

Haptic Pillow Sleeve: Enhancing Sleep Quality by Providing Vital Sound Awareness Through Vibrotactile Feedback

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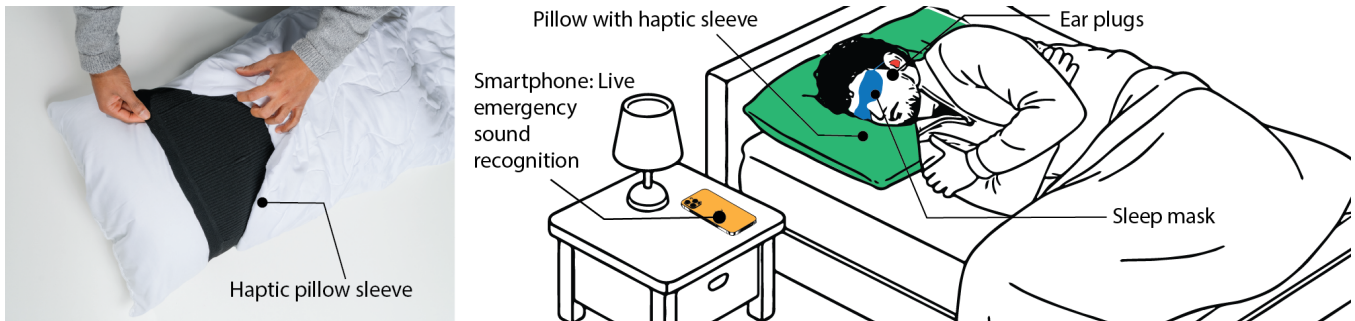


Figure 1: A haptic pillow sleeve prototype designed to support sleep quality in challenging environments where auditory and visual cues are limited, while quietly providing context-based awareness of critical sounds.

Abstract

Sleeping environments—such as shared bedrooms, hospitals, or urban settings—often present challenges due to disruptive noises and conflicting alarm schedules. These disturbances can fragment sleep or cause premature awakening. Conventional solutions like earplugs or white noise machines improve sleep quality but compromise awareness of critical sounds (e.g., fire alarms, baby crying), posing safety risks. To address this, we developed an interactive pillow sleeve that delivers vibrotactile feedback for context-based awareness during sleep. Four distinct haptic patterns were designed to represent specific events: fire alarm, smoke alarm, doorbell, and dog barking. A user study ($n = 10$) evaluated the recognizability

of these patterns under conditions eliminating auditory and visual cues. Results indicate that participants could reliably identify associated events, demonstrating the feasibility of haptic-enabled interfaces for enhancing nighttime safety and situational awareness, particularly for shared sleepers and individuals with sensory impairments.

CCS Concepts

• **Hardware** → **Emerging tools and methodologies; Emerging technologies**; *Communication hardware*; • **Human-centered computing** → *Human computer interaction (HCI)*.

Keywords

Ambient interface, Sleep, Deaf, Hard-of-hearing, Ubiquitous computing, Haptic pillow

ACM Reference Format:

Malindu Ehelagasthenna, Lars Erik Holmquist, Carlos Oliveira, Arash M. Shahidi, Pasindu Lugoda, and Theo Hughes-Riley. 2026. Haptic Pillow Sleeve: Enhancing Sleep Quality by Providing Vital Sound Awareness Through



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CHI EA '26, Barcelona, Spain

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ACM ISBN 979-8-4007-2281-3/26/04

<https://doi.org/10.1145/3772363.3798362>

Vibrotactile Feedback. In *Extended Abstracts of the 2026 CHI Conference on Human Factors in Computing Systems (CHI EA '26), April 13–17, 2026, Barcelona, Spain*. ACM, New York, NY, USA, 6 pages. <https://doi.org/10.1145/3772363.3798362>

1 Introduction

Sleep is a fundamental human necessity and a critical component of overall health: Adequate sleep plays an essential role in supporting emotional well-being, physical restoration, and cognitive functioning [17]. In shared sleeping environments (e.g., sleeping with a partner, dormitories), hospitals, and even urban environments often expose individuals to disturbing sounds and lights during sleep [6, 16, 26]. Common sources of disturbance include alarm sounds arising from different sleep schedules, snoring, emergency alerts such as fire alarms, baby monitors, repeated safety drills that contribute to alarm fatigue, and urban noise from traffic and street [12, 29, 32]. These disruptions negatively affect both the quantity and quality of sleep. Reduced continuous sleep and disruptions to circadian rhythms and normal sleep cycles (progression from light to deep stages) can lead to significant health consequences. Poor sleep quality and quantity are associated with cognitive impairments (e.g., difficulty concentrating), mood disturbances, weakened immune response, hormonal imbalances, and cardiovascular risks [3, 4, 14].

