AUDIO-INFLUENCED PSEUDO-HAPTICS: A REVIEW OF EFFECTS, APPLICATIONS, AND RESEARCH DIRECTIONS

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ABSTRACT

Haptic feedback plays an important role in interaction, but traditional haptic devices are often difficult to access due to their complexity and high cost. A cost-effective approach is to use auditory displays to evoke pseudo-haptic sensations by leveraging the brains multisensory processing. Auditory cues can enhance or modify existing haptic feedback, refine low-resolution haptic devices, or generate convincing haptic illusions without physical contact. Despite their potential, audio-influenced pseudo-haptics remain underexplored. In this survey, we provide a comprehensive overview of existing research on audio-influenced pseudo-haptics, summarizing the mapping between different auditory cues and the pseudo-haptics that they elicit, identifying key challenges, and discussing future opportunities. We aim to provide a road map in audio-influenced pseudo-haptics research and inspire further exploration in this field, fostering innovation and guiding the development of more immersive, functional, and accessible interactive systems.

1. INTRODUCTION

Integrating haptic feedback into digital environments enhances realism and immersion in virtual settings [1]. Traditional approaches rely on direct haptic feedback via wearables [2] and shape-changing interfaces [3], or by actuating physical proxies for on-demand interactions [4, 5, 6]. While effective, these methods remain costly and challenging to scale due to hardware constraints [7].

To address these limitations, researchers explore pseudo-haptics as a cost-effective and accessible alternative for recreating tangible experiences. Pseudo-haptics refers to the generation, alteration, and enhancement of haptic sensations without direct stimulation of the skin, muscles, or joints, leveraging multisensory integration of vision and sound to induce haptic illusions through cross-modal interactions [8]. It can enhance ***tactile*** sensations such as roughness, friction, and temperature [9], modify ***kinesthetic*** perceptions like force, stiffness, and body weight [10], or combine both to influence material perception, object weight, and body representation [10]. It also extends to dynamic properties like vibration, damping, and adhesion [11], offering a scalable alternative to expensive haptic hardware.

Auditory displays have been shown to strengthen pseudo-haptic experiences by enhancing multimodal integration, such as improving roughness perception in low-resolution touch interfaces [12] and reinforcing haptic illusions related to vibration, force, and elasticity with visual displays [13]. While visual-based pseudo-haptics remains dominant, audio-influenced pseudo-haptics presents unique advantages, particularly in scenarios where visual modifications are impractical or undesirable. For example, auditory display can simulate non-visual haptic sensations, such as wind perception [14], food texture in eating and drinking [15], and body weight perception [16]. It is also valuable in applications where preserving visual fidelity is critical, such as surgical simulation [17].

While there are survey papers addressing broader topics like pseudo-haptics, multimodal interaction, and perception [18, 19, 7], the specific area of audio-influenced pseudo-haptics remains largely unsummarized [1]. Existing surveys often focus on different aspects of haptics or provide general overviews, but they lack a comprehensive categorization and in-depth analysis of audio-influenced pseudo-haptics. Additionally, many of these surveys are becoming outdated as the field rapidly evolves, highlighting the need for a focused and up-to-date survey that offers clear categorization, insights, and guidance for future research in this emerging area.

This survey goes beyond categorization by identifying challenges and highlighting new research directions in audio-influenced pseudo-haptics. While significant progress has been made in pseudo-haptics research, existing methodologies would benefit from more systematic frameworks for disentangling auditory cue controls, which would enhance the generalizability of findings across applications. Moreover, as immersive technologies like augmented reality (AR) and virtual reality (VR) continue to advance, spatial auditory displays are becoming increasingly important [20]. However, the role of auditory cues in spatial audio reproduction and their impact on haptic perception remain largely understudied. Investigating how audio-influenced pseudo-haptics functions within spatial auditory displays, particularly in dynamic, multi-user, and real-time interactive environments, presents a valuable research opportunity. Additionally, several haptic perceptions remain underexplored and could potentially benefit from auditory displays. While existing research has primarily focused on pseudo-haptic sensations related to force, friction, and texture, other tactile sensations –such as temperature, pain, and itching– have received little attention.

By analyzing existing approaches and outlining key research challenges, this paper serves as both a comprehensive review and a call to action for advancing the role of auditory displays in pseudo-haptic design. We aim to provide a structured foundation for future research, emphasizing the need for more refined methodologies, expanded perceptual investigations, and novel applications of audio-influenced pseudo-haptics in interactive systems.

