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ORIGINAL ARTICLE

VR unseen gaze: inducing feeling of being stared at in virtual reality

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Abstract

The main aim of this paper is to investigate a method that can induce a VR user's feeling of being stared at. Contrary to the previous method that directly informs users of unseen gaze with a voice and subtitles, the proposed method provides an indirect subtle stimulus to induce a feeling that they are being watched. Our study began with the observations reported by the previous studies that the feeling of being stared at appears to be highly correlated with hypervigilance, anxiety, and fear of ambient information around people. To clarify this further, we additionally conducted an online survey. Based on the results of the previous studies and our online survey, we defined two types of factors that may effectively induce the user to feel that they are watched: environmental factors (*darkness*, *absence/presence of people*, *reddish color palette*, and *suspenseful background music*) and stimulative factors (*subtle changes in vision*, *subtle changes in sound*, and *feeling in the back of the neck*). Afterward, two experiments were conducted for in-depth investigation of environmental and stimulative factors, respectively. The purpose was to find out what kinds of factors should be provided at what strength to induce the user's feeling of being watched among the defined factors. Lastly, an application test was performed to not only clarify the advantages and limitations of the proposed method but also propose design guidelines for future use. We expect that our study will serve as a cornerstone for providing a new type of VR experience that the feeling of being watched.

Keywords Virtual reality · Feeling of being stared at · User interfaces · Scopaesthesia · Unseen gaze

1 Introduction

Have you ever felt that someone was looking at you and turned around to find it is the case? The phenomenon in which humans perceive that they are being stared at is called the psychic staring effect or scopaesthesia (Carpenter 2005). Interestingly, surveys conducted in Europe and North America (Titchener 1898; Coover 1913; Braud et al. 1993b; Cottrell et al. 1996; Sheldrake 1996) reported that between 68% and 97% of the population have felt the unseen gaze at least once. However, whether people are able to consciously detect unseen gazes is controversial. Some studies (Titchener 1898; Coover 1913) claimed that the belief in staring detection was empirically groundless whereas some other studies (Poortman 1959; Peterson 1978; Williams 1983) claimed that participants exhibited a sense of being stared at.

Scopaesthesia has been recognized as an interesting phenomenon for decades, and numerous researchers have investigated whether a human being actually has the ability to detect unseen gaze. In this study, we approach this topic in a slightly different view from previous studies. Our research begins with the following question "Is there any way to induce the feeling for VR users that someone is looking at them?" If this is possible, we could provide a better VR experience. Imagine a situation where a sniper is aiming at a user in an FPS game. In most FPS games, users have no way of noticing if a sniper is aiming a gun at them. Dying from a sudden sniper attack is one of the common situations in the FPS gaming experience. However, if users can feel the unseen threat and eventually escape from the sniper's aim, this will be a very exciting experience that

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might have been heard from a veteran soldier's heroic story. In horror games, it could offer a new form of horror, i.e., the feeling of an unknown gaze. Beyond gaming, this also could provide a new form of interaction methodology to the XR academia and business. For example, speakers or lecturers in the multi-user XR environment may feel that they are being watched and focused on by audiences when scopaesthesia experience is given (Campbell et al. 2019; Liu et al. 2020). In that case, their concentration or immersion in their presentations may be affected by scopaesthesia. If the degree of social anxiety can be controlled using the scopaesthesia experience, more diverse scenarios can be provided to users in public speaking training or social anxiety disorder treatment applications (Slater et al. 2006; Owens and Beidel 2015).

In computer games, there have been a few attempts to notify users that someone is watching them. For example, in an FPS game named Apex Legends (Apex legends 2019), alerts of a voice narration and a text are given to users when they are aimed at by their enemies. However, the clear and direct information from the alerts cannot provide the fear or suspense of the unknown. For this reason, the alerts of the unseen gaze are not suitable for the genres requiring the extreme tension or fear that are usually elicited by the unknown. Therefore, our research aims to introduce a new type of interface or design strategy that can induce the impression for VR users that someone is watching them rather than directly giving them information about an unseen gaze (Colwell et al. 2000).

To achieve the goal, it is essential to know the factors that trigger scopaesthesia and how to control these factors to provide a believable experience of scopaesthesia for VR users. We begin with the previous studies investigating what makes people feel that someone is looking at them. Titchener (Titchener 1898) tried to explain scopaesthesia through several psychological factors: nervousness about the people around, stimuli to the passive attention, and body nervousness about one's back or neck due to constant attention. Subconscious mental processes utilizing information from peripheral vision or subtle noise are also considered possible reasons (Sheldrake 2005; Baker 2007).

Thanks to the characteristics of the virtual environment that most stimuli provided to the user can be controlled, it seemed possible to artificially induce scopaesthesia by providing the factors mentioned above. However, we encountered three challenges. First, the factors described in previous studies are vague to be implemented because most factors are derived from the author's subjective views or simple observations instead of concrete experiments. For example, studies state that people can feel an unseen gaze when something is perceived in peripheral vision or auditory senses (Titchener 1898; Coover 1913; Poortman 1959), but the studies do not suggest what something is. Second, it is difficult to decide what kind of stimulus should be delivered at what strength. For example, factors such as stimuli to passive attention and body nervousness about one's back are just phenomena and do not contain information about the strength of the stimulus. Third, no previous study had looked into scopaesthesia in a VR environment.

To overcome such challenges, we conducted an online survey and three user experiments. In the online survey, we tried to clarify the situations where people experienced scopaesthesia in each of the real and virtual environments respectively. The survey revealed several keywords that are considered to trigger scopaesthesia which can be divided into *environmental factors* and *stimulative factors*. Then we designed three subsequent user experiments. In the first experiment (henceforth named E1), we aimed to identify what kinds of *environmental factors* make people experience scopaesthesia easier. In the second experiment (henceforth named E2), we aimed to identify what kinds of *stimulative factors* should be given at what intensity to induce an acceptable scopaesthesia experience. In the third experiment (henceforth named E3), we conducted an application test to investigate the user experience with our scopaesthesia interface and compared our interface with the previous method (Apex legends 2019).

2 Related work

In 1898, Titchener (Titchener 1898) found that the belief in scopaesthesia is quite common among his students. To examine it, he conducted a series of laboratory experiments with his students on scopaesthesia. As the experiment results did not show any effect regarding scopaesthesia, he stated that scopaesthesia is merely a superstition or belief based on nervousness. However, he did not provide details about the experiments. Therefore, in 1913, Coover(Coover 1913) performed experimental research on scopaesthesia to examine Titchener's statement. He recruited 10 participants and instructed them to guess whether they were being stared at while an experimenter sat behind the participant. Through a total of 1000 trials, Coover obtained a statistical result that participants gave the correct answer with a 50.2% chance, confirming that the belief in scopaesthesia is groundless. In 1959, Poortman (Poortman 1959) performed a staring detection study using himself as a participant of a study. During 89 trials, he attempted to guess whether or not he was being stared at by another experimenter seated in a separate room. He obtained a 59.55% accuracy rate which he stated that it was suggestive and highly promising. In 1978, Peterson (Peterson 1978) pointed out that Coover and Poortman poorly controlled test conditions in the experiments. Since the participant and the starer were in the same or opened adjoining rooms during the experiment, the participant may have detected the staring through unintentional auditory cues. Therefore, Peterson separated the space by using one-way mirrors that permitted the starer could see but could not be seen by the participant. He also masked unintended sounds by providing white noise to the participant through headphones. The experiment results indicated that participants showed significantly accurate detection of staring. Later, some studies (Williams 1983; Braud et al. 1993b, a) further improved the sensory isolation by stationing participants and starer in a separate, closed room 60feet apart and using a closed-circuit video camera/monitor arrangement. Surprisingly, all these study results showed that participants had a statistically significant ability to detect staring. Since then, several more experiments and analysis (Wiseman and Smith 1994; Schlitz and LaBerge 1994; Wiseman et al. 1995; Wiseman and Schlitz 1998; Sheldrake 2001) have been conducted on scopaesthesia, but they showed different experimental results regarding whether people have the ability to detect unseen gaze.

Although it is still controversial whether people can detect unseen gaze, many studies agree that there are external factors that make people believe that they are being stared at. For example, Titchener (Titchener 1898) stated that nervousness or anxiety makes people feel that they are being stared at. Coover and Poortman (Coover 1913; Poortman 1959) stated that unintentional noise or subtle changes in vision that can cause fear of something behind their back also lead people to believe that there is an unseen gaze. According to mental studies, anxiety, nervousness, or fear are known to lead humans to hypervigilance for threatening stimuli (Smith 1999; Eysenck 2013), to selective attentional bias for anxiogenic stimuli (Mathews and MacLeod 1986), and to concerning more with stimuli that enhance the subjective feeling of threat (Easterbrook 1959). From this, we speculated that scopaesthesia may be highly correlated with hypervigilance to information that exists behind people but cannot be identified.

