A Study of the Affordance of Haptic Stimuli in a Simulated Haunted House

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Abstract. The present study investigates the affordance of vibrotactile signals in a simulated haunted house. Participants experienced a virtual séance using a head-mounted display, sound, and haptic stimuli on the palm and thighs. In one condition, six unique, handcrafted haptic signals (*cicadas*, *frog*, *thunder*, *earthquake*, *heartbeat*, *knock*) were presented alongside appropriate events in the narrative. In another condition, a single multiplexed stimulus was presented for every event; this signal was a composite of the six distinct signals. Adjective ratings were collected for both conditions for each participant. Results showed that the extent to which a haptic signal enhanced the sense of immersion depended on the match between the signal and the natural phenomenon it represented. The unique, handcrafted signals generally were rated as more immersive than the multiplexed signal. However, the signal *cicadas* had a distinct spectral signature that stood out in the multiplexed signal. Participants rated the distinct *cicadas* signal and the multiplexed signal as similarly immersive. Our results demonstrate that carefully handcrafted vibrotactile signals can enhance the sense of immersion in virtual reality. Furthermore, participants may rate a haptic signal as more immersive if it contains features congruent with the natural event it represents, regardless of extraneous, incongruent features.

Keywords: Haptic affordance · Haptic design · Distinctiveness of haptic signals.

1 Introduction

As our ability to create rich and novel haptic sensations grows, so too does the interest in the potential of haptics to enhance immersion in remote and virtual environments. *Immersion* here refers to the degree to which a simulated environment envelopes or surrounds a user, a key factor in how engaged the user feels in the simulation [10]. Many studies have examined the role that haptics plays in enhancing users' experience from various perspectives such as affective

Fig. 1. Left: A scene simulating a séance in the virtual haunted house, with a representation of a hand on the *palmScape*. Right: A participant wearing the VR headset with one hand resting on the *palmScape* display.

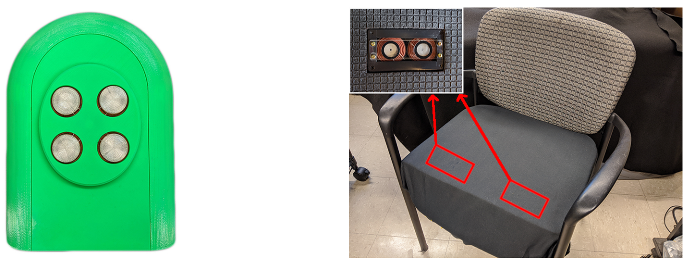

Fig. 2. The two vibrotactile displays employed in this study. Left: the *palmScape*. Right: a chair with tactors concealed, with an inset showing the two tactors on each side of the seat cushion.

communication [4, 5, 12, 18]. The present study explores the affordance of vibrotactile stimuli in a simulated haunted house VR with accompanying visual and audio events (Fig. 1).

When properly synchronized with high congruency, multimodal stimuli can enhance the user's experience in a virtual scenario by leveraging sensory experiences we are familiar with from our daily lives. While most VR environments may be dominated with sight and sound, including haptic feedback can contribute to the extensiveness (the range of sensory modalities presented) and vividness (quality) of a simulation [6]. But how distinctive and realistic those signals need to be to immerse the user is still an open question. While conventional wisdom may prefer high-fidelity systems for better immersion, research that employs stimuli of different levels of realism points to similar levels of effectiveness [11, 19]. For example, a number of relatively high-fidelity wearable haptics that simulate grasping or touching virtual objects have been shown to be effective in enhancing the user's sense of realism in VR [9]. Passive haptics —objects in the real world (often static and low-fidelity) that represent virtual objects —have also shown to be effective at enhancing presence [6]. In one study, participants wearing VR headsets experienced significantly higher changes in heart rate and skin conductance when a 20-foot pit in the virtual world was simulated by a drop in the floor of the physical world —even though the real drop was only several inches deep [6].

