified when spatial congruity is breached.

H2b: Symptoms of simulator sickness will be intensified when environmental congruity is breached.

H2c: Symptoms of simulator sickness will be intensified when thematic congruity is breached.

RQ1: Are the effects of breaches along certain dimensions of congruity more disruptive to spatial presence than others?

2 Materials and methods

2.1 Sample

Participants were recruited from a pool of students enrolled at a large urban research university in the northeastern United States (N = 138). Recruitment materials were posted to an internal web interface accessible to students enrolled in classes that made them eligible to receive academic credit for research participation. Additionally, flyers were placed around the university campus to recruit participants who were not enrolled in eligible courses, who could instead opt to receive a gift card as compensation. All recruitment materials and study protocols were approved by the Institutional Review Board of the university where the study was conducted. The only inclusion criterion was that participants were required to be at least 18 years of age. The median age of participants was 21 ($IQR = 3$), and the sample included 117 female and 20 male participants, as well as one participant who declined to report their gender.

2.2 Apparatus

Participants wore an Oculus Rift S head-mounted display (HMD) and held a single Oculus Touch motion controller in their dominant hand. This HMD has a visual resolution of 2,560 × 1,440 pixels and a refresh rate of 80 Hz. Head movement is detected using an inside-out tracking system with five cameras supporting six degrees of freedom. Audio is provided using integrated above-ear speakers in a stereo configuration. This model of HMD was selected based on its compatibility with and similarity to other hardware adopted by consumers at the time the study was conducted (Cummings et al., 2022). While this device must be connected to a PC via a cable, this allows for greater graphical fidelity and tracking performance in contrast with comparable fully wireless HMDs such as the Oculus Quest (Martindale, 2020), with limited impact on participants' range of movement given the demands of the study and available space.

A researcher checked the fit and positioning of the HMD prior to beginning the experiment. A cable suspension system allowed total freedom of movement within the designated space, and a researcher always observed each participant, ensuring their safety.

2.3 Stimuli

A VE was developed using the Unity game engine, combining commercially available and custom 3D models and texture assets. The environment used for all experimental stimuli (detailed below) was modelled on a medieval great hall and was designed to be open and expansive (see Figure 2). This environment was also intended to evoke schemata associated with history and fantasy genres through distinctive architectural features and decorative design elements (e.g., gothic arches and stained-glass windows). These cues would serve as reference points for stimuli situated within the environment as part of the experimental manipulation of thematic congruity. Each stimulus was designed to address a different dimension of congruity, appearing in either a breach (treatment) or congruous (control) condition, as described below. Each stimulus was preceded by a simple task instruction for the participant, encouraging them to maintain attentional focus. All instructions to participants and questionnaire materials were displayed within a separate, content-neutral environment (described below) to avoid interfering with the participant's perceptions of the experimental environment.

2.3.1 Sensory congruity stimulus

Participants were instructed to observe a series of balls that would be released above the top of a sloped table and to attempt to

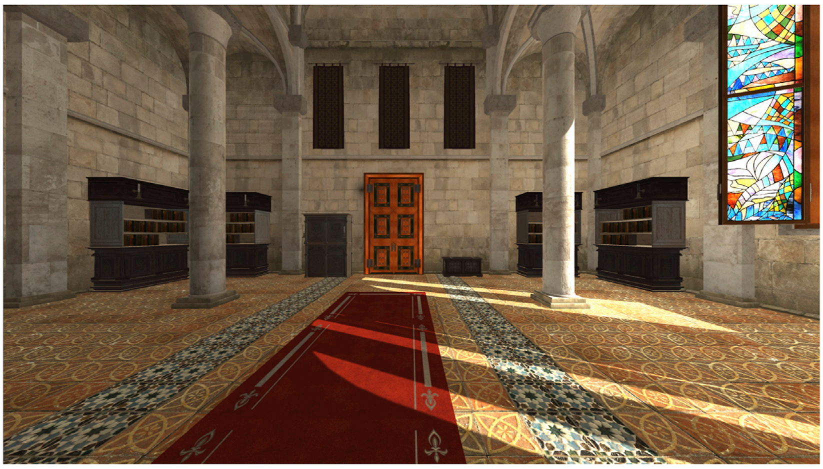

FIGURE 2
Screenshot of the experimental virtual environment, created with Unity.

predict where the balls would roll (see Supplementary Figure S1). Both the balls and the table were rendered with a woodgrain texture, intended to invoke audiovisual sensory schemata when the objects were observed to come into contact (i.e., when each ball struck the top of the table and as it subsequently rolled along the surface). Thus, in the congruous condition, this motion was accompanied by a Foley recording of wooden balls bowled across a wooden surface. Conversely, a Foley clip of water falling over river rocks was substituted in the breach condition to accompany the visual stimulus.

