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Investigating the efficacy of virtual reality exposure for crowd management: a real-world application

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Introduction: Crowded spaces, especially during significant events or rituals, pose challenges in terms of safety and management. This study introduces a novel approach to address these challenges by leveraging Virtual Reality Exposure (VRE) as a potential solution. Using the Tawaf ritual around the Kaaba and the specific act of touching the Black Stone as a case study, this research explores how VRE can be employed to alter individual behaviors and perceptions in crowded spaces. Methods: Participants completed questionnaires assessing their behaviors and perceptions before and after exposure to two types of Virtual Reality environments: visual-only Virtual Reality (VR) and multi-sensory Virtual Reality (MVR).

Results: Results indicated a marked decrease in participants' eagerness to physically interact with the Black Stone after the VR exposure. However, this eagerness saw a minor resurgence in the MVR setting, suggesting a more profound sense of immersion. Additionally, the MVR environment significantly enhanced the participants' overall sense of presence and emotional intensity compared to the visual-only VR.

Discussion: This research underscores the potential of VRE as a broader tool for crowd management in various settings, emphasizing its generalizability and contribution to the field. By harnessing the immersive capabilities of VRE, stakeholders can mitigate risks and enhance the experience in crowded scenarios.

KEYWORDS

virtual reality, crowd management, immersion, habitation, virtual reality exposure, multi-sensory

1 Introduction

Crowded spaces, especially during significant events or in areas of high importance, pose a considerable challenge in terms of safety, management, and user experience. The Hajj and Umrah pilgrimages to Mecca, Saudi Arabia, represent one of the five pillars of Islam, mandatory religious duties that carry immense significance in the life of every Muslim. Hajj and Umrah include a series of rites and rituals, one of which is Tawaf. It is the act of circumambulating the Kaaba, a cuboid structure, seven times. The Black Stone, set in the Kaaba's eastern corner, holds a special status in this ritual. Some believe part of their rituals is to touch the Black Stone during their Tawaf. Social factors can also play a role; seeing others strive to touch the Black Stone can influence one's behavior, a phenomenon explained through social proof theory (Cialdini, 2008).

It is well-known that crowdedness is one of the main significant concerns when it comes to crowd management around Kaaba and any other similar events. During the Tawaf ritual,

the crowd's density increases substantially near the Black Stone corner. Consequently, many pilgrims aim to get as close as possible to the Black Stone, leading to heightened crowd density in its vicinity. This can reach dangerous levels, posing safety risks such as stampedes, falls, and even fatalities (Taibah and Arlikatti, 2015). The crowdedness around the Kaaba, particularly near the Black Stone, represents a problem of significant complexity. This is compounded by both the beliefs and the considerable number of pilgrims participating (Showail, 2022).

Despite various attempts to manage and control the crowds during Tawaf, existing solutions have yet to be effective. Traditional methods like using barricades, signage, and on-the-ground security personnel offer only limited effectiveness and lack scalability (Elsagheer Mohamed and Parvez, 2019). Technological interventions such as real-time crowd monitoring through computer vision have also been explored but are not foolproof. These techniques of crowd analysis can help in several applications, such as crowd management, designing public spaces, visual surveillance, and intelligent environments (Bendali-Braham et al., 2021). They often fail to perform under extreme crowd conditions and can struggle with false positives and negatives (Junior et al., 2010). Moreover, these interventions do not engage with the individual behavior and emotional factors driving people to get close to the Black Stone, indicating the need for innovative solutions that deal with personal behavior and perceptions.

Hence, even though touching the Black Stone is not a mandatory aspect of Tawaf, the confluence of religious beliefs, personal spiritual goals, psychological factors, and cultural practices make it a focus for many pilgrims. Attempts to change or influence such deeply rooted behaviors would need to account for these multi-faceted influences. VR offers a promising avenue for this purpose. The Cognitive Behavioral Therapy (CBT) model serves as a theoretical underpinning for VRE. The CBT model posits that thoughts, emotions, and behaviors are interconnected and can be influenced by one another (Hofmann et al., 2012). Exposure aims to change behaviors by modifying cognitive processes and emotional responses to certain stimuli. Within a VR environment, this is achieved by exposing individuals to a simulated yet psychologically compelling situation, thus allowing them to confront and modify their thoughts and emotions in a controlled setting (Foa et al., 2006).

Exposure therapy in psychology often uses VR to treat various disorders by immersing individuals in Virtual Environments (VE) where they can confront and gradually become accustomed to stimuli they find troubling (Rothbaum et al., 2000). The effectiveness of VR in changing behaviors and beliefs is well-documented. For example, studies have shown that VR can be highly effective in treating phobias, anxiety, and fear disorders by altering individual thoughts and, therefore, behavior (Powers and Emmelkamp, 2008; Carl et al., 2019; Horigome et al., 2020). The phenomenon where interest or emotional response decreases after repeated exposure to a stimulus is often called "habituation." Habituation is a basic psychological process where an emotional or behavioral response to a specific stimulus decreases when the stimulus is repeated over time (Rothbaum et al., 1995; Rizzo and Kim, 2005; Rankin et al., 2009). Similarly, VR could expose pilgrims to virtual Black Stone experiences. By leveraging VRE, we can simulate the experience of touching the Black Stone, offering a psychologically enriching and realistic experience that could alter pilgrims' behavior about the necessity of touching the Black Stone, thereby easing the crowd density near the Black Stone.

