How Vibrotactile and Auditory Feedback Can Affect Performance in Search for Invisible Objects in Virtual Reality

Nils O. Beese
nils.beese@rptu.de
University of Kaiserslautern-Landau
Germany

Lennart Dümke
lennart.duemke@hsbi.de
University of Applied Sciences
Bielefeld
Germany

Yannic N. Döll
yannic-noah.doell@hsbi.de
University of Applied Sciences
Bielefeld
Germany

René Reinhard
rene.reinhard@itwm-fraunhofer.de
Fraunhofer ITWM
Germany

Jan Spilski
jan.spilski@sowi.uni-kl.de
University of Kaiserslautern-Landau
Germany

Thomas Lachmann
lachmann@sowi.uni-kl.de
University of Kaiserslautern-Landau
Germany

Kerstin Müller
kerstin.mueller@hsbi.de
University of Applied Sciences
Bielefeld
Germany

ABSTRACT

Virtual Reality (VR) studies tend to focus on visual aspects, yet auditory as well as tactile aspects should also be considered. Setting out to examine how an invisible object search can benefit from auditory and tactile cues, a VR game was developed to accomplish this. The game had three levels that differed on task difficulty, level one having a static invisible target, level two with a moving invisible target and level three with two moving invisible objects. Forty-two participants played this VR game, experiencing vibrotactile cues, auditory cues and a combination of both in the three levels. The participants did two playthroughs of the game. The results point towards the combination of both types of cues being the best of the different cue condition, while task difficulty overall had the biggest effects on performance.

CCS CONCEPTS

• **Applied computing** → Computer games; • **Human-centered computing** → **Virtual reality**; **Interaction techniques**.

KEYWORDS

video game, virtual reality, vibrotactile feedback cues, auditory feedback cues, search task

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1 INTRODUCTION

Virtual reality (VR) is predominantly a visual medium, but the auditory and tactile sensory systems also play a part in the experience.

In 2021, Tabrik and colleagues [32] found that the tactile sensory system shares features with the visual system during objection recognition and both can substitute for each other if one modality is absent. Similarly, auditory stimuli that do not contain spatial information can still help in a spatial visual search according to van der Burg et al. [8].

There have been quite a few studies on how different sensory cues - visual, auditory, vibrotactile - can alter performance in visual search tasks [4, 5, 8, 16]. Cues are defined as "a stimulus, event, or object that serves to guide behavior, such as a retrieval cue, or that signals the presentation of another stimulus, event, or object, such as an unconditioned stimulus or reinforcement" in the APA Dictionary of Psychology [2]. Both van der Burg et al. [8] as well as Brungart et al. [5] used auditory cues to further help with the visual search. Lehtinen and colleagues [16] used dynamic tactile cues in visual search tasks.

Binetti and colleagues [4], while still also using visual cues, used spatialized auditory stimuli as a help to locate out-of-view objects in an augmented reality setting. But those studies still dealt with tasks focused on the visual system. The performance of auditory and tactile stimuli when searching in a visually impaired or non-visual task setting can be a good way to determine how powerful both those sensory systems can be when either the visual system is not working or an object is not visible for different reasons. Lokki and Grohn [18] showed that auditory stimuli can be used for navigation without visual feedback. Similarly, Nardi and colleagues [23] tested how blindfolded sighted participants performed in spatial reorientation using auditory landmarks. In their study, participants managed to reorient based on auditory landmarks alone.

The present study sets out to examine how vibrotactile and auditory cues can help in a non-visual search task with static as well as moving target objects using a self-developed VR game. Furthermore, Grinyer and Teather [11] mentioned that the current state of research on searching hidden and out-of-sight objects in VR is relatively scarce. As stated by Hutmacher [12], there might be an inherent bias in researching the visual system. Both the article by Hutmacher [12] and Grinyer and Teather [11] as well as the following related work led this study to focus on non-visual cues and a non-visual search task.

