2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

Intensity-Based Tactile Changes are Detected Faster than Location-Based Tactile Changes

Lauren E. Horde
Department of Systems and Information Engineering
University of Virginia
Charlottesville, USA
yzr5mz@virginia.edu

J. Michael Bertsch
Department of Systems and Information Engineering
University of Virginia
Charlottesville, USA
xyp5sj@virginia.edu

Sara Lu Riggs
Department of Systems and Information Engineering
University of Virginia
Charlottesville, USA
sr4ex@virginia.edu

***Abstract*—Haptic and multimodal displays fundamentally rely on a user's ability to accurately detect when a change occurs within the display. The present study compared change detection performance between tactile stimuli defined by featural (i.e., intensity) and spatial (i.e., location) properties using a two-alternative forced choice (2AFC) paradigm to determine whether they can be considered equivalent. Electroencephalography (EEG) and the event-related potential (ERP) technique were used to complement behavioral data by providing a view into the neural characteristics and time course of tactile information processing. Results indicate that feature-based and space-based tactile stimuli do not significantly differ in sensitivity as signal detection theory defines. Despite this, behavioral responses to feature-based stimuli are nearly 100 ms faster than space-based stimuli. Participants also displayed a more conservative response bias (i.e., they were more likely to indicate that a change did not occur) for feature-based stimuli. The difference in reaction time may be related to a positive priming effect or time-distance relationship instead of early discriminatory processes. This interpretation is supported by the absence of differences in the ERP waveforms that represent such early discriminatory processes. Overall, these findings have significant implications for how tactile cues are designed for future haptic and multimodal displays.**

***Keywords*—change detection, electroencephalography, EEG, event-related potentials, haptic interfaces, human factors, signal detection theory**

I. INTRODUCTION

The tactile modality is increasingly being used to transmit information in human-machine interfaces [1], [2]. Transmitting information via the tactile channel is a promising solution in complex domains such as aviation or healthcare because it can offload the often oversaturated visual and auditory channels. While the tactile modality is a promising means of presenting information, the phenomenon of change blindness—i.e., the failure to detect changes between stimuli—has been repeatedly demonstrated in the tactile modality [3], [4], [5]. Change blindness is thought to result from the failure to accurately store and compare a set of stimuli in the working memory. This failure is possibly due to limited attentional resources, capacity, or faulty stimulus encoding [6], [7], [8]. Change detection performance has been shown to deteriorate as a result of several factors, such as a low magnitude of difference in intensity between stimuli [9] and the amount of time given to encode pre-change stimuli [8]. Originally observed in visual displays, change blindness has also been seen in the auditory channel (as "*change deafness*" [10], [11]) and the tactile channel across a variety of contexts and stimulus parameters [12], [13], [14].

Emerging vibrotactile and multimodal displays are often designed to rely on a user's ability to detect changes, such as spatial or featural aspects of tactile stimuli (e.g., [2], [15], [16], [17]). Therefore, the ability to accurately detect changes is fundamental for the viability of these displays. Despite some prior work, explorations into the phenomenon of change detection in touch remain limited with even fewer inspections at the neurological level. By using electroencephalography (EEG) and the event-related potential technique in addition to behavioral metrics, we can visualize and draw conclusions about how space- and feature-based tactile information is processed at the millisecond-level in the brain. Supplementing behavioral data with ERP evidence provides a richer comprehension of tactile change detection beyond what behavioral data alone can afford. For example, differences or failure points in the time course of tactile information processing may be identified. Event-related potentials (ERPs), extracted from an EEG, are time-locked deflections in voltage specific to an event that can be used to make inferences about neural and cognitive processes. ERPs have been used to understand characteristics of information processing such as conscious perception [18], the focusing of attention [19], and change detection [20]. For example, the P1 and N1 ERP components have been found to reflect early somatosensory processing with a particular sensitivity to attention [21], [22]. Similarly, the N2 has previously been linked to visual and auditory change detection [20] and the focusing of attention [11], [19], while the P3 is typically associated with conscious perception and decision making [23].

It is not well understood whether feature- and space-based tactile changes can be considered equivalent with regard to change detection performance. Performance differences could arise based on the different ways spatial and object-based (i.e., featural) tactile information is processed in the somatosensory cortex. It is generally thought that dorsal and ventral streams uniquely process somatosensory information in each brain hemisphere. The dorsal steam is related to the "where" in the primary somatosensory cortex whereas the ventral stream relates to the "what" in the secondary somatosensory cortex [24], [25].

The present study deliberately tests pre- and post-change tactile stimuli pairs defined by spatial (i.e., location) and

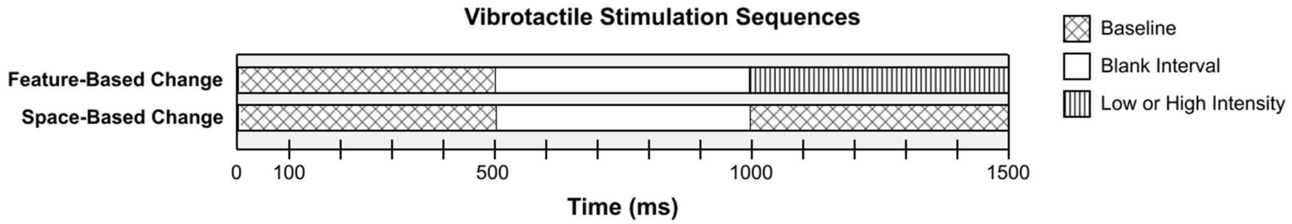

Fig. 1. The vibrotactile stimulation patterns. A feature-based change stimulus consisted of 500 ms of pre-change baseline vibration followed by 500 ms of a blank interstimulus interval (ISI), then 500 ms of post-change vibration at either a low or high intensity. A space-based change stimulus presented the pre-change baseline vibration for 500 ms followed by 500 ms of a blank ISI, then 500 ms of post-change baseline vibration using a different combination of finger digits.

featural (i.e., intensity) properties using a two-alternative forced choice (2AFC) paradigm to isolate change detection effects grounded in characteristics of the tactile stimuli. Signal detection theory metrics are used to examine the sensitivity and response bias that are individually associated with feature- and space-based tactile stimuli [26]. The ERP technique is utilized to examine whether such differences between the tactile stimuli are exhibited in higher order cognitive processing steps shown in the EEG data.