The effectiveness of any VR application is significantly influenced by its sense of presence and immersion. It can be defined as "the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant" (Slater and Wilbur, 1997), p. 605. Immersion can range from non-immersive to fully immersive (Ogle, 2002). High immersion in VR environments plays a crucial role in influencing the user's sense of presence, affecting the overall efficacy of VR interventions like VRE (Slater and Wilbur, 1997). Presence is "the subjective experience of being in one place or environment [e.g., VE], even when one is physically situated in another" (Witmer and Singer, 1998), p. 225. Others describe it as "a state of consciousness, the (psychological) sense of being in the virtual environment" (Slater and Wilbur, 1997), p. 606. A high sense of presence leads users to perceive the VE as a more engaging reality than their actual surroundings, making them view the environment as a place they've visited, not merely images they've seen (Cummings and Bailenson, 2016). Presence is not just an abstract concept but a quantifiable metric, usually assessed through questionnaires (Regenbrecht and Schubert, 2002). Presence can be impacted by hardware issues that affect immersion, reducing the VE's effectiveness (Pallavicini et al., 2013). Presence involves the user's experience of being part of the VE, while immersion reflects the technological fidelity of the VE (Schubert et al., 2001). Greater immersion typically leads to higher levels of presence, resulting in stronger psychological reactions (North and North, 2016).

Immersion and sense of presence are achieved through a combination of visual, auditory, and even haptic (touch) and olfactory (smell) stimuli, creating an environment that closely mimics the real world. In the context of the Black Stone, the smell of incense (a unique Arabian perfume named "Oud" placed on the Black Stone), the touch and feel of the Black Stone, and the actual sound from Mataf (the white-marbled area surrounding the Kaaba). By replicating these elements in the VR environment, the experience becomes visually, emotionally, and culturally immersive. For instance, a study exploring the influence of multi-sensory feedback in VR found that participants demonstrated better recall and emotional engagement when additional sensory stimuli were incorporated (Ghinea and Ademoye, 2011).

The primary aim of this study is to investigate the effect of VRE on participants' perceived need to interact with the Black Stone in the real world scenario. Stemming from this objective, Our research addressed the following questions: Can VRE effectively reduce the felt need to interact with the Black Stone in real life? How does the sense of presence in a VR environment impact the effectiveness of VRE in altering the behavior of pilgrims? Does the inclusion of multi-sensory elements (touch, smell, and sound) in the VR environment enhance the sense of presence and, thereby, the effectiveness of the exposure? Participants' interest in touching the Black Stone was measured by custom questionnaires and sense of presence by a standard questionnaire across two VR conditions.

We hypothesize that: H1: Exposure to VR conditions will reduce participants' interest in touching the Black Stone in real life. H2: The reduction in interest in touching the Black Stone will be greater in

FIGURE 1
Meta Quest 2 Head Mounted Display and controllers.

the MVR condition compared to the VR condition. H3: The MVR condition will result in a higher sense of presence compared to the VR condition. H4: Participants will rate the sense of touch (ability to touch and feel the Black Stone) as the most important sensory feature in the MVR environment.

The structure of this paper is organized as follows: Section 2 delves into the materials and methods, detailing the participant selection, apparatus used, and the experimental design. In Section 3, we present and discuss the results, highlighting the key findings and their implications. A comprehensive discussion follows this in Section 4, where we contextualize our results within the broader research landscape and explore their significance. Section 5 concludes the paper, summarizing the main contributions, acknowledging limitations, and suggesting directions for future work.

2 Material and methods

2.1 Participants

A pilot study with seven participants was carried out to offer a formative assessment of the processes and tools. The actual experiment, in which 38 participants took part, was then conducted. There were 32 men and 6 females, ranging in age from 24 to 52, with a mean age of 39. All participants were recruited from the custodians of the two holy mosques, the Institute for Hajj and Umrah Research at Umm Al-Qura University. All participants were familiar with the Black Stone, possessing prior knowledge and experience of its unique shape and distinctive scent. This familiarity is expected, as most Muslims, if not all, perform the Tawaf ritual multiple times throughout their adulthood. Ethical approval was obtained from the same institution. All individuals had eyesight that was normal or corrected to be normal.

2.2 Apparatus

2.2.1 Hardware

The Meta Quest 2 Head Mounted Display (HMD) was utilized for this study. Meta Quest 2 (Figure 1) boasts a high resolution with 1832 × 1920 pixels per eye, ensuring vivid visual clarity. It operates at a refresh rate of 90 Hz, providing smoother animations and movement perception. A critical advantage of the Meta Quest 2, and the reason for its selection in this study, is its wireless capability. This feature allows participants a free range of movement, a necessity given the requirement to walk within a spacious environment, mimicking the Tawaf ritual around the Kaaba. The built-in positional audio and the controllers further heighten the immersive experience, enabling users to interact and navigate seamlessly within the VE. Quest 2 controllers were also used to reset the view and teleport around the Kabba if the user chose to, besides walking.