2.3.2 Environmental congruity stimulus

Participants were instructed to observe a book positioned to appear balanced on the edge of a table and attempt to predict the moment when the book would fall (see Supplementary Figure S2). In the congruous condition, the motion of the book object was controlled by a physics engine with parameters consistent with gravity and atmosphere at the Earth's surface. Thus, after a brief pause, the book would gradually tip over the table's edge and fall to the floor. In the breach condition, the vector of simulated gravitational force was inverted at an oblique vertical angle, causing the book to "fall" upward and away from the participant and strike the opposing wall.

2.3.3 Thematic congruity stimulus

Participants were instructed to read and attempt to memorize a short passage of text. The passage was an excerpt from *The Tempest* by William Shakespeare, which could be read in contexts consistent with either a historical or fantasy genre. In the congruous condition, this text was displayed on a piece of parchment laid out on a wooden lectern in front of the participant, in an aesthetic style consistent with other decorative elements in the environment (e.g., bookcases). The text was also rendered in a typeface designed to emulate handwriting while remaining easily legible (see Supplementary Figure S3). In the breach condition, the same text was displayed on a computer terminal with a futuristic aesthetic intended to invoke the science fiction genre and was likewise rendered in a monospace typeface similar to that used in development environments and text-based computer interfaces (see Supplementary Figure S4).

2.4 Procedure

Participants were informed about the scope and objectives of the study and gave informed consent before the experiment began. After being fitted with an HMD, each participant completed a pre-test questionnaire measuring relevant demographic and psychometric traits using the motion controller. A content-neutral VE was created to allow participants to respond to this and subsequent post-test questionnaire instruments without removing the HMD. This environment consisted of empty white space with a textured plane extending in all directions and containing a flat, floating panel which displayed questionnaire items and with which the participant could interact by pointing and using the buttons on the motion controller.

After completing the pre-test procedure, participants were placed in the three experimental stimulus environments described above in random order. For each trial, the participant was randomly assigned to either the breach or congruous condition. Random assignment was independent for each trial so that some participants could have experienced a mixture of the breach and congruous stimuli in different environments, while there was also the potential for some participants to experience only breach or only congruous stimuli throughout all environments (see Figure 3). Following a 60 s exposure to each stimulus, the participant was returned to the neutral environment to complete a post-test questionnaire containing self-reported presence and simulator sickness measures. While these transitions did entail breaking the continuity of the VE, this was thought to be less disruptive than either inserting an incongruous questionnaire interface into the experimental stimulus environment or requiring participants to repeatedly remove and then replace the HMD between each trial.