2. METHODOLOGY

2.1. Dataset Collection

We conducted a comprehensive literature review on audio-influenced pseudo-haptics. Our initial search on Google Scholar used the query: (”audio” OR ”auditory” OR ”sound”) AND (”pseudo haptics” OR ”pseudo-haptics” OR ”pseudohaptics”), yielding 534 papers. We filtered for English-language journal or conference papers that included empirical studies, excluding seminar papers, workshop presentations, and those outside our scope. Each paper was screened by reading its introduction and conclusion, supplemented by keyword-based skimming.

We selected papers that fit within the scope of pseudo-haptics, focusing on haptic illusions or perceptual modifications rather than the use of auditory cues solely for inferring object properties without simulating physical contact or movement [21, 22, 23]. Following this, we identified 54 highly relevant papers, removed redundancies, and expanded our dataset by examining references and leveraging our expertise, adding 73 additional papers for a total of 127. Each paper was then reviewed and ranked by relevance (low, medium, high), with only medium and high-relevance papers retained. Survey papers and taxonomies were excluded to focus on original contributions. This selection process ensures a focused and comprehensive review of audio-influenced pseudo-haptics.

After the final selection, we included 89 papers published between 1979 and April 2024, covering key venues in perception, HCI, and auditory display, such as SIGCHI, IEEE WHC, Perception, Presence, and ICAD.

2.2. Data Analysis Strategy

We employed a thematic analysis approach, following an iterative open-coding process [24], to systematically analyze the selected papers. Four researchers independently coded the data and collaboratively developed a coding schema to classify each paper across several key dimensions, holding regular meetings to resolve discrepancies and ensure a shared understanding throughout.

- **Auditory Cues:** The specific auditory cues examined in each paper. This dimension includes both general category tags (e.g., naturalistic, synthesized, amplitude-related, spectral) and more detailed cue-type tags (e.g., pitch, timbre, loudness).
- **Pseudo-Haptics Components:** The types of pseudo-haptic feedback discussed in the paper, categorized under broader tags (e.g., tactile, kinesthetic) and detailed feedback types (e.g., heaviness, roughness).
- **Applications:** The domains or fields in which the research is applied, such as rehabilitation, enhancing immersion, or practical training.

For details please see our supplementary materials.

This coding framework enabled a systematic and structured synthesis of findings across the reviewed studies, ensuring consistency and comparability in the analysis.

During the coding process, detailed analytical memos were also written, documenting each paper’s emergent themes, challenges, and insights. These memos further informed the categorization of codes, enabling us to identify recurring patterns, research gaps, and potential paths for future exploration. The coding schema and analysis protocol were iteratively refined to enhance reliability and to ensure a comprehensive and nuanced representation of the literature.

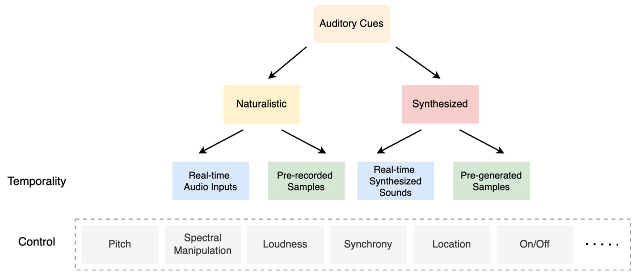

Figure 1: The Taxonomy of Auditory Cues in Audio-influenced Pseudo-haptics

3. TAXONOMY OF AUDITORY CUES IN AUDIO-INFLUENCED PSEUDO-HAPTICS

The classification of auditory cues in auditory displays and audio-influenced HCI studies can be approached in various ways. In this section, we propose a taxonomy to better support research on audio-influenced pseudo-haptics. While this categorization is not intended to be exhaustive or rigid, it serves as a useful reference for current and future studies exploring the role of auditory cues in this field. Figure 1 illustrates the taxonomy of auditory cues. The top two layers of the tree classify cues based on their origin and the temporality of their processing or generation methods, while the bottom layer represents the different controls used to process and generate these auditory cues.

3.1. Origin

Auditory cues in these studies can be classified into two main categories: naturalistic and synthesized.

