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Enhancing Body-Penetrating Phantom Sensations Through Multisensory Integration of Sound and Vibration

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***Abstract*—A body-penetrating phantom sensation refers to a tactile experience in which the perceived location shifts between the dorsal and ventral sides of the body over time, resulting in the illusion of a tactile stimulus passing through the body. This study explores the integration of auditory and tactile stimuli to enhance the perception of body-penetrating phantom sensations. Combining vibrotactile feedback with various sounds commonly used in gaming, we investigate how multisensory configurations improve their realism, directional clarity, and user satisfaction. The experimental results demonstrate that penetration-related sounds significantly enhance perceived realism and satisfaction. We also compare the changes in emotional pleasantness and arousal levels resulting from integration of sound and tactile stimuli, along with a summary of the subjective responses. Our findings highlight the critical role of semantic harmony between auditory and tactile information, offering actionable insights for improving the realism and immersion of physical interactions in virtual environments.**

***Index Terms*—Tactile phantom sensation, funneling illusion, body penetration, audio, sound, vibration, multisensory perception, crossmodal correspondence**

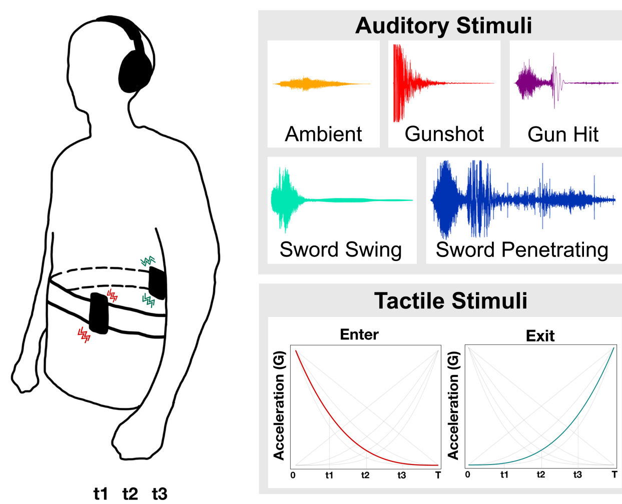

Fig. 1. Concept of providing an auditory stimulus with a body-penetrating tactile phantom sensation. Five types of sounds, shown in the top-right plot, are presented in conjunction with two vibration stimuli, which are amplitude modulated signals as depicted in the bottom-right plot. The vibration stimuli are reported to elicit a sensation of penetration through the body.

I. Introduction

Humans increasingly engage with virtual environments across diverse fields, including entertainment [1], education [2], and collaboration [3]. To enable seamless interactions, it is crucial to provide appropriate and rich sensory feedback that closely replicates real-world experiences [4], [5]. Haptic feedback, which uses different physical stimuli such as force [6], vibration [7], [8], and thermal [9], can effectively enhance the realism, immersion, and user experiences in virtual environments. Among these, haptic illusions, which utilize specific stimuli under controlled conditions to produce unexpected percepts [10], present unique opportunities to enrich sensory experiences. These illusions can simulate sensations like texture, stiffness, weight, and proprioception, offering cost-effective solutions for improving the fidelity of virtual interactions (see [11] for a review).

One branch of haptic illusions is the *funneling illusion* or *phantom sensation* that creates a perceived tactile stimulus between two real stimuli [12]. Building on this, the *body-penetrating tactile phantom sensation* was discovered recently [13], which shifts the perceived location between the dorsal and ventral sides of the body over time and results in the illusion of a tactile stimulus passing through the body. As body penetration is an unfamiliar tactile experience for most individuals, its perception and cognitive effects may vary significantly depending on contextual and other sensory inputs, such as visual or auditory stimuli. However, previous studies paired this tactile rendering method with visual stimuli only [13], [14], leaving open questions about how auditory sensory inputs interact with body-penetrating phantom sensations.

This study aimed to investigate how different auditory cues modulate the effectiveness and user experience of a body-penetrating tactile phantom sensation. As illustrated in Figure 1, we examined five types of sound commonly encoun-

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tered in gaming contexts (i.e., ambient sound, gunshot, gun hit, sword swing, and sword penetration) and four rendering methods, including unisensory and multisensory combinations of sound and vibration. We systematically evaluated the effects of these factors and provide actionable insights for improving the immersive experiences involving physical interactions with virtual objects.

The rest of this paper is organized as follows. In Section II, we review related work on two topics: tactile phantom sensations and the multisensory integration of auditory and tactile stimuli. Section III describes the methods used for a perceptual experiment, including configurations for auditory and tactile stimuli. The experiment results are presented in Section IV, followed by a discussion of their implications in Section V. Finally, we conclude this paper with a summary of our findings in Section VI.

II. Related Work

A. Tactile Phantom Sensations

Illusory tactile sensations between two physical points of stimulation are called the funneling illusion or phantom sensation [12]. Phantom sensations are a useful tool for enhancing the spatial resolution of tactile displays with only a few actuators [15]. They can be categorized by the dimension (1D [16] or 2D [17]), the stimulation type (e.g., direct skin stimulation [16], [18] or stimulation through a rigid object [19], [20]), and the presence of movement (stationary [12] or dynamic [21], [22]). Dynamic phantom sensations, where the perceived location shifts over time, effectively convey spatiotemporal information; see [23] for review.

An intriguing extension of dynamic phantom sensations is the body-penetrating phantom sensation, which creates an illusion of tactile stimulation passing through the body [13]. This effect is achieved by shifting the perceived tactile location between the dorsal and ventral sides of the body using two vibration actuators with amplitude modulation profiles [13]. Lee et al. applied this phantom sensation also to the feet to emulate the sensation of stepping on a bump in a virtual environment [14]. However, the limited effectiveness of visual feedback in their study highlights the need for further exploration of multisensory alignment.