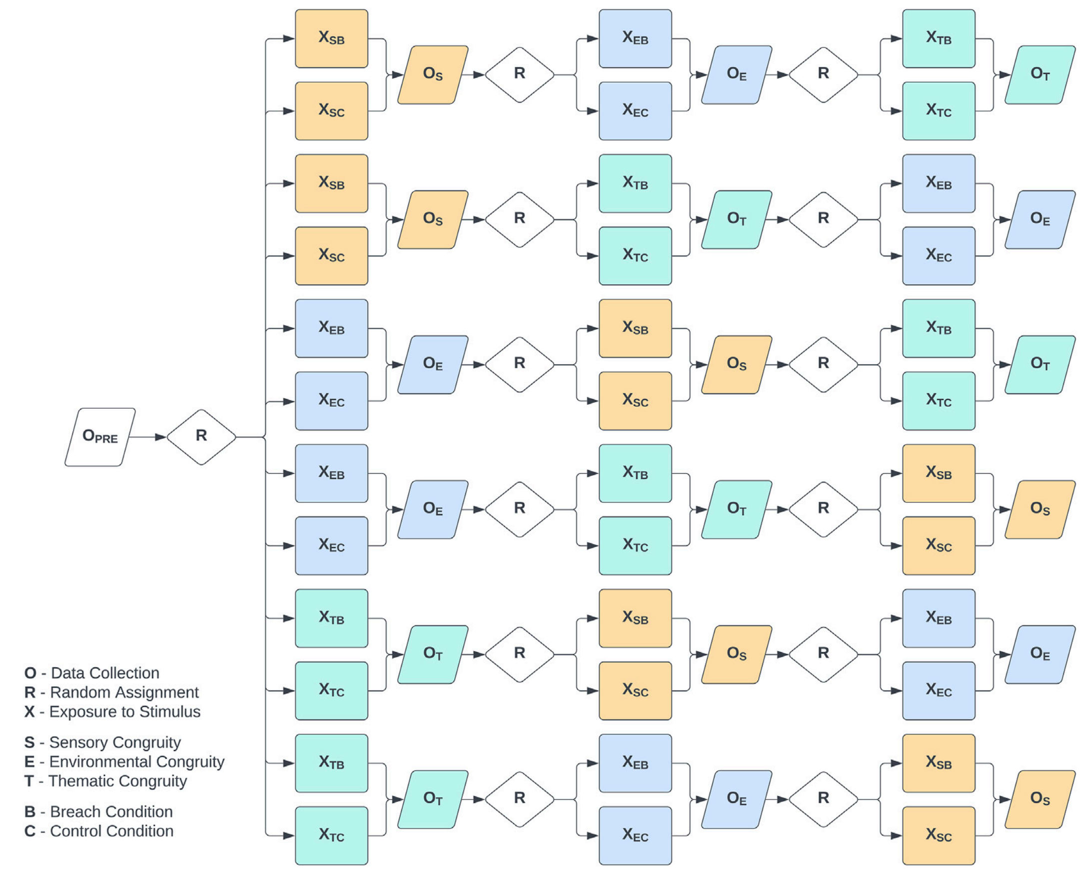

FIGURE 3
Diagram of experimental design.

Once all three trials were completed, participants were asked to remove the HMD and questioned whether they experienced any issues with the VR equipment. They were then debriefed by a researcher who reiterated the purpose and procedures of the study.

2.5 Measures

2.5.1 Immersive tendencies

Individual differences in the tendency of participants to become involved in immersive media were measured using the Immersive Tendencies Questionnaire (Witmer and Singer, 1998). These differences reflected stable psychometric traits that might influence participants' perceptions of VEs. This questionnaire instrument consists of 18 items measured on a 7-point Likert-type scale and includes four subscales to reflect aspects of *focus, involvement, emotion*, and *jeu* (play). Example items include "How good are you at blocking out external distractions when you are involved in something?" (See Supplementary Material, Section 2.1, for the complete instrument.) The separate sub-scales had poor reliability ($\alpha < .65$); however, the reliability of the aggregate scale was acceptable ($\alpha = .82$). This was also comparable to historical reliability reported by Witmer and Singer for the aggregate scale ($\alpha = .81$). For this reason, all analyses considered immersive tendencies as a single variable.

2.5.2 Spatial presence

Presence in each of the experimental environments was self-reported by participants using the MEC Spatial Presence Questionnaire (Vorderer et al., 2004). This questionnaire instrument consists of 24 items measured on a 5-point Likert-type scale and includes three subscales measuring different aspects of spatial presence: *spatial situation*, *self-location*, and *suspension of disbelief*. Example items include "I still have a concrete mental image of the spatial environment," "I felt like I was actually there in the environment," and "I didn't really pay attention to the existence of errors or inconsistencies in the environment," respectively. (See Supplementary Material, Section 2.2, for the complete instrument.) All sub-scales, as well as the aggregate scale, were found to have acceptable reliability ($\alpha > .83$; $\alpha = .81$). Vorderer et al. (2004) only report historical reliability for each sub-scale; however, these fell into a range comparable to the reliability of the sub-scales used in the present study ($.83 \leq \alpha \leq .93$).

2.5.3 Simulator sickness

Potential negative physical symptoms experienced by participants, which have been associated in past research with