Table 1. Haptic signals employed in the present study

Signal Name	Location	Description
1 Cicadas	*palm*	rough, rhythmic: 120-Hz background noise with 32-Hz amplitude modulation and four 60-Hz bursts with 32-Hz modulation
2 Frog	*palm*	rough, rhythmic: 50 Hz and 120 Hz superimposed with 1.7 Hz and 16 Hz modulation, respectively
3 Thunder	*palm*	impact then decay: initial 135 Hz and 150 Hz at high amplitude, then attenuation following Gaussian envelope
4 Earthquake	*palm*	build-up then decay: 30 Hz modulated with Gaussian envelope
5 Heartbeat	*palm*	smooth beating: 20-30 Hz pulses
6 Knock	*palm*	short pulses: 30 Hz and 300 Hz superimposed
7 Multiplex	*palm*	complex: derived from signals 1—6
8 Rattling Chair	*seat cushion*	rumble: 170 Hz pulses below each leg

The present study explores how haptic stimulation can enhance one's sense of immersion, novelty, and creepiness in a haunted house. Two types of haptic stimuli were used: distinct signals that were hand-curated to match the sight and sound of a specific event, and a single multiplexed signal that was employed for all events. Participants experienced séance-themed visual and sound effects. At key points in the narrative, such as the arrival of a croaking frog or booming thunder, vibrotactile stimuli were presented to the user's palm (Fig. 2, left). Concealed actuators embedded in the seat cushion also rattled the user's chair (Fig. 2, right). After the five minute presentation, participants completed a questionnaire on their experience. By assigning the participants randomly to the condition of distinct stimuli followed by the multiplex condition or vice versa, we hoped to determine the degree to which the distinctiveness of the haptic stimuli affected their affordance in the haunted house experience.

2 Related Work

This study utilizes the vibrotactile signals on a *palmScape* haptic display developed by Shim and Tan [14]. The *palmScape* signals were designed to imitate calm and pleasant (low arousal, high valence) natural phenomena using features like intensity, frequency, and rhythm. The present study uses a subset of these signals, shown in Table 1.

Prior to the present study, a pilot study was conducted, in which the *palmScape* signals were incorporated into a haunted house narrative [2]. Twenty-two participants volunteered to sit in a dark booth and feel haptic, visual, and audio effects as part of a fictitious séance. A questionnaire was used to determine whether the haptic effects affected the participants' sense of immersion, novelty, and creepiness. The results indicate that the *rattling chair*, *heartbeat*, *frog*, and *thunder* signals were most effective in eliciting positive perceptions and a sense of creepiness. Moreover, stimulus-label compatibility seemed to be an important factor in those perceptions; for the three most positively received *palmScape* signals, “expected,” “familiar,” and “life-like” were the most common neutral or positive adjectives chosen, and “confusing” was the most common negative adjective chosen overall.

The findings of the pilot study suggest that life-like haptic effects may increase perceived immersion and enjoyment of a haunted house. However, it is not clear to what degree the distinctiveness of the haptic stimuli determined this enjoyment, as opposed to the context in which the stimuli were presented in the narrative. It is possible that less distinctive, less unique, and even less realistic stimuli might be sufficient to achieve the same emotional effect. The present study was designed to test the affordances of distinct and scenario-specific haptic signals vs. a complex but general vibrotactile signal.

3 Methods

3.1 Participants

Thirty-one participants (10 females) aged 21 to 32 years (25 ± 3 years) took part and were compensated $10.00 for their participation. All participants signed an IRB-approved informed consent form.

3.2 Apparatus

The *palmScape* display employed in the present study is comprised of a 2-by-2 array of 30-mm diameter, wide-band audio exciters (Tectonic Elements, Model TEAX13C02-8/RH) embedded within a silicon disk, shown in Fig. 2 (left). To feel the signals, the user rests a hand on the plastic housing, with the palm covering the four tactors. For further details about the *palmScape* signals and apparatus, see [14].

Besides the *palmScape* display, an additional four actuators (Tectonic Elements, Model TEAX25C10-8/HS) were hidden in the participant’s seat cushion, two under each thigh, as shown in Fig. 2 (right). The actuators were freely suspended using a plastic attachment within the chair cushion to ensure that they could be excited up to 1.5mm under the weight of the leg. Black cloth was used to conceal the chair tactors, and participants were not informed in advance that haptic feedback would occur from that location. Audio and visual stimuli were presented using an Oculus Quest 2 headset (https://www.oculus.com/), as shown in Fig. 1 (right).

3.3 Stimuli

In trial A, the participant experienced multiple, distinct, nature-inspired haptic stimuli at key points in the narrative (see Signals 1 to 6 in Table 1). In trial B, the participant experienced a single multiplexed stimulus repeated at each of those key points in the narrative (see Signal 7 in Table 1). This composite stimulus was derived from six of the distinct stimuli used in trial A and modulated according to both frequency and amplitude to ensure that the perceptual output of key individual characteristics of each of the original six signals could be felt by the user. Amplitude, frequency, and time variations were counterbalanced such that the multiplexed signal had a similar perceived intensity as the six distinct signals [8].