2.2.2 Virtual environment

For the VE, the primary objective was to replicate the ambience around the Kaaba, ensuring that the details would evoke a realistic representation of the site. The virtual representation of the Kaaba and Black Stone was built using Unreal Engine. For detailed modeling, 3D Max was utilized. Exact measurements and dimensions of the Kaaba and the Black Stone were measured directly from Al-Masjid Al-Haram, permissions granted by The General Authority for the Affairs of the Grand Mosque and the Prophet's Mosque. To achieve a high-fidelity environment, high-resolution photographs of the Kaaba and the Black Stone were captured from varied angles. This multi-angle approach ensured a comprehensive and authentic reconstruction of the VE (Figure 2).

A notable emphasis was placed on the Kaaba door and the Black Stone, ensuring high-fidelity visuals and intricate detailing. The surrounding areas, such as the Sahan al-Tawaf (the courtyard area around the Kaaba where Tawaf is performed), were also reconstructed. However, to optimize performance and battery consumption, these adjacent areas were designed with slightly reduced resolution, considering the limitations of the Meta Quest 2's hardware capabilities.

2.2.3 Sensory integration

In the MVR condition, we meticulously combined auditory, tactile, and olfactory elements to curate an enhanced immersive experience. For the auditory Component: A 10-min audio clip recorded during a prayer call near the Black Stone, creating an authentic auditory backdrop. For the tactile Component, we materialized a 3D representation of the Black Stone and its

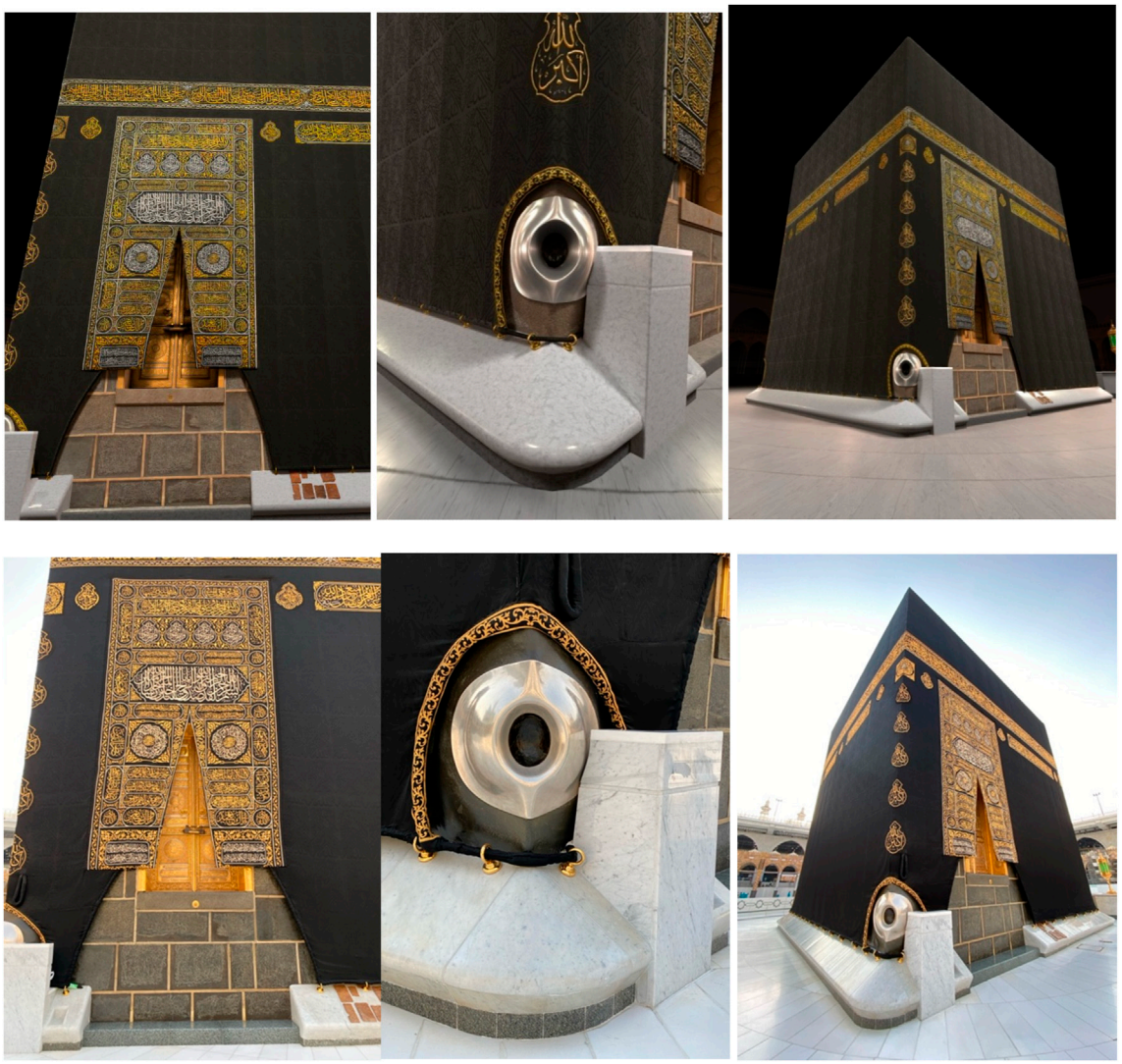

FIGURE 2
Top pictures show screenshots from the built VR environment. The bottom pictures show realistic images captured at the site.