In this study, we focus on how to artificially induce scopaesthesia for VR users. Achieving this is expected to have a significant impact on the VR field as it enables VR applications and research to use new types of VR interaction strategies that have not been discussed before. Based on the previous studies and our online survey, we speculated that scopaesthesia can be induced by eliciting a feeling of anxiety, nervousness, or fear in users. Inducing a user's emotional experience has been investigated in the field of mood induction procedures (MIP) (Riva et al. 2007; Toet et al. 2009). According to the studies, one promising methodology to induce a user's strong emotion is to control light condition (Calahan 1996; Niedenthal 2007). In many applications, darkness or ambient lighting has been widely used to induce anxiety or nervousness in users. Riva et al. (Riva et al. 2007) designed a virtual reality with ambient lighting and accentuated shadows to elicit anxiety in VR users. Toet et al. (Toet et al. 2009) found that nighttime lighting conditions effectively induce user anxiety. The use of colors is also known to be a good methodology to elicit users' emotional responses. Pandey et al. (Pandey and Pathak 2009) stated that red, orange, and yellow colors make users more alert and sensitive to external stimuli. Joosten et al. (Joosten et al. 2012) found that the red color evokes negative emotional responses such as sadness or nervousness. Many studies have also found that the control of auditory stimuli is also a promising methodology to elicit fear, stress, nervousness, and anxiety. For example, Scherer and Oshinsky (Scherer and Oshinsky 1977) found that the manipulation of acoustic parameters such as amplitude, pitch, or tempo can control the human emotion such as fear, surprise, or anger. The silence that conveys a feeling of emptiness (Takemitsu et al. 1995), forewarning sound about upcoming frightening events (Perron 2004) and misophonic sounds (Kumar et al. 2017) have effectively elicited user's stress and anxiety in horror games. Delatorre et al. (Delatorre et al. 2019) and Graja et al. (Graja et al. 2020) also stated that the use of sounds can emerge user's fear or anxiety, effectively. We also speculated that scopaesthesia can be induced by providing stimuli that make users believe that there is something behind or next to them. Generally, information about the surrounding environment has mainly been delivered to the user using sensory stimulation such as auditory stimulation (Xu et al. 2007; Wang et al. 2017), visual stimulation (Jung et al. 2018; Ghosh et al. 2018), and haptic stimulation (Dong et al. 2013; Schaack et al. 2019). If such informative sensory stimuli were provided from the back or side of the user in a barely noticeable way, it was expected that such ambiguity could induce scopaesthesia by increasing the fear or hypervigilance of the unknown.

3 Online survey

This study begins with an online survey to investigate what makes people feel that they are being stared at in each of the real and virtual environments, respectively. We aim to acquire more concrete factors that make people experience scopaesthesia and to reinterpret them into a form that can be implemented in a computer-generated virtual world.

3.1 Survey design

The survey begins with a set of consent questions and demographic questions. The survey then asked the following questions:

- Question 1 (Q1) : Have you ever perceived an unseen gaze or the feeling that you are being stared at in the real environment (daily life)?
- Question 1-1 (Q1-1): (If you answered yes to Q1) Please describe the situations and environments where you perceived the unseen gaze.
- Question 2 (Q2): Have you ever perceived an unseen gaze or the feeling that you are being stared at in the virtual environment?
- Question 2-1 (Q2-1): (If you answered yes to Q2) Please describe the situations and environments where you perceived the unseen gaze.
- Question 3 (Q3): (If you answered yes to Q1 and no to Q2) What made you have such an experience only in the real environment?
- Question 4 (Q4): (If you answered no to Q1 and yes to Q2) What made you have such an experience only in the virtual environment?
- Question 5 (Q5): Do you think your emotional state affects your feeling that you are being stared at?
- Question 5-1 (Q5-1): (If you answered yes to Q5) Under what emotional states are you more likely to feel that you are being stared at?

In VR studies (Chen et al. 2019; Li et al. 2019), investigating a user's experience both in the real and virtual worlds, looking for the similarities and differences between them, is one of the widely used research methods. To achieve this, we designed a questionnaire to investigate the user's scopaesthesia experience both in the real and virtual worlds and iteratively refined the questionnaire based on the pilot surveys with our research group members. Q1 and Q2 are designed to investigate whether respondents had ever experienced scopaesthesia. Q1-1 and Q2-1 are designed to extract factors or keywords that are expected to elicit scopaesthesia based on the respondents' experience. Q3 and Q4 are designed to investigate the factors that make people have different scopaesthesia experiences between the real and virtual environments, respectively. Q5 and Q5-1 are designed to find out whether emotional states are associated with the scopaesthesia experience, and which emotional states are associated with it. Q1, Q2, and Q5 were answered in a yes or no response style and the rest questions were answered in an open response style.

3.2 Survey results and discussion

Demographics We distributed our survey to nearby college students through their school community. We received responses from 70 respondents, and out of them only those who had experienced VR application and VR equipment were considered valid. Therefore, we analyzed responses from 40 respondents (27 males and 13 females). The mean (μ) and standard deviation (σ) of age of respondents were $\mu = 21.85$ and $\sigma = 3.10$, respectively. All respondents were undergraduate or graduate students, with normal or corrected-to-normal vision.

Experience of scopaesthesia In terms of the real environment (Q1), 28 out of 40 (70%) respondents answered that they had an experience of perceiving an unseen gaze. On the other hand, In terms of the VR environment (Q2), only 8 out of 40 (20%) respondents answered that they had an experience of perceiving an unseen gaze.

What makes the huge difference in response between Q1 and Q2? To answer this question, we designed Q3 and Q4. 22 and 2 respondents answered Q3 and Q4, respectively. Based on the answers to Q3, we speculated mainly on three reasons why people who answered to Q3 could experience scopaesthesia only in a real environment.

Our first speculation is that users may have fewer opportunities to experience scopaesthesia in VR environments compared to those in real environments since the total time spent in virtual environments is significantly less than that in real environments. Fifteen respondents mentioned *total time spent in VR*. One respondent said, "I enjoy playing VR games for about 3 hours a week, which is too short compared to the time I spend in the real world. I guess this is the reason." Another respondent said, "Enjoying VR applications for more than an hour makes me tired and dizzy. The reason seems to be the lack of opportunity to experience scopaesthesia." According to VR studies, people cannot enjoy VR applications for a long time due to motion sickness or fatigue (Chang et al. 2020; Souchet et al. 2022). This means that the opportunity to experience scopaesthesia in VR is bound to be less than in reality.

The second speculation is that users who played alone in a VR environment where no living things exist, such as rhythm games (Beat saber 2018) and sports games (Golf vr 2019), may have less chance to think that someone is watching them. It is quite different from the real world filled with other living things. Five respondents mentioned *single-player* and *no living things*. One respondent said, "I mainly play Beat Saber. As this game is single-player with no enemies or living NPCs, I never thought that someone can watch me in VR."

The third speculation is that users are given to restricted and highly controlled stimuli in VR, whereas they are given unrestricted stimuli in the real world. Most stimuli given to users are pre-designed stimuli that the content designer aimed to provide a specific experience. Two respondents mentioned *controlled stimuli*. One respondent said, "The stimuli given by VR application are highly controlled to deliver the VR experience intended by designers. Since no VR application has tried to provide the feeling that someone is watching me, it is natural that I had never felt it."

Subsequently, based on the answers to Q4, we speculated a reason why several people could experience scopaesthesia only in a virtual environment. There are many VR games where extreme tension is required for a long time, such as survival games, horror games, FPS games, and so on. Under such prolonged tension, people sometimes felt that they were being stared at by enemies. In contrast, prolonged extreme tension is difficult to find in a real situation. For this reason, it seems that several people have experienced scopaesthesia only in a virtual environment. Among two respondent, one mentioned *survival FPS game* while the other mentioned *horror game*. One respondent said, “When I play horror games, I mostly feel extremely tense and sometimes feel that someone is watching me. However, since such extreme tension does not exist in reality, I guess I have never thought that someone is watching me.”

Under what conditions did people experience scopaesthesia? Based on the analysis of responses to Q1-1 and Q2-1, we extracted several keywords that are considered to make people experience scopaesthesia. The result is presented in Table 1. In terms of real environment (Q1-1), the most frequently mentioned keywords were *darkness* (25.8%) and *subtle changes in sound* (25.8%). For example, one comment said, “*As I was walking down the dark road, I thought I could hear footsteps behind me and felt like someone was looking at me.*” Interestingly, both the *presence of people* (16.1%) and *absence of people* (12.9%) were mentioned. One comment said, “*I felt like someone was looking at me when I was walking in a crowded square*,” while the other comment said, “*I felt that I'm being stared at when I was walking alone in an empty building.*” *Subtle changes in vision* (9.7%) was also recognized as a trigger for scopaesthesia. People seemed to experience scopaesthesia when they sense a change that something is moving, but do not know exactly what the change is. They seemed to feel threatened or feared by this unknown. One comment said, “*When I was taking a walk in the park, I thought I saw a human silhouette next to me, but there was nothing. Then I got frightened and the feeling that someone was looking at me.*” Several people mentioned *feeling in the back of the neck* (9.7%). One comment said, “*A few days ago, I got the feeling that someone was looking at me when I felt a tickling in the back of my neck.*” Most comments seemed to do with emotions like fear, anxiety, and tension. One respondent stated that he had experienced scopaesthesia under prolonged tension even though there was no external stimulation. He said, “*When I was playing the game at the workplace, I used to feel extreme tension for fear that someone would notice. At this time, I kept feeling that someone was looking at me.*”

In terms of VR environment (Q2-1), similar keywords were extracted: *subtle changes in sound* (33.3%), *sudden silence* (22.2%), *darkness* (22.2%), *subtle changes in vision* (11.1%), and *suspenseful music* (11.1%). Unlike the responses to Q1-1, there were comments including the keyword *sudden silence*. For example, one comment said, “*When I was walking down the corridor in the VR game, all sounds suddenly disappeared. Then, I got scared and felt like someone was looking at me.*” Similar to the real environment, most comments seemed to relate to emotions like fear, anxiety, nervousness, and tension.