Preventive measures such as earplugs, white noise devices, and sleep masks can mitigate sound and light disturbances to some extent [12, 19, 22]; however, these solutions introduce safety risks by completely blocking auditory and visual cues, leaving individuals vulnerable to life-threatening alerts (e.g., real fire alarms, burglar alarms) [15, 17]. Even simple interventions like earplugs can result in missing personal alarms, such as a morning wake-up call. Since emergency alerts are essential for initiating timely pre-evacuation and pre-movement actions [28], such preventive measures compromise sleep safety and reduce user confidence.

This study presents the design and development of a novel interactive solution to improve quality of sleep: a haptic pillow sleeve equipped with vibrotactile feedback to enhance safety and confidence in challenging sleep environments where ambient sound and light disturbances are suppressed. Unlike wearable devices such as noise-canceling headphones, earplugs, or sleep masks, this approach requires minimal user adaptation, as it integrates seamlessly into a conventional pillow under the pillow cover without imposing additional requirements [34]. To enable further context-sound awareness with tactile feedback, we developed distinct vibration patterns to differentiate alerts such as fire alarm, smoke alarm, doorbell, and dog barking. User trials and empirical evaluations were conducted to validate the effectiveness of these vibrotactile patterns, including an assessment of any acoustic artifacts produced by the vibration system. This study proposes a promising approach to improving sleep quality in shared and noisy environments while maintaining responsiveness to critical sounds.

2 Related Work

2.1 Technological Enhancements for Sleep and Vibrotactile Alerting

Technological enhancements aimed at improving sleep quality, facilitating wake-up process, improving sleeping experience, and reducing sleep disturbances have been widely investigated in various studies [8, 20, 38]. To address sleep quality compromised by sound and light, several alarm systems have integrated vibration-based alerting mechanisms. Among the available sensory modalities, vibrotactile stimulation has been rated as one of the most pleasant yet effective methods for inducing sleep-to-awake transitions, particularly in scenarios where auditory and visual cues are limited [20].

Prominent vibration-based alarm technologies for sleep include bed shakers [2, 11], pillow vibrators [2, 11, 13], wearable vibrating devices [9, 23, 27, 30], and mobile phones placed under pillows [30]. Wearable solutions such as wristbands, smartwatches, and vibrating sleep masks require users to wear them throughout the night [9, 21, 33], raising concerns regarding comfort, user burden, and long-term adaptability. Additionally, user willingness to adopt such devices remains uncertain, especially in contexts where sleep comfort and device unobtrusiveness are priorities.

Specially, using a mobile phone under the pillow is a minimalistic, low-tech approach for vibration alerts; however, it poses significant risks, including exposure to radio-frequency emissions [7, 18], overheating hazards, and potential fire risks [37], and the possibility of the device falling from the bed. Bed and pillow shakers avoid wearability requirements and may therefore reduce adaptation barriers. Nonetheless, bed shakers can disturb co-sleepers due to non-localized vibration propagation across the mattress [26]. By contrast, pillow-based actuation offers more individualized, spatially targeted stimulation that can be directed toward one sleeper, reducing the likelihood of disturbing a partner.

2.2 Interactive Pillow Systems for Sleep Support and Alerting

Interactive pillow systems that employ tactile vibration have been explored across multiple research directions, including sleep relaxation, gentle wake-up mechanisms, and alert interfaces [1, 13, 24]. These interactive pillows function as ambient interfaces, providing subtle and non-intrusive cues embedded into everyday objects within the sleep environment. As sleep safety poses significant challenges for individuals with hearing impairments, a range of conceptual and fully developed pillow-based alarm systems have been proposed to support nighttime alerting [5, 35]. Under-pillow vibrating alarm units, commonly referred to as *pillow shakers*, are specifically designed for deaf or hard-of-hearing users and are often described as compact devices capable of producing strong, attention-grabbing vibrations.