2 RELATED WORK

2.1 Auditory Feedback Cues

Fialho and colleagues [10] studied spatial navigation of blindfolded but sighted participants using audio sources in a virtual environment (VE). Fialho et al. [10] designed three virtual scenes where the participants had to locate a target position and then return on the same path. The three VEs differed in their level of difficulty, i.e., in their number of obstacles and the arrangement of obstacles. The environments were used for two different trials, a learning and a retrieval trial. In the learning trial, the participants had to move to the location of a sound source and return to the starting point. In the retrieval trial, this sound source was removed and participants had to rely on auditory cues of the obstacles instead. Fialho et al. [10] observed that participants navigated better in the retrieval trial. Another area where auditory feedback can be important are 360° videos which can be used with a VR headset. In a study by Meghanathan et al. [19] participants had to locate targets in a VE. The VE consisted of a 360° video which showed a handball arena. To study the effect of auditory and visual noise on search tasks, the videos were available in two versions, one with an empty arena and one with a match being played. The auditory feedback consisted of either no sound, stereo sound or binaural sound. Meghanathan et al. [19] discovered that participants performed best with binaural audio.

Other factors could also influence the localization of audio sources. A study by Brungart et al. [5] showed that walking could improve auditory localization in comparison to standing. Participants were asked to perform four tasks twice, once standing and once walking on a treadmill. In front of them was a canvas on which the VE was projected. Behind this canvas was an array of 64 speakers. During the first task participants had to locate the source of the auditory cue. The second task was a visual discrimination task in which the participants had to answer whether one or three dots were displayed. The third task was a visual search task on the VE canvas, supported by audio cues coming from the speakers behind the canvas. The fourth task was like the third task, but without audio cues. Participants were faster in tasks 1 and 3 and fastest in those tasks when walking. Brungart et al. [5] suggested that this was partly due to the increased activity during walking and partly due to the slight head movements that resulted in auditory cues being located more easily or at all.

2.2 Vibrotactile Feedback Cues

Vibrotactile feedback, i.e., vibration passively felt on the skin, is a subcategory of tactile feedback. One aspect of vibrotactile cues are patterns [14, 25]. Vibrotactile patterns can either be comprised of static or dynamic vibration. In dynamic patterns, actuators are alternated, and different amplitudes and frequencies are used to create dynamic vibration on the skin. Kaul et al. [14] designed and evaluated spatial tactile patterns on the head. They found that their participants could more easily recognize static patterns they constructed. The dynamic patterns, however, were preferred by the participants. Plouzeau et al. [25] compared two different vibrotactile patterns in a task. The patterns were delivered through vibrating ankle bracelets. In the compass pattern, only the actuator closest to the target vibrated. The push pattern, as the name suggests, vibrated either on the front or back as well as left or right to "push" the participant in the right direction. They observed that a compass pattern was more efficient than a push pattern on the back of the ankles. In another study, Kaul and Rohs [13] found that vibrotactile cues on the head led to faster performance than auditory cues in a VR search task.

Nonino et al. [24] used the vibrotactile actuators of the VR controllers to help participants locate targets. Their participants could move freely in a VE and had to find ten hidden objects in succession, always starting from the same location. Nonino et al. used the actuators of both controllers, and only the controller closest to the target vibrated. Even when the controllers pointed in the opposite direction of the target, vibrotactile feedback was generated. The vibration amplitude and frequency were determined by the distance between the controller and the target. One limitation was that the vibrotactile feedback could not provide information about the object's elevation. Nonino et al. [24] concluded that the two methods of attention guidance improved the target search, in contrast to no feedback at all.

Morelli et al. [21] evaluated an exergame that offered both vibrotactile and auditory cues to better engage visually impaired indiviuals in exercising and physical activities. Another study by Morelli and Folmer [22] presented a real-time video analysis solution to substitute visual cues into tactile cues. In their experiment, they found no difference in player performance between visual and vibrotactile cues in a gesture-based game. Tessendorf et al. [33] used vibrotactile cues to help localizing sound sources in a game. Their results showed that hearing impaired users achieved similar performance to users with normal hearing.