II. METHOD

A. *Participants*

Sixteen students (8 men and 8 women; mean age = 25, *SD* = 3.14) at the University of Virginia participated in this study. This experiment complied with the Declaration of Helsinki and was approved by the institutional review board at the University of Virginia (IRB#: 6160). All participants were required to have no known disorder or injury that affects the sense of touch based on self-report. Participants gave written informed consent to take part in the experiment.

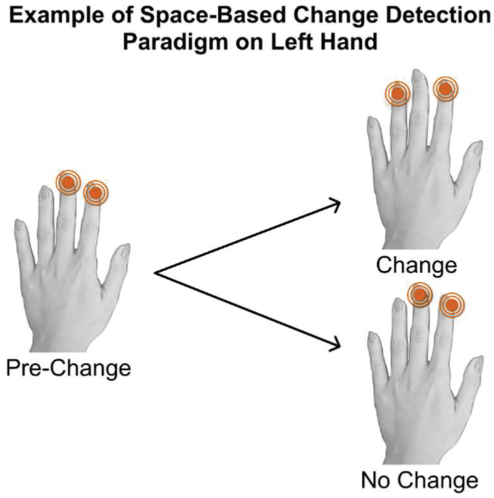

Fig. 2. Example of the space-based change detection paradigm on the left hand. The pre-change stimulus consists of two fingertips stimulated (e.g., the pointer and middle). If there is no change, the same two fingertips are stimulated. If there is a change, one of the two pre-change fingertips will change location (e.g., from the middle to the ring finger).

B. *Apparatus and Stimuli*

Participants were presented with two 2AFC tasks [26], akin to change detection tasks, using 10 mechanical tactors (Tactor, Dancer Design, UK) measuring 18 mm in diameter attached to the distal phalanges of both hands with hypoallergenic adhesive tape. The tactors were controlled by an amplifier driver circuit and manipulated using a microcontroller (Arduino Uno, Arduino, Italy). A routine in E-Prime (E-Prime 3.0, Psychology Software Tools, USA) communicated with the microcontroller via serial port to selectively control which fingers to activate on each trial. Tactile stimulation was driven by sound files preloaded in E-Prime. During the experiment, participants were seated comfortably in an armchair in a windowless, dimly lit room, facing toward a wall with a crosshair fixation point. The participant's hands were shielded from view while resting approximately 8 cm apart on a cushioned desk mat.

The experiment consisted of 160 trials separated into two task blocks (Task 1 = space-based change detection, Task 2 = feature-based change detection). Tasks 1 and 2 consisted of a pair of pre-change and post-change tactile stimuli presented for 500 ms each, separated by a 500 ms blank interstimulus interval (Fig. 1). Pilot testing found the two tasks to be of similar difficulty. Tactile stimuli could appear on any two fingers of the same hand and were delivered at a constant 100 Hz frequency to enable detectability based on the proportion of mechanoreceptors in the fingertips [27], [28], [29]. Participants were given verbal instructions to focus their eyes on a fixation point posted on the wall in front of them and to indicate whether they felt a change in consecutive tactile cues using foot pedals located on the floor (left foot pedal = change, right foot pedal = no change). The foot pedals could be used at any time following the onset of the pre-change stimulus. Participants wore foam ear plugs and white noise was continuously played over a loudspeaker to mask any noise from the vibrotactile stimuli that could influence participant responses. Participant response times were limited to a maximum of 5 s for each trial. Trials without a response were removed from further analysis. The accuracy and response times associated with each trial were automatically recorded by E-Prime. Participants completed 10 practice trials after receiving verbal instructions. A 1-minute break was taken between blocks. Task blocks were counterbalanced across participants and trials within each block were presented in random order with equal probability. An equal number of trials were presented to the left and right hands, with changes present in 50% of the trials.

