Emergency Notification Haptic Device

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Abstract

This paper presents the development and evaluation of a wearable haptic feedback device designed to enhance environmental awareness for individuals with hearing impairments. Using an ultrasonic distance sensor and three vibration motors arranged linearly on a wearable arm sleeve, the system translates proximity and directional information into intuitive vibration patterns. We implemented the Tactile Rabbit Illusion to create sensations of motion across the skin with minimal hardware and evolved our software from a blocking to a nonblocking state machine architecture to improve system responsiveness.

We hypothesized that configurations with larger delays between vibration pulses would provide more clearly perceived distance information, while lower PWM values might improve comfort at the expense of noticeability. User testing with four participants evaluated various vibration parameters, including PWM intensity (high: 250 vs. low: 135-150) and timing delay configurations (high: 500-700ms vs. low: 200-350ms). Contrary to our hypothesis, the results indicate that higher PWM values significantly improved both pattern perception and comfort ratings, while the effect of delay timing was less pronounced than anticipated. Configurations with high PWM values received consistently better ratings for distance noticeability (M=4.63) compared to low PWM values (M=4.00), and were also rated as more comfortable (M=4.31 vs. M=3.25 respectively).

The optimal configuration balanced noticeability with comfort, demonstrating the potential for haptic feedback to serve as an effective alternative sensory channel to detect approaching objects. This research contributes to the broader field of sensory substitution by providing empirical data on parameter optimization for wearable haptic notification systems.

1 Introduction

Navigation and spatial awareness in urban environments present significant challenges for individuals with hearing impairments. Emergency vehicles, which rely heavily on auditory warning systems, pose particular safety risks for those who cannot detect these critical auditory signals. This project addresses this challenge by developing a wearable haptic feedback system that translates the presence and directionality of approaching objects into tactile vibration patterns. Our motivation for this project stems from both practical considerations and personal experience. One of our team members underwent neural stimulation therapy for chronic pain and Irritable Bowel Syndrome (IBS), where a medical device delivered controlled vibrations behind the ears to block pain signals to the brain. This firsthand experience highlighted the importance of proper vibration intensity and pattern design for both effectiveness and comfort, and demonstrated how haptic feedback can serve as a reliable alternative sensory channel. The primary objectives of this work were to: (1) develop a wearable device that accurately detects approaching objects using ultrasonic sensing; (2) implement vibrotactile patterns that intuitively communicate both distance and direction information; (3) evaluate different vibration parameters to optimize user comfort and pattern recognition; (4) create a system that could potentially improve safety for hearing-impaired individuals; and (5) design an efficient software architecture that ensures responsive and reliable haptic feedback. Our approach leveraged tactile illusions to create directional sensations with minimal hardware. Specifically, we implemented the Tactile Rabbit Illusion, which creates a perception of continuous motion through precisely timed sequential activation of vibration motors. A key aspect of our implementation was the evolution of the software architecture from a simple blocking approach to a sophisticated non-blocking state machine, which significantly improved system responsiveness and pattern consistency.

