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Identification of Spatio-Temporal Vibrotactile Stimuli Across the Torso: Toward Egocentric Haptic Navigation

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I. Introduction

The torso has been recognized as a promising site for conveying directional information due to its large surface area, centralized position, and strong egocentric association. Previous studies have explored spatial encoding using vibrotactile arrays along azimuth and elevation, as well as temporal encoding strategies for representing distance. Spatial encoding is critical for conveying orientation [1]. In addition, temporal encoding is essential for encoding proximity or distance to objects in tactile navigation and assistive devices [2].

The combined use of spatial and temporal tactile cues forms a fundamental basis for haptic navigation systems for visually impaired individuals [3], [4]. Previous research has examined identification tasks involving spatiotemporal patterns using vibrotactile grid arrays [5]. However, there has been no systematic investigation into the perception of spatiotemporal patterns designed to intuitively convey egocentric direction across the entire torso.

This work aims to evaluate the identification performance for spatiotemporal vibrotactile stimuli distributed over the anterior torso. These stimuli consist of combinations of discrete tactor locations (spatial) and pulse per second (temporal) presented concurrently. Our goal is to provide insights into designing egocentric haptic navigation systems that convey both directional and distance information. An overview of the experimental setup is shown in Fig. 1.

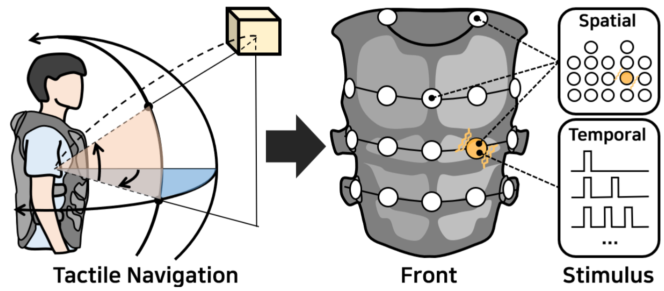

Fig. 1. Overview of the grid array representing egocentric directions on the torso. The distribution of vibration motors across the anterior torso enables both spatial (tactor location) and temporal (pulse per second) encoding for tactile navigation.

Fig. 2. The customized haptic suit (a) and its worn appearance (b).

II. Methods

1) Participants: Twelve participants (six males and six females) without somatosensory disorders took part (age 22.3 ± 3.6 years).

2) Apparatus: We used a customized haptic vest with 17 vibration motors placed on the front side of the torso (Fig. 2): two on the shoulders and fifteen on the torso, as previously implemented in our study [1]. Each motor was mounted in a 3D-printed housing and attached to adjustable belts, enabling consistent skin contact and precise positioning across different body shapes. The fifteen motors on the torso were arranged in three horizontal rows: upper chest, solar plexus, and navel, with five motors evenly spaced per row. This layout formed a uniform spatial grid in both the vertical and horizontal directions.

3) Experimental Conditions: Two experimental factors were defined based on the types of vibrotactile stimuli: spatial (SPA) and temporal (TEM).

The SPA factor represented the location of the stimulus, delivered through 17 vibration motors evenly distributed across the anterior torso. Each spatial stimulus corresponded to a specific tactor location. The TEM factor represented the pulse per second (pps), defined as the number of short bursts (200 ms each) delivered per second. Five levels were used: 1, 2, 3, 4 pps, and continuous vibration (the same as 5 pps).

A total of 85 unique spatiotemporal stimulus conditions (17 spatial × 5 temporal) were generated. Each stimulus was repeated three times during the experiment.

4) Experimental Task: Participants wore a custom haptic suit and performed a spatiotemporal identification task using a touchscreen-based graphical user interface (GUI). In each trial, participants voluntarily initiated the stimulus and stopped it themselves when they perceived and identified the spatiotemporal vibrotactile pattern. The response time