3.4 Experimental Conditions

Each participant completed two trials, A and B, varying only in the haptic stimuli presented to the palm. The order of the two trials was randomly assigned to each participant. The *rattling chair* setup remained identical for both trial A and trial B and therefore was expected to garner similar responses in each trial.

3.5 Procedure

For each trial, participants were asked to sit down in the chair with the concealed actuators, lay their right hand gently on the *palmScape*, and watch a five-minute 3D video via the VR headset. In virtual reality, participants were led by a narrator through a fictitious séance, a form of ghostly entertainment popular in the 19th century in which participants sit in the dark, join hands, and attempt to commune with spirits [15]. Scenes of a haunted marsh and wooden cabin were rendered using Unity (https://unity.com/). Participants could lean, twist, and turn their heads to explore their surroundings. Synchronous sounds, visuals, and haptics were integrated into the narrative. For instance, the narration "come quickly now; there is a storm approaching" was accompanied by the *thunder* vibration delivered by the *palmScape*, visuals of lightning striking a nearby virtual tree, and the sound effect of thunder. At the end of the séance, the actuators in the chair vibrated to signify a spirit's arrival.

Afterward, participants sat with an experimenter and answered a questionnaire. First, they were asked a series of open-ended questions:

How did it go?
Have you been to a haunted house before?
Have you been to a séance before?
What did you expect (to feel, sense, or see)?
What surprised or was novel to you?
Tell me about an experience that stands out to you.
Did the haptic sensations make you feel more/less immersed?

Next, participants chose an adjective to describe each of the haptic stimuli in the order of their first appearance in the narrative. A word bank of suggested adjectives, shown in Table 2, was provided, and participants were given the choice to select from these suggestions or to choose another word entirely.

Table 2. Adjectives provided in random order to participants as suggestions during the questionnaire.

Immersive	**Neutral**	**Not Immersive**
Exciting	Calm	Boring
Clear	Complex	Confusing
Effective	Expected	Ineffective
Satisfying	Unpredictable	Undesirable
Consistent	Familiar	Inconsistent
Comfortable	Unconventional	Overwhelming
Engaging	Slow	Distracting
Creepy	Fast	Simplistic
Scary		

These adjectives were sourced from the Microsoft Desirability Toolkit, with the exception of "creepy" and "scary," which were haunted house context-specific additions [1]. The numbers of words with positive, negative, and neutral connotations were balanced in the word bank, based on the recommendations of the Toolkit designers. The order of the words in the bank was randomized for each participant. Unbeknownst to the participants, these adjectives were categorized by experimenters as "immersive," "neutral," and "not immersive," as shown in Table 2. *Creepy* and *scary* were categorized as "immersive" given the haunted house context. If participants generated an adjective from outside the word bank, e.g. "realistic," clarification was sought by the experimenter. The word would then be categorized accordingly and kept consistent across all participants. Likewise, if participants selected a "neutral" adjective with ambiguous valence (e.g. "expected"), clarification was sought, and the response was categorized as "immersive" or "not immersive" if possible. This was done in order to gather as much information as possible related to immersion. Participants also chose a modifier for their adjective on a 5-point Likert scale ranging from "Not ______" to "Very ______."

During the questionnaire, participants were provided a *palmScape* to feel the stimuli again if desired. For trial A, these stimuli were the distinct, nature-inspired haptic signals. for trial B, the single multiplexed stimulus was presented every time, just like during the narrative experience. Experimenters did not comment on the fact that the same stimulus was being repeatedly presented in trial B, or the fact that the stimuli differed at all between the two trials.

After completion of the questionnaire, the VR experience and adjective rating exercise were repeated for the second trial.