3.1.1. Naturalistic Auditory Cues

Naturalistic auditory cues are sounds originating from real-world acoustic sources, from events or environments. These can be delivered directly to the listener’s ears, captured by a microphone, and processed in real time using digital signal processing (DSP), or recorded for later playback. Examples include footsteps [16], or the sound of biting an apple [25].

3.1.2. Synthesized Auditory Cues

Synthesized auditory cues are generated electronically through software or hardware, using computer algorithms or electronic circuits. Synthesized sounds range from simple tones, like sine waves or white noise [26], to more complex models that mimic real-world sounds, such as the sound of interaction with a textured surface [27]. Granular synthesis [28], despite using recorded samples, operates by deconstructing and reconstructing sound at the grain level, making it distinct from the original source and thus still considered synthesized in this context.

3.2. Processing and Generation Methods: Temporality

At this layer, auditory cues are categorized by temporality, distinguishing between sounds captured or generated in real time and those that are pre-recorded or pre-generated.

3.2.1. Real-Time Audio Input or Synthesized Sound

Real-time audio input or synthesized sound refers to sounds processed or synthesized in real time, responding instantly to user actions or environmental changes [29]. These cues provide interactive feedback and adapt dynamically. While real-time processing enables natural interaction, it is limited in complexity and may introduce delays, potentially affecting experimental results.

3.2.2. Pre-recorded or Pre-generated Samples

Pre-recorded or pre-generated samples refer to sounds previously captured or synthesized and later triggered by specific events or actions [30]. While such sounds may respond to user interactions, their adaptability is limited. Pre-recorded samples allow for more complex processing but generally offer less interactivity than real-time audio, making them better suited for event-based scenarios. Using pre-recorded or pre-generated samples also ensures playback consistency for each trial during the study.

3.3. Processing and Generation Methods: Controls

At the bottom layer, the taxonomy presents various controls used to modify or generate auditory cues from the previous layers, identified through our paper search. We consolidated terms where different terminologies referred to the same concept or where the controls were conceptually similar. The 12 main auditory cue controls are: pitch, spectral manipulation, timbre/texture, harmony, loudness, envelope, synchrony, location, reverberation, audio content, on/off, and special effects/synthesis methods.

Each of these controls plays a specific role in shaping the auditory cue. Pitch is the perceived frequency, adjusted by modifying sound frequency. Spectral manipulation involves altering the frequency content of sound through methods like equalization. Timbre and texture describe sound characteristics that differentiate sources, even when pitch and loudness are identical, while harmony refers to the relationship between multiple frequencies, such as consonance and dissonance.

Loudness is the perceived intensity of sound and is often used interchangeably with terms like volume, intensity, amplitude, sound pressure level, and sound level. The envelope shapes a sounds amplitude over time, including parameters like attack and decay. Synchrony/delay aligns auditory cues with other sensory inputs. Location controls spatial positioning relative to the listener, while reverberation affects how sound reflects in the acoustic space, altering the perception of the environment.

Audio content refers to the use of different audio recordings or sources [31], while on/off controls determine whether auditory cues are present. This can be achieved by either providing or withholding playback of pre-recorded samples [32], masking sounds with noise [33], or turning the microphone on or off for real-time audio input [25]. Special effects and synthesis methods modify cues or emulate real-world sounds using techniques like glissandi, vibrato, granular synthesis, and playback speed manipulation.