B. Multisensory Integration of Sound and Haptics

Multisensory integration is the process by which the human brain combines and processes information from multiple sensory modalities, such as vision, hearing, and touch, to form a coherent perception of the environment [24]–[26]. Effective integration of multisensory stimuli can enhance immersion in virtual environments, improve learning and attention, and facilitate fast and appropriate reactions [5], [27], [28]. A critical factor for successful multisensory integration is the crossmodal correspondence, which refers to matching stimulus properties across different modalities to high consistency. This phenomenon can arise from spatiotemporal congruency [29], [30], as well as statistical, structural, or semantic relationships among the stimuli [31]–[33].

Research has shown that auditory stimuli can alter tactile perception in various dimensions, such as texture [34]–[36], intensity [37], and duration [38]. Etzi et al. [34] demonstrated that auditory cues, such as the sound of sandpaper, could modulate the perceived roughness and pleasantness of a tactile surface. Similarly, Cho et al. [35] combined vibrotactile stimuli with scratch sounds to enhance the perception of surface texture, friction, and realism, showing improved accuracy and shorter reaction times under multisensory conditions. Freeman [36] found that white noise sound enhanced the perceived roughness of ultrasonic tactile stimuli.

While existing studies emphasize the significant role of auditory feedback in modulating tactile perceptions, the interaction between auditory stimuli and the metaphoric illusions of body-penetrating haptic sensations remains unexplored.

III. Methods

We conducted a perceptual experiment to evaluate the effects of auditory stimuli on body-penetrating phantom sensations under various auditory and tactile configurations. This experiment was approved by the Institutional Review Board at the authors's Institution (PIRB-2024-E005).

A. Participants

We recruited 20 participants (10 males and 10 females; aged 22 to 30 years). No participants reported any known hearing and sensorimotor abnormalities. Participants were informed of the experimental procedure and signed a written consent form. They were paid USD 15 for their participation.

B. Stimuli

1) Sound Stimuli: We included five types of sound effects—Ambient, Gun Shot, Sword Swing, Gun Hit, and Sword Penetration—commonly encountered in gaming contexts, which are available in the supplementary video. These sounds were selected to reflect typical scenarios in VR action games, with the aim of semantically evoking illusory tactile experiences. Ambient is an alert sound from *League of Legends*, and it is not semantically related to body penetration. Gun Shot and Sword Swing sounds are associated with offensive actions, often serving as triggers for penetration events. In contrast, Gun Hit and Sword Penetration sounds generated in defensive or passive scenarios, reflecting physical impacts on the body or the sensation of being pierced. Thus, Gun Shot and Sword Swing correspond to the causes, whereas Gun Hit and Sword Penetration are the respective results. We hypothesized that these different types of sound could have different effects on the perception of penetrating sensations.

2) Vibration Stimuli: As illustrated in Figure 2, we implemented a vibrotactile belt to stimulate the ventral side (abdomen) and dorsal side (back) of the torso. Two linear-resonant actuators (LRAs; Jahwa Electronics, 122792; resonance frequency $125 \pm 15\,\mathrm{Hz}$) were enclosed by a 3D-printed cover made from PLA with a contact area of 16.4×31.5 mm and a thickness of 3 mm. The cover was slotted onto the belt, enabling it to slide for positional adjustment across

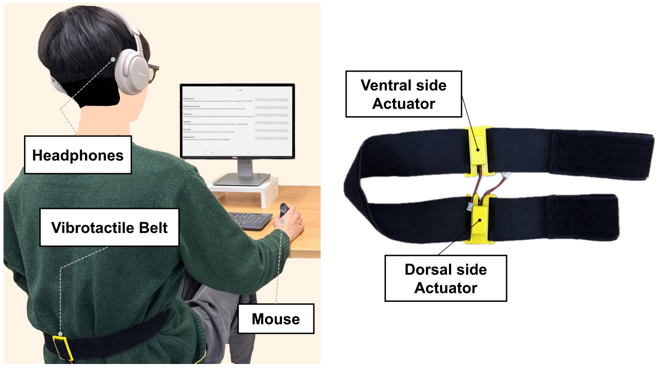

Fig. 2. Experimental setup (left) and design of our vibrotactile belt (right).

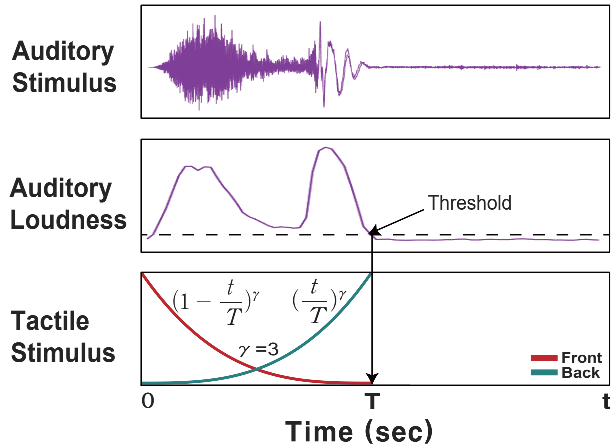

Fig. 3. Design of vibration stimuli for penetrating phantom sensations. Vibration stimuli are provided up to the point where the loudness of the sound falls below a specific threshold for each SOUND TYPE.

participants with different body sizes. The LRAs were driven by an audio amplifier (Stereo 3.7W Class D MAX98306). The haptic signals were generated as sinusoidal waveforms using the oscillator function within a multichannel audio processor (CTAG, Bela).