Do emotional states affect scopaesthesia? According to the responses to Q5, 36 out of 40 (90.0%) respondents thought that there may be a relationship between the emotional states and the experience of scopaesthesia. The three major emotional keywords and their frequencies included in the responses are fear (17), nervousness (12), and tension (7). There seem to be mainly two reasons. One respondent said, “*When I was in a state of extreme tension, I became very sensitive to the external stimuli, and I thought I got the feeling that someone was looking at me.*” Another respondent stated, “*Feeling that I was being stared at appeared to be a phenomenon related to the animal's sixth sense to protect itself from external threats. Therefore, I think that emotional states related to fear or panic may affect the feeling that I am being stared at.*”

Environmental and stimulative factors Previous studies and our online survey reveal potential factors that may cause scopaesthesia (Calahan 1996; Berger 1981; Campbell et al. 2019; Rabiner and Schafer 2007). After thorough discussion and deliberation, we selected several major factors and categorized them into two groups: *environmental factors* and *stimulative factors*. *Environmental factors* are the factors that can be considered when configuring the VR environment. They include *darkness*, *absence/presence of people*, *reddish*

Table 1 Keywords that seem to be related to the conditions that make people experience scopaesthesia. Keywords are extracted from the online survey

Real environment		VR environment	
Keyword	Mention frequency	Keyword	Mention frequency
Darkness	25.8% (8)	*Subtle changes in sound*	33.3% (3)
Subtle changes in sound	25.8% (8)	*Sudden silence*	22.2% (2)
Absence of people	16.1% (5)	*Darkness*	22.2% (2)
Presence of people	12.9% (4)	*Subtle changes in vision*	11.1% (1)
Subtle changes in vision	9.7% (3)	*Suspenseful music*	11.1% (1)
Feeling in the back of the neck	9.7% (3)		

Table 2 Based on the previous studies and our online survey result, we derived factors that seem related to the condition making people experience scopaesthesia and categorized them into two types: environmental and stimulative factors. [Our] means the factor is derived from our online survey result

Environmental factors	Stimulative factors
Darkness [Our], (Calahan 1996), (Niedenthal 2007)	*Subtle changes in vision* [Our], (Berger 1981), (Le Prell et al. 2012), (Rabiner and Schafer 2007)
Absence/presence of people [Our], (Campbell et al. 2019), (Liu et al. 2020)	*Subtle changes in sound* [Our], (Berger 1981), (Rabiner and Schafer 2007)
Reddish color palette (Joosten et al. 2012), (Pandey and Pathak 2009)	*Feeling in the back of the neck* [Our], (Dong et al. 2013), (Schaack et al. 2019)
Suspenseful background music [Our], (Scherer and Oshinsky 1977)	

color palette, and *suspenseful background music*. On the other hand, *stimulative factors* are the factors that can be given to VR users temporarily when it is needed to induce scopaesthesia. They include *subtle changes in vision*, *subtle changes in sound*, and *feeling in the back of the neck*. See Table 2.

4 Experiment 1: under what environmental conditions will users experience scopaesthesia easier?

In E1, we focused on the *environmental factors*. To test the four keywords presented in Table 2, four different VR environments were implemented by applying the characteristics of each keyword. For example, *darkness* is tested in an environment where the luminance condition is lower than the normal environment. Then, we conducted E1 with those four environments to answer two research questions: "RQ1: what kinds of *environmental factors* effectively cause people to experience scopaesthesia?" and "RQ2: How much the intensity of each factor affects scopaesthesia experience?"

4.1 Participants

Twenty participants (16 males and 4 females) were recruited for this experiment. The mean and standard deviation of age were $\mu = 23.5$ years and $\sigma = 2.69$. All participants were undergraduate or graduate students with normal or corrected-to-normal vision. All participants had experience with VR applications. Each participant was paid 5 USD for participation.

4.2 Apparatus and test settings

In E1, we used an HTC VIVE Pro Eye. It supports real-time tracking of 6 degrees of freedom (DOF) of two handheld controllers. During the experiment, two VIVE trackers were attached to both shoes and one was placed on the lower back of the participant. Therefore, we were able to measure the participant's full-body motion through three trackers and two controllers. The tracked data was processed by Unreal

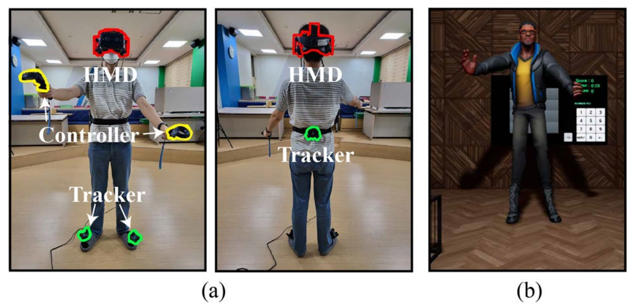

Fig. 1 Apparatus setup for E1. **a** Participant's motion can be tracked by two controllers and three trackers; **b** The virtual avatar mimics the motion of the participant

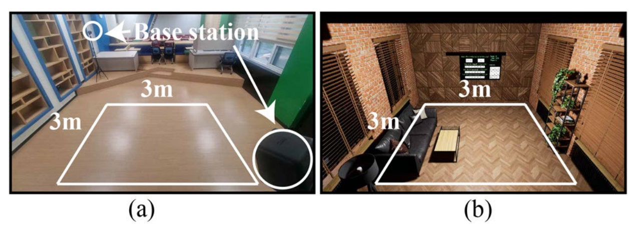

Fig. 2 Test environments used for E1. **a** The physical environment; **b** the virtual environment

Engine 4 and mapped to the motion of the virtual avatar. With this setup, we expected users to be more immersed in the VR environment (Schuemie et al. 2001) and experience scopaesthesia just like in the real world. See Figure 1.

VR environment and feel the invisible gaze when feeling threatened or tense from the outside, just like in the real world.

The physical environment for the experiment is presented in Fig. 2a. A 3 m × 3 m × 3 m of empty space was used for the experiment. The corresponding virtual environment is presented in Fig. 2b. The theme of the virtual environment is a contemporary modern office style, which is characterized by neat lines and a color palette of brown and brick red. The dimensions of the office are 3 m × 3 m × 3 m which correspond to an empty space in the physical environment. There is a fluorescent lamp on the ceiling in the center of the office. To implement realistic and controllable lighting, the lamp was implemented with the point light model of Unreal Engine 4 defined using physically-based lighting units. The luminance is set to 8.0*cd*, and the light color of the lamp is set to white (HSL: 0, 100, 100). The value has been determined through an internal test to make the lighting condition of the virtual office similar to that of the real office. As background music, dark and mysterious music (Logos 2020) with 67 beats per minute (bpm) was played repeatedly.

4.3 Test conditions

In E1, we conducted a comparative user study with 13 test environments which comprise one control environment and 12 experimental environments. 12 experimental environments are defined as four different *environmental factors* with three levels of intensity. Details are as follows:

- *Control Condition Environment (CCE)*: This is a control condition for comparative analysis. Luminance, people density, lamp color, and music tempo are set to the initial setting: the luminance of the lamp is 8.0*cd*, there is no one except for a user, the lamp color is set to white (HSL: 0, 100, 100) and background music with 67 bpm is played repeatedly. Figure 3a shows an example of *CCE*.
- *Dark Environment (DE)*: Three levels of *DE* are defined as *DE1*, *DE2*, and *DE3*. This environment is related to the keyword of *darkness* and claims in previous studies that darkness makes people more alert and sensitive to external threats (Calahan 1996; Niedenthal 2007). The luminance of the lamp is gradually reduced as the level of intensity increases. In our pilot study, the luminance level decreased from 8*cd* to 0*cd*, and participants were asked to report the luminance level at the moment when they were barely aware of the office interior. The average reported luminance level was 0.5*cd* and was set to the luminance level in *DE3*. Then the luminance levels in *DE1* and *DE2* were determined by linear interpolation between the luminance level in the initial setting and that in *DE3*. Therefore, the luminance levels used in *DE1* and *DE2* were 3.0*cd* and 5.5*cd*, respectively. Figure 3b shows an example of *DE3*.
- *Crowded Environment (CE)*: Three levels of *CE* are defined as *CE1*, *CE2*, and *CE3*. This environment is related to the keyword of *absence/presence of people* and claims in previous studies that social nervousness may elicit scopaesthesia (Campbell et al. 2019; Liu et al. 2020). The number of non-player characters (NPCs) is gradually increased as the level of intensity increases. In our pilot study, the number of NPC increased from 0 to 10, and participants were asked to report the number of NPC when they began to feel the office was very crowded. The average reported number of NPCs was six and set to the number of NPCs in *CE3*. Then the numbers of NPCs in *CE1* and *CE2* were determined by linear interpolation between the number of NPCs in the initial setting and that in *CE3*. Therefore, the numbers of NPCs used in *CE1* and *CE2* were 2 and 4, respectively. Figure 3c shows an example of *CE3*.
- *Red Tone Environment (RE)*: Three levels of *RE* are defined as *RE1*, *RE2*, and *RE3*. This environment is related to the claims in previous studies that red, orange, and yellow colors make people more alert and sensitive to external threats (Pandey and Pathak 2009; Joosten et al. 2012). In our pilot study, the change of entire textures to red elicited considerable inconvenience to users. Therefore, we decided to change the color tone of light instead of that of textures. The perceived red component of the lamp light's color increases as the level of intensity increases. This is achieved by decreasing the lightness component of the lamp light's color in the HSL color space. The lamp light's color in *RE3* was set to red (HSL: 0, 100, 50). Then the lamp light's color used in *RE1* and *RE2* was determined by linear interpolation between the color in the initial setting and that in *RE3*. Therefore, the HSL colors used in *RE1* and *RE2* were (HSL: 0, 100, 84) and (HSL: 0, 100, 66), respectively. Figure 3d shows an example of *RE3*.
- *Fast Music Environment (FE)*: Three levels of *FE* are defined as *FE1*, *FE2*, and *FE3*. This environment is related to the keyword of *suspenseful music* and claims in previous studies that music tempo can control fear and tense (Scherer and Oshinsky 1977). The tempo of the background music gradually increases as the level of intensity increases. In our pilot study, the tempo gradu-

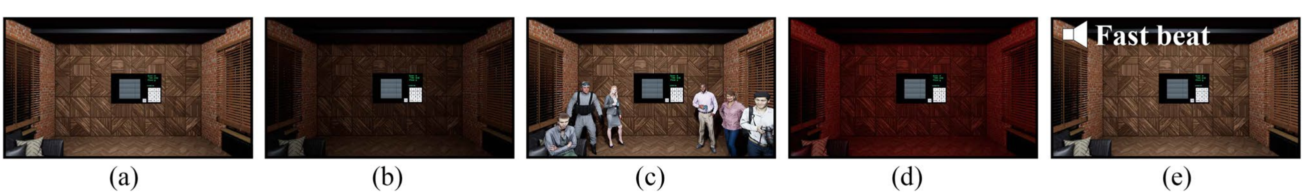

Fig. 3 Five types of test environments used in E1 are illustrated: **a** *CCE* **b** *DE3* **c** *CE3* **d** *RE3* **e** *FE3*. For visualization purposes the luminance shown in screenshots is brighter than that used in the actual experiment

ally increased, and participants were asked to report when they feel most tense without uncomfortable. The average reported tempo was 73.7 bpm and set to the music tempo in *FE3*. Then the music tempo in *FE1* and *FE2* were determined by linear interpolation between the tempo in the initial setting and that in *FE3*. Therefore, the music tempos used in *FE1* and *FE2* were 69.23 bpm and 71.46 bpm, respectively. Figure 3e shows an example of *FE3*.

