Audio-influenced Pseudo-haptics: A Review of Effects, Applications, and Research Directions

Supplementary Materials: Detailed Paper Findings

	Roughness (24)	Stiffness (7)	Surface Adhesiveness (4)	Thickness (1)	Material (6)	Dynamic Surface Properties (3)	Touch (6)
Pitch (15)	**(4)** [3] Higher pitch results in lower roughness sensation for electrode stimulated virtual surface [52] Higher pitch results in lower roughness sensation for virtual surface [13, 138] Higher pitch lead to higher roughness sensation for fabric when touching physical surface/ultrasounic surface	**(2)** [52] Higher pitch results in lower stiffness for virtual object		**(1)** [13] Lowering the pitch when touching the fabric makes it feel thicker		**(2)** [58] Greater decay suggests softer materials [131] Higher frequency relates to higher perceived elasticity	**(2)** [65] Pressing sounds enhance the perceived physicality of applying force on a rigid surface [99] Only sounds with the same frequency as the vibrotactile frequency enhance tactile detection
Spectral Manipulation (12)	**(4)** [43,140] Boosting high frequency sounds makes surfaces feel rougher [50] Boosting high frequency when rubbed their palms together makes skin feel smoother [56] Boosting lower frequency sounds makes surfaces feel rougher	**(2)** [4] Higher spectral centroid values correlate with greater perceived stiffness [22] Biting sounds with high-frequency attenuation reduces the perceived hardness of apple samples	**(2)** [43,50] Boosting high frequency sounds makes surfaces feel dryer			**(1)** [61] Sound frequencies of 256 Hz or 966 Hz make the most realistic virtual vibration perception	**(1)** [65] Pressing sounds enhance the perceived physicality of applying force on a rigid surface
Timbre/Texture (3)							**(1)** [102] Providing auditory feedback that matches the object's texture can enhance tactile perception of distant objects
Harmony (2)	**(2)** [19,53] Inharmonic sound makes the virtual surface feels rougher	**(1)** [19] Inharmonic sound makes the virtual surface feels softer					
Loudness (17)	**(6)** [3,13,112,138,140] Greater loudness corresponds to greater roughness [50] Increasing loudness when rubbing palms together makes skin feel smoother		**(1)** [50] Increasing loudness when rubbing palms together makes skin feel dryer	**(1)** [13] Increasing loudness when rubbing palms together makes the fabric feel thicker		**(1)** [131] Louder sounds correspond to greater perceived elasticity	**(2)** [65] Pressing sounds enhance\ the perceived physicality of applying force on a rigid surface [102] More amplified sounds are suitable for inducing the perception of hand movement that are closer to the user
Envelope (2)						**(1)** [58] Faster decay suggests softer materials and slower decay suggests harder materials	**(1)** [65] Pressing sounds enhance the perceived physicality of applying force on a rigid surface
Synchrony (9)							
Location (4)							**(3)** [65] Pressing sounds enhance the perceived physicality of applying force on a rigid surface [89] Auditory cues in the right position enhancing the perception of being cut by a sword [99] Only monaural sounds on the same side increased detection
Distance (4)							
Reverberation (1)							**(1)** [65] Pressing sounds enhance the perceived physicality of applying force on a rigid surface
Audio Content (20)	**(10)** [37,113,114] White noise increases perception of roughness [37] Pure tones have no significant effect [113,114] Pure tones lead to smoother sensations [3,56,112] Consistent auditory feedback enhances overall perception of texture; inconsistent auditory feedback distorts roughness perception [32] Sounds of rougher materials creates roughner sensation for virtual interface; While smoother sound no significant impact [63,69] Touch-produced sound can help users judge the roughness accordingly [73] Sounds with higher frequencies and more irregular patterns tend to increase perceived roughness of surfaces	**(1)** [73]: Higher-pitched, short-duration sounds are associated with stiffer surfaces	**(1)** [73]:Sounds that suggest friction or drag may indicate increased stickiness or wetness, while smoother, higher-pitched sounds may indicate slipperiness		**(2)** [120] Sound-based interaction techniques can change perceived material properties [129] Walking speed is altered when listening to simulated sounds of walking	**(1)** [131] Use stretching sound when the fingers are moving, use popping sound when the virtual controls snap back to original position	