4. AUDIO-INFLUENCED PSEUDO-HAPTICS

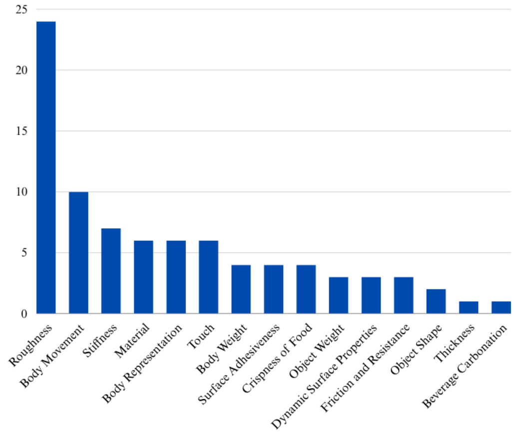

Figure 2: Pseudo-Haptic Effects Trend

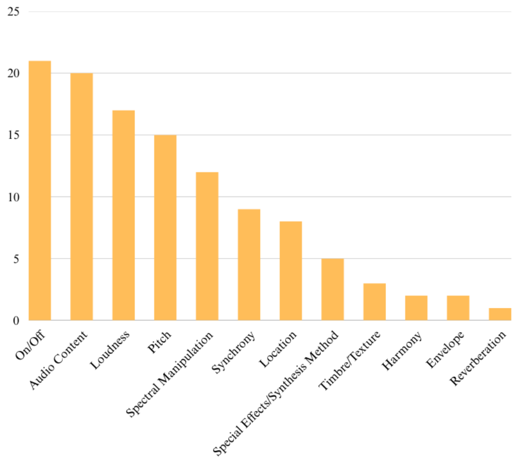

Figure 3: Auditory Cue Controls Trend

We summarize a comprehensive overview of how various auditory cues influence perceived haptic experiences. We also summarize key research trends and highlight notable findings. A detailed summary of these findings is provided in Figure 2 and Figure 3, and a heatmap showing how many papers have been found in our literature search regarding each audio-haptic combination can be seen in Figure 4.

4.1. Trend

Figure 2 illustrates the distribution of papers exploring various pseudo-haptic effects. The research focus across different effects is highly uneven, with a clear trend towards studying roughness, which is explored by 24/89 papers. This prominence may be due to the subtle and complex nature of roughness as a haptic sensation. Detailed texture information, such as surface particles, is difficult to convey through other sensory inputs like vision, making it particularly effective to generate through auditory cues.

Beyond roughness, other relatively frequently studied pseudo-haptic effects include body movement, stiffness, material percep-

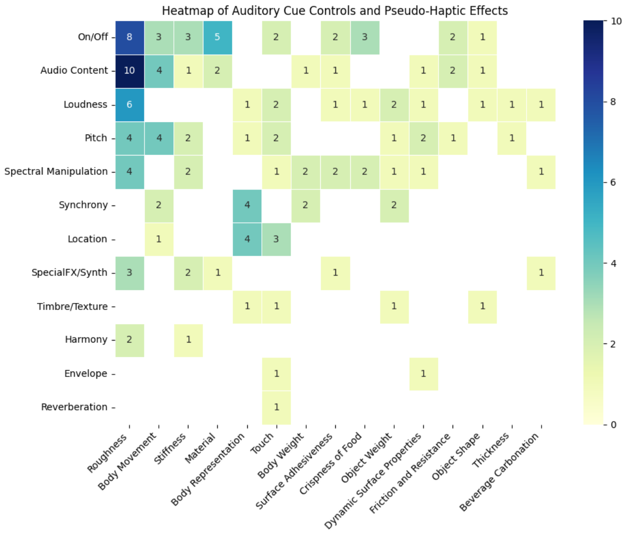

Figure 4: Heatmap of Auditory Cue Controls and Pseudo-Haptic Effects

tion, and body weight. Sensations like object shape, for instance, may be predominantly dominated by visual sensory input, which could explain the relatively limited studies exploring how this can be influenced by auditory cues. Sensations like fabric thickness or beverage carbonation focus on specific, particular objects or contexts, which are naturally less explored.

Figure 3 illustrates the distribution of papers exploring various auditory cue controls. Among these, on/off and audio content are the most frequently used controls in studies of audio-influenced pseudo-haptics, likely because they result in noticeable changes in auditory output, making the effects more distinct. These controls are often used to investigate how the semantic meaning of sound affects haptic perception. For instance, presenting participants with sounds produced by different materials and observing whether their perception of roughness changes can help explore how the high-level meaning of sound influences tactile experiences. However, providing or withholding an auditory cue, or replacing the audio samples used in a study, can affect multiple auditory attributes simultaneously, such as pitch, loudness, and timbre, making it difficult to isolate which auditory attribute has the actual impact on pseudo-haptics.

Pitch and loudness are also extensively studied, likely because they are more fundamental and can more readily be disentangled from other auditory attributes, allowing for more precise manipulation. In contrast, temporal cues like synchrony are less frequently examined, and spatial auditory cues such as location and reverberation receive even less attention, despite their growing importance in the context of immersive technologies.

4.2. Key Findings

We summarize the key findings here from the reviewed papers on how auditory displays can influence haptic experiences. For a detials of each reviewed paper's findings, please refer to the supplementary materials.