3.6 Results

Overall impressions were positive for both trials. From the open-ended questions, it was learnt that most participants (24 out of 31) had previously been to a haunted house, though none had experienced a séance. Overall, all

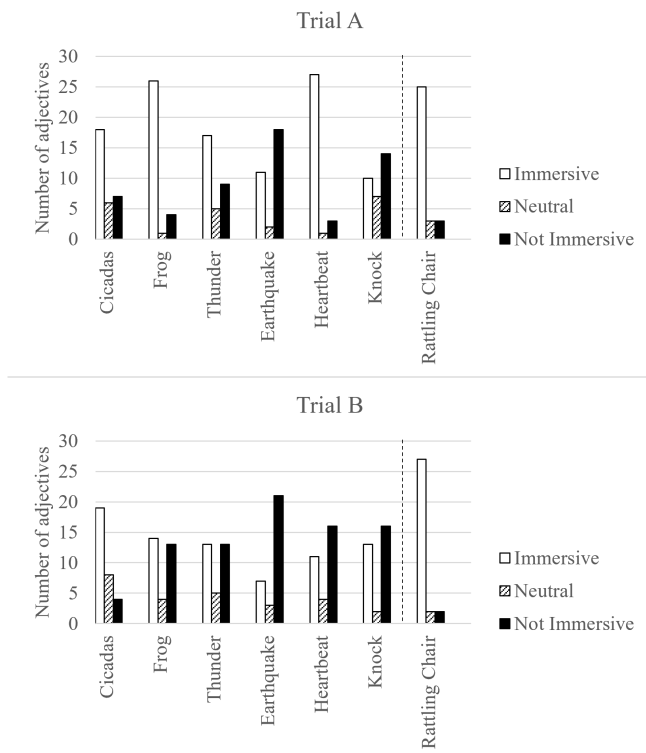

Fig. 3. Adjective responses for distinct *palmScape* signals in trial A (top) and repeated multiplexed signal in trial B (bottom). The number of "immersive" (white), "neutral" (striped), and "not immersive" (black) adjective responses aggregated across all 31 participants are shown for each of the 6 haptic stimuli presented to the palm in order of first appearance. The *rattling chair* stimulus (right of the dotted line) was the same for trials A and B.

but one participant responded positively to the question, "how did it go?" after experiencing the first trial. Twenty-three participants explicitly stated that the haptic effects made them feel "more" immersed after experiencing the first trial; on this question, little difference was observed between those who experienced trial A first (of whom 11 reported "more" immersed) and those who experienced trial B first (12 reported "more" immersed). Like in the pilot study, the *rattling chair* was cited most often as surprising, novel, or stand-out; twenty participants mentioned it in their freely recalled answers. Feelings of creepiness were definitely achieved; the words "creepy" or "scary" were mentioned 49 times across the 31 questionnaires, with the *rattling chair*, *knock*, and *thunder* signals receiving the most accolades.

Responses to the distinct, nature-inspired signals varied. Fig. 3 summarizes the adjective responses. The upper plot shows responses from trial A, in which participants felt distinct, nature-inspired *palmScape* signals. These signals are listed along the x-axis. The adjectives that participants chose to describe these signals were categorized as "immersive," "neutral," or "not immersive." The total number of adjectives in each category for each signal were aggregated across all participants and plotted as columns. The higher the "immersive" column (in white), the more participants chose words like "effective" and "realistic" to describe that signal. The higher the "not immersive" column (in black), the more participants chose words like "confusing" and "distracting."

As might be expected for the diverse signals presented in trial A, the adjectives chosen by participants varied from signal to signal. For the *heartbeat*, *frog*, and *rattling chair*, participants largely responded positively and overwhelmingly selected "immersive" adjectives. Likewise for *cicadas* and *thunder*, the majority of responses were "immersive." However, for *earthquake* and *knock*, more participants responded with "not immersive" adjectives than with "immersive" ones. Participants' answers to the open-ended questions offer some insight into this variation, as will be discussed in the following section.

Responses to the multiplexed signal were not uniform. The lower plot of Fig. 3 shows responses from trial B, in which the same multiplexed signal was repeated each time a haptic stimulus was presented to the palm. Even though only a single repeated signal was presented to the palm in trial B, the responses to that multiplexed signal were not uniform across the narrated events. Adjective responses were more positive when the signal was labelled as *cicadas* (19 positive responses) than when labelled as *earthquake* (7 positive responses), for example. This may reflect the different ways that the multiplexed signal used in trial B resembled the sensations felt with the six distinct signals used in trial A, as will be discussed in the next section.

Distinct signals were perceived as "more immersive" than the multiplexed signal in most cases. Comparing the two trials in Fig. 3, participants generally selected more "immersive" adjectives and fewer "not immersive" adjectives when describing the handcrafted *palmScape* signals used in trial A than when describing the repeated multiplexed stimulus used in trial B. This was true when responses were aggregated across all signals and participants. It was also true for four of the six signals presented to the palm (*frog*, *thunder*, *earthquake*, *heartbeat*); for each of these signals, participants chose more "immersive" adjectives and fewer "not immersive" adjectives in trial A than B. One of the two exceptional cases was *cicadas*, for which the multiplexed stimulus garnered responses very similar to the signal specifically designed to imitate a cicada. The other exception was *knock*, which was described more neutrally in trial A than in B but with otherwise similar responses between the two trials.