We used a frequency of 120 Hz to generate body-penetrating phantom sensations. A vibration at this frequency is reliably perceived on the torso [39], [40]. It is close to 100 Hz known as effective for body-penetrating phantom sensations [13]. The output acceleration was measured using a high-precision accelerometer (Kistler, 8765A with a coupler 5134B) mounted on the custom 3D-printed cover attached to the LRA while its input amplitude was varied. The measured accelerations were fitted to a linear function of the input amplitude for each LRA. The goodness of fit was sufficiently high; $R^2 = 0.932$ (front) and 0.973 (back).

The sound and vibration stimuli started simultaneously, but the vibration ended when the sound loudness dropped below a predefined threshold, as shown in Figure 3. This method prevented unnatural perception caused by a vibration persisting during residual sound after impact. The sound and vibration durations for each SOUND TYPE were as follows: Ambient (Sound: 0.98 s and Vibration: 0.5 s), Gun Shot (1.44 s and 0.3s), Sword Swing (0.95 s and 0.6 s), Gun Hit (0.36 s and 0.15 s) and Sword Penetration (1.46 s and 1.2 s).

For vibration rendering, we changed the amplitude using a power function with the exponent 3 of time; see Figure 3. This power rate was effective for body-penerating phantom sensations in both the previous study [13] and our pilot test.

Finally, we found the amplitude of a back vibration perceived as equally strong as the front vibration of the maximum output (8.27 G) by a method of adjustment [41] with four volunteers (aged 24 to 29 years). This amplitude (i.e., 6.29 G) was used as the maximum amplitude of back vibrations.

C. Experiment Conditions

We adopted a two-factor within-subjects factorial design. One independent variable was the type of sound stimulus, SOUND TYPE, with five levels: Ambient, Gun Shot, Sword Swing, Gun Hit, and Sword Penetration. The other variable was RENDERING METHOD, which refers to how sound or vibration stimuli were presented. It had four levels: Sound (S), Penetrating Vibration (PV), Sound with Penetrating Vibration (S+PV), and Sound with Stationary Vibrations (S+SV). Here, the penetrating vibration used the vibration profiles described in Section III-B2. For the stationary vibrations, the front and back LRAs were excited with the same perceived intensity and duration. In the S and PV conditions, only sound or vibration was provided, respectively. In contrast, S+PV and S+SV conditions simultaneously delivered sound and vibration.

D. Measures

We designed six measures to evaluate the perceptual and user experiences of the body-penetrating phantom sensations. Participants rated them based on the presented stimuli, which could be auditory-only, vibrotactile-only, or combined.

- *Penetration*: How realistic does the stimulus feel when an object penetrates the body? (0: unrealistic, 100: realistic)
- *Directional Clarity*: How clear do you feel the directionality of the stimulus? (0: unclear, 100: clear)
- *Harmony*: How harmonized are the auditory and vibrotactile stimuli? (0: disharmonious, 100: harmonious)
- *Valence*: How pleasant or unpleasant are the evoked emotions? (0: unpleasant, 100: pleasant)
- *Arousal*: How much arousal do the emotions cause? (0: calm, 100: excited)
- *Satisfaction*: How satisfying is the stimulus? (0: dissatisfied, 100: satisfied)

Penetration and *Directional Clarity* were adapted from the quality indicators for tactile illusions of motion used in previous studies [13], [14], [42]. In addition, we included *Harmony* to assess whether the matched auditory cues enhance or interfere with the perception of the vibrotactile phantom sensations. The *Satisfaction* metric was added to evaluate participants' overall experience with each stimulus condition. Note that participants were informed that they could respond with zero scores if they did not perceive the described quality.

Valence and *Arousal* were used to capture affective responses, guided by the circumplex model of affect [43]. To help participants better understand these dimensions, we provided exemplary emotions using visual aids such as the Self-Assessment Manikin (SAM) [44]. Participants were also informed that they could use neutral ratings if they did not experience any emotional effects.

E. Task and Procedure

Prior to the experiment, participants read written instructions, and the experimenter verbally explained them again. Afterward, participants wore a vibrotactile belt and tightened it to maintain proper contact to their upper body. The experimenter adjusted the LRAs to ensure they were positioned in the centers of the abdomen and back. Participants wore noise-canceling headphones to listen to auditory stimuli while blocking the external noise produced by the LRAs. They rated the measures using a slider of 8 cm on a monitor using a mouse. This visual analog scale reduces central tendency and extreme response biases [45], while offering finer resolution than discrete numeric entry or Likert-type scales. No calibrations for the visual analog scales were performed.

In each trial, participants clicked the play button to generate the stimulus (sound, vibration, or sound + vibration) assigned to the trial. They could experience the stimulus as many times as they wanted. After rating all measures, they clicked the next button to proceed to the next trial. During the experiment, participants were required to maintain an upright sitting posture without leaning their back on the chair.

Before the main sessions, participants completed a training session to familiarize themselves with the rating criteria and scales. Then, participants performed four main sessions consisting of 20 trials (4 RENDERING METHODS × 5 SOUND TYPES). To prevent potential order effects, we used a Balanced Latin Square to determine the order of the 20 experimental conditions. A one-minute break was given between sessions. After completing the main sessions, participants freely described the associated situations, objects, and subjective sensations by typing while re-experiencing all the stimuli. The entire experiment took approximately 60 minutes. The data collected in the training session was excluded from data analysis.

IV. RESULTS

To check the normality assumption for statistical testing, we conducted the Shapiro-Wilk test on the data of each experimental condition. Some cases violated the normality assumption in the test ($p > .05$), but their QQ plots indicated that the data closely followed normal distributions[1].

To ensure robust interpretation, we report both parametric and nonparametric results. Two-way repeated-measures ANOVAs and Friedman tests were conducted for each measure, using RENDERING METHOD and SOUND TYPE as within-subject factors. For the ANOVAs, Mauchly's test was used to assess sphericity, and the Greenhouse–Geisser correction was applied when violations were detected.