Despite these benefits, existing vibrotactile pillow solutions typically rely on vibration modules that are either rigidly attached to the pillow surface or placed loosely underneath it [10, 13, 24, 25]. Such configurations introduce several practical limitations: pillow shakers may cause discomfort due to lumpiness, can shift position during sleep, and lack secure integration with the bedding. Additionally, pillows incorporating attached vibrotactile modules often

depend on bulky electronics or low-tech attachment strategies that negatively impact usability and long-term comfort. Notably, current technologies lack evidence of context-based vibratory alerting, an important capability that would allow sleepers to distinguish between different environmental sounds through uniquely encoded vibration patterns.

3 Why a Pillow Sleeve?

Prior work underscores (i) the value of vibrotactile cues for reliable, low-intrusion sleep-to-wake transitions [20], and (ii) the practical challenges of sustained adoption with wearable form factors [9, 21, 33]. At the same time, existing sleep-safety technologies show notable limitations in both usability and adaptability. Bed shakers produce strong vibrations that often disturb co-sleepers, while pillow shakers compromise comfort due to their bulk, and are prone to shifting out of place during sleep. As a result, people who need these systems most do not always use them [31]. Integrating vibration into everyday pillow as an ambient interface further enables personalized alerts without disturbing co-sleepers [13].

A pillow sleeve that can be donned over a conventional pillow and covered with a standard pillowcase is a uniquely suitable platform for sleep-related haptics because it is (a) *inconspicuously present* in common sleep environments; (b) *high-contact* with the head and upper body across all sleeping postures; and (c) *habitual*—requiring no additional wearability, nightly adaptation and allowing users the freedom to customize their preferred pillow sleeve (see Figure 2). In contrast to wearable solutions (e.g., wristbands, smartwatches, vibrating masks), a pillow does not require continuous on-body use which reduce comfort, long-term uptake [9, 21, 33]. Compared to bed-wide actuators, a pillow-localized approach concentrates haptic feedback near the user, reducing vibration propagation and minimizing disturbance to a sleeping partner [13].

To enable more effective haptic alerting and to enhance sleep quality, this paper addresses the following core research questions (RQs):

- **RQ1: Context awareness via haptics.** How effectively can context-based vibrotactile patterns help sleepers distinguish among common household alerts (e.g., fire/smoke alarm, doorbell, dog barking), including co-occurring events (e.g., a doorbell followed by dog barking)?
- **RQ2: Acoustic artefacts.** What acoustic artefacts are produced by the vibration patterns embedded within the pillow sleeve, and how might these affect the surrounding sleep environment or co-sleepers?

4 Design and Implementation

The pillow sleeve was seamlessly knitted to form a hollow cylindrical structure with additional tubular channels running lengthwise along its upper surface to form a ribbed surface. Haptic electronic yarns (E-yarns) developed in our previous studies were inserted into these knitted tubular channels. Four haptic E-yarns were strategically positioned to cover the interactive surface of the pillow, ensuring effective tactile feedback across different head positions (see Figure 2). This design preserves key textile properties such as breathability, flexibility, and stretchability while incorporating haptic functionality.

The distal (non-contact) edge of the pillow sleeve includes a knitted pocket designed to house the controller circuit including the microcontroller (Arduino Nano 33 IoT, Arduino[®], Monza, Italy) and the battery. The control system was developed to wirelessly connect with smart devices. In this prototype, the pillow sleeve was paired with an iPhone 13. A low-power IoT platform (Blynk v3.8.2, Blynk Technologies Inc., New York, USA) supported the development of a graphical user interface (GUI) on the iPhone to control the vibrotactile feedback of the pillow sleeve.

The iPhone connectivity demonstrates seamless integration with smart home alarm systems and the potential for customizing alerts based on user preferences (e.g., detecting specific sounds such as a dog barking). For this study, as a proof of concept, we utilized the sound recognition feature of Apple iOS to identify specific sounds and trigger vibration alerts on the pillow sleeve. This was achieved by linking iOS Shortcuts with HTTP network services to notify the Arduino Nano 33 IoT via Wi-Fi. For real-world applications, Bluetooth Low Energy (BLE) communication with smart devices can also be incorporated using the microcontroller used. BLE provides a more resilient option during power outages and can reduce latency issues associated with Wi-Fi—an important consideration in emergencies such as fires or other disruptive situations.