Notably, the magnitude of the difference between trials A and B was the greatest for the two signals that garnered the most "immersive" adjective responses in trial A, *frog* and *heartbeat*. For all other signals, the difference in the number of "immersive" adjective responses in the two trials was small (no more than 4 adjectives difference).

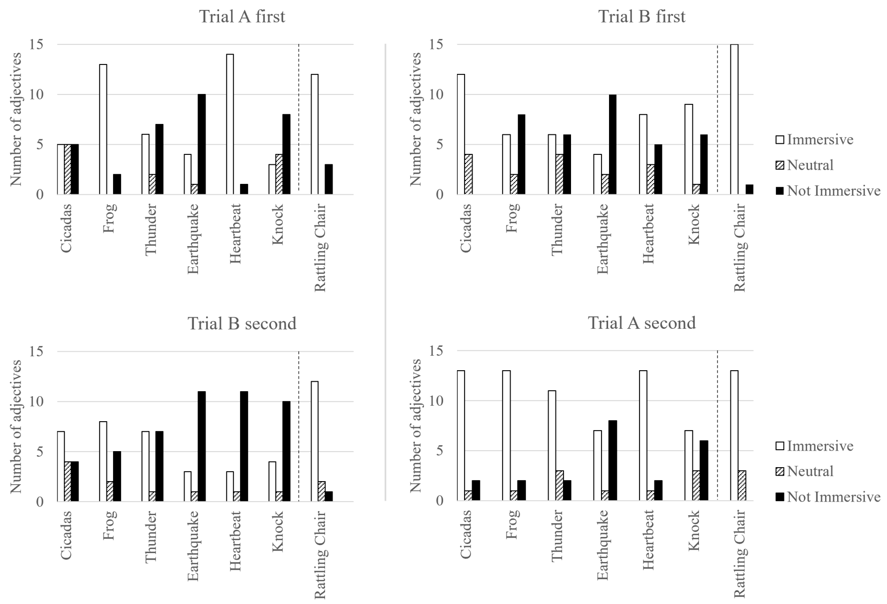

Fig. 4. Adjective responses for distinct *palmScape* signals in trial A (top) and repeated multiplexed signal in trial B (bottom), for two groups of participants: those who experienced trial A then trial B (left, $n = 15$), and those who experienced trial B then trial A (right, $n = 16$). The number of "immersive" (white), "neutral" (striped), and "not immersive" (black) adjective responses aggregated across all n participants are shown for each of the 6 haptic stimuli presented to the palm in order of first appearance. The *rattling chair* stimulus (right of the dotted line) was identical for trials A and B.

The difference in response between the two trials is also apparent when we divide the participants into two groups based on trial order. The left hand side of Fig. 4 shows the responses for the 15 participants who experienced the handcrafted signals in trial A first (above) and the multiplexed signal in trial B second (below). These participants gave many more "not immersive" responses in trial B (49) than they had in trial A (36). For each individual signal presented to the palm, they selected at least as many "not immersive" adjectives to describe trial B than they had selected for trial A, with one exception (*cicadas*).

Likewise, the right hand side of Fig. 4 shows responses for the 16 participants who experienced trial B (above) then A (below). These participants gave more "immersive" responses to describe trial A (51) than they had in trial B (42). For each *palmScape* signal, they selected more "immersive" adjectives in trial A than they had in B, with the exception of *knock*. On the whole, these results suggest participants responded positively to most of the handcrafted signals after previously experiencing the multiplexed signal — and responded mostly negatively to the multiplexed signal after having previously experienced the handcrafted signals.

Likert scores offer some support of preference for distinct signals. Due to a programming error, the instructions for the Likert score portion of the questionnaire were inconsistent. Fifteen of the participants were asked, "how [insert adjective] was the signal?" while the remaining sixteen participants were asked specifically "how lifelike was the signal?" For the first question, responses tended to be stronger for the distinct trial A signals than the multiplexed trial B signal, save for *knock* and *cicadas*, though no statistically significant difference was found between the trials ($p = 0.10$). For the second question, the distinct trial A signals were by far perceived as more lifelike than the multiplexed signal ($p << 0.001$).