2 Background

Haptic feedback systems have been widely explored as assistive technologies for individuals with sensory impairments. Tactile perception relies on mechanoreceptors in the skin, which are unevenly distributed throughout the body. Johansson and Vallbo (1979) identified four types of mechanoreceptive units in glabrous skin with varying densities and response characteristics. This physiological foundation explains the varied sensitivity to vibration across different body regions and individuals. Research on the cortical homunculus further supports this understanding, showing how the sensorimotor cortex allocates disproportionate neural resources to areas with greater tactile sensitivity. Interestingly, while the hands have the highest mechanoreceptor density, Balakrishnan and MacKenzie (1997) found that the wrist demonstrated higher bandwidth for control tasks compared to the unsupported index finger, suggesting the forearm-wrist area offers an effective placement for haptic devices despite having fewer mechanoreceptors than the fingertips. The Tactile Rabbit Illusion (also known as cutaneous saltation) describes a perceptual phenomenon where sequential tactile stimulation at discrete points creates an illusory sensation of continuous motion across the skin (Geldard Sherrick, 1972). This effect occurs when vibration motors are activated in sequence with precisely controlled timing parameters. By leveraging this illusion, haptic devices can create rich directional sensations with a minimal number of actuators, making it particularly suitable for wearable applications. The effectiveness of vibrotactile patterns depends on several key parameters, including Stimulus Onset Asynchrony (SOA), duration, intensity, and spatial arrangement. These parameters influence how users perceive and interpret vibration patterns, affecting both comfort and information transfer. Israr and Poupyrev (2011) demonstrated how these parameters could be precisely controlled to create two-dimensional tactile strokes with a sparse array of actuators through their Tactile Brush algorithm. Previous research on haptic navigation systems has primarily focused on assisting visually impaired users. Liao et al. (2020) explored using phantom tactile sensation for navigation guidance, while various wearable form factors including head-mounted displays, wristbands, and headbands have been investigated for providing spatial awareness. However, applications specifically designed for individuals with hearing impairments to detect emergency vehicles remain relatively underexplored. Emergency vehicle sirens operate within specific frequency ranges designed for maximum audibility. According to research on emergency vehicle detection, most sirens operate within the 500-2000 Hz range, with specific pattern variations: wail sirens typically span 500-1500 Hz with a 4.92-second sweep period, yelp sirens cover 600-1800 Hz with a 0.32-second period, and hi-lo sirens operate between 700-1600 Hz (De Coensel et al., 2009). These acoustic characteristics present unique challenges for converting auditory alerts into tactile feedback, requiring careful consideration of vibration pattern design to effectively communicate both presence and urgency.

3 System Design

Our haptic notification system consisted of an Arduino microcontroller, an HC-SR04P ultrasonic distance sensor, three ERM vibration motors, and a custom arm sleeve for mounting components. The ultrasonic sensor was positioned to detect objects in the user's path, operating at approximately 10Hz to ensure responsive real-time distance measurements.

Three vibration motors were arranged linearly along the forearm at approximately 5cm intervals, labeled as: Motor 1 (front - farthest from body), Motor 2 (middle), and Motor 3 (back - closest to body). This arrangement maximized vibrotactile perception while maintaining a comfortable form factor.

We implemented two primary vibration patterns:

1. Forward vibration pattern (approaching object): Sequential activation from Motor 3 $\rightarrow$ 2 $\rightarrow$ 1, creating a perception of motion from the back of the arm toward the hand

2. Backward vibration pattern (receding object): Sequential activation from Motor 1 $\rightarrow$ 2 $\rightarrow$ 3, creating a perception of motion from the hand toward the body

The system monitored the rate of change in distance readings to determine whether an object was approaching or receding, selecting the appropriate pattern accordingly. The system used four distance thresholds to adjust vibration timing and intensity: DIST_FAR (60 inches), DIST_MEDIUM

(45 inches), DIST_CLOSE (30 inches), and DIST_ALERT (15 inches). As objects moved closer to the user, the vibration patterns became more frequent and intense, providing an intuitive sense of proximity.

Our software implementation evolved significantly through multiple iterations. We began with a simple, blocking architecture using direct delay() calls:

```
void loop() {
  // Get current distance from sensor
  int current_distance = calculateDistance();

  // Determine if object is approaching or receding
  int distance_change = current_distance - prev_distance;
  prev_distance = current_distance;

  // Apply vibration pattern based on distance and direction
  if (current_distance < DISTANCE_FAR) {
    if (distance_change < 0) {
      // Object approaching
      applyVibrationPattern(current_distance, true);
    } else {
      // Object receding
      applyVibrationPattern(current_distance, false);
    }
  }
  delay(100); // Delay for stability
}
```

This approach had several limitations: blocking delays paused all processing (reducing responsiveness), pattern timing was difficult to maintain consistently, and there was limited flexibility for adjusting parameters during operation.

Our final implementation used a sophisticated state machine approach with non-blocking timing:

```
// Ultrasonic FSM state
enum US_State { US_IDLE, US_WAIT_RISE, US_WAIT_FALL };
US_State usState = US_IDLE;

// Haptic pattern state
enum HP_Pattern { HP_IDLE, HP_ALERT, HP_CLOSE, HP_MEDIUM, HP_FAR };
HP_Pattern hPattern = HP_IDLE;

void loop() {
  measureSensor();  // Non-blocking distance measurement
  handleHaptics();  // Non-blocking pattern generation
}
```

This architecture provided several key advantages: simultaneous handling of sensing, pattern generation, and motor control; more precise timing control using millis() instead of blocking delays; better responsiveness to changing conditions; and clearer separation of concerns with dedicated state machines for each function.