surroundings, offering participants a tangible interaction (Figure 3). Each session began with the precise calibration of this model, aligning it with its virtual counterpart to ensure genuine haptic feedback during VR interactions. The Meta Quest 2 headset is equipped with advanced tracking technologies that provide a seamless and immersive user experience, even during activities such as teleportation. It utilizes an inside-out tracking system with built-in headset cameras to scan the surrounding environment and track its position and orientation using computer vision algorithms. This allows for precise location tracking without external sensors.

Additionally, the headset manages the calibration of the virtual environment automatically. As users teleport within the virtual space, the headset's software adjusts the rendering of virtual objects to align with the user's new viewpoint, ensuring that spatial relationships remain consistent and accurate. The Meta Quest 2 also incorporates the Guardian system to enhance user safety and spatial awareness by helping users stay within a

FIGURE 3
3D printed Black Stone matching the exact dimensions and height of the actual Black Stone.

FIGURE 4
Participants performing the experiment.

designated play area and recalibrating the virtual environment boundaries when users approach the limits of the physical space, which was set before the experiment.

Olfactory Component: The evocative power of scent is integral to creating a realistic and immersive virtual experience. In this study, we utilized a unique perfume applied to the 3D model of the Black Stone, carefully replicating the authentic aroma traditionally added to the actual Black Stone daily. This specific fragrance, approved and sourced with the kind permission of The General Authority for the Affairs of the Grand Mosque and the Prophet's Mosque, is characteristic of the Black Stone and a familiar scent found in many local households. The study leverages their familiarity to significantly enhance the sense of presence and immersion within the virtual environment. These elements coalesced in the MVR, aiming to transport participants to a holistic and profoundly immersive virtual pilgrimage experience.

2.2.4 Experiment setting

Considering the need for participants to walk around and explore, a spacious environment measuring 8 × 10 m was chosen for the experiment. Additionally, participants could teleport around the Kaaba using the VR controller to aid mobility and exploration. Ambient lighting and reflections were controlled to optimize the HMD tracking and ensure participants' uninterrupted and genuine experience. A specific platform was designed to hold the Black Stone at the right height to match the actual height in VR and the real world (Figure 4). The platform was easily movable, allowing quick calibration between the virtual and physical Black Stone at the beginning of each experiment. Each participant starts 1 m away from the Black Stone, and a mark is placed on the ground for participants to start from.

2.3 Measure

2.3.1 Black Stone experience perception

To assess participants' perceptions and experiences related to the Black Stone, the author developed a custom questionnaire before and after exposure to the VR. The questionnaire employed a 7-point Likert scale, ranging from "Strongly Disagree" to "Strongly Agree," to measure participants' responses across four key dimensions:

- Eagerness to Engage: This dimension evaluated participants' anticipation and interest in interacting with the Black Stone. Prior to the VR experience, participants responded, "I am eager to touch and experience the real Black Stone at the

Kaaba." Following the VR experience, they addressed, "I still feel eager to touch and experience the Black Stone after this VR experience."

- Emotional Response: This aspect focused on the emotional reactions elicited by both the real and virtual encounters with the Black Stone. Statements included: "Touching the real Black Stone at the Kaaba would evoke a strong emotional response in me" before VR, and "My emotional response to this VR/MVR environment is intense."
- Curiosity and Exploration: This dimension captured the participants' drive to explore and interact with the Black Stone. It included: "I have a strong curiosity and desire to touch the Black Stone in person" pre-VR, and "I feel a strong curiosity and desire to touch the Black Stone after this VR environment" post-VR.
- Habituation and Responsiveness: This measured changes in participants' adaptability and responsiveness to repeated exposure to the virtual Black Stone. Queries addressed were: "I believe I would never grow accustomed or less responsive to the real experience of the Black Stone" pre-VR, and "I feel I have become accustomed to and less responsive to the real experience of the Black Stone after the VR experience" post-VR.

These dimensions were designed to capture a comprehensive range of attitudes, expectations, and experiences regarding the Black Stone in both its physical and virtual presentations.

2.3.2 Sense of presence and realism

The perceived sense of presence was assessed using the IPQ questionnaire (Regenbrecht and Schubert, 2002). The IPQ is a well-established questionnaire with a reported Cronbach's alpha of .85. The questionnaire consists of 13 questions that measure three different factors: involvement (four questions), spatial presence (five questions), and realism (three questions), and contains an additional question to assess general presence. Each question is answered on a 7- 7-point Likert-like scale, ranging from −3 to 3. The overall sense of presence is calculated by averaging the scores from all answers. The questionnaire was also translated into Arabic for those who are not comfortable using the English version.