Most participants — but not all — were aware that the haptic signals changed between the two trials. When asked "how did it go?" over half of the participants (18 of 31) mentioned unprompted that the haptic signals in the second trial felt different than those in the first. Most of those participants (10 of 18) expressed a preference for the distinct *palmScape* signals in trial A; one expressed preference for the multiplexed signal in trial B, and the remainder (7 of 18) noted the difference but didn't mention any preference. Those who preferred the handcrafted *palmScape* signals described them as "completely different," "much better," and "more realistic" compared to the "not as clear," "more nois[y]" multiplexed signal. Some described differences in perceived magnitude (i.e. signals in trial A were "stronger," "closer," "more aggressive," "powerful") or synchronicity (more "in sync," "flows better") that led them to prefer the handcrafted signals.

Interestingly, other participants were less certain that a change had occurred. In fact, some (3 of 31) thought there was clearly no difference between the haptic signals in trials A and B. When asked "how did it go?" after experiencing trial B then trial A, one participant attributed the increased "fun" of the second trial to "now knowing what to expect," supposing that he "could focus more on calibration between audiovisual and [haptics] on the hand" after experiencing two trials. Another hypothesized that any perceived differences were attributable to experiencing the signals "separate" from context (while completing the questionnaire) versus the "immersion" of feeling the signals "together." A third participant confirmed in debriefing that he had no idea that trials A and B featured different signals, or that trial B featured repetitions of the same signal. The remaining participants (10 of 31) fell somewhere between on the spectrum between full awareness and total lack of awareness. Many noticed the multiplexed signal was being repeated only midway through the questionnaire, after being allowed to replay the signal multiple times.

3.7 Discussion

Touch is a particularly promising channel for enhancing immersion. First, touch is well-suited for presenting information unobtrusively in the ambience rather than at the center of attention [7]. Second, touch is inherently affective. We are socialized to convey intimate emotions through touch, so even haptic feedback generated mechanically can be laden with emotional implication [17]. Third, touch requires proximity. By encroaching on the user's personal space, touch has the unique potential to invoke uncomfortable, unsettling, or even creepy feelings [3,13].

In our everyday lives, we are constantly experiencing haptic sensations that accompany visual and auditory stimuli. Yet except for a few cases where we focus on the haptic sensations alone (such as a heartbeat), most haptic sensations do not convey specific meanings when they are presented alone in the absence of visual or auditory counterparts. One of the authors vividly remembers how, in the absence of any auditory stimuli, moving the end effector of a force-feedback display back and forth gave rise to friction and viscosity perception but not the mental image of a cello bow. During the development of the *palmScape* display [14], each handcrafted vibrotactile signal was explicitly designed for a target scenario, such as *cicadas* and *thunder*. One may argue that such an approach invariably *biased* or *tainted* the users' perception of the *palmScape* signals. If that were the case, then we would expect the signals in trial A to lead to more positive and neutral adjective responses than that in trial B. A second possibility is that users may exhibit a haptic form of "confirmation bias," in that participants can selectively focus on characteristics of a haptic signal that are relevant to the current context. As long as the haptic signals in either trial A or trial B contain sufficient features that may lend themselves to the context, similar adjective responses are expected in trials A and B. The third possibility is that the adjective responses to the multiplexed signal in trial B would be more positive than those to the individual haptic signals in trial A. This seems unlikely given the effort in designing the trial A signals to fit the context they were mapped to. The results of the present study yield evidence towards the first two possible outcomes.

In some cases distinct, handcrafted signals may be preferable to a multiplexed signal. For certain events in the present study (*heartbeat*, *frog*, *thunder*, and *earthquake*), the handcrafted signals had a more immersive effect than the multiplexed signal when placed in the same narrative context. In the most extreme case (*heartbeat*), perceptions of the signal totally reversed between the two trials; when presented the handcrafted signal, the majority of participants chose "immersive" adjectives (e.g. "expected" or "familiar" in a positive way), whereas for the multiplexed signal, the majority chose "not immersive" adjectives ("confusing" or "inconsistent").

It is possible to induce selective focus on specific characteristics of a multiplexed signal relevant to the current context. For *cicadas*, results were similar when the handcrafted and multiplexed signals were presented, with the majority of participants selecting "immersive" adjectives in both cases. If anything, participants may have favored the multiplexed signal slightly. Likewise for *knock*, results were similar between the two trials, though the multiplexed signal was the more polarizing of the two options, garnering fewer "neutral" adjective responses.