A controlled Wizard-of-Oz user trials was conducted with ten participants (6 (F), 4 (M); Age: 2(18-29), 6(30-39), 2(50+)), who live in either urban settings, share sleeping space with a partner or have lived in shared dormitories. The objective of the study was to evaluate participants' ability to identify and distinguish environmental sounds solely through tactile feedback delivered by the pillow sleeve on a standard pillow, without access to auditory or visual cues. To ensure this condition, participants wore noise-canceling headphones throughout the experiment. Vibrotactile feedback corresponding to specific events (e.g., a fire alarm) were encoded into distinct vibration patterns as shown in Figure 3. Each participant experienced six event types, including two paired co-occurring events: Doorbell, Dog Barking, Smoke Alarm, Fire Alarm, Dog–Doorbell, and Fire–Smoke Alarm. A brief 5-minute familiarization session was conducted at the beginning of the study to allow participants to experience and learn the vibration patterns associated with each event. Following this, each event type was presented six times per participant in a Latin-square order, resulting in a total of 60 trials per event. Participant responses were recorded as either correct or incorrect identifications. After completing the experiment, a short semi-structured interview (approximately 5 minutes) was conducted to gather subjective feedback and suggestions. This user study received ethical approval and informed consent was obtained from all participants.

Additionally, an acoustic study was performed to characterize the noise generated by the vibrations of the haptic pillow sleeve. A calibrated microphone unit (Type 4966-H-041, Brüel & Kjær, Nærum, Denmark) was used to collect detailed acoustic data. The microphone and pillow sleeve were placed at varying distances from 0 to 67.5 cm in 13.5 cm increments, simulating the spacing between two sleeping partners on a standard double bed. The acoustic single (6 s samples) was Fast-Fourier transformed and the root mean square (RMS) of the peak frequency was obtained.

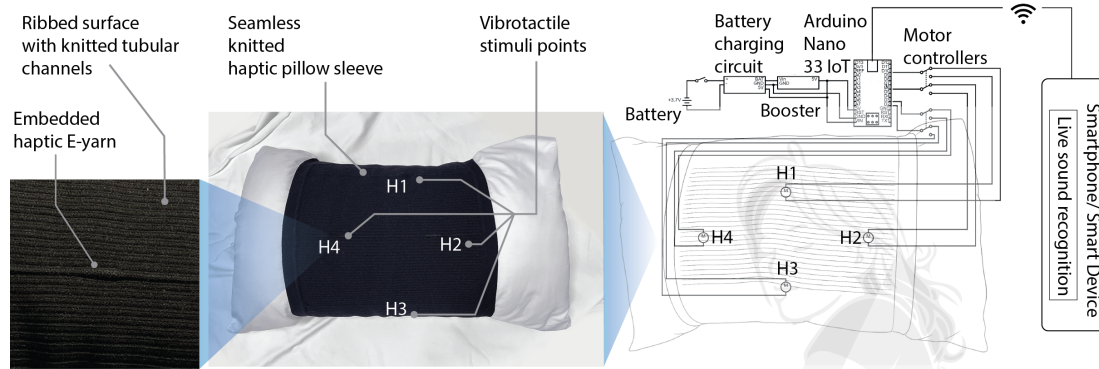


Figure 2: Prototype haptic pillow sleeve showing the placement of vibrotactile haptic actuators (H1, H2, H3, H4) on the pillow, along with the implemented control system.

5 Results and Discussion

5.1 Event Identification Accuracy

Overall identification accuracy was high across all event types (see Figure 3). Mean accuracy ranged from 90.0% for Dog Barking to 100% for Dog–Door and Fire–Smoke. Doorbell events were correctly identified in 59 out of 60 trials (98.3%). Smoke Alarm and Fire Alarm events showed comparable performance, each with an accuracy of 91.7%. To quantify the reliability of these binomial proportions, 95% Wilson confidence intervals were computed for each event type. Confidence intervals were narrow for all conditions, indicating stable performance across participants. Events involving combined cues (Dog–Doorbell and Fire–Smoke) achieved perfect accuracy.

Identification accuracy for all event types was significantly above chance level of 16.7% (binomial tests, all $p < 0.001$), suggesting that participants were able to reliably distinguish between events. Due to the presence of ceiling effects and the exploratory nature of the study, no inferential comparisons between event types were emphasized.

The qualitative feedback provided by participants reflected their lived experiences during and after the test. Embedded quotes were grammatically adjusted using “[]” for clarity. Some participants reported skepticism about placing vibration on the head (“[I’m] not sure I like to keep my head on this. But as I use [a] pillow between [my] knees, I would use it [as my haptic pillow].”_{p3}). Other participants expressed feeling uncertain, unsafe, or isolated when using noise-cancelling devices while sleeping suggesting the significance of a haptic pillow sleeve (“I don’t want to cancel out all sounds. I want to have the connection with [my] surroundings. Otherwise I feel scared.”_{p1}).