4.4 Procedure

E1 was run with two experimenters. On arrival, each participant was asked to fill in a consent form and a demographics questionnaire. Subsequently, each participant was provided 15 minutes of the training session. The training session consists of five minutes of introduction to the experimental procedure and 10 minutes of rehearsal time for the experiment. During the introduction, experimenters explained that our goal is to give VR users the impression that someone is watching them indirectly rather than to give the information of unseen gaze directly. During the rehearsal, participants were asked to look around all 13 types of test environments. They were also shown that an NPC would be spawned behind them and watch them, which made them more immersed in feeling the unseen gaze in the main experiment. Subsequently, they were provided with a test procedure to be tested in the main experiment.

After the training session, the main experiment began. Each participant went through 10 blocks throughout the experiment. In each block, 13 test environments were tested for each participant through 13 trials, and the order of test environments was random. Therefore, each participant experienced each environment 10 times. When each trial began, experimenters moved the participant's avatar to an office where one of 13 test environments was applied. Then, they asked each participant to look around for five seconds. Subsequently, they asked each participant to solve a puzzle game for 20 seconds and never look back during the trial. While solving the puzzle, an NPC was spawned behind the participant. The spawned NPC either stared at the participant or not. For each test environment that was provided to each participant 10 times, half were tested with the NPC staring at the participant, and the other half were tested with the NPC not staring at the participant. The order of being stared at by NPC was counterbalanced between participants. The puzzle and spawned NPC are illustrated in Fig. 4. After each trial, a participant was temporarily moved to the black space and asked to answer the question "E1-Q: Do you think someone was staring at you from behind while you were solving a puzzle? Please answer yes or no." After the answer, the correct answer is given to the participant. Each trial took about 25 seconds, including question and answer, and 2-min

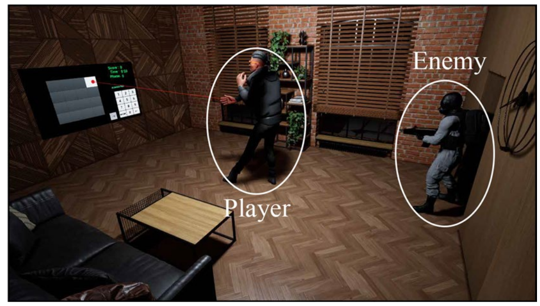

Fig. 4 The screenshot shows the moment that the NPC is staring at a participant when the participant is solving a puzzle

break was provided between blocks to reduce the effects of participant fatigue. Therefore, each participant took part in E1 for about 72 minutes.

To investigate what environmental conditions make users experience scopaesthesia easier, we investigated the average number of 'yes' responses to the question of whether they thought someone was looking at them. If participants answered 'yes' significantly more in a specific environment, it can be said that users experience scopaesthesia easily in that environment than in the other environments. Note that the guessing accuracy was not analyzed for two reasons: 1) The aim of E1 is to find conditions that make users experience scopaesthesia easier, not to find conditions that increase their ability to detect unseen gaze; 2) accuracy analysis is meaningless since no different stimuli were given depending on whether the NPC was watching them.

Comparative analyses were conducted to answer two research questions of RQ1 and RQ2. Rather than comparing all 13 test environments at once, we divided them into four comparison groups named after four different *environmental factors* and compared only within each group. Each group includes one *CCE* and three environments that are defined by the same *environmental factors*, but with different intensities. For example, a comparison group of *DE* includes *CCE*, *DE1*, *DE2*, and *DE3*.

Comparisons between responses to E1-Q within the four groups are shown in Fig. 5. For each group, we first performed the Shapiro-Wilk and Kolmogorov-Smirnov tests and found that not all responses were normally distributed. Therefore, we performed nonparametric tests of the Friedman and Wilcoxon signed-rank tests with a Bonferroni correction. The Friedman test found significant differences between participant responses within all four comparison groups: a group of *DE* ($X^2(3) = 21.826, p < .001$), group of *CE* ($X^2(3) = 10.860, p < .05$), group of *RE* ($X^2(3) = 29.511, p < .001$), and group of *FE* ($X^2(3) = 39.486, p < .001$). The post hoc analysis results are shown in Table 3.

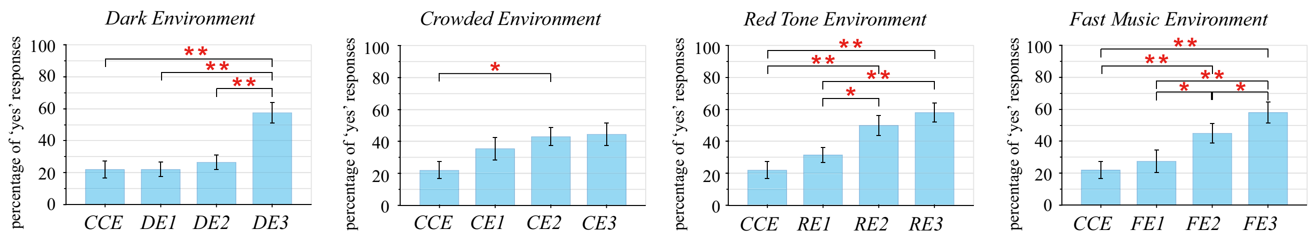

Fig. 5 The average percentage of 'yes' responses to E1-Q in each test condition. Error bars denote standard errors. Square brackets indicate significant differences ($*$: $p < .0083$, $**$: $p < .0016$)

4.5 Discussion

RQ1: What kinds of environmental factors effectively causes people to experience scopaesthesia? The percentage of 'yes' response is about 20% in *CCE*. This implies that participants do not experience scopaesthesia mostly in the control condition. In contrast, the percentage of 'yes' response is significantly higher than *CCE* in *DE3*, *CE2*, *RE2*, *RE3*, *FE2*, and *FE3*. This implies that all *environmental factors* that we tested could make people experience scopaesthesia more if they are provided with appropriate intensity. The maximum percentage of 'yes' response is about 60%, 40%, 60%, and 60% in each comparison groups of *DE*, *CE*, *RE*, and *FE*, respectively. This implies that *presence of NPCs* showed a weaker effect on inducing scopaesthesia compared to the other *environmental factors*. Therefore, we conclude that *darkness*, *reddish color palette* and *fast suspenseful background music* are effective *environmental factors* to induce scopaesthesia.

RQ2: How much does the intensity of each factor affect people's scopaesthesia? In terms of *DE* group, the maximum percentage of 'yes' response is about 60%. However, the percentage does not significantly increases from 20% even if the luminance decreases from 8.0*cd* to 3.0*cd*, as shown in *CCE*, *DE1*, and *DE2*. This implies that the reduction of luminance level does not significantly affect the induction of scopaesthesia until the luminance falls below a certain threshold, whereas it induces scopaesthesia very effectively when the luminance level goes below that threshold.

In terms of *CE* group, the percentage of 'yes' responses significantly increases from 20% to 40% when four NPCs are added to the virtual office. However, the percentage does not significantly increase even if two more NPCs are added to the office, as shown in *CE3*. We speculate that an increasing number of NPCs does not intensify either feeling that the place is crowded or a social nervousness if the number of NPCs exceeds a certain threshold. Therefore, we can say that adding NPCs to the virtual environment makes people experience scopaesthesia easier until the number of NPCs reaches a certain threshold.

The effect of intensity change shown in *RE* group and *FE* group are similar. In both groups, the percentage of 'yes' responses significantly increases from 20% to 60% as the factor intensity increases. Therefore, we can say that using a red light and fast background music makes it easier for people to experience scopaesthesia. In practical implementation, however, increasing the intensity of both factors is not infinite. For example, the perceived red component of the lamp light's color cannot be increased infinitely. In the case of background music, the use of a too-fast tempo often causes discomfort and irritation degrading the quality of the VR experience.

Table 3 The post hoc analysis result of the responses to E1-Q. Wilcoxon signed-rank tests with a Bonferroni correction were performed to compare responses to E1-Q for each comparison group. In each cell, the negative Z-value is presented and its statistical significance is marked by $*$ for $p < .0083$ and $**$ for $p < .0016$

Dark environment					Crowded environment			
	CCE	DE1	DE2	DE3		CCE	CE1	CE2	CE3
CCE	–	0.059	0.973	3.460**	CCE	–	2.045	2.935*	2.591
DE1	–	–	0.905	3.380**	CE1	–	–	1.241	0.632
DE2	–	–	–	3.385**	CE2	–	–	–	0.306
Red tone environment					Fast music environment				
	CCE	RE1	RE2	RE3		CCE	FE1	FE2	FE3
CCE	–	2.012	3.397**	3.658**	CCE	–	1.193	3.621**	3.722**
RE1	–	–	2.783*	3.541**	FE1	–	–	2.999*	3.621**
RE2	–	–	–	2.224	FE2	–	–	–	2.973*

5 Experiment 2: what stimulus will cause users to experience a believable scopaesthesia?

In E2, our interest shifted to the *stimulative factors*. Through the pilot test, we repeatedly provided participants *stimulative factors* with random intensities. During the test, *stimulative factors* seemed to give participants a feeling that someone was watching behind them when they are given with an appropriate intensity. Therefore, we designed E2 to identify an appropriate stimulus intensity that can indirectly give people a feeling of an unseen gaze without directly notifying them. For example, giving an overly strong stimulus may be perceived as obvious information whereas giving a too-weak stimulus may have no effect on users as they will not be aware of it. E2 is conducted with the same 20 participants who took part in E1. The time interval between E1 and E2 is an hour.