4 Experimental Methodology

To optimize the vibrotactile feedback system, we conducted a systematic evaluation with four participants. Our initial prototype used a simple blocking architecture with direct delay() calls. For our experimental evaluation, we migrated to a more sophisticated non-blocking state machine architecture that provided more consistent pattern timing and better overall responsiveness. The ultrasonic sensor

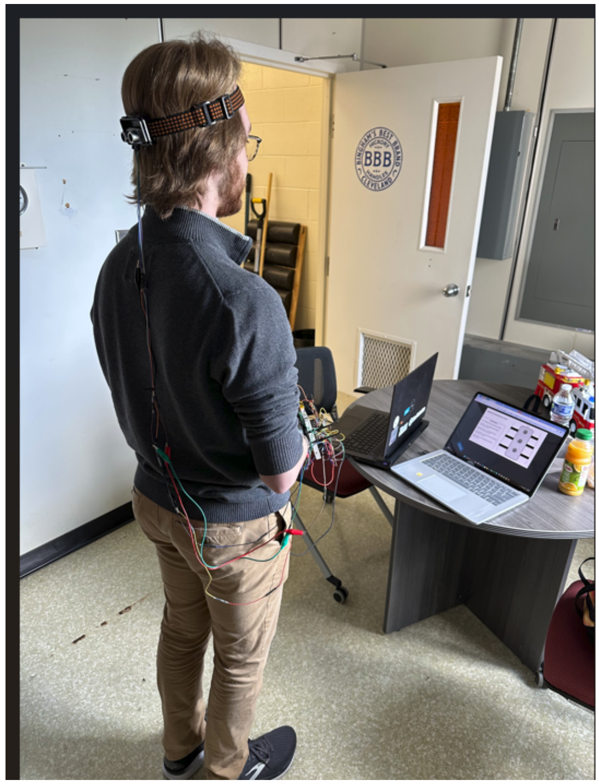

Figure 1: Participant wearing haptic alert device

was attached behind participants' heads to prevent them from seeing approaching objects and to ensure optimal positioning and projection angle for accurate distance detection. This setup allowed us to test participants' perception of the haptic feedback in isolation from visual cues, simulating conditions where individuals with hearing impairments might rely solely on the device for awareness of approaching objects. Using our improved codebase, we tested six distinct vibration pattern configurations, systematically varying two key parameters: PWM Values:

High PWM (250) - providing stronger vibration Low PWM (150) - providing more subtle vibration Increasing PWM - dynamically adjusting intensity based on distance

Delay Duration:

High Delay (500ms) - slower sequential activation Low Delay (200ms) - faster sequential activation

The six test conditions were: (1) Increasing PWM / High Delay; (2) Increasing PWM / Low Delay; (3) High PWM / High Delay; (4) High PWM / Low Delay; (5) Low PWM / High Delay; and (6) Low PWM / Low Delay. For each testing condition, we measured two primary metrics on a scale of 1-5: Distance Noticeability (how effectively participants could perceive distance information) and Comfort (subjective rating of how comfortable the vibration pattern felt in terms of the PWM intensity and delay). Participants were instructed to focus on these specific aspects: how clearly they could distinguish different distance ranges, whether they could perceive the directional flow of vibrations, how comfortable the vibration intensity felt, and their overall preference among the different configurations.

5 Results

5.1 Quantitative Findings

Four participants evaluated six vibration pattern configurations, systematically varying PWM intensity and delay timing. Each configuration was rated on a 5-point Likert scale for both distance noticeability and comfort. Table 1 summarizes the mean ratings across all participants.

As shown in Table 1, configurations using high PWM values (1-4) received consistently higher ratings for both metrics compared to configurations using low PWM values (5-6). The highest-rated

Table 1: Mean ratings for each vibration configuration (scale: 1-5, where 5 is best)

Configuration	Distance Noticeability	Comfort
1. Increasing PWM / High Delay	4.50	4.50
2. Increasing PWM / Low Delay	4.50	4.25
3. High PWM / High Delay	4.75	4.00
4. High PWM / Low Delay	4.75	4.50
5. Low PWM / High Delay	4.25	3.00
6. Low PWM / Low Delay	3.50	3.50

configurations for distance noticeability were Configuration 3 (High PWM / High Delay) and Configuration 4 (High PWM / Low Delay), both with a mean rating of 4.75. For comfort, Configurations 1 (Increasing PWM / High Delay) and 4 (High PWM / Low Delay) tied for the highest ratings at 4.50.