2.3.3 Multi-sensory questionnaire

To assess the importance of multi-sensory immersion within the VR environment, participants were presented with specific questions developed by the author to evaluate three primary sensory modalities. For the tactile sense, participants answered: "How do you evaluate the importance of the ability to touch and feel the Black Stone in the VE?" In assessing auditory experiences, they were asked: "How do you evaluate the importance of hearing the Adhan sound within the virtual environment?" The olfactory experience was gauged with: "How do you evaluate the importance of the smell of Oud associated with the printed Black Stone?" Each question precisely measured the sensory impact and was rated on a 7-point Likert scale, where higher scores indicated a greater perceived importance. This structured inquiry allowed for a nuanced comparison of how tactile, auditory, and olfactory inputs contribute to the overall immersive quality of the virtual environment, providing detailed insights into the relative value participants place on these stimuli in enhancing their virtual reality experiences.

2.4 Design

This study adopts a within-subjects experimental approach to probe the influence of VR environments on participants' perceptions and experiences associated with the Black Stone. The investigation hinges on two VR conditions: a primary visual simulation and an advanced multi-sensory simulation infused with touch, hearing, and olfactory sensations. To understand participants' experiences holistically, their perceptions are charted across four key dimensions: eagerness to engage, emotional response, curiosity and exploration, and habituation and responsiveness. These perceptions are gauged before any VR exposure and subsequently after each VR session, rendering insights into the evolution of participants' attitudes through immersive experiences. Additionally, to pinpoint the immersive depth of both VR conditions, the sense of presence—a vital barometer of immersion—is evaluated after each VR exposure. As a concluding step, participants share feedback on the multi-sensory elements of the enriched VR exposure, illuminating the sensory constituents that amplified their virtual experience. All participants experienced the VR condition and then the MVR condition. This is to see the effect of the added sensory information on participants' experience perception.

2.5 Procedure

Upon participant arrival, they are initially greeted and introduced to the purpose and objectives of the study. After this warm welcome, participants receive an informed consent form detailing the study's various facets, including procedures, goals, potential risks, and confidentiality measures. Once a thorough understanding is achieved and consent is obtained, participants fill out a demographic questionnaire. This questionnaire not only gathers essential demographic data but also queries their prior VR experience. This latter component serves to gauge the necessary training required for each participant to use the VR headset comfortably.

Once baseline data is established, participants complete the Experience Perception Questionnaire (in Arabic) to measure their anticipatory feelings and beliefs about the Black Stone. Following this, participants are exposed to the VR conditions. The Experience Perception Questionnaire is re-administered post-exposures to assess any shifts in their perceptions (questions before and after exposures are discussed in the 2.3.1 Section). Furthermore, a Sense of Presence questionnaire (translated to Arabic) is issued to evaluate the depth of their immersion in the VR environment. This sequence—VR exposure followed by the Experience Perception and Sense of Presence questionnaires—is repeated for the MVR condition. Conclusively, a Multi-Sensory Questionnaire is administered to capture participants' sentiments about the enriched multi-sensory VR experience. The procedure culminates with an open-ended feedback session, after which participants are extended gratitude for their invaluable contribution to the research.

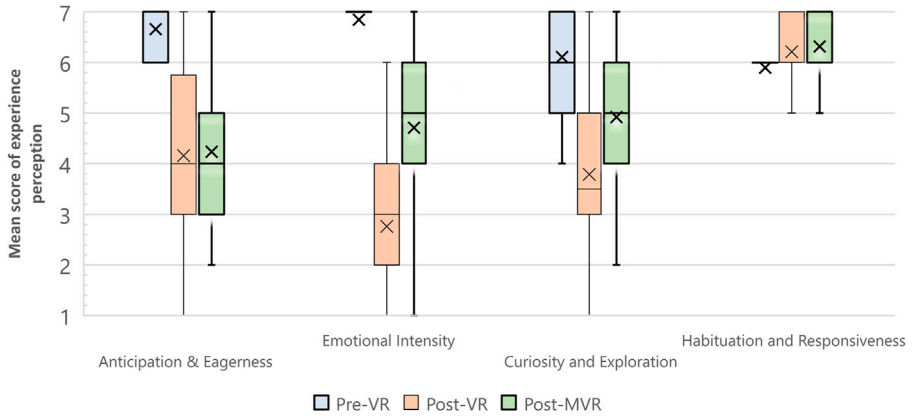

FIGURE 5
Boxplot represents the median, mean (as "X"), quartiles (colored boxes), range, minimum and maximum.

3 Result

3.1 Experience perception

3.1.1 Anticipation & eagerness

The study aimed to discern how different VR exposures could potentially modulate participants' "Anticipation and Eagerness" related to the Black Stone. Initial attitudes were captured with the prompt: "I am eager to touch and experience the real Black Stone at the Kaaba." This was measured before any VR immersion. The corresponding sentiment during the VR experience was evaluated using the statement: "I still feel eager to touch and experience the Black Stone after this VR experience." Results from a within-subjects ANOVA indicated a profound effect of the type of VR exposure on participants' anticipation and eagerness, F (2, 74) = 50.779, $p < .001$, accompanied by a substantial effect size ($\eta^2 = 0.578$). Participants initially reported high eagerness to interact with the real Black Stone, reflected in an average score of 6.658. However, their enthusiasm waned after the visual-only VR exposure, dropping to a mean of 4.158. Following the multi-sensory VR condition, eagerness showed a minor uptick, resulting in a mean of 4.237 (Figure 5).