5.1 Test conditions

In E2, we conducted a comparative user study with 13 test stimuli which comprise one control stimulus and twelve experimental stimuli. Twelve experimental stimuli are defined as three different *stimulative factors* with four levels of stimulus intensity. Details are as follows:

- *Control Condition Stimulus* (*CCS*): This is a control condition for comparative analysis. No stimulus is given to the participant. Figure 6a shows an example of *CCS*.
- *Visual Stimulus* (*VS*): This stimulus is related to the keyword of *subtle change in vision* and claims in previous studies that uncertain changes in vision make people more alert and sensitive to external threats. Based on the previous studies (Taylor 1965; Rayner 1975; Bailey et al. 2009; Chwesiuk and Mantiuk 2017, 2019), *VS* was designed to present silhouettes of the NPC character in the peripheral vision. Silhouettes are presented 30° away from the line of sight. When *VS* is triggered, the opacity of the silhouette changes along a Gaussian function which means that it smoothly increases until the *target opacity* is reached and then decreases after that within two seconds. We defined four experimental stimuli [*VS1*, *VS2*, *VS3*, *VS4*] with four different *target opacities* [0.14, 0.21, 0.35, 0.42]. Four *target opacities* were determined by [50%, 75%, 125%, 150%] of the detection threshold of 0.28 which was identified in our pilot test. Figure 6b shows an example of *VS*.
- *Auditory Stimulus* (*AS*): This stimulus is related to the keyword of *subtle change in sound* and claims in previous studies that uncertain changes in auditory cues make people more alert and sensitive to external threats. Based on the previous studies (Berger 1981; Rabiner and Schafer 2007; Le Prell et al. 2012), *AS* was designed to present a footstep sound. When *AS* is triggered, sound intensity increases from 0dB SPL along a Gaussian function until the *target intensity* is reached and then decreases after that within two seconds. We defined four experimental stimuli [*AS1*, *AS2*, *AS3*, *AS4*] with four different *target intensities* [35.3, 37.9, 41.7, 43,3]. Four *target opacities* were determined by [50%, 75%, 125%, 150%] of the detection threshold of 39.8dB SPL which was identified in our pilot test. Figure 6b illustrates an *AS*.
- *Haptic Stimulus* (*HS*): This stimulus is related to the keyword of *feeling in the back of the neck* and claims in previous studies that body nervousness about one's neck may elicit scopaesthesia. *HS* was designed to deliver a haptic feedback at the back of the neck by using a vibrotactile actuator HapCoil-One (Tactile Labs). We used a sinusoidal waveform with a frequency of 50 Hz for the haptic feedback. Our internal testing found that waveforms with too low frequencies delivered a dull stimulus quite different from the *feeling in the back of the neck*. In contrast, waveforms with too high frequencies were difficult to control the pattern and noise. When *HS* are triggered, the amplitude of waveform changes along a Gaussian function which means that it increases from 0 to a *target amplitude* and then decreases to 0 within two seconds. Similar to *VS* and *AS*, our pilot test identified that the detection threshold of the feedback force was $5.28m/s^2$. We defined four experimental stimuli by [50%, 75%, 125%, 150%] of the detection threshold. Therefore, *target amplitudes* of [*HS1*,*HS2*,*HS3*,*HS4*] were [2.64

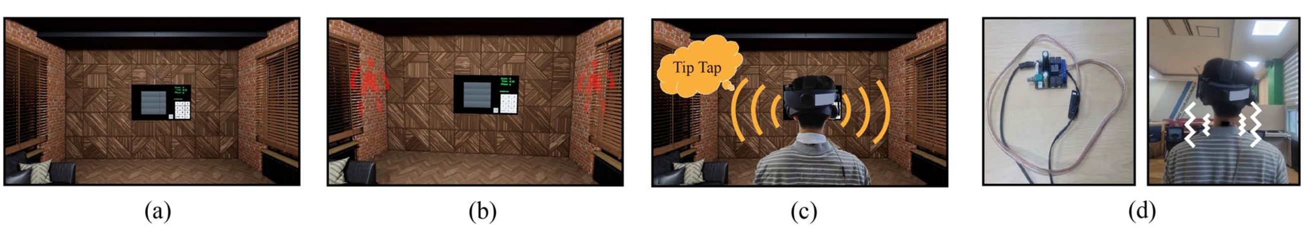

Fig. 6 Four types of test stimuli used in E2 are illustrated: **a** *CCS* **b** *VS* **c** *AS* and **d** *HS* For visualization purposes the *Visual Stimulus* and the luminance shown in screenshots are clearer and brighter than those used in the actual experiment

m/s^2, 3.96 m/s^2, 6.60 m/s^2, 7.92 m/s^2], respectively. Figure 6d shows an example of *HS*.

5.2 Procedure

The apparatus and test environments used in E2 were the same as those used in E1. Since we can obtain the gaze direction from the HTC VIVE Pro EYE in real-time, the visual stimulus can be provided in the peripheral vision in *VS*.

E2 was run with two experimenters. On arrival, each participant was asked to fill in a consent form and a demographics questionnaire. Subsequently, each participant was provided 10 minutes of the training session. The training session consists of five minutes of introduction to the experimental procedure and five minutes of rehearsal time for the experiment. During the introduction, experimenters explained that our goal is to give VR users the impression that someone is watching them indirectly rather than to give the information of unseen gaze directly. During the rehearsal, participants were asked to experience all 13 types of test stimuli. Subsequently, they were provided with a test procedure to be tested in the main experiment.

After the training session, the main experiment began. We adopted temporal two-alternative forced choice (2AFC) method (Vogels and Orban 1985; Kröse and Julesz 1989). Each participant went through 10 blocks through the experiment. Each block consisted of 13 trial pairs and each trial pair consisted of a *standard stimulation trial* and a *test stimulation trial*. No stimulus was given in the *standard stimulation trial* and one of 13 test stimuli was given in the *test stimulation trial*. No *Test stimulation trials* in the same block provides the same types of the test stimulus. The orders of the trials in each pair and test stimuli in each block were random.

When each trial pair began, experimenters moved the participant's avatar to the center of the virtual office and spawned NPC behind the avatar's back. In the first trial, they asked each participant to solve a puzzle game for 20 seconds and never look back during the trial. After the first trial, the HMD screen faded out for one second and faded in another second. Then, the second trial began. Experimenters renewed the puzzle and asked each participant to solve a puzzle game for 20 seconds again. Among two consecutive trials, one is *standard stimulation trial* and the other is *test stimulation trial*. In *standard stimulation trial*, the NPC did not stare at the participant. In contrast, in *test stimulation trial*, the NPC was staring at the participant, and a test stimulus was given once at a random moment and lasts four seconds. The order of *standard stimulation trial* and *test stimulation trial* was counterbalanced between participants. The procedure is illustrated in Fig. 7.

When a trial pair ended, participants were asked to guess when the NPC stared at them over two consecutive trials and were asked whether they are confident in their guess. To this end, two questions "E2-Q1: Among the first and second trials, when do you think the NPC looked at you?" and "E2-Q2: Are you 75% sure about your answer to the E2-Q1 is correct?" were used. E2-Q2 was designed to investigate the degree of certainty about a choice made in E2-Q1. The term "75% sure" comes from the certainty scale (Bruttomesso et al. 2003), which means to be somewhat certain. Both questions were answered on a two-level scale. Each trial pair took about 50 seconds and a 2-min break was provided between blocks to reduce the effects of participant fatigue. Therefore, each participant took part in E2 for about 119 minutes.

5.3 Result

The percentage of correct answers was analyzed for responses to E2-Q1 while the percentage of 'yes' was analyzed for responses to E2-Q2. Then we compare the responses to two questions. Rather than comparing all 13 test stimuli at once, we divided them into three comparison groups named after three different *stimulative factors* and compared only within each group, as we did in E1. Each group includes one *CCS* and four test stimuli that are defined by the same type of *stimulative factor*, but with different intensities. For example, comparison group of *VS* includes five test stimuli: *CCS*, *VS1*, *VS2*, *VS3*, and *VS4*.