[1]There is evidence that when the number of observations for each variable exceeds 10 (20 in our case), the normality assumption does not noticeably affect the results of ANOVA [46].

TABLE I
RESULTS OF TWO-WAY REPEATED-MEASURES ANOVA.

Measure	Factor	df_M	df_E	F	p	η^2	$1-\beta$
Penetration	Render*	2.2	41.2	47.37	<.001	0.39	0.84
	Sound*	2.5	47.2	12.57	<.001	0.08	0.18
	Render×Sound*	5.7	108.8	6.69	<.001	0.04	0.10
Directional	Render*	2.1	39.6	45.61	<.001	0.49	0.95
	Sound*	2.6	50.0	7.01	<.001	0.02	0.08
	Render×Sound*	5.0	95.1	7.09	<.001	0.03	0.09
Satisfaction	Render*	1.7	31.8	19.14	<.001	0.09	0.19
	Sound*	2.8	52.9	7.42	<.001	0.49	0.96
	Render×Sound*	6.1	116.5	5.57	<.001	0.04	0.11
Harmony	Render	1.0	19.0	1.13	.30	0.16	0.30
	Sound*	2.8	49.7	13.07	<.001	0.11	0.23
	Render ×Sound*	4.4	83.8	7.50	<.001	0.12	0.24
Valence	Render	1.7	30.2	1.33	.27	0.02	0.06
	Sound*	2.8	49.7	8.38	<.001	0.12	0.25
	Render×Sound*	12.0	228.0	5.35	<.001	0.04	0.10
Arousal	Render*	2.1	40.2	28.50	<.001	0.20	0.57
	Sound*	2.6	50.2	45.80	<.001	0.24	0.64
	Render×Sound*	5.8	109.7	20.00	<.001	0.10	0.20

Asterisks indicate significant effects with $p < .05$. Power values ($1-\beta$) were estimated based on the effect sizes (η^2), with $n = 20$ and $\alpha = 0.05$.

Table I summarizes the results of the repeated-measures ANOVAs. *1)* RENDERING METHOD had significant effects on all measures: *Penetration* ($F(2.17, 41.17) = 47.37$, $p < 0.001$), *Directional Clarity* ($F(2.09, 39.64) = 45.61$, $p < 0.001$), *Satisfaction* ($F(1.67, 31.78) = 19.14$, $p < 0.001$), and *Arousal* ($F(2.12, 40.24) = 28.5$, $p < 0.001$), except *Harmony* and *Valence*. *2)* SOUND TYPE significantly affected all measures: *Penetration* ($F(2.48, 47.17) = 12.57$, $p < 0.001$), *Directional Clarity* ($F(2.63, 50.03) = 7.01$, $p < 0.001$), *Satisfaction* ($F(2.78, 52.9) = 7.42$, $p < 0.001$), *Harmony* ($F(2.76, 49.73) = 13.07$, $p < 0.001$), *Valence* ($F(2.76, 49.73) = 8.38$, $p < 0.001$), and *Arousal* ($F(2.64, 50.17) = 45.8$, $p < 0.001$). We also conducted Friedman tests across all combinations of SOUND TYPE and RENDERING METHOD. The results showed that the significant cases were the same as the results of the ANOVAs. Those complete statistics results are provided in the supplemental material.

Significant interaction effects between RENDERING METHOD and SOUND TYPE were also observed across all measures: *Penetration* ($F(5.73, 108.80) = 6.69$, $p < 0.001$), *Directional Clarity* ($F(5.00, 95.09) = 7.09$, $p < 0.001$), *Satisfaction* ($F(6.13, 116.52) = 5.57$, $p < 0.001$), *Harmony* ($F(4.41, 83.83) = 7.50$, $p < 0.001$), *Valence* ($F(12, 228) = 5.35$, $p < 0.001$), and *Arousal* ($F(5.78, 109.74) = 20.0$, $p < 0.001$).

Then, we conducted Tukey's HSD tests for pairwise comparisons for the significant cases. Figure 6 represents the mean responses and standard errors by the level of each independent variable for all six questions. Statistically significance was indicated with asterisks in Figure 6, which provides a compact