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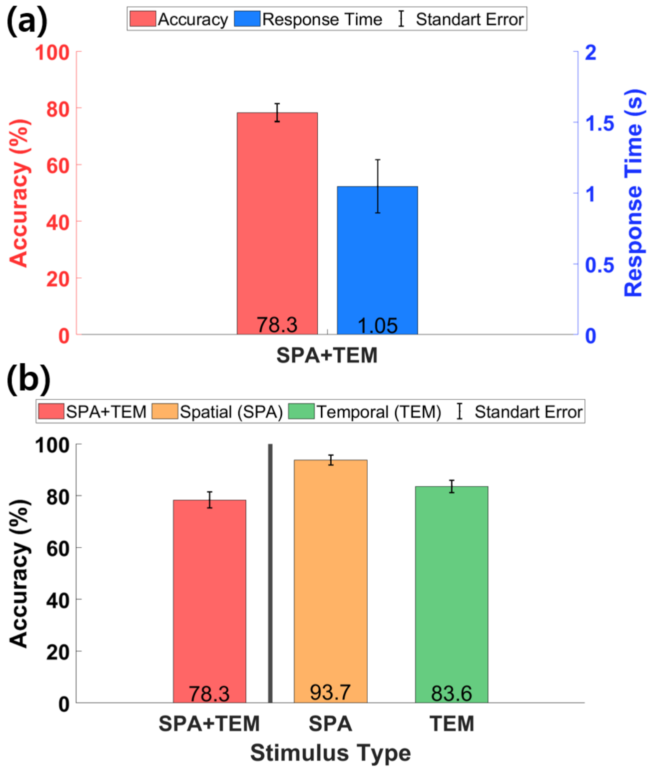

Fig. 3. Identification accuracy and response time performance: (a) Accuracy and response time for spatiotemporal stimuli (SPA+TEM), (b) Accuracy for spatial (SPA) and temporal (TEM) separately.

was measured as the interval between stimulus onset and termination. Afterward, participants selected the perceived spatial location and pulse-per-second (pps) by pressing the corresponding buttons on the GUI. No time constraints were imposed during the task, and participants were encouraged to respond based on confident perception.

III. Results and Discussion

A summary of identification accuracy and response time performance is shown in Fig. 3.

The overall identification accuracy for the combined spatiotemporal stimuli was 78.3%, indicating that both spatial and temporal components were correctly identified. The mean response time was 1.05 seconds, corresponding to the time elapsed after the first 1-second cycle. Given that the combined condition involved 85 distinct spatiotemporal stimulus pairs, this accuracy represents a relatively high performance, demonstrating the feasibility of simultaneously perceiving and identifying both spatial and temporal cues on the torso. In addition, it took approximately two cycles of the spatiotemporal stimulus for perception, suggesting a practical latency for tactile navigation.

we separately analyzed the identification performance for spatial stimuli (SPA) and temporal stimuli (TEM). The identification accuracy for SPA was 93.7%, indicating that participants could reliably identify the location of vibrotactile cues distributed across the anterior torso. In contrast, the accuracy for TEM was 83.6%, which is also relatively high but showed greater perceptual challenges than SPA. Participants experienced more difficulty in identifying temporal stimuli, likely due to small perceptual differences between the five levels (1–4 pps and continuous vibration). We speculate that adopting the burst interval and duration could improve the discriminability of temporal patterns.

Additionally, we evaluated the information transmission (IT) efficiency to quantify the effective information conveyed through the stimuli. For the combined spatiotemporal stimuli, the estimated information transmission (IT_{est}) was 5.45 bits out of a maximum of 6.41 bits, which corresponds to the ability to perfectly identify approximately 43.7 stimuli out of 85. For spatial stimuli (SPA), IT_{est} was 3.72 bits out of 4.09 bits, equivalent to identifying approximately 13.2 out of 17 spatial locations. For temporal stimuli (TEM), IT_{est} was 1.63 bits out of 2.32 bits, corresponding to identifying about 3.1 out of 5 temporal patterns.

The relative performance scores, computed as the ratio of observed accuracy to randomness, were 15.9 for SPA and 4.2 for TEM, indicating that spatial information was transmitted more efficiently than temporal information. These findings demonstrate that the torso is a highly effective site for delivering spatial cues, yielding high identification accuracy. The temporal information showed potential but requires further optimization to enhance perceptual discriminability.

IV. Future Works

Future research will focus on optimizing spatial and temporal stimulation patterns to further improve identification performance. Specifically, we will explore the spatial tactor layout across the entire torso, including the back, to support intuitive egocentric cueing. Temporal parameters such as pulse interval and duration will also be adjusted to enhance perceptual discriminability and reduce cognitive load.

Additionally, we plan to conduct systematic association studies to examine how each spatial location and temporal pulse-per-second level are perceived in terms of real-world directions and distances. This work will provide critical insights for designing intuitive and effective haptic navigation systems that can deliver egocentric spatial guidance through torso-based vibrotactile stimulation.

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