A comparative analysis result of responses to E2-Q1 is presented in Fig. 8. For each comparison group, we first ran Shapiro-Wilk and Kolmogorov-Smirnov tests at a 5% significance level to determine the normality of the data. As not all responses were normally distributed, we used the Friedman and Wilcoxon signed-rank tests with a Bonferroni correction. The Friedman test found significant differences

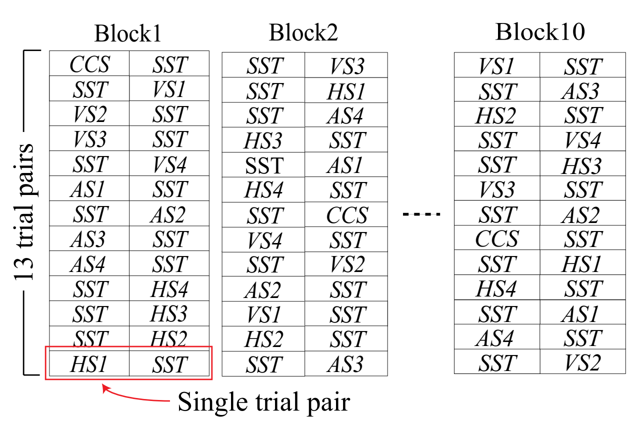

Fig. 7 A illustration of the procedure in E2. *SST* denotes the *standard stimulation trial*

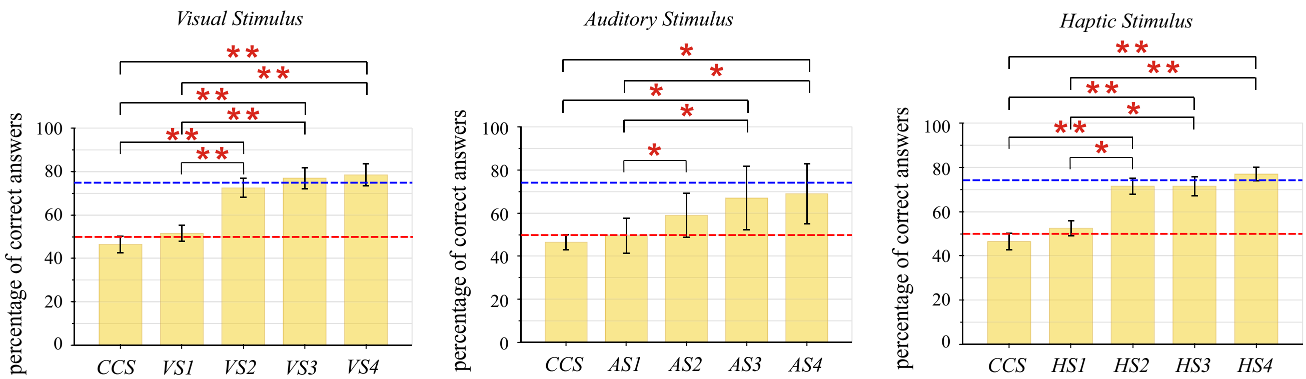

Fig. 8 The average percentage of the correct answer to the E2-Q1 in each test condition. Error bars denote standard errors. Square brackets indicate significant differences ($*$: $p < .005$, $**$: $p < .001$)

between participant responses within all three comparison groups: a group of *VS* ($X^2(4) = 30.619, p < .001$), group of *AS* ($X^2(4) = 23.988, p < .001$), and group of *HS* ($X^2(4) = 33.115, p < .001$). The post hoc analysis results are shown in Table 4.

Similarly, a comparative analysis result of responses to E2-Q2 is presented in Fig. 9. For each comparison group, we first ran Shapiro-Wilk and Kolmogorov-Smirnov tests at a 5% significance level to determine the normality of the data. As not all responses were normally distributed, we used the Friedman and Wilcoxon signed-rank tests with a Bonferroni correction. The Friedman test found significant differences between participant responses within all three comparison groups: a group of *VS* ($X^2(4) = 44.518, p < .001$), group of *AS* ($X^2(4) = 29.275, p < .001$), and a group of *HS* ($X^2(4) = 48.959, p < .001$). The post hoc analysis results are shown in Table 5.

5.4 Discussion

The analysis result shown in Fig. 8 is the 2AFC analysis. Test stimulus showing approximately 50% means that it did not affect inducing scopaesthesia. According to the analysis result, providing *VS1*, *AS1*, and *HS1* is not different from

Table 4 The post hoc analysis result of the E2-Q1. Wilcoxon signed-rank tests with a Bonferroni correction were performed to compare responses to E2-Q1 for each comparison group. In each cell, the negative Z-value is presented and its statistical significance is marked by $*$ for $p < .005$ and $**$ for $p < .001$

	CCS	VS1	VS2	VS3	VS4
Visual stimulus					
CCS	–	1.316	3.569**	3.589**	3.661**
VS1	–	–	3.380*	3.301**	3.373**
VS2	–	–	–	1.213	1.796
VS3	–	–	–	–	0.325
	CCS	AS1	AS2	AS3	AS4
Auditory stimulus					
CCS	–	0.318	2.115	3.116*	2.909*
AS1	–	–	2.910*	3.001*	3.099*
AS2	–	–	–	2.460	2.393
AS3	–	–	–	–	0.412
	CCS	HS1	HS2	HS3	HS4
Haptic stimulus					
CCS	–	1.209	3.419**	3.528**	3.695**
VS1	–	–	3.045*	3.073*	3.666**
VS2	–	–	–	0.106	1.654
VS3	–	–	–	–	1.468

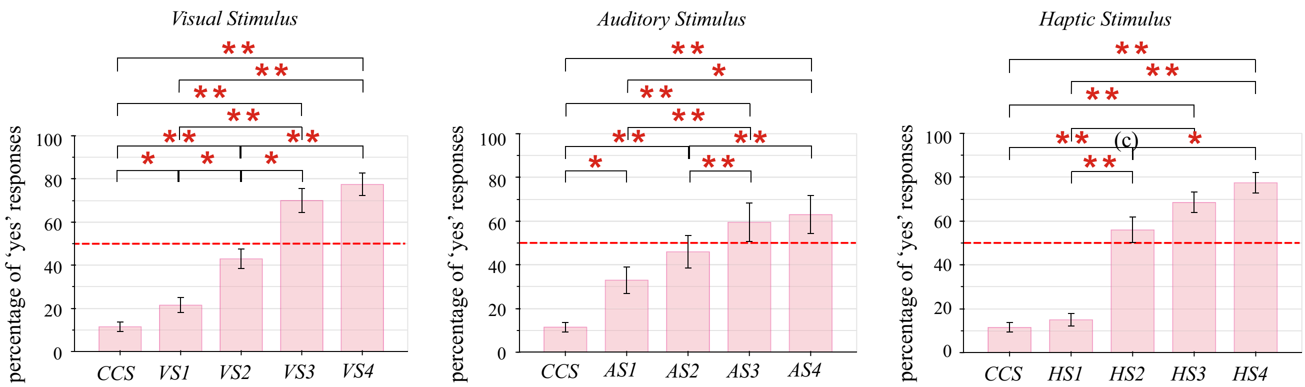

Fig. 9 The average percentage of 'yes' responses to the E2-Q2 in each test condition. Error bars denote standard errors. Square brackets indicate significant differences ($*$: $p < .005$, $**$: $p < .001$)

Table 5 The post hoc analysis result of the E2-Q2. Wilcoxon signed-rank tests with a Bonferroni correction were performed to compare responses to E2-Q2 for each comparison group. In each cell, the negative Z-value is presented and its statistical significance is marked by $*$ for $p < .005$ and $**$ for $p < .001$

	CCS	VS1	VS2	VS3	VS4
Visual stimulus					
CCS	–	2.933*	3.816**	3.923**	3.917**
VS1	–	–	3.264*	3.839**	3.855**
VS2	–	–	–	3.219*	3.541**
VS3	–	–	–	–	1.801
	CCS	AS1	AS2	AS3	AS4
Auditory stimulus					
CCS	–	3.151*	3.401**	3.419**	3.624**
AS1	–	–	2.400	3.196**	3.544**
AS2	–	–	–	3.296**	3.264*
AS3	–	–	–	–	1.180
	CCS	HS1	HS2	HS3	HS4
Haptic stimulus					
CCS	–	0.931	3.715**	3.817**	3.913**
VS1	–	–	3.714**	3.836**	3.909**
VS2	–	–	–	2.358	3.164*
VS3	–	–	–	–	2.366

providing nothing in terms of inducing scopaesthesia. Contrarily, test stimuli showing close to 100% mean that they were detected by participants very clearly. In our field observations and internal tests, these clear stimuli are perceived as direct information or notifications like the alerts of the voice narration and text used in the game Apex Legends. This is a completely different experience from what we are trying to provide. Therefore, we regard test stimuli showing a score greater than 75% are too clear to induce the feeling that someone is watching. According to the analysis result, stimuli used in *VS3*, *VS4*, and *HS4* are too clearly perceived by participants. In summary, responses to E2-Q1 reveal that *VS2*, *AS2*, *AS3*, *AS4*, *HS2*, and *HS3* are candidates for the appropriate stimulus interface for inducing scopaesthesia.

The analysis result shown in Fig. 9 presents the participants' subjective confidence about how clearly they perceived the stimulus. A test stimulus showing 0% means that the stimulus did not provide evidence that made the participants answer E2-Q1 with confidence. In contrast, a test stimulus showing 100% means that the stimulus provided clear evidence that made participants answer E2-Q1 with high confidence. Since the interface we aim is to provide the ambiguous and unknown feeling that someone is watching, we consider the test stimuli that show around 50% is appropriate for our goal. Among candidate stimulus interfaces, the stimulus interface that shows a score of around 50% is selected for each stimulative factor. In conclusion, three stimuli are selected for scopaesthesia interface: *VS2*, *AS2*, and *HS2*.

What we found from the experiment and field observations was that *VS* was the easiest type of stimulus to manipulate. It was possible to provide all types of experiences from barely felt experiences to very clear experiences through simple parameter manipulation without considering the type of game or the surrounding environment. The factors that seemed to affect the effectiveness of *VS* are the color tone of the surrounding environment and the luminance condition. However, their effect also seemed to be minor.

In contrast, we found that *AS* should be tuned carefully depending on the background music or effect audios. Contrary to the experimental environment where the background sound can be completely controlled, most applications provide different audio depending on the situation. As this audio diversity will affect the user's perception of *AS*, it will affect the induced scopaesthesia experience as well.

In terms of *HS*, we found that *HS* is not suitable to sensitively control the scopaesthesia experience. Despite the gradual increase in the intensity of *HS*, the percentage of correct answers and the percentage of 'yes' responses between *HS1* and *HS2* jumped sharply. This seemed to be related to the characteristics of the haptic stimulus receptors. Stimuli below the potential threshold are barely detected, whereas stimuli above the threshold fire an action potential and allow the participant to clearly feel the haptic stimuli. However, the feeling given by the *HS* seemed to have great potential and deserved to be investigated further. Many participants stated that the unfamiliar feeling that *HS* provided to the back of the neck was fairly accepted as a feeling that someone was watching them.