4.2.1. Bodily and Movement Perception

Previous works show that auditory display significantly influences bodily perception, including body weight, representation, and movement awareness. By shaping sensory integration, auditory display can alter the perceived weight of the body, extend or distort limb representation, and enhance motion awareness in both real and virtual environments.

For body weight perception, auditory cues modulate the sense of gravity and heaviness. Footstep sounds with lower center frequency filters make virtual avatars feel heavier in VR, while synchronized audio-tactile feedback in the "Marble-Hand Illusion" increases perceived hand weight and stiffness, an effect disrupted by incongruent or asynchronous sounds. Similarly, synchronized movement-related sounds can create a pseudo-haptic sense of gravity, influencing perceived body weight during motion.

Auditory display also shapes body representation, altering how users perceive their own limbs. For example, rising-pitch sounds during finger-pulling make fingers feel longer, and synchronized auditory cues extend perceived limb length, with the effect diminishing when sounds are delayed or inconsistent.

For movement awareness, real-time sonification enhances motor learning and strengthens the perception of motion. In virtual environments, synchronized footstep sounds increase gait awareness, leading to longer stride lengths, cautious gait adjustments, and greater immersion. However, in tasks requiring precise control, such as virtual drilling, kinesthetic cues are more critical than sound alone, and distracting noise can impair motor awareness. When visual feedback is limited, users rely more on auditory and tactile cues, increasing gesture variability and movement times.

Auditory displays can enhance the perception of force during movement. Low-pitched sounds are commonly associated with greater force, reinforcing sensations such as friction and resistance when pushing or dragging objects. In digital writing, reproducing friction-induced oscillations and the characteristic sounds of different tools improves engagement and realism, heightening the sense of resistance and material interaction.

4.2.2. Texture, Surface, and Material Perception

Auditory display can effectively shape the perception of textures, surfaces, and materials by modulating sensations such as roughness, stiffness, and elasticity. By integrating sound with haptic interactions, auditory feedback can enhance or even alter how users perceive contact surfaces in both physical and virtual environments.

For texture perception, auditory display influences roughness perception through pitch and spectral composition. High-pitched sounds generally reduce the perceived roughness of virtual surfaces but can also increase roughness when interacting with physical fabrics and ultrasonic surfaces. Spectral manipulation, such as boosting high-frequency components, often enhances roughness perception, though in specific cases, such as rubbing palms together, it can create the illusion of smoother textures. Inharmonic sounds further amplify the sense of roughness in virtual environments, while louder auditory feedback intensifies roughness perception across both digital and physical materials. Additionally, white noise enhances roughness perception, whereas pure tones create a smoother sensation or have no significant effect.

Auditory display also strengthens the perception of material properties, assisting users in judging texture and surface characteristics. High-pitched and irregular auditory feedback increases the perception of roughness, while lower-pitched sounds and gradual pitch changes contribute to the sense of softness. Synthesized auditory cues paired with haptic feedback can generate realistic sensations of roughness and texture, enhancing immersion and interaction quality. Furthermore, auditory feedback correlates with surface rigidity, where high-pitched sounds suggest stiffer materials, and increased loudness implies greater elasticity.

Beyond texture, auditory display influences the perception of material properties such as thickness and stiffness. Low-pitched auditory cues make fabrics feel thicker, and increasing sound intensity has a similar effect. Sound-based interactions can also modulate the perception of softness and simulate vibratory feedback in virtual environments, further enriching material interactions. Additionally, the decay rate of auditory feedback affects material perceptionfaster sound decay suggests softer materials, while slower decay is associated with harder surfaces.

4.2.3. *Object Physicality and Realism*

Auditory display enhances the perceived physical presence of objects and the perceived attributes of objects in interactive systems. By integrating auditory feedback, virtual object interactions can feel more tangible, and real-world objects can be perceived with altered physical properties, improving immersion and accessibility.

For object contact and force perception, auditory display amplifies the sensation of physical presence when interacting with rigid surfaces. Pressing sounds increase the perceived resistance of virtual objects, making force application feel more tangible. Auditory feedback that aligns with a virtual objects visual appearance, such as texture, can also enhance the realism of the touch illusion. Sonifications of friction, clicking, and vibratory effects reinforce the illusion of physical contact, allowing users to infer object shape, layout, and size without visual input, thereby enhancing accessibility.