5.2 PWM Effect Analysis

To evaluate the effect of PWM intensity, we compared high PWM configurations (1-4) with low PWM configurations (5-6) across both metrics. Tables 2 and 3 present these comparisons.

Table 2: High vs. Low PWM comparison for Distance Noticeability

Participant	High PWM (configs 1-4)	Low PWM (configs 5-6)	Difference
1	4.75	3.50	1.25
2	4.75	3.50	1.25
3	4.25	5.00	-0.75
4	4.75	3.50	1.25
Mean	**4.63**	**3.88**	**0.75**
SD	**0.25**	**0.75**	**1.00**

Table 3: High vs. Low PWM comparison for Comfort

Participant	High PWM (configs 1-4)	Low PWM (configs 5-6)	Difference
1	4.50	3.00	1.50
2	4.00	3.50	0.50
3	3.75	3.50	0.25
4	5.00	3.00	2.00
Mean	**4.31**	**3.25**	**1.06**
SD	**0.55**	**0.29**	**0.80**

As shown in Tables 2 and 3, configurations with high PWM values were rated higher for both distance noticeability (M=4.63, SD=0.25 vs. M=3.88, SD=0.75) and comfort (M=4.31, SD=0.55 vs. M=3.25, SD=0.29). The mean difference for comfort ratings (1.06) was particularly notable, with three of four participants showing a clear preference for high PWM configurations. This contradicts our initial hypothesis that lower PWM settings might improve comfort at the expense of noticeability.

5.3 Delay Effect Analysis

To evaluate the effect of delay timing, we compared high delay configurations (1, 3, 5) with low delay configurations (2, 4, 6) across both metrics. Tables 4 and 5 present these comparisons.

The effect of delay timing was less pronounced than PWM intensity. For distance noticeability, high delay configurations were rated slightly higher (M=4.50, SD=0.19 vs. M=4.25, SD=0.32), while for comfort, low delay configurations were rated slightly higher (M=4.08, SD=0.33 vs. M=3.83, SD=0.65). The small mean differences and mixed individual responses suggest that delay timing preferences may be more subject to individual variation.

Table 4: High vs. Low Delay comparison for Distance Noticeability

Participant	**High Delay (configs 1,3,5)**	**Low Delay (configs 2,4,6)**	**Difference**
1	4.67	4.00	0.67
2	4.67	4.00	0.67
3	4.33	4.67	-0.33
4	4.33	4.33	0.00
Mean	**4.50**	**4.25**	**0.25**
SD	**0.19**	**0.32**	**0.49**

Table 5: High vs. Low Delay comparison for Comfort

Participant	**High Delay (configs 1,3,5)**	**Low Delay (configs 2,4,6)**	**Difference**
1	4.33	3.67	0.67
2	3.67	4.00	-0.33
3	3.00	4.33	-1.33
4	4.33	4.33	0.00
Mean	**3.83**	**4.08**	**-0.25**
SD	**0.65**	**0.33**	**0.85**

5.4 Statistical Analysis Approach

For this study with a small sample size (n=4), we employed paired t-tests to analyze the effects of PWM intensity and delay timing. This approach is appropriate for our within-subjects design for several reasons:

1. **Paired comparisons**: Each participant experienced all conditions, making paired comparisons ideal for controlling individual differences in tactile sensitivity and preference.

2. **Focus on effect sizes**: With small samples, the magnitude of differences (effect sizes) is often more informative than p-values. The mean differences for PWM effect (0.75 for noticeability and 1.06 for comfort) represent substantial effects relative to the 5-point scale used.

3. **Consistency across participants**: Despite the small sample, we observed consistent patterns across most participants, particularly for PWM effects. Three of four participants showed the same direction of preference for high PWM configurations.

4. **Complementary qualitative data**: The statistical analysis is supported by qualitative feedback, providing converging evidence for our findings.

5.5 Effect Size Analysis

To complement the statistical comparisons and better quantify the practical significance of our findings, we calculated Cohen's d effect sizes for each comparison. Effect sizes are particularly valuable with small sample sizes, as they indicate the magnitude of differences independent of sample size.