6 Experiment 3: application test

The aim of E3 is twofold. One is to investigate the VR user experience using our scopaesthesia interface. The other aim is to compare our interface with the previous interface that directly informs users of the information that someone is watching them. Ultimately, we clarify the advantages and limitations of our scopaesthesia interface and introduce a design strategy for future use.

6.1 Test settings

The physical environment and the apparatus used in E3 are the same as those used in E1 and E2. In contrast, the virtual environment is changed to the forest theme, as shown in Fig. 10a. There is a circular path with a diameter of 3*m* in the forest. There are large trees planted along the road, blocking the view. The luminance conditions, the light color code of the lamp, and the background music are set to the same as those used in E1 and E2. When a user raises the VR controllers overhead and presses a trigger button, bushes are created on the virtual avatar's hands to hide the avatar. This is shown in Fig. 10b.

6.2 Participants

Twenty participants (17 males and 3 females) were newly recruited for E3. The mean and standard deviation of age were $\mu = 23.55$ years and $\sigma = 2.07$. All participants were undergraduate or graduate students with normal or corrected-to-normal vision. Each participant was paid 5 USD for participation.

6.3 Test conditions

In E3, a comparative user study was conducted with the four test conditions defined by four test interfaces:

- *Interface used in APEX Legends* (*APEX*): In this condition, participants receive a voice and text notification

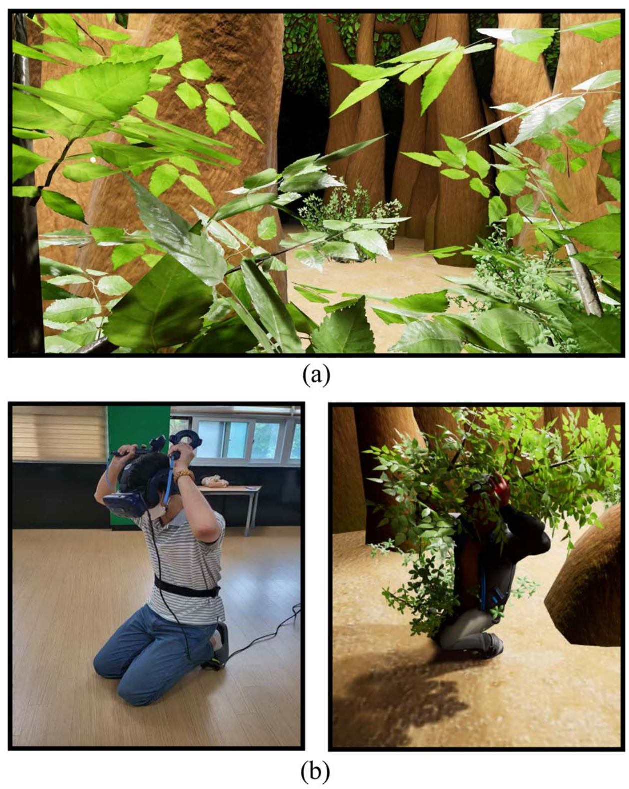

Fig. 10 The screenshots of the virtual and physical environments used in E3: **a** Forest-themed virtual environment. **b** Participants can hide in the bushes by raising their controllers

simultaneously when someone is watching them. This is the interface already used in the game Apex Legends (Apex legends 2019).

- *Interface used Visual Stimulus 2* (*VS2*): In E2, we selected *VS2*, *AS2*, and *HS2* were the most appropriate stimuli for scopaesthesia interface. Among them, *VS2* was found to be the easiest type of stimulus to manipulate the scopaesthesia experience, from barely felt to very clear experiences. Therefore, *VS2* is selected for further investigation.
- *Interface used Visual Stimulus 4* (*VS4*): In E2, we assumed that test stimuli showing a percentage of correct answers greater than 75% were too clear to induce the feeling that someone is watching. To examine our hypothesis, *VS4* is selected for further investigation.
- *Interface used Visual Stimulus 2 and Fast Music Environments 3* (*VS2+FE3*): In this condition, we aim to investigate the effect on scopaesthesia experience when *environmental factors* and *stimulative factors* are jointly used. In E1, we found that *darkness*, *reddish color palette*, and *fast suspenseful background music* were the *environmental factors* that effectively cause people to experience scopaesthesia. Among them, only *fast suspenseful background music* is not related to the visual sensory system and does not conflict with *VS2*. Therefore, the combination of *VS2* and *FE3* is selected for further investigation.

6.4 Procedure

The genre of the application is a stealth game inspired by Metal Gear Solid (Metal gear solid 1998). The goal of the game is to collect items spread out in the forest without being harmed by enemy snipers. During the game, participants are instructed not to make any drastic movements as the enemy sniper is keeping an eye on the path. They are also instructed to create bushes to hide if they feel the sniper is aiming a gun at them.

E3 was run with two experimenters. On arrival, each participant was asked to fill in a consent form and a demographics questionnaire. Subsequently, each participant was provided a 20-min training session. The training session consists of a 5-min introduction to the experimental procedure and 15-min rehearsal time for the experiment. During the rehearsal, participants were asked to experience all four types of test conditions. Subsequently, they were asked to play the stealth game to be tested in the main experiment.

After the training session, the main experiment began. The experiment was composed of four trials, each of which was tested with distinct test conditions. The order of test conditions was randomly determined for each participant. At the beginning of each trial, participants were asked to lower their bodies and walk slowly along the path to collect items without being detected by the enemy sniper. To confine the walking speed, a beep was given if their walking speed exceeded $0.25m/s$. During the trial, the sniper aimed at participants five times in total, and the aiming interval was randomly determined between 10 and 60 seconds. On aiming, one of four test interfaces was given. If the participant did not create the bushes within two seconds, the screen would turn red for 0.25 seconds with a bullet-firing sound. Each trial ended after the sniper aimed at the participant five times.

After each trial, a participant was asked to answer the Presence Questionnaire (Presence questionnaire 2004; Witmer and Singer 1998). The aim of investigating the Presence Questionnaire is to identify the test interface that significantly increases or decreases participants' sense of presence compared to other interfaces. Subsequently, answering three Subjective Evaluation Questionnaires (SEQ) were also requested: "SEQ-1: Were you nervous about the sniper attacking you?", "SEQ-2: Do you enjoy playing games made with a given stimulus?", and "SEQ-3: How convincing was the association between the given stimulus and the sniper's gaze?". Every question was answered on a 7-point Likert scale (SEQ-1: 7 = very nervous; 1 = not nervous, SEQ-2: 7 = very enjoyable; 1 = not enjoyable, SEQ-3: 7 = very convincing; 1 = not convincing). Each trial took about five minutes and a 5-min break was provided between trials to reduce the effects of participant fatigue. Therefore, each participant took part in E3 for about 35 minutes.

At the end of the main experiment, an interview was performed with each participant. The interview began with the following three questions:

- E3-Q1: Given the four test interfaces, what do you think is the best interface for stealth games?
- E3-Q2: Given the four test interfaces, what do you think is the best interface for horror games?
- E3-Q3: Given the four test interfaces, what do you think is the best interface for FPS games?

Subsequently, an open-ended interview was conducted for further investigation.

6.5 Result

For the comparative analysis, we first ran Shapiro-Wilk and Kolmogorov-Smirnov tests at a 5% significance level to determine the normality of the data. If not all data were normally distributed, we used the Friedman and Wilcoxon signed-rank tests with a Bonferroni correction.

We first compared the perceived presence between the four interfaces measured by the Presence Questionnaire. As shown in Table 6, only the Realism score reveals a significant difference. The post hoc analysis with Wilcoxon signed-rank tests found that *VS2+FE3* provided significantly higher realism than *APEX* ($Z = -2.689, p < .0083$).

Subsequently, a comparative analysis of responses to SEQs was performed. The result is presented in Fig. 11. The Friedman test found significant differences between participant responses within all SEQs: SEQ-1 ($X^2(4) = 26.685, p < .001$), SEQ-2 ($X^2(4) = 13.23, p < .005$), and SEQ-3 ($X^2(4) = 11.505, p < .005$). The post hoc analysis results are shown in Table 7.

Lastly, we analyzed participants' responses to the E3-Q1, E3-Q2, and E3-Q3. The result is presented in Fig. 12. In terms of E3-Q1, 40% of participants selected *VS2+FE3* as the best interface, while only 10% of participants selected *APEX* as the best interface for stealth games. In terms of E3-Q2, 45% of participants selected *VS2+FE3* as the best interface, while no participant selected *APEX* as the best interface for horror games. In terms of E3-Q3, 45% of participants selected *APEX* as the best interface, while 5% of participants selected *VS2* as the best interface for FPS games.

6.6 Discussion

In terms of the sense of presence, participants thought that our scopaesthesia interface provided a more realistic experience than *APEX*. We speculate that the direct notification of unseen gaze seems to break the immersion. "*The voice that might I have heard before in some games aroused an artificial atmosphere that could not be immersed in the virtual world (P5)*". "*The voice reminded me of the narration system of a car or airplane (P8)*".