3 RESEARCH QUESTIONS

This study was designed to answer whether vibrotactile cues, auditory cues or a combination of both are better in the absence of visual cues in a search setting in a VR game. Based on the literature by Semionov et al. [28] as well as Lokki and Gröhn [18], auditory cues should be more helpful, while Kaul and Rohs [13] found that vibrotactile cues led to better search performances than auditory cues. Furthermore, multimodal cues, i.e., the combination of both, should lead to better performance than unimodal cues, i.e., only auditory or vibrotactile, even if the target is moving [21]. This study should have similar results regarding performance and feedback type in all three levels. There should also be a learning or training effect involved in the search task, as the literature suggested a learning effect for feedback types in other tasks [30] as well as a training effect in search tasks [1, 7].

Thus, the research questions focus on the following effects on performance: Effect of feedback cue (**RQ1**), Effect of training (**RQ2**), and Effect of task difficulty (**RQ3**).

4 MATERIALS AND METHODS

4.1 Hardware, Overall Game Design and Data Collection Implementation

The VR game was developed using the Unity3D Game Engine and the SteamVR Plugin. The HMD used in this study was the HTC Vive Pro virtual reality headset in combination with the Valve Index controllers. Three different levels were created. Furthermore, a tutorial was created where players learned the controls and the different types of feedback before they played the actual game. Each level consisted of a 6x6 meter room where participants could move freely. To complete the tutorial, each player had to catch a visible ghost with each of the three kinds of feedback cue conditions to ensure that the controls and feedback types were understood by each participant.

Each of the three levels had a different degree of difficulty. In the first level there was a single static ghost to be found. Each time the participants played the level, the static ghost would be in a different position. These positions were the same for all participants In the second level, there was a single dynamic ghost. This ghost was constantly moving. To prevent participants from finding the ghost by accident, the ghost continuously flew away from the player. However, the ghost moved slower than walking speed. The ghost could also move up and down, as well as fly through objects. In the third level participants had to find two dynamic ghosts that moved and behaved identically to the ghost in the second level. The starting position for a dynamic ghost was the corner of the virtual room farthest from the player's current position.

The sequence of events in the three ghost levels was the same. Shortly after entering a level, a grandfather clock started striking midnight, signaling to the players that the trial had begun. At the same time, the visible ghost(s) came through the ceiling of the room, briefly flew around and then became invisible. This served as a way to show players how many ghosts they needed to catch to complete the level. Once the ghosts were invisible, players could start catching them. To prevent the trials from becoming unreasonably long for the participants, a time limit of five minutes was set for each level.

The game recorded the time taken to find the ghost(s) in seconds and the distance travelled per level. Additionally, it stored which feedback type was used and how the level was completed, i.e., whether the ghost was caught or whether the timeout occurred.

4.2 Implementation of Feedback Cues

The three different feedback conditions were auditory, vibrotactile and a combination of both. With auditory feedback, the ghost emitted a sound every three seconds. Unity's built-in sound engine was used to create the 3D sounds. The closer the player was to the ghost's sound source, the louder the sounds became. Players could hear from which direction and distance the sounds were coming. If a ghost hid in an object, like a crate or cupboard, its sound was muffled. If there were two ghosts in a room, they made different sounds so that the player could distinguish between them.

In a trial with vibrotactile feedback, participants had to find the ghosts with the help of vibration of the right controller. The strength and repetition of vibration was based on the distance to the target and direction of the target. When the player pointed the weapon in the approximate direction, the weapon began to vibrate at an interval. The more accurately the player pointed in the ghost's direction, the shorter the vibration interval was. If the player pointed directly at the ghost, the controller vibrated continuously. The closer the player was to the ghost, the stronger the vibration was. If the participant did not point in the direction of the ghost, no vibrotactile feedback was generated.