On/Off (21)	**(8)** [22] Rough material sound make it feel rougher; smooth material sound make it feel smoother [37] Auditory cues can make haptic sensations feel rougher [48] Audio-haptic interface allows perception of surface roughness, friction, and softness of virtual fabrics [68] Touch-produced sound helps roughness judgement [73] The presence of audio feedback enhances the perception of roughness [76] Auditory cues influence perception of material properties such as hardness, roughness, and glossiness [82] Mid-air haptics and congruent sound feedback influenced perception of texture attributes [100] Sound can simulate a stylus rubbing against a textured surface	**(3)** [73] The presence of audio feedback enhances the perception of roughness [76] Auditory cues influence perception of material properties such as hardness, roughness, and glossiness. [82] Mid-air haptics and congruent sound feedback influenced perception of texture attributes	**(2)** [73]: Tactile feedback is still dominant [82]: Mid-air haptics and congruent sound feedback influenced perception of texture attributes		**(5)** [10] Auditory feedback can simulate and improve recognition of material textures [39] Auditory cues influence the perception of the materials participants walked on [76] Auditory cues influence perception of material properties such as hardness, roughness, and glossiness [98] Synchronized auditory feedback can convey material properties such as friction, elasticity, or roughness [129] Walking speed is altered when listening to simulated sounds of walking		**(2)** [49] Task-irrelevant sounds can create an auditory-tactile illusion where participants perceived more tactile stimuli than presented [70] Auditory feedback can provide a more natural and immersive interaction
Special Effects/Synthesis Method (5)	**(3)** [11] Real-time synthesis of vibrotactile haptic and audio stimuli can generate realistic roughness and texture feedback [19] Higher modulation frequencies makes it feels rougher [73] Different synthesis methods, such as wavelet-based models, can recreate more realistic rough textures through audio	**(2)** [19] Low and gradual pitch changes makes it feel softer [73] Synthesized sounds that accurately reproduce sharp, sudden, and high-frequency audio cues can greatly enhance the perception of stiffness	**(1)** [73] Impact of auditory cues on stickiness or wetness perception is moderate, with tactile cues playing a larger role		**(1)** [120] Sound-based interaction technique can change perceived material properties		

	Resistance and Friction (3)	Object Shape (2)	Object Weight (3)	Body Weight (4)	Body Representation (6)	Body Movement (10)	Crispness of Food (4)	Beverage Carbonation (1)
Pitch (15)	**(1)** [44] Lower pitch suggests greater force		**(1)** [51] Lower frequency corresponds to higher perceived weight		**(1)** [124] Participants feel their fingers are longer after hearing rising pitch sounds during finger-pulling	**(4)** [27,28] Real-time sonification (using pitch as a key parameter) with visual and proprioceptive feedback enhances motor learning in indoor rowing [93] Surgeons and intermediate-level trainees rely heavily on the pitch and sound of drilling to assess bone density and guide their movements [109] Sound with various pitches increases body movement awareness		
Spectral Manipulation (12)			**(1)** [64] Lower brightness corresponds to higher perceived weight	**(2)** [107] Footstep sounds with lower center frequency filters made participants perceive the virtual avatar as heavier in VR [118] High-frequency augmented walking sounds led to the perception of a thinner body			**(2)** [22] Biting sounds with high-frequency attenuation reduces the perceived crispness of apple samples [141] Auditory feedback (increased loudness or amplified high frequencies) altered the perception of potato chip crispness	**(1)** [141] High-frequency amplification of auditory cues increased the perception of carbonation when holding beverages near the ear, vice versa
Timbre/Texture (3)		**(1)** [104] Natural sounds produced by an object being placed on a surface can influence the scaling of grip aperture	**(1)** [139] Virtual collision sound can altere weight perception		**(1)** [102] Auditory feedback that matches the object's texture is more suitable for enhancing tactile perception of distant objects			