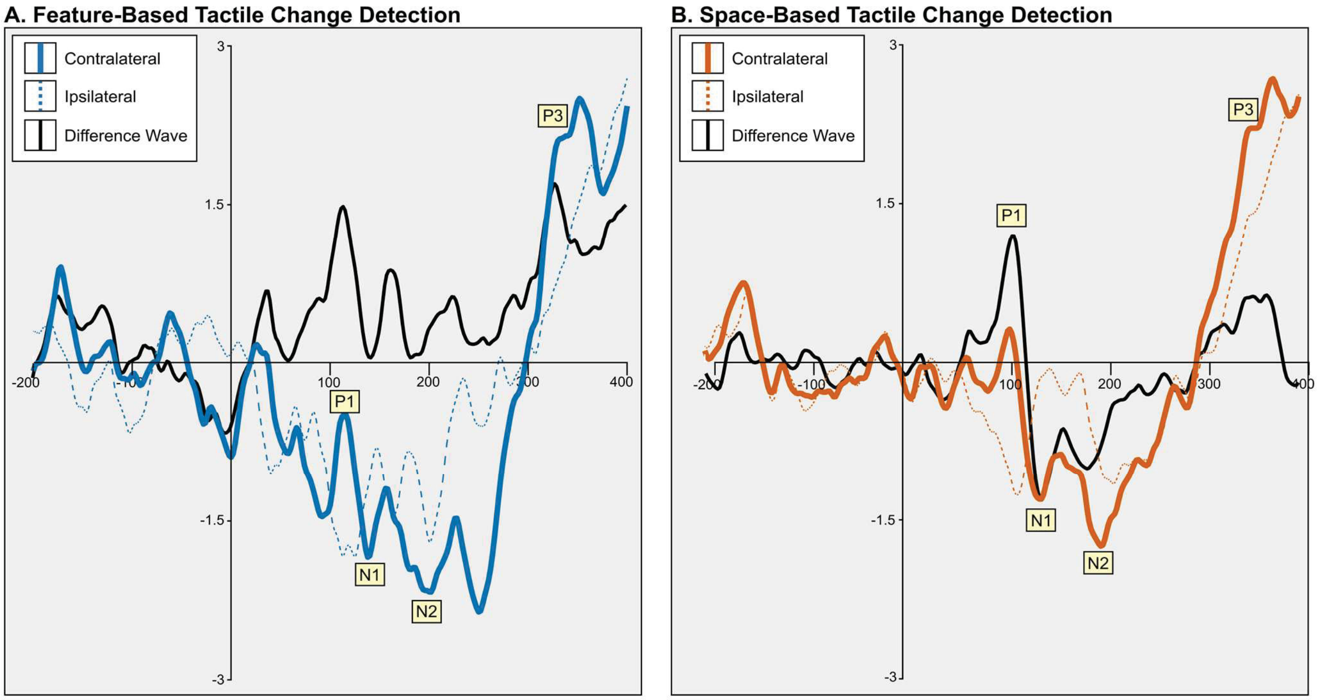

Fig. 3. Grand average ERPs generated in response to feature-based and space-based tactile changes measured at electrodes C3/C4 (overlaying somatosensory cortex) contralateral and ipsilateral to the task-relevant hand. Thick colored lines (blue = feature-based, orange = space-based) designate the contralateral waveform, thin dashed colored lines designate the ipsilateral waveform; black lines represent the contralateral-ipsilateral difference wave. The yellow highlighted boxes denote the mean onset of the P1, N1, N2, and P3 components.

C. *Space-Based (Location) Change Detection Task*

In the location change detection task, two fingers on the same hand were chosen at random for pre-change stimulation. During a change trial, the location of one of the two fingers initially stimulated changed to another digit on the same hand (Fig. 2). For change and no-change trials, intensity was held constant at the baseline intensity for all digits stimulated.

D. *Feature-Based (Intensity) Change Detection Task*

In the intensity change detection task, pre-change stimuli were presented at baseline intensity (30% sound file amplitude) to two fingers on the same hand. The location of the fingers were held constant for change and no-change trials. During a change trial, the intensity of the vibrotactile stimulus could be presented at either low (10% sound file amplitude) or high (90% sound file amplitude) intensity to both digits (Fig. 1). Pilot testing confirmed these values to be distinguishable as lower and higher than the baseline intensity.

E. *EEG Data Acquisition*

EEG data was sampled at a rate of 500 Hz and DC-recorded using the BrainVision Recorder (actiCHamp Plus, Brain Products GmbH, Germany) from 32 Ag/AgCl active electrodes placed at locations according to the extended 10-20 International System. Electrode impedances were kept below 10 kΩ. The continuous EEG recording was online referenced to the midline frontal (Fz) electrode and later re-reference offline to the average of the left and right mastoids (electrodes TP9 and TP10).

F. *EEG Preprocessing*

Raw EEG data was pre-processed using EEGLAB [30] and ERPLAB [31]. The data was offline filtered using a high-pass filter with a half amplitude cutoff at 0.1 Hz (Butterworth, II order) to remove slow drift and a low-pass filter of 30 Hz to remove line noise. The EEGLAB extension 'trimOutlier' [32] was used to identify and remove data points with bad channels that were not within a voltage window of 2-200 microvolts. Independent component analysis (ICA) was used to identify and remove artifacts corresponding to eye blinks. EEG epochs were then created for an 800 ms period after the onset of the post-change stimulus. Epochs were baseline corrected relative to the mean of a 200 ms pre-stimulus baseline. Artifact rejection was applied using a simple voltage threshold of 50 μV on the epoched data. Participant data was removed from further analysis if >30% of trials were rejected. On average, 18% of trials were rejected among participants. ERPs were subsequently measured in selected electrodes (C3 and C4) overlaying the somatosensory cortex contralateral and ipsilateral to the task-relevant hand (Fig. 3). Further statistical analyses were performed for 'hit' trials to examine instances of successful change detection.

G. *ERP Analysis*

Component onset latency and mean amplitude were calculated for the P1, N1, N2, and P3 ERP components across participants for instances of successful change detection. Onset latency was calculated using jackknife-based methods [33], [34] and fractional area latency [35, Ch. 10.8] on contralateral-ipsilateral difference waves. Mean amplitude analyses were performed on single participant waveforms using measurement windows aligned with the latencies of the P1 (90-130 ms), N1 (110-160 ms) [36, p. 369], N2 (170-240 ms) [19], and P3 components (300-500 ms) based on prior literature and verified by visual inspection of the grand average waveforms.