4.3 General Procedure

The procedure of the experiment was first explained to each participant. Subsequently, participants signed a consent form. At the beginning of the experiment, participant completed the pretest questionnaire. This included a demographic questionnaire, the Karolinska Sleepiness Scale (KSS; [29]) and the Simulator Sickness Questionnaire (SSQ; [15]). After participants answered all pretest questions, the head-mounted display (HMD) was fitted to their head. The participants played the tutorial to familiarize themselves with the hardware and controls. Afterwards, they started the first level, in which they had to catch a static ghost. The static ghost hid in a different location each trial but stayed there during each trial. The second level was catching a dynamic ghost, making it more difficult compared to level 1. The third level was more difficult compared to level two, as two dynamic ghosts had to be caught.

The participants played three trials per level, one per each feedback cue condition (auditory, vibrotactile, combination of both). Since each participant played two playthroughs and each of those consists of three levels with three feedback cue conditions, every participant played a total of 18 trials plus one tutorial level at the beginning. Between the two playthroughs, participants were given a five-minute break to rest. The order of feedback types used in the levels was evenly distributed and counterbalanced among all participants and levels. In the first and second playthrough, each participant had two different feedback type sequences, i.e., no level in the second playthrough had the same sequence of feedback types as the first playthrough. At the end of the experiment, participants completed the posttest questionnaire. The posttest questionnaire included the Igroup Presence Questionnaire (IPQ; [27]) and the posttest version of the SSQ.

4.4 Sample

Forty-two participants (26 male, 16 female, 0 diverse/non-binary) took part in the study. All participants received either money or study credits as a reward after completing the experiment. The participants' age ranged from 19 to 32 years old (M = 24.84, SD = 5.15, Mdn = 25). Of the 42 participants, 29 have had prior experience with VR. Of these 29, 26 reported that they play VR games less than once a month, two play once a month and one participant reported playing VR games several times a week. All participants reported normal or corrected-to-normal vision. None of the participants reported auditory impairments. According to the KSS [29], participants were rather alert to alert.

4.5 Analysis

The aforementioned expected effects of feedback condition, level and playthrough are formulated as linear mixed effects model. This is then analyzed using R 4.3.1 [26] with the lme4 [3] and afex [31] packages for the computation of the linear mixed effect models and the emmeans [17] package for post hoc tests and effect sizes of the possibly underlying effects.

The linear mixed effects model is defined as follows:

$$\text{leveltime}_{ij} = b_0 + u_{0j} + b_1(\text{feedback})_{1ij} + b_2(\text{playthrough})_{2ij} + b_3(\text{level})_{3ij} + e_{ij} \quad (1)$$

5 RESULTS

The posttest SSQ showed no noticeable problems regarding simulator sickness. According to Melo et al. [20], the participants rated the General Presence as being very good (grade B). To test whether the participants' previous VR experience influenced the performance, a Wilcoxon test was calculated. There were no significant effects of prior VR experience on performance in any of the three levels, p > .05.

Table 1 shows the descriptive statistics per playthrough, feedback condition and level. The residuals were normally distributed, Shapiro-Wilk $p = 0.08$. Testing the model against the null model revealed that the model fit of the linear mixed effects model is significant, Chi2 (5) = 120.8, $p < 0.001$. The p-values computed by the afex package, using the Satterthwaite approximation, revealed significant effects for feedback ($F(2, 709) = 7.72$, $p < 0.001$), playthrough ($F(1, 709) = 6.88$, $p = 0.009$) and level ($F(1, 709) = 54.19$, $p < 0.001$).

The post hoc test for feedback conditions (**RQ1**) showed that the combination of both kinds of cues led to significantly faster completion of the task ($p < 0.001$) in comparison to just using the auditory cue over all levels, Cohen's $d = 0.35$, 95% CI [0.17, 0.53]. Furthermore, the combination cue condition also led to a shorter time to catch the ghost compared to the vibrotactile cue. While this was not significant, there was a trend ($p = 0.0528$), Cohen's $d = 0.21$, 95% CI [0.03, 0.39]. The difference between auditory cues only and vibrotactile cues only was not significant ($p = 0.25$). The post hoc test for the playthrough (**RQ2**) revealed a significant effect of playthrough ($p = 0.009$). The participants were faster in the second playthrough, Cohen's $d = 0.19$, 95% CI [0.04 0.34]. The post hoc test for the levels (**RQ3**) showed significant differences between the different levels. Participants were significantly faster in level 1 than level 2 ($p < 0.001$), Cohen's $d = 0.62$, 95% CI [0.44 0.81], significantly faster in level 1 than level 3 ($p < 0.001$), Cohen's $d = 0.91$, 95% CI [0.72 1.09], as well as significantly faster in level 2 than level 3 (p = 0.005), Cohen's $d = 0.28$, 95% CI [0.10 0.46].