Auditory display also modulates object weight perception. Lower-frequency sounds are commonly associated with heavier objects, while increased loudness intensifies the perceived weight of both physical and virtual objects. Virtual collision sounds further reinforce weight perception, strengthening the connection between auditory feedback and the physical attributes of digital objects.

Additionally, the synchronization of auditory feedback with user actions enhances the sensation of direct physical interaction. When auditory cues are spatially and temporally aligned with touch-based interactions, users experience heightened physical realism, such as the illusion of being cut by a sword or detecting subtle tactile stimuli in virtual environments.

4.2.4. *Food and Drink*

Previous research also studied how auditory display influences the perception of food texture and beverage carbonation by modulating crispness, stiffness, and effervescence. By integrating sound with eating and drinking experiences, auditory feedback enhances sensory integration, altering how food and beverages are perceived.

For food texture perception, auditory display influences the crispness and stiffness of various foods. Increasing volume or amplifying high-frequency components enhances the perceived crispness of snacks like potato chips. The absence of air-conducted sounds reduces both the crispness and stiffness of apples, while attenuating high-frequency biting sounds similarly diminishes crispness perception. Additionally, pseudo-chewing sounds, such as “crunchy” electromyographic (EMG) feedback, make nursing care foods feel stiffer, rougher, and richer in ingredients, improving the eating experience for individuals with dietary restrictions.

For beverages, auditory display enhances carbonation perception through sound manipulation. Amplifying high-frequency carbonation sounds and increasing loudness make sparkling water feel more effervescent, reinforcing the sensation of fizziness. Additionally, adjusting the playback speed of carbonation sounds influences carbonation perception, with faster playback creating a stronger impression of fizz.

5. EXAMPLE APPLICATIONS OF AUDIO-INFLUENCED PSEUDO-HAPTICS

Audio-influenced pseudo-haptics use auditory cues to generate, modify, or enhance haptic sensations, creating immersive and interactive experiences across multiple domains. From our research, we extracted three main areas of application, as discussed below.

5.1. Enhancing Virtual Experience

Auditory feedback can induce pseudo-haptic effects to enhance interactions within AR and VR settings. By simulating contact, texture, and force feedback, sound enables realistic interactions without requiring physical actuators. Examples include virtual button presses [34], contact-based illusions [35], object collisions [36], perceived elasticity in above-surface gestures [37], modified impact forces [27], and enhanced hand-rubbing sensations [38, 39].

5.2. Accessibility and Rehabilitation

In accessibility and rehabilitation, audio-influenced pseudo-haptics has been explored for aiding sensory impairments and physical therapy. Hotting et al. found that sighted individuals are more susceptible to cross-modal illusions than those congenitally blind [40]. Ribeiro et al. introduced an auditory AR system to enhance spatial awareness for the visually impaired [41]. Singh et al.s Go-with-the-Flow framework supports movement and breathing in chronic pain patients through sonification [42], while Vogt et al.s PhysioSonic system demonstrated the benefits of movement sonification in physiotherapy [43].

5.3. Training

Sonification of motion plays a crucial role in training and skill acquisition, as it provides real-time auditory feedback that refines motor control. Studies show that movement sonification enhances accuracy and coordination [44, 45], and auditory guidance has improved performance in industrial and medical tasks [46]. For example, sonification improves orthopedic drilling precision [17] and enhances learning in virtual surgery simulations [31].

6. CHALLENGES AND FUTURE WORK

6.1. Technical and Design Challenges

Creating a consistent, synchronized sensory experience by integrating multiple realistic modalities (e.g., visual, auditory, and tactile) is significant for investigating pseudo-haptics, but highly difficult from both technical and design perspectives. As some studies highlighted [47], to generate a convincing pseudo-haptic effect, it is essential to maintain consistent, synchronized auditory display when interacting with other sensory modalities (e.g., vision, proprioception). However, achieving synchronized and convincing multisensory integration remains a technical and design challenge due to space constraints [48], limited accuracy and robustness [37], high latency [49], and inadequate audio or visual rendering capabilities [11]. The choice of auditory reproduction system–whether headphones, loudspeakers, or specialized spatialization techniques for rendering auditory cues–represents unique modalities [50] and may impact the results of pseudo-haptics studies. However, this aspect is often overlooked in the design of experiments or systems. Additionally, the lack of high-fidelity devices and the challenges of generating precise tactile sensations using wearable technology further hinder progress [48].