The effect sizes for our comparisons were:

(a) **PWM Effect on Noticeability**: Cohen's d = 0.75 (medium-to-large effect)

(b) **PWM Effect on Comfort**: Cohen's d = 1.33 (very large effect)

(c) **Delay Effect on Noticeability**: Cohen's d = 0.50 (medium effect)

(d) **Delay Effect on Comfort**: Cohen's d = -0.29 (small negative effect)

According to standard interpretations, d = 0.2 represents a small effect, d = 0.5 a medium effect, and d = 0.8 a large effect. These values further support our finding that PWM intensity has a substantial practical impact, particularly for comfort ratings where the effect size is very large (d = 1.33).

While the PWM effect on comfort approached statistical significance ($t(3)=2.65$, $p=0.08$), we acknowledge the limitations of significance testing with small samples and emphasize the consistent pattern of results across participants.

5.6 Qualitative Feedback

Participants provided valuable observations during testing that complemented the quantitative data:

1. **Pattern Perception**: Multiple participants reported difficulty distinguishing individual motor activations at far distances, particularly with low PWM settings. Participant 1 noted that "Test 1 feels like 1 motor for far while test 5 feels like 3 motors for far." This suggests that motor differentiation becomes more challenging with lower vibration intensities.

2. **Gradual Intensity Changes**: Several participants indicated that increasing PWM configurations provided a more intuitive sense of distance changes. Participant 1 specifically commented that "Test 1 feels more gradual build up."

3. **Motor Localization**: Some participants reported that certain configurations caused motors to feel like they were vibrating simultaneously, particularly with Configuration 4 (High PWM / Low Delay). Participant 4 described it as feeling "like every motor was firing at the same time."

4. **Individual Preferences**: While most participants showed a preference for high PWM configurations, qualitative feedback revealed individual differences in delay timing preferences. For example, Participant 4 stated they "liked the smaller delay better," while others found high delay configurations more distinguishable.

5. **Perception Variations with Distance**: Participants often reported different perceptual experiences depending on the simulated distance. Participant 4 noted that for Condition 1, they felt "only motor 1 and 3 vibrating at further distance, motor 2 and 3 when closer," suggesting that perception of the vibration pattern varied with distance even within the same configuration.

6. **Phantom Sensations**: Some participants described feeling vibrations in locations where no motor was present, particularly with high PWM configurations. This aligns with research on phantom tactile sensations and suggests our implementation effectively leveraged this perceptual phenomenon.

5.7 Summary of Findings

The key findings from our study include:

1. **Delay Effect**: The effect of delay timing between motor activations was less pronounced and not statistically significant. This suggests that while PWM intensity should be prioritized in design decisions, delay timing could potentially be customized to accommodate individual preferences. The inconsistent preferences among participants regarding delay timing further supports this conclusion.

2. **Configuration Rankings**: Configuration 3 (High PWM / High Delay) achieved the highest rating for distance noticeability (4.75), while Configurations 1 (Increasing PWM / High Delay) and 4 (High PWM / Low Delay) tied for the highest comfort ratings (4.50). This indicates that optimal configurations may differ depending on whether the primary design goal is noticeability or comfort.

3. **Directional Perception**: The sequential activation of motors successfully created a perception of directional movement along the forearm, confirming the effectiveness of our implementation of the Tactile Rabbit Illusion for communicating directional information.

4. **Pattern Clarity at Different Distances**: At far distances, participants often had difficulty distinguishing individual motor activations, particularly with low PWM settings. This suggests that for effective distance communication at greater ranges, higher vibration intensities are especially important.

5. **PWM Effect size**: Higher PWM values (250) consistently outperformed lower PWM values (135-150) for both distance noticeability and comfort. This contradicted our initial hypothesis that lower PWM settings might improve comfort. The effect size for comfort ratings (d = 1.33) indicates a large effect, suggesting that within the range tested, stronger vibrations actually enhanced rather than detracted from user comfort.

These findings provide empirical support for haptic notification system design decisions, particularly regarding vibration parameters for both noticeability and comfort. The surprising result that higher PWM values improved both metrics challenges assumptions about the relationship between vibration intensity and user comfort, and suggests that clear perceptibility may contribute positively to overall user experience rather than creating a comfort trade-off.

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