In terms of the feeling of tension and nervousness, our scopaesthesia interface provided a significantly more intense feeling than *APEX*. In our field observation, participants were deeply immersed in the VR game to detect the sniper's gaze when our scopaesthesia interface is used. In contrast, when using *APEX*, they appeared to react to a given voice without any effort to detect a sniper's gaze. "*To detect ambiguous stimuli, extreme concentration on changes in the surrounding environment was required. When I noticed the sniper's attack after such concentration, I felt as if I could feel the sniper's gaze (P11)*". In this

Table 6 The analysis result of the Presence Questionnaire using the Friedman tests. Mean scores and standard deviations are presented for each test condition. For each subscale, the Chi-square values and a significant difference are also presented ($*: p < .0083$)

N=20	Subscales	APEX	VS2	VS4	VS2+FE3	χ^2	p
	Realism	4.40(1.34)	5.10(1.33)	5.07(1.09)	5.54(0.90)	13.41	*
	Possibility to act	5.13(1.13)	4.72(1.17)	4.97(0.99)	4.94(0.96)	3.04	
	Interface quality	2.77(1.19)	2.35(1.01)	2.52(0.99)	2.56(1.08)	3.51	
	Possibility to examine	4.86(1.11)	4.77(1.33)	4.65(1.38)	4.83(1.18)	1.71	
	Performance	5.09(1.16)	5.00(1.15)	5.03(1.35)	5.19(1.16)	2.03	

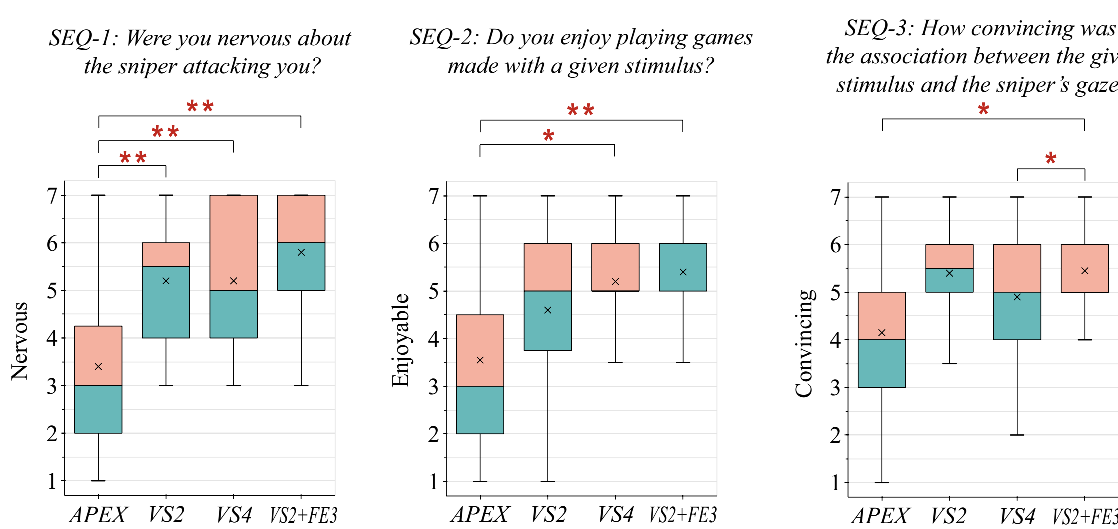

Fig. 11 The result of the subjective evaluation questionnaire The graph plots the median (-) mean (x) interquartile ranges and maximum/minimum values (whiskers). Square brackets indicate significant differences ($*: p < .0083$, $**: p < .0016$)

Table 7 The post hoc analysis result of the subjective evaluation questionnaire. Wilcoxon signed-rank tests with a Bonferroni correction were performed to compare responses to SEQs between test conditions. In each cell, the negative Z-value is presented and its statistical significance is marked by $*$ for $p < .0083$ and $**$ for $p < .0016$

	APEX	VS2	VS4	VS2+FE3
SEQ-1				
APEX	–	3.540**	3.630**	3.826**
VS2	–	–	0.064	2.469
VS4	–	–	–	2.331
	APEX	VS2	VS4	VS2+FE3
SEQ-2				
APEX	–	2.024	2.831*	3.190**
VS2	–	–	1.452	2.040
VS4	–	–	–	0.635
	APEX	VS2	VS4	VS2+FE3
SEQ-3				
APEX	–	2.628	1.627	2.873*
VS2	–	–	2.440	0.187
VS4	–	–	–	2.771*

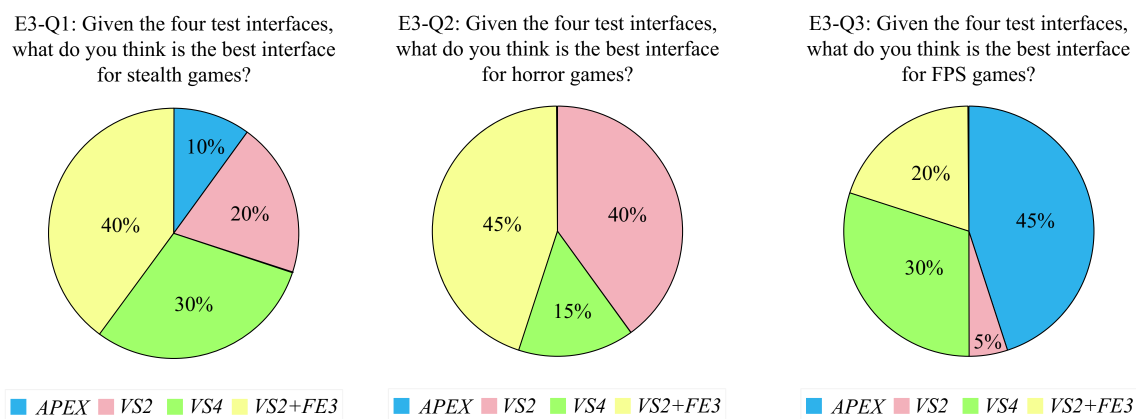

Fig. 12 Percentage of participant responses to E3-Q1 E3-Q2 and E3-Q3

context, it seems that our scopaesthesia interfaces were evaluated to provide a more enjoyable stealth experience than *APEX*.

In terms of the conviction about the association between the given interface and scopaesthesia experience, *VS2*, *VS4*, and *VS2+FE3* scored greater than 4.00 (neutral) in SEQ-3. This can be said that the association between our scopaesthesia interface and the unseen gaze was accepted as quite convincing. "*I think that the feeling of unseen gaze is similar to the tension felt from the unknown threat. In this context, the feeling aroused by the ambiguous visual stimulus is quite convincing for me as a feeling of unseen gaze (P3)*". Furthermore, we can also say that the use of *environmental factor* significantly increases the convincingness since *VS2+FE3* scored the highest.

One notable fact is that the scores of *VS4* are similar to those of *VS2* and *VS2+FE3* in all SEQs. In E2, *VS4* was considered as an interface that was too clear because people detected it with about 80% probability. However, we observed that *VS4* provided a quite different experience from the *APEX* interface that provided perfectly clear information. Instead, *VS4* seemed to provide a very similar experience to *VS2* according to the analysis results of the Presence Questionnaire and SEQs. We speculate that participants cannot help concentrating on the VR game due to the 20% chance of failing in detecting unseen gazes. Then, such concentration brings users an experience similar to that brought by *VS2*.

For future development and design, we investigated suitable genres for the scopaesthesia interfaces. For the stealth and horror games, *VS2+FE3* was selected as the most suitable interface. Furthermore, more than 90% of participants selected our scopaesthesia interfaces were suitable for such games while less than 10% of participants selected *APEX* as suitable. The most frequently mentioned reasons that appeared in the comments were tension and fear. "*Narrative voices cannot provide a tense and frightening atmosphere since they articulate the threat too clearly (P4)*". "*I think the fear of the unknown that someone might be looking at me is a key to the horror games. However, the narrative voices completely blows away the fear of this unknown (P17)*". For the FPS games, contrary to the stealth and horror games, *APEX* was selected as the most suitable interface (45%). The reason seems that the goal of FPS games is to eliminate enemies, and the clearer the warning, the more efficiently this can be achieved. "*How quickly I can react to the enemies' intentions to attack me determines whether or not I can survive. Therefore, I bet most FPS users will use narrative voices. (P19)*". However, participants who chose *APEX* as the best interface thought that *APEX* was a notification rather than the interface inducing the feeling of being stared at. Still, 55% of participants chose that our scopaesthesia interfaces are suitable for FPS games because they thought that it could be a new type of interaction that amplify the tension of games. "*When I played the game called Counter Stike, there was no way to dodge the attacks of hidden snipers. However, the scopaesthesia interface gives the sniper a risk that the attack may fail. Furthermore, users being attacked by a sniper have a chance to evade the attack by using the scopaesthesia interface. As the chance of evading may depend on their concentration on detecting scopaesthesia interface, this is a completely novel experience that no existing FPS can provide. (P2)*".

7 Conclusion

To the best of our knowledge, this is the first study to devise an interface that can provide VR users with a feeling of an unseen gaze. Starting with an online survey about the feeling of being stared at, three experiments were conducted to design scopaesthesia interface. The application test has shown that the proposed interface successfully induces scopaesthesia experience that has never been provided by other applications. We expect that our scopaesthesia interface will be applied to various VR applications to provide new experiences. For example, the feeling that someone is staring at me can be used as a means of communication or as a means of expressing other users' concentration on me in the multi-user metaverse world. It can also be used as a means to intensify users' anxieties or tensions beyond simply inducing the feeling of being stared at.

In the future, we would like to develop this research in three directions. One direction is to conduct our experiment with more diverse participants. Currently, the experiment result is derived from a small number of participants (N = 20) aged between 20s-30s. To obtain a more convincing and interesting result, we would like to hire more participants, taking into account more various conditions such as diversity of VR experiences, total time of VR experience, and age. Another direction is to consider a multi-user environment. Currently, our study only considers the single-player environment. For this reason, the observations and design strategies obtained from the experiments cannot be directly applied to the multi-user environment. For example, the E1 result revealed that *presence of NPCs* did not show a strong effect on inducing scopaesthesia. However, it is still unknown whether *presence of other users' avatars* affects scopaesthesia induction. The other direction is to apply our scopaesthesia interface to the XR environment. With the development of extended reality (XR) devices, interest in XR applications such as games, social networks, or metaverse platforms is also increasing. Therefore, the application of scopaesthesia interface to the XR environment will bring a great impact on the commercial and academic fields as it is a novel interaction method that has not been introduced before.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This work was approved by the Institutional Review Board of Kyung Hee University (IRB number: KHGIRB-21-214)

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