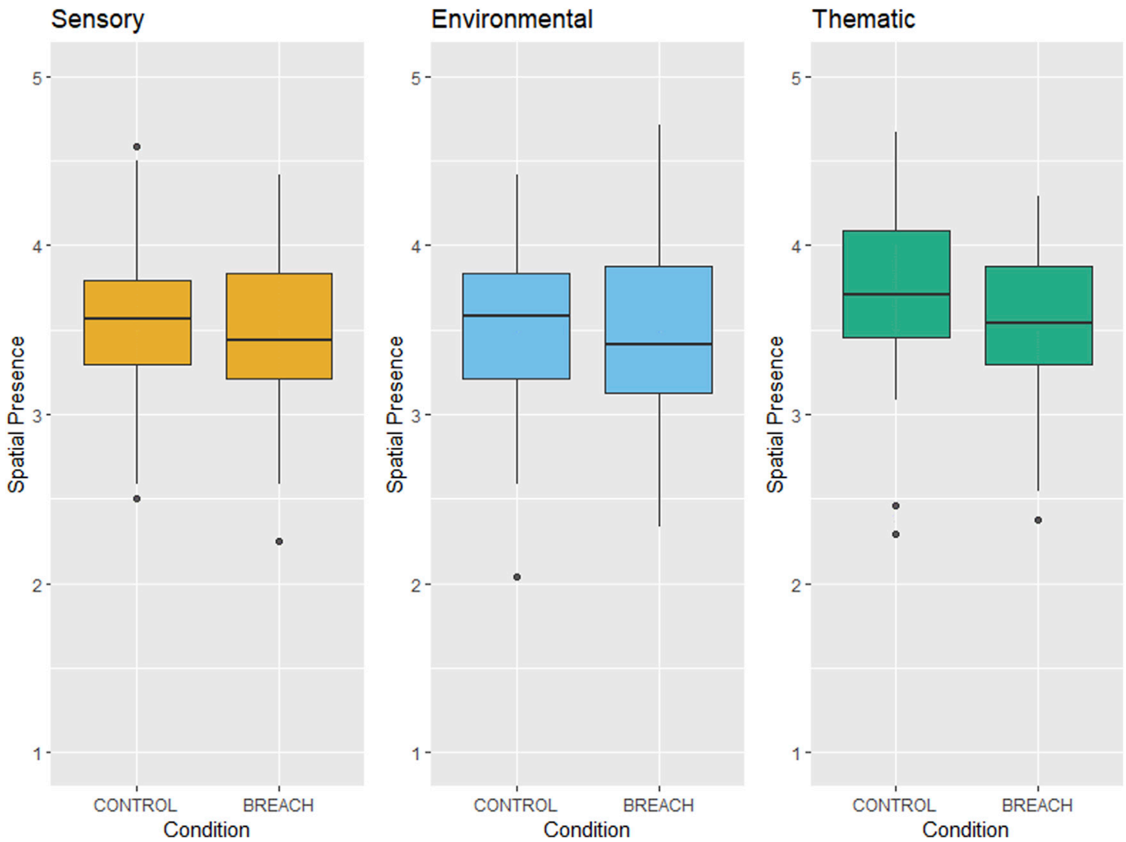

FIGURE 4
Differences in spatial presence by experimental condition.

disruptions in presence, were measured following each trial using an adapted version of the Simulator Sickness Questionnaire (Kennedy et al., 1993). This instrument consists of 16 items describing different symptoms of simulator sickness, such as "Fatigue," "Headache," and "Nausea." (See Supplementary Material, Section 2.3, for the complete instrument.) Participants indicated the extent to which they experienced each symptom on a four-point scale, anchored at "None" and "Severe." Each item was then multiplied by a factor weight and summed according to the three-factor solution provided by Kennedy et al. (1993)[2] Given that the SSQ is intended to be an aggregate measure of a variety of different physical symptoms, which are not presumed to co-occur reliably, rather than a measure of latent psychological traits or states, no reliability scores were computed for this measurement.

2.6 Analytic strategy

Following data collection, self-report questionnaire items were scored and reliability indices for each measure were computed, using the *psych* package for R (Revelle, 2022). The distributions of dependent variables of interest were then plotted and visually interpreted. In cases where a near-normal distribution was assumed for later analysis, this assumption was confirmed with a Shapiro-Wilk test. The Pearson correlation between self-reported spatial presence and immersive tendencies was then calculated to confirm that—as anticipated—immersive tendencies were a relevant personality covariate for analyses involving spatial presence as a dependent variable.

For Hypothesis 1, the assumption of homogeneity of variances was confirmed with Bartlett's test. A two-sample Student's t-test was then performed to contrast the self-reported presence in breach and control conditions for each of the three dimensions of congruity. However, given that immersive tendencies had previously been identified as a covariate of interest, a one-way ANCOVA was also performed using the *rstatix* package (Kassambara, 2022), as the preferred test of these hypotheses. These analyses were conducted using Type II sums of squares, with immersive tendencies entered as an observed covariate.

It was anticipated that the distribution of simulator sickness measures would be heavily skewed, given that experiences of mild or isolated symptoms, or where no symptoms are encountered at all, are generally presumed to be far more common than experiences of severe or wide-ranging symptoms (Kennedy et al., 1993). Furthermore, simulator sickness was not significantly correlated with individual differences in immersive tendencies, nor is there any theoretical reason to anticipate

[2]The three factors described by Kennedy et al. (1993) reflect clusters of related symptoms thought to affect different "systems" in the human body. These are *nausea*, *disorientation*, and *oculomotor strain*.

such a relationship. For these reasons, the Mann-Whitney U test was used as a non-parametric alternative for testing elements of Hypothesis 2. As part of these analyses, Cliff's delta was calculated as a measure of effect size using the *rcompanion* package (Mangiafico, 2022).

3 Results

3.1 Effects on presence

As expected, a weak correlation was observed between individual differences in immersive tendencies and self-reported spatial presence across all conditions ($r\,(412) = .257, p < .001$). When controlling for immersive tendencies, a small but significant difference was observed between spatial presence reported in breach and control conditions ($F\,(1, 411) = 4.51, p = .034, \eta_G^2 = .010$). Hypothesis 1, taken as a whole, was thus weakly supported.