A series of repeated measures analyses of variance (ANOVAs) with the levels of trial type (space-based or feature-based) were performed on the mean amplitude data for contralateral P1, N1, and P3 components. *T*-tests were performed on the onset latency data. The N2 component was assessed separately with a repeated measures ANOVA with the levels of Trial Type and Laterality (contralateral or ipsilateral) to determine if the presence of a lateralized N2 component could be confirmed [19]. The *t*-statistics and *p*-values for onset latency analyses using the jackknife approach were adjusted according to [33] and [37, pp. 322–323].

H. *Behavioral Analysis*

Statistical analyses for behavioral data were performed with the dependent measures of response accuracy and reaction time (RT). Nonparametric signal detection theory measures of sensitivity (*A'*) and response bias (*B''D*) were calculated across the task conditions using response accuracies (hit, miss, false alarm, correct rejection) [38], [39]. Nonparametric measures were used due to the limited number of participants. Sensitivity (1) describes the signal to noise ratio, while response bias (2) explains whether subjects took a conservative (i.e., responding ‘no’ more often) or liberal (i.e., responding ‘yes’ more often) approach to the task. In (1) and (2), *H* indicates the hit rate, in which the number of hits is divided by the total number of signal trials; *F* is the false alarm rate, in which the number of false alarms is divided by the total number of noise trials. The results were analyzed using a series of paired *t*-tests subjected to Holm corrections.

$$A' = \begin{cases} .5 + \dfrac{(H-F)(1+H-F)}{4H(1-F)} & \text{when } H \geq F \\ .5 - \dfrac{(F-H)(1+F-H)}{4F(1-H)} & \text{\&when } F < H \end{cases} \quad (1)$$

$$B''D = \begin{cases} \dfrac{H(1-H)-F(1-F)}{H(1-H)+F(1-F)} & \text{when } H \geq F \\ \dfrac{F(1-F)-H(1-H)}{F(1-F)+H(1-H)} & \text{\&when } F < H \end{cases} \quad (2)$$

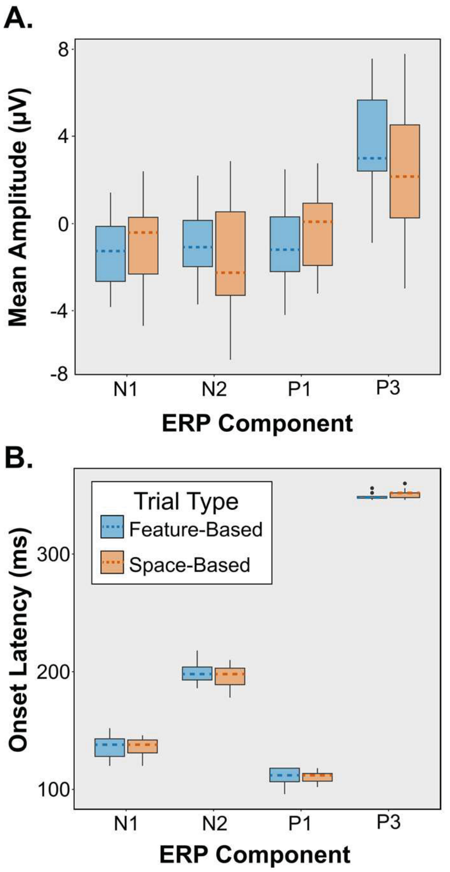

Fig. 4. The mean amplitude and onset latency for ERPs elicited in response to feature-based (blue) and space-based (orange) tactile stimuli across all participants. The dashed colored lines denote the mathematical mean in each boxplot. (A) Mean amplitude, measured in microvolts, of the N1, N2, P1, and P3 ERP components for feature-based and space-based tactile stimuli. There were no significant differences in the amplitude of ERPs for feature-based and space-based tactile stimuli. (B) Onset latency, measured in milliseconds, for the N1, N2, P1, and P3 ERP components. There were no signfiicant differences in the onset of ERPs elicited in response to feature-based and space-based tactile stimuli.

III. RESULTS

A. *ERP Mean Amplitude*

The mean amplitudes of the P1 N1, and P3 ERP components at electrodes C3/C4 were analyzed using a repeated measures ANOVA with the factor Trial Type (feature-based or space-based). There was not a significant main effect of trial type on mean amplitude found for the P1, N1, or P3 component (Fig. 4A).

The mean amplitude of the N2 component was analyzed using a separate repeated-measures ANOVA with the factors Laterality (electrodes contralateral or ipsilateral to the task hand) × Trial Type. There was not a significant main effect of trial type or laterality on the mean amplitude of the N2 component. Prior work has reported lateralized N2 components associated with successful change detection, in which the contralateral N2 exhibits a larger amplitude than the ipsilateral N2 over specific electrode regions (e.g., the N2pc [20] and N2ac [11]). However, the presence of such a component over somatosensory cortex electrodes C3/C4 (e.g., the N2cc [19]) could not be confirmed beyond visual inspection in our data due to the lack of a main effect of laterality for N2 component amplitude (Fig. 3). Spatial priming associated with the stimulus presentation design in both space- and feature-based trials may have prevented an appreciable difference in N2 amplitude [40].