Post-hoc analyses delineated these shifts further. There was a marked decrease in anticipation and eagerness transitioning from real-world aspirations (pre-VR) to the VR (mean difference = 2.500, $p < .001$) and the MVR condition (mean difference = 2.421, $p < .001$). Yet, differences in eagerness between the VR and MVR conditions were not statistically significant (mean difference = −0.079, $p = 0.780$).

3.1.2 Emotional intensity

Participants expressed a high emotional intensity towards the idea of touching the real Black Stone at the Kaaba, with a mean score of 6.842 (SD = 0.370). The question prompted this response: "Touching the real Black Stone at the Kaaba would evoke a strong emotional response in me." However, during the VR exposure, when participants were presented with the query, "My emotional response to this VR environment is intense," there was a marked decrease in the emotional intensity with a mean score of 2.763 (SD = 1.403). When examining the emotional intensity reported by participants, a significant main effect was observed across the three conditions (pre-VR, VR, and MVR) with F (2,74) = 131.509, $p < .001$, and a large effect size ($\eta\hat{}2 = 0.780$).

Interestingly, when transitioning to the MVR condition, there was a rebound in emotional intensity, averaging at 4.711 (SD = 1.431). Post hoc tests indicated significant differences between all paired conditions. The difference between pre-VR and VR was the most pronounced, with a mean difference of 4.079, t (37) = 16.212, $p < .001$. The difference between pre-VR and MVR was also substantial, with a mean difference of 2.132, t (37) = 8.472, $p < .001$. However, the transition from the VR to the MVR condition showed a significant but more modest increase in emotional intensity with a mean difference of −1.947, t (37) = −7.740, $p < .001$. The graphical representation elucidates this trajectory (Figure 5).

3.1.3 Curiosity and exploration

For the factor "Curiosity and Exploration," the statistical results and the graphical trends shed light on the dynamic nature of participants' curiosity across different conditions. The repeated measures ANOVA indicated a significant difference in the participants' levels of curiosity across the three conditions: Pre-VR, VR, and MVR (F (2, 74) = 37.425, $p < .001$, $\eta\hat{}2 = 0.503$). The questions prompting this response were: before any VR condition, " I have a strong curiosity and desire to touch the Black Stone in person." after the VR and MVR exposure, "I still feel a strong curiosity and desire to touch the Black Stone after this VR environment."

Visual inspection of the graph reinforces this (Figure 5): there is a sharp decline from the Pre-VR (M = 6.105, SD = 0.953) to the VR condition (M = 3.789, SD = 1.580), signifying a considerable reduction in curiosity when participants first engaged with the virtual representation of the Black Stone. Yet, the trend does not remain linear. When introduced to the multisensory stimuli in the MVR condition, there's a noticeable uptick in curiosity (M = 4.921, SD = 1.459). While this rebound in the MVR scenario is evident, it does not reach the initial heightened levels of the Pre-VR condition. This is corroborated by *post hoc* tests, which highlight significant differences across each pair of conditions: the drop from Pre-VR to VR (mean difference = −2.316, $p < .001$), the increase from VR to

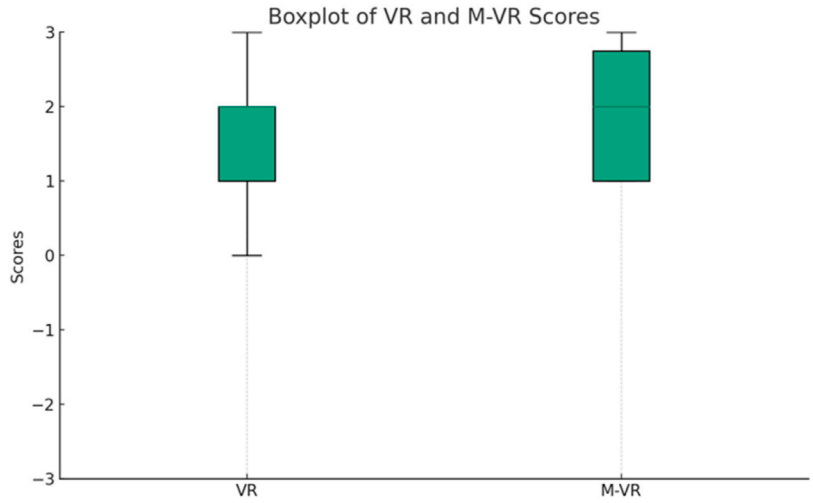

FIGURE 6
Boxplot of the overall sense of presence for the VR and MVR condition. Box plots represent the median, interquartile (colored boxes), minimum, and maximum.

MVR (mean difference = 1.132, $p < .001$), and the overall difference between the Pre-VR and MVR conditions (mean difference = −1.184, $p < .001$).