The effects of breaches in each of the three dimensions of congruity were then examined independently (see Figure 4). Surprisingly, breaches in sensory and environmental congruity did not have a significant effect on spatial presence. However, when thematic congruity was breached, spatial presence reported in the breach condition was significantly lower than in the control condition ($F\,(1, 135) = 5.23, p = .024, \eta_G^2 = .034$). Hypotheses 1a and 1b were thus not supported, while Hypothesis 1c was. This finding strongly suggests that the overall lower level of presence observed in conditions where congruity was breached was mainly driven by the effect of breaches in thematic congruity.

3.2 Effects on simulator sickness

As with the analysis of spatial presence, a small but significant overall effect of breaches in congruity was observed on simulator sickness ($U = 19125, p = .020, \delta = .106$). Likewise, when examining the effect of breaches in each of the dimensions of congruity, no significant effect was observed from breaches of sensory or environmental congruity. However, simulator sickness was significantly higher in conditions where thematic congruity was breached, contrasted against the control condition ($U = 1968, p = .026, \delta = .173$). Thus, Hypotheses 2a and 2b were not supported, while Hypothesis 2c was, further indicating the relatively stronger effects of breaches in thematic congruity on user experience.

4 Discussion

To briefly reiterate the cornerstones of the theoretical framework: *congruity* is a multi-dimensional construct intended to predict the experience of *presence* based on intersections between particular types of mental models and sensory cues presented as part of a VE. The state of presence has been theorized to depend in part on the illusion of plausibility: that is, that events, behaviours, and interactions that occur in the virtual world are consistent with expectations of plausible events, behaviours, and interactions established for the physical world (Slater, 2009). It is understood that presence is supported by more than mere graphical or auditory fidelity, although these factors certainly play a role (Cummings and Bailenson, 2016). Rather, affective, narrative, and aesthetic cues presented to the user as elements of a VE also impact the extent to which the user feels present in that environment (Baños et al., 2004; Riva et al., 2007).

Recent work by other researchers has expanded and built upon Slater's (2009) concept of the *plausibility illusion* in ways that complement the present theoretical framework. In a recent update, Slater et al. (2022) have argued that plausibility illusion is one of the "key illusions of virtual reality" and "the most interesting and complex illusion to understand and . . . worthy of significant more [*sic*] research" (1). They observe that taking into account recent technological advancements, "in a typical VR with at least head-tracked stereo wide field-of-view HMD . . . [place illusion] will be the default sensation" (9). Thus, the more pressing concern for designers and developers of VR content is currently the maintenance of plausibility illusion since this is contingent on environmental design rather than technological factors.

Along similar lines, Weber et al. (2021) have recently made the theoretical argument that existing conceptualizations of presence, in centering on the experience of "being there," overemphasize attentional allocation to virtual stimuli at the expense of relevant considerations of "perceived realism." They note that many explications of presence imply that realism in the VE is a precondition for the experience but do not address realism in their definitions of the term. Notably, they point toward the need to consider realism not only in terms of visual fidelity but also in the evaluation of "narrative elements (e.g., the story line or the historical embedding of the narrative) and characters (e.g., their fidelity or actions) . . . in terms of consistency and plausibility" (4). Jung and Lindeman (2021) have also recently proposed a model for integrating these concepts (of coherence and realism) with longer-standing theories of illusion, presence, and immersion.

Skarbez (2016) has proposed *coherence* as a content variable capturing characteristics of a VE that may contribute to the instantiation and maintenance of the illusion of plausibility, paralleling *immersion* as a precursor to the illusion of place. This concept is explicated in terms that roughly describe the alignment of the behaviour of virtual objects with user expectations, for example, "the extent to which virtual humans are present in the scenario and act appropriately for the scenario, the extent to which those interactions are correct or predictable, and the extent to which a scenario accurately depicts what it purports to depict" (Skarbez, 2016, 44). In this way, congruity can be seen as an extension of the concept of coherence (Skarbez, 2016; Skarbez et al., 2021), and similar constructs such as *experiential fidelity* (Beckhaus and Lindeman, 2011) and *authenticity* (Gilbert, 2016). Skarbez et al. (2021) articulate coherence in terms of "reasoning about the degree to which the virtual environment behaves in a reasonable or predictable way," while also commenting on "the difficulty of defining what is 'reasonable' behavior" (3840–3841).