B. *ERP Onset Latency*

ERP onset latency was analyzed using a repeated measures ANOVA with the factor Trial Type (feature-based or space-based). There was not a significant main effect of trial type on component onset latency for the P1, N1, N2 or P3 (Fig. 4B). Prior work has shown that the onset of N2 components can

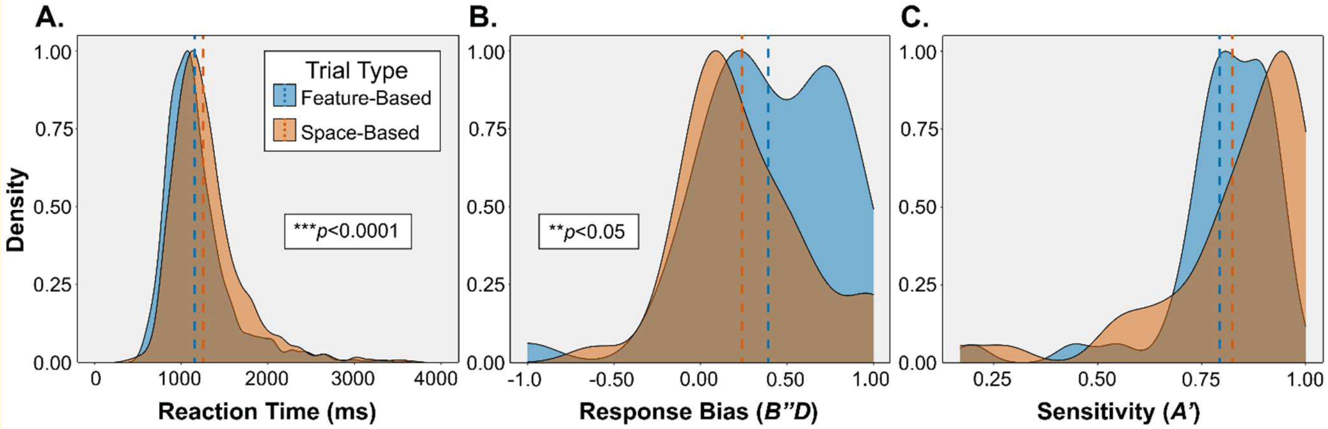

Fig. 5. Behavioral data results for all participants for feature-based (blue) and space-based (orange) tactile stimuli compared using t-tests. The dashed colored lines denote the mathematical mean for feature- and space-based stimuli in each density plot. (A) Reaction times (RTs) for space- and feature-based trial types across all trials. RTs differed by 100 ms on average, with a faster RT for feature-based stimuli. (B) Response bias measured by *B''D* across participants. *B''D* is measured on a scale from -1 to +1: when positive, the response bias exhibited is conservative; when negative, the response bias is liberal. A *B''D* score equal to 0 indicates neutrality. Feature-based trials were responded to more conservatively on average than space-based trials. (C) Sensitivity measured using *A'* across participants. An *A'* of 0.5 is considered near-chance performance, or guessing, while an *A'* = 1 is perfect sensitivity [38]. There was not a significant difference in sensitivity between feature- and space-based tactile changes.

reflect the time at which stimulus discrimination occurred and correlate with reaction time. While our results did not reach significance, the mean N2 onset for feature-based (M = 186.25 ms) and space-based (M = 193.75 ms) trials exhibited this trend. That is, N2 onset was faster on average for feature-based trials in which participants also responded faster.

Visual inspection of the feature-based and space-based ERP waveforms shows a delayed ipsilateral P1 and N1, however, this simply demonstrates the process of communication from contralateral to ipsilateral hemispheres. A delayed ipsilateral waveform is typical to observe as information flows between brain hemispheres [36].

C. Reaction Time

Reaction time (RT) was analyzed using a paired samples *t*-test. A significant difference in RT for feature-based and space-based tactile changes was observed, $t(1279) = -6.67$, $p < 0.001$ (Fig. 5A). Participants responded, on average, 99.46 ms faster when presented with feature-based (M = 1158.26 ms, SD = 458.59 ms) trials than space-based (M = 1257.72, SD = 504.65 ms) trials. This pattern was observed across response accuracies (i.e., hit, miss, correct rejection), except in the case of false alarms in which space-based trials were responded to more quickly. Table 1 shows the average RTs for the response accuracies of space-based and feature-based trials, with cells highlighted in yellow denoting instances of shorter RTs by trial type.

TABLE I. MEAN REACTION TIMES FOR FEATURE-BASED AND SPACE-BASED RESPONSE ACCURACIES

		Trial Type	
		Feature-Based	Space-Based
Response Accuracy	Hit	1141.62 ms	1311.16 ms
	Miss	1274.48 ms	1583.71 ms
	False Alarm	1346.80 ms	1211.67 ms
	Correct Rejection	1165.93 ms	1244.10 ms

D. Response Bias

Response bias, assessed using *B''D*, was analyzed using a paired samples *t*-test and showed a significant difference between feature-based and space-based tactile changes, $t(41) = 2.04$, $p = 0.048$ (Fig. 5B). Participants took an overall conservative approach to both feature-based (M = 0.40, SD = 0.40) and space-based (M = 0.25, SD = 0.36) trials. However, participants had a greater tendency to deny that a target was present for feature-based trials and therefore exhibited a more conservative approach than what was observed for space-based trials.

E. Sensitivity

Feature- and space-based tactile changes exhibited a high level of sensitivity, measured with signal detection theory metric *A'* (M = 0.80, SD = 0.14 and M = 0.83, SD = *0.18*, respectively). A paired samples *t*-test did not reveal a significant difference in sensitivity between trial types, $t(41) = -1.34$, $p = 0.19$ (Fig. 5C).