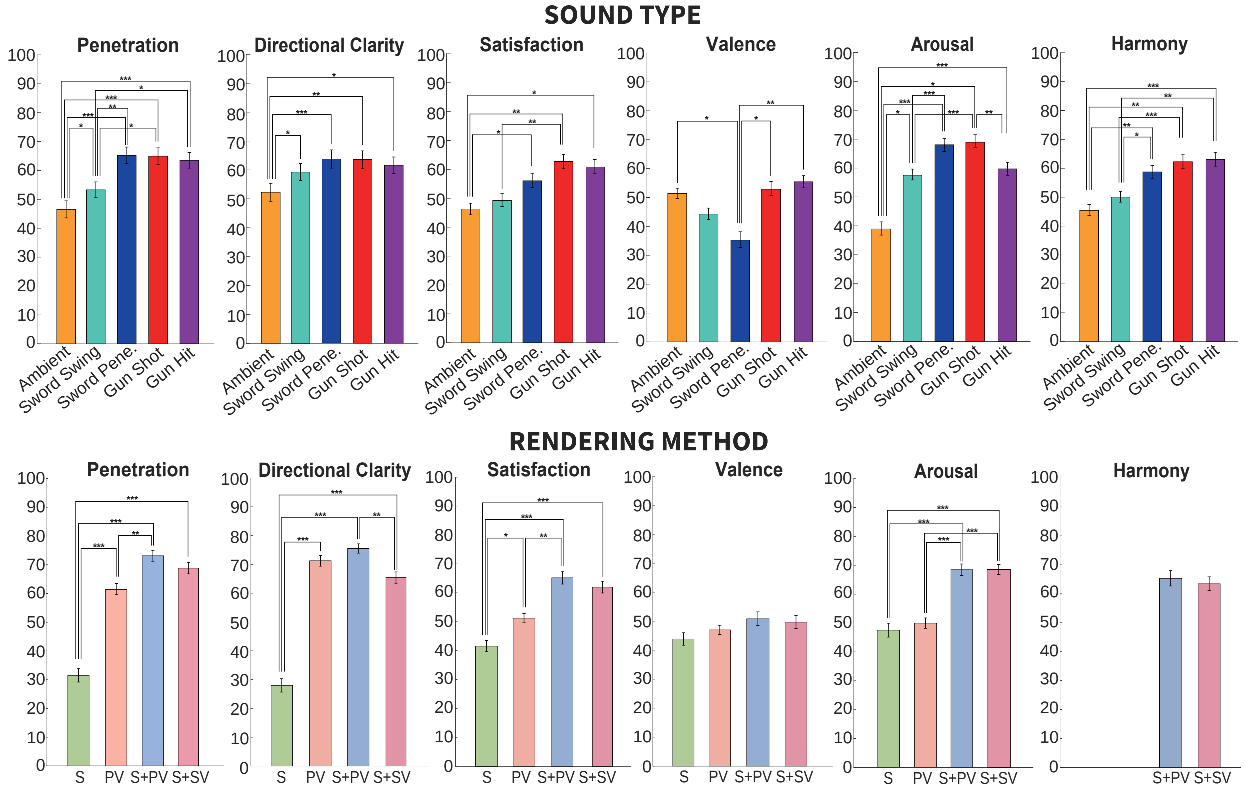

Fig. 4. Mean scores and standard errors for SOUND TYPE (top) and RENDERING METHOD (bottom). Error bar represents standard errors. Pairs grouped by asterisks were significantly different by Tukey's HSD tests (*: $0.01 < p < 0.05$, **: $0.001 < p < 0.01$, ***: $p < 0.001$).

summary of how specific combinations of SOUND TYPE and RENDERING METHOD influenced each perceptual measure. The complete results of the above statistical tests are available in the supplemental material.

V. DISCUSSION

In this section, we first examine the influence of multisensory effects on penetrating illusion about *Penetration*, *Directional Clarity*, *Satisfaction* and *Harmony*. We then analyze how each stimulus type modulates emotional responses, specifically in terms of *Valence* and *Arousal*. Subsequently, we explore how these multisensory effects change subjective interpretations. Lastly, we address the limitations of the present study and outline potential directions for future research.

A. Multisensory Effects on Penetrating Illusions

1) Effects of Rendering Method: Figure 4 (bottom) depicts the main effects of each RENDERING METHOD for the six subjective measures. Three of the measures, *Penetration*, *Directional Clarity*, and *Satisfaction*, account for the performance of penetrating sensation rendering. The sound-only rendering S showed the lowest scores for the three measures, with all means between 25 and 45. These scores were significantly improved to be between 50 and 75 when the rendering method was switched to the body-penetrating phantom sensation PV. This result reconfirms the effectiveness of the body-penetrating tactile rendering technique proposed in [13]. When the sound and penetrating vibration were combined (S+PV), the three scores were further increased to between 65 and 80, clearly demonstrating the synergy between the auditory and tactile stimuli, with significant improvements in *Penetration* and *Satisfaction*. However, when the sound was rendered together with the stationary vibrotactile effects (S+SV), no significant differences were observed in the three measures, even with a decreased score for *Directional Clarity*. Therefore, these results clarify that the body-penetrating tactile rendering method is effective even when it is presented with sound stimuli.

Harmony between the auditory and vibrotactile stimuli was assessed as mildly matched, with mean scores between 60 and 70. No significant difference was found between the two vibration rendering methods (S+PV and S+SV). These results suggest that the participants accepted the addition of the unfamiliar body-penetrating tactile phantom sensation to the familiar sounds as reasonably synchronized and natural body-penetrated experiences.

2) Effects of Sound Type: Figure 4 (top) illustrates the main effects of SOUND TYPE on the six subjective measures. Notably, three measures—*Penetration*, *Directional Clarity*, and *Satisfaction*—revealed distinct patterns across sound conditions. The Ambient sound consistently showed the lowest scores, with all means between 45 and 55. In contrast, impact-related sounds, such as Gun Shot, Gun Hit, and Sword Penetration, resulted in significantly higher scores between