Congruity theory builds upon and differentiates itself from these earlier concepts with the significant addition of an explicit framework accounting for the source of user expectations of virtual experiences. For instance, Gilbert's (2016) explication of authenticity describes it as "a human-based factor that influences presence, and as measured by whether it aligns with the expectations of users in terms of Bayesian priors," (323) but does not address the origin of these expectations. Description of users' expectations of the VE in Bayesian terms does, however, parallel the application of Bayesian cognitive modelling to describe how humans form mental models (i.e., schemata) of how objects behave in physical reality based on prior observation (Battaglia et al., 2013). By incorporating these schemata into its account of the state of presence, congruity expands upon the predictive potential of earlier theories.

Normative schemata are based on experience, either of the material world (in the case of sensory and environmental congruity) or of cultural domains (in the case of thematic congruity). Humans form causal models of expected outcomes through experience (Battaglia et al., 2013), which in turn allow for perceptual cues to be anticipated with confidence. Congruity generally describes the alignment of cues within VEs with these schemata. Three dimensions of congruity have been proposed, addressing different categories of schemata and different levels of anticipated sensory stimulus (Cahill, 2018). At the most basic level, sensory congruity relates to schemata that predict sensory input in one modality from sensory input in another modality. Conversely, environmental congruity deals with objects' observed movement and behaviour in relation to an environment and is thought to be formed based on observations of physical objects in motion.

While sensory and environmental schemata are generalizable to a wide variety of circumstances, encompassing both physical and simulated experiences, it is worth considering the constructed nature of simulated experience in particular. The "dualistic media experience" described by Hartmann and Hofer (2022) is one approach that integrates the "media awareness" of users into theories of presence. They propose that "Whenever users consciously approach a medium or representation (and recognize it as such …) the belief that "this is not really happening" will be accessed from the propositional knowledge and will be activated " (5), with implications for how users perceive and respond to the mediated experience. Notably, they ground media awareness in the formation of mental models of mediated experience acquired in childhood, which parallels developmental components of metacognition such as theory of mind. Moreover, they suggest that media awareness might be made more salient amid an immersive mediated experience when sensory or semantic inconsistencies become apparent in the presentation. However, in this framework, media awareness is conceptualized as a parallel state rather than an antecedent of presence, potentially accounting for a level of awareness of relevant thematic schemata during media experience that need not interfere with the suspension of disbelief.

Provided that users of VEs are aware of the fact that they are experiencing a simulation—which, given the current level of sensory fidelity afforded by VR technology, may typically be assumed—they may also anticipate content based on experience with cultural texts. Even first-time users of VR will likely still have formed mental models around generic configurations they have encountered in other media, giving them a basis for anticipating aesthetic and narrative elements within a VE that is recognized as a constructed and mediated experience. The extent to which the elements presented within a VE align with these models may be described as *thematic congruity*.

Skarbez et al. (2021) suggest that the degree of coherence—and thus, plausibility illusion—for a particular user of a particular VE is likely contingent upon both that user's life experiences and primed expectations of the experience. While this priming is assumed to be explicit for the purposes of defining coherence (e.g., the user is "specifically told that a VE represents a real-life scenario" or "told that this VE represents a future city"), these variable expectations are also accounted for within the framework of thematic congruity schemata articulated as genres. In the context of the present study, for instance, participants were not explicitly informed of the intended setting for the experimental VE and were instead left to form expectations by implication, based on visual cues in the environment.

It is worth considering more recent empirical studies of coherence that have operationalized aspects of "physical coherence" and "scenario coherence" in ways that roughly parallel the manipulation of environmental and thematic congruity in the present study (Skarbez et al., 2017). Coherence has also been tested using breaching experiments that methodologically parallel the present study. Skarbez et al. (2021) manipulated coherence, in part, by adjusting the simulated effect of gravity on virtual balls dropped by participants, such that in the low-coherence (i.e., breaching) condition, dropped balls could be subject to gravitational effects that were noticeably stronger, weaker, or even reversed from normal, Earth-like conditions. While other aspects of that experiment differ significantly from the present study—focusing primarily on the interactions between coherence and immersion, in contrast to our exploration of distinct dimensions of congruity—the operational similarities between the manipulation of physical coherence and the manipulation of environmental congruity are remarkable, and may point towards opportunities for future theoretical synthesis.

4.1 Major findings

It was hypothesized that participants' experience of spatial presence would be negatively affected by breaches in congruity (H1). In testing, the effect of breaches in sensory and environmental congruity upon spatial presence was found to be limited; however, breaches in thematic congruity were observed to have a significant effect on spatial presence. Likewise, it was hypothesized that symptoms of simulator sickness would be exacerbated by breaches in congruity (H2). Here again, the effects of breaches to sensory and environmental congruity were limited, while breaches in thematic congruity were associated with more severe simulator sickness. Based on the results of this exploratory study, it appears that the state of presence is much more strongly contingent upon thematic congruity than upon sensory or environmental congruity, to the extent that it is affected by these latter two at all. Put simply, the user state of presence appears remarkably contingent on thematic elements of the VE.