5.2 Acoustic Artefacts

Mean acoustic pressure ($P_{a,ms}$, dB scale) was measured at increasing distances (0–67.5 cm) for three vibration intensity levels (LOW, MEDIUM, HIGH), tested both with and without a pillow cover (over the haptic pillow sleeve). Across all vibration intensities, acoustic pressure decreased monotonically as the distance from the vibration source increased (see Figure 4). As expected, higher vibration intensity levels resulted in greater measured acoustic pressure at

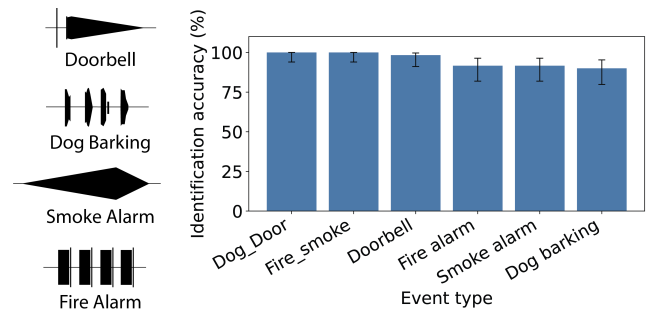


Figure 3: Simulated vibration patterns for each event tested on the haptic pillow sleeve and the mean identification accuracy for each event type across 60 trials per condition. Error bars represent 95% Wilson confidence intervals. Co-occurring events (Dog–Doorbell, and Fire–Smoke Alarm) exhibit ceiling effects.

every distance. At 0 cm, the HIGH intensity produced substantially larger acoustic pressures than the MEDIUM and LOW levels, with differences of approximately 30–40 dB. Placing a pillow cover over the haptic pillow sleeve generally reduced the measured acoustic pressure across distances and intensity levels, although the magnitude of attenuation varied depending on the vibration level. At larger distances, the effect of the pillow cover became more variable.

Overall, the results indicate that LOW and MEDIUM vibration intensities produce very quiet acoustic artefacts, falling below ambient sound levels at distances of 30 cm or more. This suggests that vibration-generated noise is unlikely to disturb a co-sleeping partner and remains within the WHO-recommended night-time noise exposure limit of < 45 dB [36]. Therefore, the HIGH intensity setting may be appropriate for urgent alerts such as fire or smoke alarms, while LOW and MEDIUM intensities can be customized for personal morning alarms or user-defined sound awareness notifications.

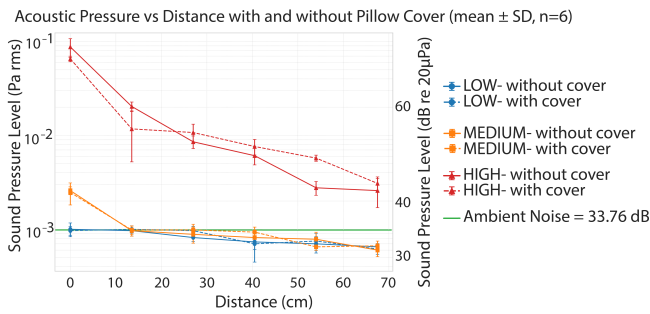


Figure 4: The attenuation of acoustic amplitude (peak sound pressure) generated by vibrotactile feedback with distance with and without pillow cover across three vibration intensity levels (LOW, MEDIUM, HIGH). Error bars represent \pm standard deviation across six repeated measurements at each distance.

6 Conclusion

We developed a haptic pillow sleeve that can be worn over a conventional pillow to enable sound awareness when auditory and visual cues are blocked during sleep. Situations such as using noise-cancelling earplugs, wearing eye masks in noisy shared or urban living environments, or living with deafness or hearing loss can remove access to life-threatening alerts and other essential everyday sounds. This sleeve provides context-based sound awareness in such scenarios, offering perceivable yet quiet vibrotactile feedback without disturbing sleeping partners. The system functions as an ambient display embedded into an everyday object, eliminating the need for users to wear additional devices or adapt their behaviour. Qualitative feedback further highlighted its broader potential across different sleep postures and use cases, suggesting opportunities such as knee pillows, cushion covers for driver alertness, and supportive applications for deaf or hard-of-hearing individuals.

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