3.1.4 Habituation and responsiveness

The investigation into the dimension of "Habituation and Responsiveness" addressed users' acclimatization to the actual Black Stone compared to their anticipated responsiveness after the virtual balck stone experience. Participants were asked to indicate their beliefs regarding how they might acclimate to the real experience compared to the VR representation. Initial attitudes were captured with the prompt: "I believe I would never grow accustomed or less responsive to the real experience of the Black Stone." This was measured before any VR immersion. The corresponding sentiment during the VR experience was evaluated using the statement: "I feel I have become accustomed to and less responsive to the real experience of the Black Stone after the VR experience."

The within-subjects effects showed a small yet statistically significant variation across the three phases (F (2) = 4.762, p = 0.011, η^2 = 0.114). Specifically, the descriptive data reveals a slight incline in mean scores from the pre-VR phase (M = 5.895, SD = 0.863) to the VR condition (M = 6.211, SD = 0.875) and subsequently to the MVR condition (M = 6.316, SD = 0.620). See graph (Figure 5). In the *post hoc* comparisons, there was a statistically significant difference between the pre-VR and MVR phases (Mean Difference = −0.421, p = 0.012*). However, differences between pre-VR and VR and MVR did not reach the conventional statistical significance threshold (p = 0.058 and p = 0.461, respectively).

3.2 Sense of presence

Utilizing the IPQ questionnaire, the perceived sense of presence was quantitatively evaluated between VR and MVR conditions. A paired samples *t*-test was employed to ascertain the differences in presence scores between the two experimental conditions. The results revealed a statistically significant enhancement in the perceived sense of presence in the MVR condition (M = 1.921, SD = 0.784) in comparison to the VR condition (M = 1.605, SD = 0.790), t (37) = −2.941, p = 0.006. The medium effect size, quantified by Cohen's d = −0.477, underscores the practical significance of this finding. The graphical representation of the descriptive statistics also visually corroborates this inference (Figure 6), with a discernible elevation in presence scores transitioning from the VR to the MVR environment. This increment suggests that modifications or enhancements inherent to the MVR condition were efficacious in augmenting the participants' general sense of presence.

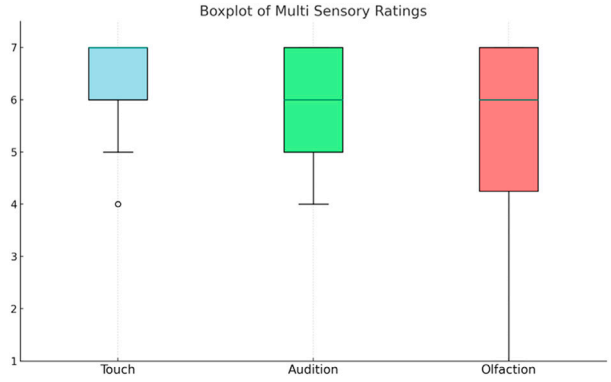

FIGURE 7
Boxplot illustrating the distribution of ratings for the three sensory modalities: Touch, Audition, and Olfactio. Box plots represent the median, interquartile (colored boxes), minimum, and maximum.

3.3 Multi-sensory VR experience

The distinct effects of touch, hearing (audition), and smell (olfaction) were examined to evaluate the significance of multi-

sensory immersion within the VE. Participants were asked to rate the experience of each sense using a 7-point Likert-like scale (ranging from not important to very important). A repeated measures analysis of variance (ANOVA) was performed to analyze these effects. The within-subjects effects revealed a significant effect of the sensing factor, $F(2, 74) = 5.852$, $p = 0.004$, $\eta\hat{}2 = 0.137$. The descriptive (Figure 7) plot illustrates the mean scores for each sensory experience. Touch received the highest average score, followed closely by audition, and then olfaction, which had a noticeable decrease in score compared to the other two senses.

Post hoc pairwise comparisons were conducted to investigate the differences between the three senses further. The most significant difference was found between touch and olfaction with a mean difference of 0.895, $t(37) = 3.352$, $p = 0.004$ (adjusted for multiple comparisons). This indicates that participants rated the sense of touch significantly higher in terms of importance and impact within the VR environment compared to the sense of smell. Comparisons between audition and olfaction approached significance with a p-value of 0.053, suggesting a trend towards higher ratings for audition over olfaction. The difference between touch and audition was not statistically significant.

4 Discussion

The primary objective of this study was to explore the potential of VRE in altering the perceptions and behaviors of pilgrims regarding their interest in touching the Black Stone during the Hajj and Umrah pilgrimages. The results obtained provide compelling evidence that VRE, especially when enhanced with multi-sensory stimuli, can significantly modulate participants' eagerness, emotional intensity, and curiosity related to the Black Stone.