This finding was surprising, given that sensory and environmental congruity, as theoretical concepts, are suggested by a large body of scientific literature. In contrast, thematic congruity is a comparatively novel concept developed out of work in literary and critical theory rather than empirical research. To account for the apparently outsized effect of thematic congruity, one might consider the possibility that VR users may have an above-average tolerance for deviations from norms associated with physical reality. Such a tolerance could be derived from schemata associated with escapist narratives or entertainment media more generally—noting, for instance, that fantasy and sci-fi narratives frequently depict occurrences that would violate sensory and environmental schemata derived from real-world experience.

User expectations may also be affected by cultural depictions of VR technology in fiction or advertising, which emphasize the potential of the technology to afford experiences that are definitively *unreal* but are nonetheless shown to provoke credulous responses from characters (e.g., ads for the Meta Quest 2 VR platform depicted individuals wearing the HMD and reacting with dramatic gestures to an unseen VE). Such depictions may ironically lower the threshold for suspension of disbelief when individuals do engage with VR technology themselves.

A tolerance for breaches in sensory and environmental congruity might also be the result of past experiences with technical failures in other forms of immersive digital media, such as video games. With the schematic awareness that VEs are essentially software products and that software products can malfunction, it is possible that participants in breach conditions accounted for breaches to sensory and environmental congruity as *glitches*. In contrast, breaches to thematic congruity, lacking a ready-made explanation, might be more disorienting. In this sense, the cognitive behaviour of participants in the present experiment may parallel the account-making observed in seminal breaching studies (Garfinkel, 1963; Garfinkel, 1967). It is worth noting that while several study participants offered comments on the perceived realism (or lack thereof) of the VE during post-test debriefings, in no case did they describe their experience in terms of "errors" or "mistakes" or suggest that either the hardware or software used in the experiment was not operating as intended. However, this lack of explicit and conscious adoption of a glitch schema does not entirely negate the possibility that past experiences with error-prone media technologies may have instilled a subconscious tolerance for breaches of certain dimensions of congruity in study participants.

4.2 Impact

The apparent primacy of thematic congruity in the results of these experiments suggests that aspects of content design, which have been traditionally understudied and undertheorized in the fields of media psychology and human-computer interaction, may be crucially important to understanding the psychological states of VR users. As this technology matures and becomes more embedded in mainstream development and distribution of entertainment media, there will likely be substantial economic and societal incentives to systematize design principles that support states of presence in users.

On a theoretical level, the present study is, to our knowledge, the first attempt to empirically test and provide preliminary support for the propositions of the *congruity* framework, thus providing a basis for further development. The congruity framework is a development and integration of existing theory—expanding upon the work of Slater (2002), Slater (2009), Slater et al. (2022), Baños et al. (2004), Garau et al. (2008), Rovira et al. (2009), Skarbez (2016), Skarbez et al. (2017), Skarbez et al. (2021), and others—and, with further refinement, can serve as a practical tool for systematically predicting user states based on content parameters. More generally, this study contributes to the theoretical understanding of user states in immersive environments by demonstrating the relevance of narrative and aesthetic dimensions of immersive design to the psychological state of users. The limitations of current theoretical models of user engagement with immersive virtual environments are also strongly suggested by the results of this study, which point towards the necessity of incorporating cultural context as a potential moderator of salient user states such as presence.

Additionally, to the extent that thematic congruity invokes normative schemata drawn from the cultural domain (see Figure 1), these findings provide an impetus for scholars and designers of XR and immersive media content to better understand the cultural structures in which their output will be embedded. It should be noted that literary and critical scholars such as Apperley (2006), Arsenault (2009), and Clarke et al. (2017) have discussed at length how the typology and dynamics of genre should be adapted to account for the unique attributes of interactive media. It is generally understood that consumers of entertainment media have an intuitive understanding of the generic categories to which the media objects they engage with belong; however, systematizing this understanding has proven challenging, particularly when considering dimensions of interactivity, platform and hardware effects, and intersections between ludic, narrative, and aesthetic design characteristics.

4.3 Limitations

As an exploratory study investigating a previously untested theoretical framework, there are substantial limitations to the methods employed, which should be acknowledged. The decision was made to design and develop purpose-built VEs for the study to eliminate as many potential confounding and distracting elements as possible and maximize experimental control and comparability between the breach and control conditions. Consequently, the VEs used are relatively superficial compared to many commercial offerings, with users limited to a single room and with few options for autonomously interacting with virtual objects.