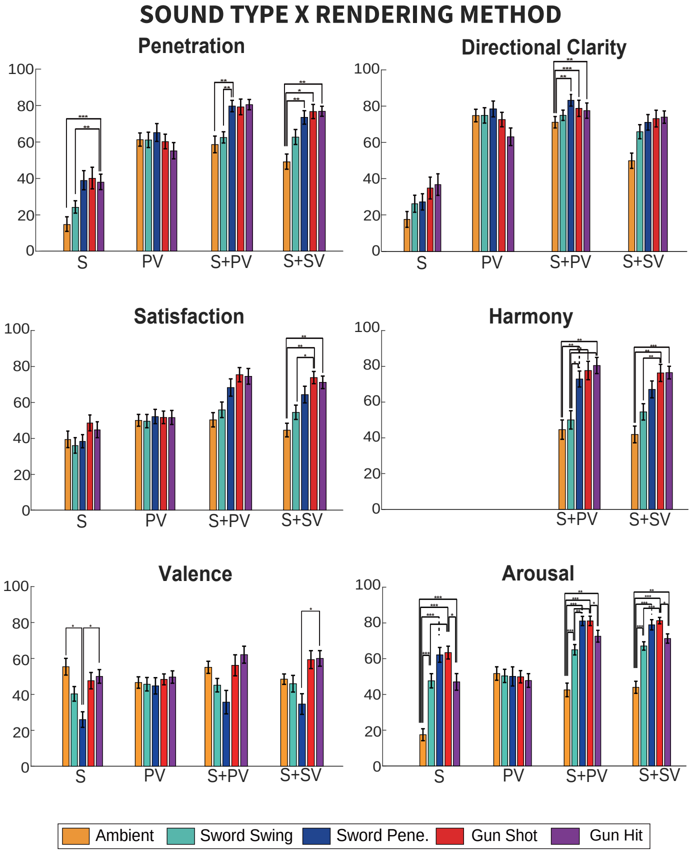

Fig. 5. Mean scores of all conditions about Rendering Method. Error bar represents standard errors. Pairs grouped by asterisks were significantly different by Tukey's HSD tests (*: $0.01 < p < 0.05$, **: $0.001 < p < 0.01$, ***: $p < 0.001$).

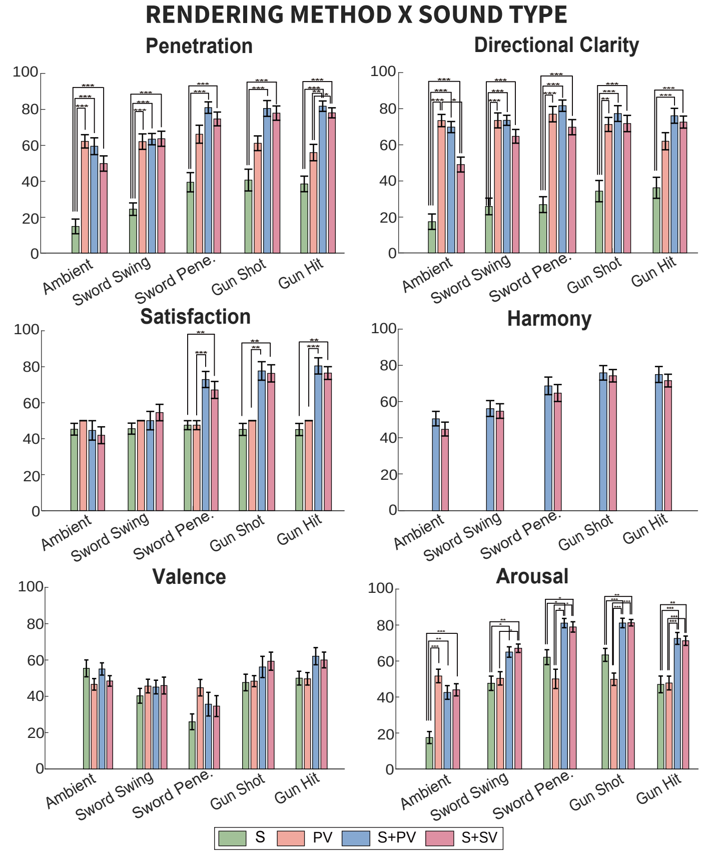

Fig. 6. Mean scores of all conditions about Sound Type. Error bar represents standard errors. Pairs grouped by asterisks were significantly different by Tukey's HSD tests (*: $0.01 < p < 0.05$, **: $0.001 < p < 0.01$, ***: $p < 0.001$).

55 and 65, indicating that sharp, physically suggestive sounds facilitate stronger tactile impressions. For *Penetration* and *Directional Clarity*, both gun-related sounds yielded the highest ratings, with significant differences compared to Ambient and Sword Swing sounds.

The *Harmony* ratings, which reflect the perceived coherence between auditory and tactile stimuli, showed significant variation between 45 and 65. While Ambient produced the lowest Harmony ratings, Sword Penetration and Gun Hit scored the highest, with significant differences from Ambient and Sword Swing. These results suggest that impact sounds that carry clear semantic alignment with tactile feedback are more likely to be perceived as harmonized, supporting the multisensory integration necessary for coherent perceptual experiences.

3) Effects of Sound Type × Rendering Method: We can derive more informative results by also considering the effects of SOUND TYPE in Figure 4 (top) and referring to the scores of all 20 experimental conditions in Figure 6. For the three main measures of *Penetration*, *Directional Clarity*, and *Satisfaction*, the sound Ambient resulted in the lowest mean scores between 45 and 55. In fact, when presented alone without vibrotactile effects, the scores of Ambient for *Penetration* and *Directional Clarity* were below 20 (Figure 6). This result was expected because Ambient was unrelated to the events causing the body-penetrated experiences perceived by users.

When the sound effect was replaced with Sword Swing, the scores of the three measures were all increased to some extent to be between 45 and 60, as shown in Figure 4 (top). This sound represents an event that would cause a result of body penetration. For another sound Sword Penetration that occurs because of Sword Swing, the three measures showed further increased scores, with a significant improvement for *Penetration*. In particular, when Sword Penetration was combined with S+PV, the scores were very high, around 80[2] for *Penetration* and *Directional Clarity* (Figure 6). Therefore, this case of Sword Penetration & S+PV can be regarded as one of the best examples for audio-tactile effects that elicit the perception of body-penetrated experiences.

The last two sounds, Gun Shot and Gun Hit, are about guns and represent the cause and result of gunfire, respectively. Figure 4 (top) shows that their mean scores for the three measures were all high, around 65, and close to the scores of Sword Penetration. When combined with S+PV, their scores in Figure 6 were all very high, being close to 80 for

[2]In our experiences with rating experiments using a 0–100 scale, participants rarely give scores over 80 as they avoid making extreme judgments.