IV. DISCUSSION

This work directly compared the change detection performance of tactile stimuli defined by featural and spatial properties using the ERP technique in addition to behavioral methods. The electrophysiological data obtained provided a window into the time course of tactile information processing and demonstrates the ERP components that are associated with tactile change detection for both feature-based and space-based tactile stimuli. While feature-based and space-based trials did not differ in terms of performance, they were responded to at significantly different speeds. Feature-based trials were responded to nearly 100 ms earlier than space-based trials when averaging across all response types. This result is not reflected in the ERP data, indicating that the difference in reaction time may be related to a spatial priming effect, time-distance relationship, or response selection (such as deciding which foot pedal to press) instead of earlier discriminatory processes.

Feature-based changes may have been responded to faster due to a spatial priming effect [41], [42]: for feature-based trials, the post-change stimulus was always enclosed in the pre-change fingers stimulated. The same priming effect could not have applied to space-based trials because change stimuli were always outside of the pre-change digits stimulated. Prior work has shown that visual objects used as prime-probe pairs in a change detection task can positively prime, or exhibit a *positive compatibility effect*, on secondary tasks. For example, in [43], response times in a secondary task were roughly 100 ms faster when visual objects that underwent a change in a primary task (i.e., a shift in orientation) were then the immediate subject of a secondary task. Similar priming effects were observed even under instances of visual change blindness [44]. It is unclear whether this effect may apply beyond secondary tasks to the context of change detection performance itself. Contrary evidence comes from [45]: when comparing shifts in the location (i.e., spatial changes) and shifts in color (i.e., featural changes) of a visual stimulus, the opposite response time effect was observed.

Similarly, in [27] participants were tasked with determining whether a tactile stimulus was present or absent at a secondary body location. It was determined that a time-distance relationship existed for tactile stimuli presented to different body sites, in which reaction time increased with the Euclidean distance between body locations. The slowed reaction time for spatially defined tactile stimuli observed in the present study could thus be related to the phenomena described by [27], such that spatial change-trials required shifts in spatial attention for distances across the finger. The same shifts in attention were not required for feature-based tactile stimuli. Further, the magnitude of the change in finger distances in space-based trials was not isolated for analysis in this study.

Previous work has also reported slowed reaction times under circumstances in which the tactile stimulus and response mechanism are spatially incompatible (i.e., stimulus-response compatibility or S-R compatibility) [46]. In the present work, S-R incompatibility could have exacerbated a delayed reaction time for space-based stimuli compared to feature-based stimuli. Space-based stimuli already required spatial selective attentional resources, the demand of which likely increased under S-R incongruency (e.g., when a tactile change-stimulus was presented to the right hand that required a left foot pedal press). An increased strain on such attentional resources could thus delay the time it took for participants to make a response. Work must be done to verify whether the response times observed here can be specifically attributed to a positive priming effect, time-distance relationship, or S-R compatibility instead of some difference inherent to the stimulus properties themselves.

These results could have serious implications for safety critical domains that wish to deploy displays using the tactile modality. If speed of response is important to a domain, feature-based tactile cues (e.g., cues that change in intensity) may be favorable. Further, a more conservative response strategy was taken for feature-based stimuli. A conservative response strategy is indicative of a higher false negative rate, the importance of which will vary by domain. If false negatives are more severe to encounter than false positives in a particular domain, space-based tactile cues may be favorable for the design of haptic and multimodal displays.

Future work can expand upon these findings to further investigate tactile change detection performance by manipulating other aspects of feature-based and space-based tactile stimuli, such as the distance between locations stimulated on the body [27] or temporal properties of the stimuli. Additionally, future studies may uncover the electrophysiological correlates of tactile change *blindness* in response to space- and feature-based tactile stimuli. A prior study on visual change blindness found electrophysiological predictors of successful change detection during pre-change stimulus processing [47]; future work may therefore also benefit by analyzing ERPs time-locked to both pre- and post-change stimuli. The results of such work may lend itself to determining the stages and time course of information processing critical for successful tactile change detection.

REFERENCES

[1] M. Janidarmian, A. Roshan Fekr, K. Radecka, and Z. Zilic, “Wearable Vibrotactile System as an Assistive Technology Solution,” *Mob. Netw. Appl.*, vol. 27, no. 2, pp. 709–717, Apr. 2022, doi: 10.1007/s11036-019-01304-9.

[2] S. Kammoun, R. Bouaziz, F. Saeed, S. N. Qasem, and T. Al-Hadhrami, “HaptiSole: Wearable Haptic System in Vibrotactile Guidance Shoes for Visually Impaired Wayfinding,” *KSII Trans. Internet Inf. Syst.*, vol. 17, no. 11, pp. 3064–3082, Nov. 2023, doi: 10.3837/tiis.2023.11.009.

[3] A. Gallace, H. Z. Tan, and C. Spence, “The failure to detect tactile change: A tactile analogue of visual change blindness,” *Psychon. Bull. Rev.*, vol. 13, no. 2, pp. 300–303, Apr. 2006, doi: 10.3758/BF03193847.

[4] S. A. Lu and N. Sarter, “Tactile Change Blindness in an Unmanned Aerial Vehicle Control Task,” *Proc. Hum. Factors Ergon. Soc. Annu. Meet.*, vol. 58, no. 1, pp. 1706–1710, Sep. 2014, doi: 10.1177/1541931214581356.

[5] S. L. Riggs and N. Sarter, “Tactile, Visual, and Crossmodal Visual-Tactile Change Blindness: The Effect of Transient Type and Task Demands,” *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 61, no. 1, pp. 5–24, Feb. 2019, doi: 10.1177/0018720818818028.

[6] M. S. Jensen, R. Yao, W. N. Street, and D. J. Simons, “Change blindness and inattentional blindness,” *WIREs Cogn. Sci.*, vol. 2, no. 5, pp. 529–546, Sep. 2011, doi: 10.1002/wcs.130.