6 DISCUSSION

This study examined how different kinds of feedback can help the player in localizing invisible objects, in this case ghosts in a ghost hunting setting. This study also took into account possible training and difficulty effects. A linear mixed effects model showed that the effects of feedback, playthrough and level on time to catch the ghost(s) were significant.

Regarding the three research questions defined a-priori, taking a closer look into the post hoc tests and effect sizes is necessary. For the first research question on the effect of different kinds of feedback the post hoc tests revealed that the combination of both auditory and vibrotactile cues was significantly faster than the auditory cues and trended towards being significantly faster than the vibrotactile cues. There was no significant difference in performance between the two cues on their own. The effect sizes for the combination vs auditory were small to medium and small for the combination vs vibrotactile, according to Cohen [6]. Regarding the second research question on the effect of training training did make participants significantly faster, but the effect would be considered small [6]. The third research question on task difficulty, showed a significant difference between the levels, level 1 being by far the easiest with a medium to large effect size when compared to the other two more difficult levels [6].

Bringing these results into the bigger picture, task difficulty played the biggest part in performance when searching for invisible objects. Taking the effect sizes into account, it can be argued that the static invisible ghost of level 1 was considerably easier to find and catch than the moving ghost(s) of level 2 and 3. This might also add to the findings of Grinyer and Teather [11]. They found that field of view (FOV) had a stronger influence on performance than movement in an out-of-view, but still visual search. When searching for an invisible object like in this study, movement does seem to strongly influence performance. The results of this study also do support other literature concerning multimodal vs unimodal cues [21], showing the combination of cues to be better than both unimodal variants on their own.

Considering the design of this study and its statistically significant results, applications, and implications of these findings in real-world settings seem to be hard to find. Since completely invisible objects are typically only found in gaming settings, the findings suggest using multimodal cues to enable the player to find these objects without too much frustration. If we extend the findings to temporarily invisible, hidden or out-of-view objects, however, applications are more easily defined. While navigating to an out-of-view building, the combination of a vibrotactile cue, e.g., a smartwatch that vibrates based on the target position, and an auditory cue, e.g., the voice of the navigation system, might make finding the building easier. The findings of this study also show that situations that do not allow for visual cues might benefit from vibrotactile and auditory cues. This could be used for training of hazard situations for firefighters, similar to what Feder et al. [9] did. Although their setting did use visual cues and visual auxiliary equipment, this setting and the equipment might be enhanced by also using vibrotactile and auditory cues to detect the source of a fire in a smoke-filled room.

Table 1: Descriptive Statistics for Time to Catch the Ghost(s) per Playthrough, Level and Feedback Cue Condition.

		Level 1			Level 2			Level 3		
	N	M	SD	SE	M	SD	SE	M	SD	SE
First Playthrough										
Auditory	42	180.110	110.520	17.054	207.769	108.185	16.693	195.885	102.718	16.693
Combination	42	109.995	103.436	15.961	155.861	107.796	16.633	209.825	102.494	15.815
Vibrotactile	42	121.302	93.856	14.482	186.775	111.750	17.243	199.491	108.686	16.771
Second Playthrough										
Auditory	42	137.551	118.216	18.241	167.118	113.774	17.556	189.663	107.297	16.556
Combination	42	85.014	81.639	12.597	149.649	108.549	16.749	195.444	103.207	15.925
Vibrotactile	42	110.873	98.615	15.217	186.674	118.331	18.259	203.326	96.619	14.909

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