Penetration, 75 for *Directional Clarity*, and 75 for *Satisfaction*. These scores of Gun Shot and Gun Hit were greatly improved from their sound-only scores, around 40 for *Penetration*, 35 for *Directional Clarity*, and 45 for *Satisfaction*. Therefore, Gun Shot and Gun Hit are also eligible for the instances that present the best multisensory experiences.

Interestingly, no significant differences were observed between Gun Shot and Gun Hit, unlike the pair of Sword Swing and Sword Penetration. This discrepancy may be attributed to the low *Harmony* scores between the auditory and tactile stimuli in Sword Swing. As illustrated in Figure 4 (top), the mean *Harmony* scores for Sword Swing were significantly lower than those for Sword Penetration, Gun Shot, and Gun Hit. A possible explanation is the higher pitch of Sword Swing than the other penetration-related sounds (the sound files are available in the supplemental video). Because the vibration frequency was 120 Hz, it might have failed to deliver a sharp or high-pitched sensation that aligned with the sound, reducing perceived harmony. Consequently, adding vibration to Sword Swing seems to have a limited impact on enhancing the penetrating sensation compared to the others.

4) Summary of Multisensory Effects: The experimental results discussed above highlight the critical role of both auditory semantics and the harmony between sound and vibration for body-penetrating illusory effects. Both *Harmony* and *Penetration* scores were the highest for Gun Shot, Gun Hit, and Sword Penetration sounds, while the scores for Ambient and Sword Swing were substantially lower. That is, sounds unrelated to penetration (i.e., Ambient) and disharmonious to vibration reduced the effectiveness of the penetrating illusion. These observations align with the significant interaction effects reported in Table I, confirming that the perceptual effect of the rendering method depends on the sound type.

We also observed that penetrating sounds alone could not induce penetrating illusions. However, people rated significantly higher scores in *Penetration* when vibrotactile effects were applied simultaneously to the torso's front and back in conjunction with penetration-relevant sounds. A previous study [47] showed a similar result. Strong and short impacts to the torso's ventral side, combined with audiovisual cues like gunshots or sword slashes, showed the potential to convey a body-penetrating sensation. In contrast, we showed that penetrating vibration alone is sufficient to elicit a penetrating illusion. Furthermore, this sensation was significantly enhanced when the vibration was paired with harmonious auditory cues, such as Penetration, Gun Shot and Gun Hit.

Lastly, it is notable that the vibration effect for body-penetrating sensations clearly improved *Directional Clarity* (Figure 4, bottom) compared to a similar dual-actuator but stationary vibration effect to the body. Moreover, the positive correlation between *Penetration* and *Satisfaction* scores ($r = 0.896$, $p < 0.001$) suggests that the effectiveness of illusory effects positively affects user satisfaction.

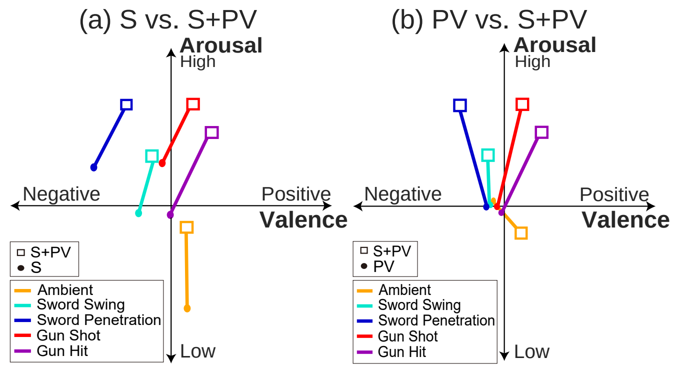

Fig. 7. Comparison of emotional responses. (a) Between sound only and sound with penetrating vibration conditions. (b) Between penetrating vibration only and sound with penetrating vibration conditions.

B. Changes in Emotional Responses

The emotional responses were significantly affected by SOUND TYPE. As illustrated in Figure 7a, the sound Ambient was perceived as positive valence and low arousal emotions (e.g., calm). Gun Shot sound had neutral valence but high arousal emotions (e.g., fear) and Gun Hit sound was neutral in both valence and arousal (e.g., neutral). Sword Swing was perceived as negative valence and moderate arousal (e.g., negative), and Sword Penetration as highly negative and strong arousal (e.g., disgust). In contrast, as shown in Figure 7b, the penetration vibrations elicited neutral valence and arousal scores, suggesting they were not emotionally charged.

The combination of auditory and vibrotactile stimuli slightly changed emotional responses. Gun Shot and Gun Hit was shifted to positive valence and high arousal (e.g., surprised, excited). Sword Swing and Sword Penetration remained negative but become more intense in terms of arousal (e.g., fear). In particular, for *Arousal*, the scores of the unisensory stimuli were around the neutral score between 40 and 50. When combined, the multisensory stimuli significantly increased the average arousal level to over 65, eliciting more intensified emotional experiences. However, the changes in the *Valence* scores by the rendering method were not statistically significant (Figure 4, bottom). Their trends across the five sound types (see S for *Valence* in Figure 6) were preserved even when vibration effects were added in S+PV and S+SV.

C. Changes in Subjective Descriptions

Table II shows the descriptions of events associated with the experimental conditions, obtained from the participants. In the vibration-only condition, participants successfully associated their experiences with sensations of penetration, as well as being hit, pushed, stopped, or shot. They also correctly associated most sounds with their original context in the sound-only condition. For example, Ambient was often linked to gaming or magical elements. Sword Swing was perceived as the sound of a sword clashing, while Sword Penetration as a squelch or a sword slashing and penetrating. Both Gun Shot and Gun Hit were predominantly identified as gunshots.

TABLE II
DESCRIPTIONS OF ASSOCIATED EVENTS DEPENDING ON RENDERING METHODS AND SOUND TYPES.