What could account for this variation? Why were only certain handcrafted signals preferred to the multiplexed signal, whereas in other cases, the multiplexed signal was sufficient to garner a similar response? And what role do other modalities play in inducing focus on selective characteristics of multiplexed signal? We offer several conceivable possibilities to address these questions:

Suitability of signals: One explanation is that some handcrafted signals were more successful than others in fitting their labels. For example, of all the handcrafted signals, *knock* garnered the fewest positive or "immersive" responses. In fact, the most commonly adjectives chosen to describe it were "simplistic" (4 participants) and "boring" (3 participants). Even among the group of participants who experienced the multiplexed signal before the handcrafted signals — and who otherwise expressed preference for the handcrafted signals across the board (see Fig. 4, right) — *knock* was the one signal that was received more negatively in the second trial than the first. It is therefore possible that neither the handcrafted haptic *knock* nor the multiplexed signal resemble the sensation of a real knock. It is reasonable that the bias toward handcrafted, artificial haptic signals would only extend to signals that bear resemblance to the real phenomena they are intended to imitate.

The inability to disentangle participants' perceptions of realism and immersion is perhaps a limitation of the present study. Given the open-ended nature of the adjective selection process, participants were not questioned explicitly about the appropriateness of the signals. Future studies on this topic could employ a multidimensional rating system that polls participants about realism and immersion separately, to better understand this potential link. It could also be revealing to ask participants what they expect each phenomenon to feel like, particularly phenomena that are not usually experienced haptically. For instance, most participants had likely heard or seen cicadas but not held a cicada in their hands. Exploring what it means for a haptic representation of a typically aural or visual experience to be "realistic" is a subject ripe for exploration, though beyond the scope of this study.

Myriad multiplexings: The particular multiplexed signal employed here could also be a factor in why participants exhibited bias toward certain handcrafted signals but not others. The composite signal used in trial B was created from the six handcrafted signals using amplitude and frequency modulation [8]. Although care was taken to balance the perceived intensity of the multiplexed signal against the other *palmScape signals*, and to conserve the characteristics of the individual signals, this was a design process done by hand. The resulting signal may have borne more resemblance to some *palmScape* signals than others. Therefore, it could be that counter balancing modulated amplitude and frequency parameters to achieve a combination of considerably different hand crafted signals, which may have originally had various degrees of perceptual arousal, stripped them of their unique tactile signatures.

To understand how the original and multiplexed signals were rendered on the *palmScape* device itself, we utilized spectrograms to compare both outputs. The purpose of doing so was to ensure limitations in the output efficiency (resonance

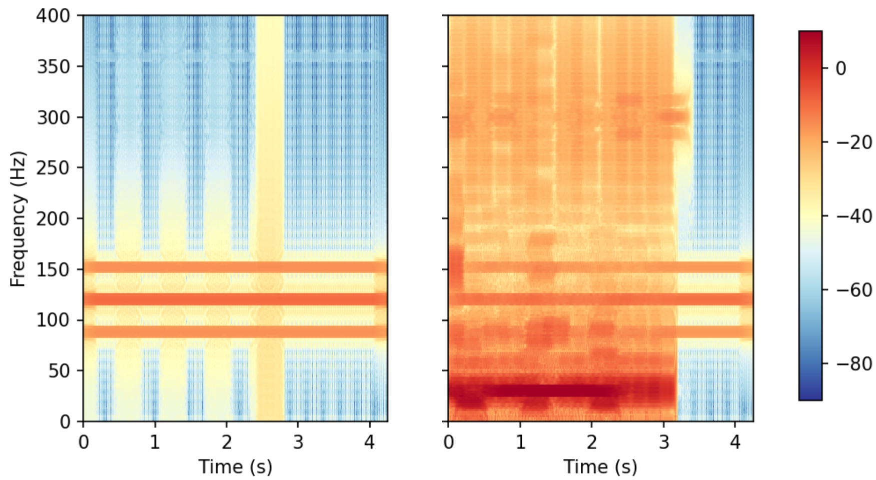

Fig. 5. Spectrograms of the signal on tactor #1 of the *palmScape* device for the *cicadas* (left) and the multiplexed (right) haptic effects. The color scale ranges between 10 dB (red) and -90 dB (blue) for the energy of the signals.

frequency, acceleration, displacement etc.) of the actuation components utilized within the *palmScape* device did not affect the results. For that reason, we focused on energy distribution for both the handcrafted and multiplexed signals. The spectrograms from Fig. 5 compare the energy distribution of the signals from the *palmScape cicadas* (left) and the multiplexed (right) haptic effects. The spectrograms were estimated using a multitaper approach with 4 Discrete Prolate Spheroidal Sequences (or DPSS tapers) and 400 ms-long segments (for more information about spectrum estimation using DPSS see [16]). Three distinct frequencies at approximately 90, 120 and 150 Hz are constantly present with high energy in both plots. They are some of the most salient features of the multiplexed signal. This similarity may explain the similar responses garnered by the *palmScape cicadas* and multiplexed signals when both signals were labeled as "cicadas."