[7] F. Wu, H. Ma, K. He, Y. Yang, Z. Gao, and M. Shen, “The Role of Amodal Object-based Attention in Retaining Bindings in Working Memory,” *J. Vis.*, vol. 16, no. 12, p. 1436, Sep. 2016, doi: 10.1167/16.12.1436.

[8] T. D. Bancroft, P. Servos, and W. E. Hockley, “Mechanisms of Interference in Vibrotactile Working Memory,” *PLoS ONE*, vol. 6, no. 7, p. e22518, Jul. 2011, doi: 10.1371/journal.pone.0022518.

[9] J. A. Harris, I. M. Harris, and M. E. Diamond, “The Topography of Tactile Working Memory,” *J. Neurosci.*, vol. 21, no. 20, pp. 8262–8269, Oct. 2001, doi: 10.1523/JNEUROSCI.21-20-08262.2001.

[10] N. Ball, M. Wisniewski, B. Simpson, and E. Mercado, “The impacts of training on change deafness and build-up in a flicker task,” *PLOS ONE*, vol. 17, no. 11, p. e0276157, Nov. 2022, doi: 10.1371/journal.pone.0276157.

[11] M. L. Gamble and S. J. Luck, “N2ac: An ERP component associated with the focusing of attention within an auditory scene,” *Psychophysiology*, vol. 48, no. 8, pp. 1057–1068, Aug. 2011, doi: 10.1111/j.1469-8986.2010.01172.x.

[12] A. Gallace, H. Z. Tan, and C. Spence, “Do ‘mudsplashes’ induce tactile change blindness?,” *Percept. Psychophys.*, vol. 69, no. 4, pp. 477–486, May 2007, doi: 10.3758/BF03193905.

[13] K. Gomes, S. Betza, and S. L. Riggs, “Now You Feel It, Now You Don’t: The Effect of Movement, Cue Complexity, and Body Location on Tactile Change Detection,” *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 62, no. 4, pp. 643–655, Jun. 2020, doi: 10.1177/0018720819850278.

[14] T. Ferris, K. Stringfield, and N. Sarter, “Tactile ‘Change Blindness’ in the Detection of Vibration Intensity,” *Proc. Hum. Factors Ergon. Soc. Annu. Meet.*, vol. 54, no. 18, pp. 1316–1320, Sep. 2010, doi: 10.1177/154193121005401803.

[15] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, “Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives,” *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 580–600, Oct. 2017, doi: 10.1109/TOH.2017.2689006.

[16] J. M. Bertsch, M. Ayyat, T. Nadeem, and G. J. Gerling, “NetworkTouch: A vibrotactile check-in device for cyberattack detection and monitoring,” in *2024 IEEE Haptics Symposium (HAPTICS)*, Apr. 2024, pp. 341–346. doi: 10.1109/HAPTICS59260.2024.10520845.

[17] F. Quintal and M. Lima, “HapWheel: In-Car Infotainment System Feedback Using Haptic and Hovering Techniques,” *IEEE Trans. Haptics*, vol. 15, no. 1, pp. 121–130, Jan. 2022, doi: 10.1109/TOH.2021.3095763.

[18] D. Hoefer, M. Handel, K. -M. Müller, and T. R. Hammer, “Electroencephalographic study showing that tactile stimulation by fabrics of different qualities elicit graded event-related potentials,” *Skin Res. Technol.*, vol. 22, no. 4, pp. 470–478, Nov. 2016, doi: 10.1111/srt.12288.

[19] T. Katus and M. Eimer, “The N2cc component as an electrophysiological marker of space-based and feature-based attentional target selection processes in touch,” *Psychophysiology*, p. e13391, May 2019, doi: 10.1111/psyp.13391.

[20] M. Eimer and V. Mazza, “Electrophysiological correlates of change detection,” *Psychophysiology*, vol. 42, no. 3, pp. 328–342, May 2005, doi: 10.1111/j.1469-8986.2005.00285.x.

[21] J. E. Desmedt, Nguyen Tran Huy, and M. Bourguet, “The cognitive P40, N60 and P100 components of somatosensory evoked potentials and the earliest electrical signs of sensory processing in man,” *Electroencephalogr. Clin. Neurophysiol.*, vol. 56, no. 4, pp. 272–282, Oct. 1983, doi: 10.1016/0013-4694(83)90252-3.

[22] M. Eimer and B. Forster, “Modulations of early somatosensory ERP components by transient and sustained spatial attention,” *Exp. Brain Res.*, vol. 151, no. 1, pp. 24–31, Jul. 2003, doi: 10.1007/s00221-003-1437-1.

[23] M. Salti, Y. Bar-Haim, and D. Lamy, “The P3 component of the ERP reflects conscious perception, not confidence,” *Conscious. Cogn.*, vol. 21, no. 2, pp. 961–968, Jun. 2012, doi: 10.1016/j.concog.2012.01.012.

[24] R. J. Caselli, “Ventrolateral and dorsomedial somatosensory association cortex damage produces distinct somesthetic syndromes in humans,” *Neurology*, vol. 43, no. 4, pp. 762–762, Apr. 1993, doi: 10.1212/WNL.43.4.762.

[25] M. Tommerdahl, O. V. Favorov, and B. L. Whitsel, “Dynamic representations of the somatosensory cortex,” *Neurosci. Biobehav. Rev.*, vol. 34, no. 2, pp. 160–170, Feb. 2010, doi: 10.1016/j.neubiorev.2009.08.009.