Rendering Method	Sound Type	Descriptions
Penetrating Vibration	All	Being penetrated (28%), Being hit/pushed/stopped/shot (21%/10%/7%/7%), Phone alarm (10%), Etc (21%)
Sound	Ambient	Game (25%), Magic (15%), Alarm (10%), Being affected by magic (5%), Etc (15%)
	Sword Swing	Sword clashing (30%), Sword (10%), Sword drawing (5%), Being slashed (5%), Etc (20%)
	Sword Penetration	Squelch (25%), Sword slashing/penetrating (15%/5%), Slashing (10%), Mud (10%), Etc (15%)
	Gunshot	Gunshot (55%), Gun (15%), Explosion (10%), Thunder (5%)
	Gun hit	Gun/Arrow/Laser shot (35%/10%/5%), Gun (10%), Being shot (10%), Gun hit (10%), Etc (15%)
Sound with Penetrating Vibration	Ambient	Game (25%), Being affected by magic (15%), Magic (10%), Alarm (5%), Etc (15%)
	Sword Swing	Being slashed (45%), Sword (10%), Sword slashing (5%), Sword clashing (5%), Metal clashing (5%)
	Sword Penetration	Squelch (25%), Being penetrated/slashed/shot (25%/15%/5%), Sword penetrating (5%), Etc (15%)
	Gunshot	Being shot/penetrated (55%/5%), Gun (5%), Gunshot (5%), Explosion (10%)
	Gun hit	Being shot/penetrated/slashed (35%/10%/5%), Gun (10%), Gun/Arrow shot (5%/5%), Etc (10%)

However, when sound and penetrating vibration were combined, participants altered their subjective descriptions of the stimuli. They often linked Sword Swing and Sword Penetration to being slashed or penetrated. Gun Shot and Gun Hit were associated with being shot by bullets or arrows. In other words, adding penetrating vibrations to sounds that originally implied penetration-triggering events, such as Sword Swing, Gun Shot, and Gun Hit, transformed their interpretation into the direct experience of being penetrated. This phenomenon can be attributed to the fact that auditory and tactile stimuli often originate from the same physical event, naturally signaling a unified perception of that event [33]. Even when the sound itself was unrelated to penetration like Ambient, the penetrating vibration altered its interpretation, making it feel as if the participant was passively influenced by magic. These results reconfirm the effectiveness of the multisensory stimuli for enhancing the penetrating sensations.

As mentioned in Section III-B1, we initially expected that sounds representing the effect of body penetration (e.g., Sword Penetration and Gun Hit) would achieve higher scores in penetration perception than those representing the cause (e.g., Sword Swing and Gun Shot). However, as shown in Table II, participants did not interpret both categories of sounds as being penetrated when only the sounds were presented. Instead, the rendering method showed greater effects on the experiences of being penetrated. When vibrotactile effects were provided together, sounds closely associated with physical impact (excluding ambient sounds) were interpreted as indicating body penetration. These results suggest that the perceived meaning of a multisensory penetration illusion is more triggered by tactile stimuli.

D. Limitations and Future Work

This study has a few limitations that should be addressed in future research. First, we fixed the vibration frequency at 120 Hz, while the auditory characteristics varied. However, Kim et al. [48] showed that high-frequency vibrations (above 198 Hz) align better with high-pitch sounds, whereas low-frequency vibrations (below 100 Hz) suit low-pitch sounds. Future research should consider varying vibration frequencies to enhance perceptual harmony and penetrating sensations.

Second, the direction of penetrating vibrations was limited to a ventral-to-dorsal. Exploring alternative directions—such as dorsal-to-ventral or lateral-to-lateral (e.g., from the left waist to the right waist)—could reveal different multisensory effects and user experiences. Additionally, future studies could extend this concept to other body sites beyond the torso.

Third, using spatial audio with penetrating vibrations could further enhance directional clarity. This new combination has the potential to serve as a practical tool for conveying task-relevant information in virtual environments, such as navigation, manipulation, and warning [49], while also enriching user experiences like realism and immersion.

Fourth, the experimental procedure permitted participants to repeat the stimuli at their discretion, potentially leading to inter-individual variability. This uncontrolled variation may have induced adaptation or learning effects, thereby affecting the consistency of subjective ratings. Controlling for these external variables may lead to more consistent and reliable subjective outcomes across participants.

Finally, direct questions on penetrating sensations may have led participants to recognize what the study was intended to assess, potentially including response biases. To minimize such effects and enhance objectivity, we can adopt quantitative measures. For instance, physiological data (e.g., heart rate variability, skin conductance) can be recorded during experiences of *unfamiliar* body-penetrating sensations. Moreover, perceptual accuracy can also be analyzed by comparing actual and perceived stimulus directions.

VI. CONCLUSIONS

This study is the first systematic investigation of the multisensory effects of auditory-tactile integration on body-penetrating phantom sensations. We demonstrated that combining penetration-related sounds with penetrating vibrations significantly enhances the perceived realism, directional clarity, and satisfaction of penetrating illusions, confirming the critical role of the perceptual and semantic harmony between sound and vibration. Moreover, our findings revealed that auditory-tactile integration not only enhances the perception of body-penetrating sensations but also alters the interpretation of auditory events. For instance, when the Gunshot sound was presented as an auditory stimulus alone, participants perceived it as an external event. However, when combined with penetrating vibrations, the same sound was interpreted as the sensation of being shot. It highlights the ability of haptic illusory effects to modify the semantic meaning of auditory stimuli, reinforcing the strong crossmodal relationship between sound and touch. Our research expands the possibilities of auditory-tactile interactions, enhancing realism, intensifying emotional experiences, and intuitively reshaping sensory perception in various immersive environments.

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