Certain haptic features may be more critical than others for characterizing a signal, and the fact that this relative importance should be taken into consideration when multiplexing various tactile primitives is one of the main outcomes of this research. We could hypothesize that for some phenomena, frequency and rhythm variations might be the key and that amplitude variations play a lesser role. A muffled heartbeat still feels like a heartbeat; even at a lower amplitude, a heartbeat still maintains the frequency characteristics that makes it so distinctive. Conversely, amplitude variations are key to conveying the impact and rumbling decay of a thunderbolt. In fact, in their open-ended responses, fourteen participants mentioned being underwhelmed by the amplitude of the thunder or earthquake signals, a comment rarely made of the other four *palmScape* signals.

There are a whole host of features that could prove essential to defining haptic phenomena. Perhaps some signals can't be selectively picked out of a multiplexed signal at all; the broadband nature of the multiplexed signal might be fitting for a buzzy cicada but unusual for a crisp, discrete knock on wood. Perhaps some phenomena are so deeply familiar that they must be rendered exactly to be effective (like the feel of one's own heartbeat), while others are abstract enough to leave room for interpretation (like the arrival of a ghostly spirit). Familiarity, rhythm, liveliness — these factors and more were not expressly considered in this study but ought to be explored. One could imagine designing a variety of multiplexed signals, each with different features of the constituent signals emphasized, and comparing their effectiveness in mimicking the original signals. Using this approach, it would be possible to develop an algorithm to dynamically assign weights to core parameters of the varied signals, to be multiplexed and achieve a more consistent outcome. However, as yet this work opens up more questions than answers.

Inability to identify changes within tactile output parameters: Perhaps the most unexpected result was participants' awareness or lack thereof regarding the multiplexed stimulus. Some participants experienced a haptic analogue to the visual phenomenon of *change blindness*. To varying degrees, these participants did not notice that the haptic signals were different in the two trials or that the multiplexed signal was being repeated. This outcome seems to support the idea that participants can selectively focus on relevant components of the multiplexed stimulus. In fact, more than one of these participants mistook their positive perceptions of the *palmScape* signals for merely improved focus, remarking on their newfound ability to notice the differences among the signals better than they had before. Yet participants who exhibited this effect still followed the overall pattern of responding more positively to the distinct trial A signals than to the trial B signal — even if they justified these changes as the result of improved clarity. A larger sample size would be useful to determine the significance of this intriguing trend.

4 Conclusion

This study provides evidence for the utility of vibrotactile stimuli for enhancing immersion, novelty, and creepiness in a simulated haunted house. Most participants in the study reported that the haptic signals helped them feel immersed in the virtual environment. Unique signals that were handcrafted to imitate natural phenomena were more effective at eliciting this sense of immersion than a repeated multiplexed signal — with two exceptions. First, the handcrafted *knock* signal failed to resemble a real knock, and participants did not prefer it to the multiplexed signal. This result suggests a bias toward signals that are both distinctive and evocative of their labels. In another exception, the handcrafted *cicadas* signal and multiplexed signal had similar characteristics in the spectral domain, and participants gave very similar responses to both signals. In doing so, participants demonstrated an ability to selectively focus on the relevant features of the multiplexed signal.

The present study opens up future questions, especially regarding the potential of multiplexed stimuli. Some participants did not notice the changes in haptic stimuli between the two trials or failed to note the repetition of the multiplexed stimulus, which warrants further investigation. New multiplexing algorithms that give relative weight to specific parameters of the modulated signal could also yield results more capable of mimicking a wider range of signals. Additional research may also be required to gauge how the efficiency of actuation components (*palmScape*) being used to create the feedback play a role in delivering the multiplexed signals to the skin contact. We hope this research and its subsequent findings encourage the design and development of even more evocative vibrotactile stimuli and novel multiplexing methods.

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