For similar reasons to the above, there is also some question as to whether the experimental manipulations were effective, particularly given the limited effects observed under breach conditions of sensory and environmental congruity. Contrasts between breach conditions of different dimensions of congruity should be made with extreme caution, as there is no way to directly compare the magnitude of one breaching condition with another at this stage of research. This caveat also raises the theoretical question of whether "breaches" in congruity occur along a continuum of magnitude, with the potential for some disruptions to be more severe than others, or whether congruity is dichotomous, similar to how some scholars have theorized presence (Slater, 2002; Wirth et al., 2007).

Given that each participant in this study experienced three stages of stimulus—corresponding to the three theorized dimensions of presence—and was randomly assigned to either a breach or congruous stimulus condition at each stage, it is possible that there may have been residual effects from earlier stimulus conditions that would confound later trials. There is not yet a consensus on how long disruptions to the state of presence persist, how long it takes users to recover from breaches in presence, and whether such a recovery is even possible (Garau et al., 2008; Slater, 2009; Rey et al., 2011). While any impact on the findings of the study was minimized through random sequencing (see Figure 3), future studies may prefer to rely on a pure betweensubjects design to eliminate any potential confounding effects between breach conditions. There is also a need for additional research to measure and quantify the time to recovery following breaches in presence.

Given that thematic congruity, in particular, is predicated on schemata derived from experience in the cultural domain, the cultural background of users could potentially influence evaluations of VEs in this respect. For the purposes of this exploratory study, relatively simple manipulations of thematic congruity were used that were likely to have similar schematic associations for most participants. However, further research—utilizing more nuanced manipulations of thematic cues and participant samples from a variety of cultural backgrounds—is warranted to better understand the practical implications of cultural context for user evaluations of congruity, and by extension, states of presence.

As with most studies conducted during the present period of gradual yet sustained growth in the commercial availability of VR hardware, the sample likely included participants with varying levels of experience with the technology. As noted above, this may have affected their perception of or tolerance for breaches in congruity. Qualitatively, some participants commented during debriefing that they were overwhelmed by the novelty of the experience, particularly when entered into the experimental "great hall" environment for the first time and may thus have had difficulty following the instructions meant to focus their attention on the experimentally relevant elements of the stimulus.

Some participants also reported that certain items within the post-test questionnaires seemed confusingly or ambiguously worded, particularly within the MEC-SPQ scale of spatial presence. A small number of participants sought clarification about which "environment" these items were referring to: the experimental "great hall" VE, the neutral VE in which the questionnaire was administered, or the physical lab environment in which the study was conducted. This confusion was despite a clarification added to the questionnaire prompt that all statements were "about the experience you just had."

4.4 Future directions

Several directions present themselves for future research projects, addressing the limitations above and building off the present study's findings. While this study used purpose-built software to generate a VE and administer questionnaires through an HMD, future studies should attempt to reproduce these manipulations within commercially produced and available VR games and entertainment software in the interest of ecological validity.

Additionally, given the preliminary support that these results lend to the theoretical framework of congruity, future studies should expand on this methodological foundation to compare different approaches to inducing breaches in congruity in each of the three dimensions and different magnitudes of manipulation. This step would help to clarify whether the construct should be conceptualized in terms of continuous scales or discrete states and provide a sounder basis for validating experimental manipulations of congruity. This study also used a single VE as the setting for all experiments for the sake of simplicity. Given the significant linkages between thematic congruity and genre presentation, it would be prudent to reproduce these findings in VEs with different genre cues: for example, reversing the manipulation used here to test breaches of thematic congruity by having medieval/fantasy-style objects appear in a more futuristic/science fiction-themed setting.

To the extent that congruity is theorized as a product of both media content and the internalized mental models of the user, it should be possible to develop self-report measures of the extent to which congruity in each dimension is perceived by a user in a given VE. Such an advancement would likewise be helpful in administering manipulation checks in future experiments, so some thought should be given to developing and validating such instruments. Comments by participants given during debriefing also suggest that the instrument used in this study to measure spatial presence—one commonly deployed in past research—may need to be revised and updated to include more explicit instructions to participants, especially in contexts where questionnaires may be administered using the same VR hardware as an experimental stimulus.

Data availability statement

The datasets presented in this article are not publicly available because participant data for this study is considered private and confidential per the research protocol approved by the Boston University Charles River IRB. Requests to access the datasets should be directed to TC, tjcahill@bu.edu.

Ethics statement

The studies involving human participants were reviewed and approved by the Boston University Charles River Institutional Review Board (IRB). The participants provided their written informed consent to participate in this study.

Author contributions

TC designed the study, developed materials, conducted analysis and wrote the first draft of the manuscript. JC secured space and equipment, and helped to refine the study design and manuscript. Both authors jointly oversaw and took part in data collection. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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