The decline in eagerness, emotional, and curiosity intensity after VR exposure suggests that the virtual representation of the Black Stone, while not entirely replicating the real-world experience, offers a sufficiently immersive alternative. This is further corroborated by the increased sense of presence reported in the multi-sensory VR environment. This highlights that while participants' eagerness diminished after the VR, the intensity of their decline was consistent across both VR and MVR. The study underscores a noteworthy observation: While participants began with strong anticipation and eagerness to physically engage with the Black Stone, their immersion in VR environments—regardless of the sensory depth—tempered this excitement. This may be due to the participant's ability to interact with the virtual Black Stone freely and for extended periods, unlike the real-world scenario, where opportunities to reach or touch it are severely limited. In the virtual world, participants' desire is satisfied by unrestricted interaction, reducing their overall anticipation and emotional intensity toward the real-world experience.

Emotional and curiosity intensity began at a peak during the pre-VR phase, saw a significant dip during the VR experience, and experienced a partial resurgence in the multi-sensory environment. This suggests that while the VR environment could not entirely replicate the emotional gravity attached to the real Black Stone, the multi-sensory experience provided a more enriched emotional context than the VR condition. This suggests that while the VR environment might not emulate the profound emotions and curiosity linked with the real Black Stone, introducing multisensory stimuli brings back some initial inquisitiveness. The heightened curiosity and emotional response in the MVR environment underscore the importance of tactile, auditory, and olfactory stimuli in enhancing the VR experience.

As discussed in the introduction, the habituation phenomenon was evident in the results. Participants initially believed they would remain highly responsive and less accustomed to the real Black Stone. However, with the VR representation, there was an anticipation of increased habituation, albeit gradual. This trend implies that the VE might not entirely replicate the actual experience's novelty and awe but exhibits a modest increase in familiarity as users navigate the VR space. This indicates that participants' anticipated habituation to the actual Black Stone remained relatively constant. Still, there was a slight, yet statistically significant, increase in habituation to the VR representation over time. This is unsurprising, as participants had ample time to fulfill their emotional, curiosity, and eager needs without interruption from the crowd or the limited time frame they would face if they were fortunate enough to reach and touch it in real life.

The multi-sensory VR environment bridges the gap between real-world anticipation and virtual representation. The tactile elements, in particular, stood out as being of paramount importance to the participants. This finding aligns with the theoretical underpinnings of the cognitive Behavioral Therapy (CBT) model and VRE principles, where exposure to stimuli in a controlled environment can lead to changes in behaviors and beliefs. The results also shed light on the potential of VR as a crowd-management tool. The reduced eagerness to physically interact with the Black Stone after VR exposure suggests that VR could be used to manage and potentially alleviate the challenges associated with crowd density near the Black Stone.

In summary, the findings of this study provide a nuanced understanding of how VR, especially when augmented with multi-sensory stimuli, can influence deeply rooted behaviors and perceptions. The results underscore the potential of VRE not just as a technological marvel but as a tool with profound implications for other real-world challenges not only in clinical setup. The implications of this result are profound, underscoring the potential benefits of MVR adaptations in enhancing users' immersive experience. Further exploration into the specific attributes or facets of the MVR condition that contributed to this enhanced sense of presence could provide pivotal insights for future virtual reality design and applications.

5 Conclusion and future work

In conclusion, this study underscores the potential of VR as a tool to manage and alleviate the challenges associated with crowd management during the Hajj and Umrah pilgrimages. The immersive nature of VR, especially when augmented with multi-sensory stimuli, offers a promising avenue for influencing deeply rooted behaviors and perceptions. This study offers several pivotal contributions to the broader research community. Firstly, it pioneers

the innovative application of VRE beyond its conventional confines of psychological treatments, showcasing its potential as a strategic tool for crowd management in high-density areas. Such an approach suggests a transformative shift in how we can leverage VRE, not just in therapeutic contexts but also in urban planning, event management, and other domains where effective crowd control is paramount. Additionally, this research underscores the importance of a holistic multi-sensory approach in VR applications. By integrating touch, sound, and smell into the VE, we emphasize the significance of creating comprehensive immersive experiences that resonate more deeply with users. This multi-sensory emphasis can guide future VR designs, ensuring they are more engaging, realistic, and impactful.

While the findings are promising, several limitations should be noted. The participant sample was skewed in terms of gender distribution, which might affect the generalizability of the results. The study utilized the Meta Quest 2 HMD, and while it offers several advantages, its limitations in terms of hardware capabilities might have influenced the results. Additionally, despite its high fidelity, the VE cannot entirely replicate the profound emotional and spiritual significance of the real-world pilgrimage experience.

Future research should aim to incorporate a more diverse and larger sample of participants to enhance the generalizability of the findings. Exploring other VR platforms with advanced capabilities might also offer deeper insights. Additionally, integrating feedback mechanisms within the VR environment to capture real-time emotional and physiological responses could provide a more holistic understanding of participants' experiences. Given the importance of multi-sensory stimuli in enhancing the VR experience, future studies should also delve deeper into optimizing the balance and intensity of these stimuli to enhance immersion and presence further. The questionnaires developed for measuring participants' experience perceptions and the multi-sensory questionnaire have not yet been validated. Future studies could aim to validate these measures.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Custodian of the two holy mosques and the Institute for Hajj and Umrah Research at Umm Al-Qura University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

AA: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Writing–original draft, Writing–review and editing.

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Conflict of interest

The author declares 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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