[26] L. A. Jones and H. Z. Tan, “Application of Psychophysical Techniques to Haptic Research,” *IEEE Trans. Haptics*, vol. 6, no. 3, pp. 268–284, Jul. 2013, doi: 10.1109/TOH.2012.74.

[27] S. Lakatos and R. N. Shepard, “Time—distance relations in shifting attention between locations on one’s body,” *Percept. Psychophys.*, vol. 59, no. 4, pp. 557–566, Jun. 1997, doi: 10.3758/BF03211864.

[28] M. Morioka, D. J. Whitehouse, and M. J. Griffin, “Vibrotactile thresholds at the fingertip, volar forearm, large toe, and heel,” *Somatosens. Mot. Res.*, vol. 25, no. 2, pp. 101–112, Jan. 2008, doi: 10.1080/08990220802045574.

[29] R. T. Verrillo, S. J. Bolanowski, and G. A. Gescheider, “Effect of aging on the subjective magnitude of vibration,” *Somatosens. Mot. Res.*, vol. 19, no. 3, pp. 238–244, Jan. 2002, doi: 10.1080/0899022021000009161.

[30] A. Delorme and S. Makeig, “EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis,” *J. Neurosci. Methods*, vol. 134, no. 1, pp. 9–21, Mar. 2004, doi: 10.1016/j.jneumeth.2003.10.009.

[31] J. Lopez-Calderon and S. J. Luck, “ERPLAB: an open-source toolbox for the analysis of event-related potentials,” *Front. Hum. Neurosci.*, vol. 8, p. 213, 2014, doi: 10.3389/fnhum.2014.00213.

[32] *sccn/trimOutlier*. (Jul. 25, 2024). MATLAB. Swartz Center for Computational Neuroscience. Accessed: Dec. 06, 2024. [Online]. Available: https://github.com/sccn/trimOutlier

[33] J. Miller, T. Patterson, and R. Ulrich, “Jackknife-based method for measuring LRP onset latency differences,” *Psychophysiology*, vol. 35, no. 1, pp. 99–115, Jan. 1998.

[34] A. Kiesel, J. Miller, P. Jolicœur, and B. Brisson, “Measurement of ERP latency differences: A comparison of single-participant and jackknife-based scoring methods,” *Psychophysiology*, vol. 45, pp. 250–274, 2008, doi: Psychophysiology.

[35] S. J. Luck, “Applied Event-Related Potential Data Analysis,” 2022, doi: 10.18115/D5QG92.

[36] *The Oxford Handbook of Event-Related Potential Components*. Oxford University Press, 2011. doi: 10.1093/oxfordhb/9780195374148.001.0001.

[37] “An Introduction to the Event-Related Potential Technique,” MIT Press. Accessed: Aug. 13, 2024. [Online]. Available: https://mitpress.mit.edu/9780262525855/an-introduction-to-the-event-related-potential-technique/

[38] N. A. Macmillan, “Signal detection theory,” in *Stevens’ handbook of experimental psychology: Methodology in experimental psychology, Vol. 4, 3rd ed*, Hoboken, NJ, US: John Wiley & Sons, Inc., 2002, pp. 43–90. doi: 10.1002/0471214426.pas0402.

[39] H. Stanislaw and N. Todorov, “Calculation of signal detection theory measures,” *Behav. Res. Methods Instrum. Comput.*, vol. 31, no. 1, pp. 137–149, Mar. 1999, doi: 10.3758/BF03207704.

[40] P. Praamstra, “Prior information of stimulus location: effects on ERP measures of visual selection and response selection,” *Brain Res.*, vol. 1072, no. 1, pp. 153–160, Feb. 2006, doi: 10.1016/j.brainres.2005.11.098.

[41] R. Nicoletti and C. Umiltà, “Attention shifts produce spatial stimulus codes,” *Psychol. Res.*, vol. 56, no. 3, pp. 144–150, 1994, doi: 10.1007/BF00419701.

[42] E. Wascher and M. Wolber, “Attentional and intentional cueing in a Simon task: An EEG-based approach,” *Psychol. Res.*, vol. 68, no. 1, pp. 18–30, Feb. 2004, doi: 10.1007/s00426-002-0128-z.

[43] C. Caudek and F. Domini, “Priming effects under correct change detection and change blindness,” *Conscious. Cogn.*, vol. 22, no. 1, pp. 290–305, Mar. 2013, doi: 10.1016/j.concog.2012.08.003.

[44] M. E. Silverman and A. Mack, “Change blindness and priming: When it does and does not occur,” *Conscious. Cogn.*, vol. 15, no. 2, pp. 409–422, Jun. 2006, doi: 10.1016/j.concog.2005.08.003.

[45] A. N. Gusev, O. A. Mikhaylova, and I. S. Utochkin, “Stimulus determinants of the phenomenon of change blindness,” *Psychol. Russ. State Art*, vol. 7, no. 1, pp. 122–134, 2014, doi: 10.11621/pir.2014.0112.

[46] E. B. Gardner and A. W. Ward, “Spatial compatibility in tactile-visual discrimination,” *Neuropsychologia*, vol. 17, no. 3, pp. 421–425, Jan. 1979, doi: 10.1016/0028-3932(79)90088-5.

[47] G. Pourtois, M. De Pretto, C.-A. Hauert, and P. Vuilleumier, “Time course of brain activity during change blindness and change awareness: performance is predicted by neural events before change onset,” *J. Cogn. Neurosci.*, vol. 18, no. 12, pp. 2108–2129, Dec. 2006, doi: 10.1162/jocn.2006.18.12.2108.