Harmony (2)								
Loudness (17)		**(1)** [104] Natural sounds produced by an object being placed on a surface can influence the scaling of grip aperture	**(2)** [51] Greater loudness corresponds to higher perceived weight [139] Smaller loudness corresponds to lower perceived weight		**(1)** [102] Sound pressure should follow physical distance laws to enhance tactile perception of distant objects		**(1)** [141] Auditory feedback (increased loudness or amplified high frequencies) altered the perception of potato chip crispness	**(1)** [141] Increasing the overall loudness of the auditory feedback led participants to perceive the sparkling water as more carbonated, vice versa
Envelope (2)								
Synchrony (9)			**(2)** [51] Longer delay corresponds to higher perceived weight [64] Audio delay has no significant impact on perceived weight	**(2)** [86] Walk-In music synchronizes with steps, creating a pseudo-haptic sense of gravity [105] In the Marble-Hand Illusion, synchronized audio-tactile feedback made participants perceive their hand as heavier and stiffer, while unsynchronized feedback had no effect	**(4)** [95] Synchronous auditory cues enhance the rubber-hand illusion, while asynchronous auditory cues weakened the illusion [121,123,125] Synchronized auditory feedback made participants perceive their arm as longer, while asynchronous feedback had no effect on body representation	**(2)** [46] Synchronized footstep sounds reduces stride length and walking speed, encouraging cautious gait and enhancing presence in the virtual environment [105] Synchronized audio-tactile feedback makes participants perceive their hand as heavier and stiffer, while unsynchronized feedback had no effect		
Location (4)						**(1)** [45] Varying location of auditory feedback enhances the sense of movement		
Distance (4)					**(4)** [102] Slower sound feedback is more suitable for enhancing tactile perception of distant objects [121,123,125] Perceiving tapping sounds from a farther distance made participants feel their arm was longer, but this effect diminished at very far distances			
Reverberation (1)								
Audio Content (20)	**(2)** [14] Reproducing friction-induced oscillation and sound of different writing tools can improve user engagement and realism in digital writing [44] Lower pitch suggests greater force	**(1)** [33] Auditory display can be used for layout detection and object shape identification via sonification		**(1)** [105] Hearing marble-like sounds in sync with tactile impact made participants perceive their hand as heavier and stiffer, while non-material sounds, like pure tones, failed to induce the illusion.		**(4)** [27,28] Real-time sonification (using different musical instruments) with visual and proprioceptive feedback enhances motor learning in indoor rowing [105] Hearing marble-like sounds in sync with tactile impact makes participants perceive their hand as heavier and stiffer, while non-material sounds, like pure tones, failed to induce the illusion [128] Footstep sounds affect women's bodily sensations		
On/Off (21)	**(2)** [44] Lower pitch suggests greater force [48] Audio-haptic interface allows perception of surface roughness, friction, and softness of virtual fabrics	**(1)** [33] Auditory display can be used for layout detection and object shape identification via sonification				**(3)** [87] Sound alone doesn't significantly impact virtual drilling performance, kinesthetic cues are more crucial [93] Distracting noise (blocking drill sounds) impairs orthopedic bone drilling performance [100] Non-visual feedback increased gesture variability, including trajectory dispersion, and prolonged movement time, indicating that users rely more on tactile and auditory cues when visual feedback is limited	**(3)** [22] The absence of air-conducted sound significantly reduced the perceived crispness and hardness of the apple [30,31] The "crunchy" EMG pseudo-chewing sound made nursing care foods seem stiffer, rougher, and containing more ingredients	
Special Effects/Synthesis Method (5)								**(1)** [141] Altering the playback speed of carbonation sounds affected perception; speeding up the sounds made participants perceive the water as more carbonated, vice versa

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