In addition to these technical challenges, audio-influenced pseudo-haptic systems face challenges in simulating complex sensations like temperature, fine textures, and a convincing sensation of force. This remains a technical limitation for applications that require high tactile precision.

6.2. Auditory Cue Controls Disentanglement

As mentioned in Section 4.1, an auditory cue control parameter can involve multiple attributes simultaneously, making them difficult to disentangle. Pitch and loudness, for example, are distinct yet interdependent auditory attributes. The equal-loudness-level curve [51], also known as the Fletcher-Munson curve, illustrates how loudness perception varies across frequencies. According to this curve, changes in pitch require adjustments in sound pressure level to maintain perceived loudness, a principle applied in several reviewed studies [11].

Similarly, spatial cues such as elevation are closely linked to pitch perception. Elevation judgments rely on spectral cues [52], and higher-pitched sounds are often perceived as originating from elevated sources. Understanding these interactions is essential for accurately modeling their effects on pseudo-haptic perception.

Moreover, on/off controls, among the most frequently used in studies, affect multiple auditory attributes simultaneously, such as pitch, loudness, and timbre. This overlap makes it challenging to isolate the contribution of each attribute to pseudo-haptic perception. A systematic approach is needed to disentangle these interactions and minimize cross-attribute influences, ensuring more precise control over audio-influenced pseudo-haptic effects.

6.3. Spatial Auditory Controls

As immersive technologies such as AR and VR continue to advance, the role of auditory cues in shaping haptic perception remains understudied in spatial auditory displays. Spatial auditory controls, including localization parameters such as azimuth, elevation, and distance, require further investigation to understand their impact on pseudo-haptic effects. Most immersive systems rely on head-related transfer functions (HRTFs) to spatialize sound in AR and VR environments [52]. However, the use of generic, non-individualized HRTFs can introduce perceptual mismatches in spatial representation, potentially affecting pseudo-haptic effects.

Beyond localization, environmental auditory attributes such as reverberation (e.g., room size and decay time) may shape pseudo-haptic effects by reinforcing or altering haptic expectations. While previous research has established associations between auditory cues and pseudo-haptic perception, a key open question is how these effects manifest in spatial auditory displays. Investigating how spatialized sound influences pseudo-haptic experiences, particularly in dynamic, multi-user, real-time AR and VR environments, presents a valuable research opportunity.

6.4. Underexplored Haptic Perceptions

Many audio and haptic elements remain underexplored yet hold great potential for interaction design. For example, cognitive research has shown that people can distinguish between hot and cold water based on the sound of pouring [53]. However, the illusion of temperature change has not been thoroughly studied. In our literature review, only a few studies have briefly touched on the illusion of temperature change when discussing other pseudo-haptic sensations, such as material properties [54], and some did not clarify whether the temperature sensation was triggered by visual or auditory cues [35], providing little insight into how auditory cues specifically influence temperature perception. Similarly, some sensations, such as pain and itching, could be useful for safety education and training, but are also underexplored. Therefore, further research is needed to understand how auditory cues influence underexplored pseudo-haptics, such as temperature perception, sensations of pain, and itching.

7. CONCLUSION

This survey provides a comprehensive review of 89 papers on audio-influenced pseudo-haptics, categorizing auditory cues and mapping them to the pseudo-haptic effects they produce. We summarized key findings and applications, highlighting the role of auditory display in enhancing haptic perception across various domains. While significant progress has been made, many research opportunities remain.

Future work can build on existing findings by refining methodologies for disentangling auditory cue effects, which may lead to a more systematic understanding of their role in pseudo-haptic effects. Additionally, spatial auditory reproduction remains an underexplored factor in pseudo-haptics, particularly in interactive, multi-user AR and VR environments. Investigating how audio-influenced pseudo-haptic effects can be integrated into spatial auditory displays could contribute to more immersive and precise multimodal feedback.

Additionally, investigating underexplored pseudo-haptic effects, such as temperature and pain perception, could further expand the scope of audio-driven haptic illusions. Advancing these areas will deepen our understanding of the interplay between audio and haptics, paving the way for more immersive and effective multimodal interfaces that enhance both virtual and real-world interactions.

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