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Jure, Fabricio Ariel; Spaich, Erika G.; Malesevic, Jovana; Kostic, Milos; Strbac, Matija; Dosen, Strahinja

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MAIN TEXT

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Encoding of spatial patterns using electrotactile stimulation via a multi-pad electrode placed on the torso

Fabricio A. Jure[1] | Erika G. Spaich[1] | Jovana Malešević[2] | Miloš Kostić[2] | Matija Štrbac[2] | Strahinja Došen[1]

[1]Neurorehabilitation Systems, Department of Health Science and Technology, Faculty of Medicine, Aalborg University, Aalborg, Denmark

[2]Tecnalia Serbia, Belgrade, Serbia

Correspondence
Strahinja Dosen,Department of Health Science and Technology, Faculty of Medicine, Aalborg University, Fredrik Bajers Vej 7, 9220 Aalborg Ø, Aalborg, Denmark.
Email: sdosen@hst.aau.dk

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Abstract

Background: Tactile stimulation can be used to convey information to a user in different scenarios while avoiding overloading other senses. Tactile messages can be transmitted as spatial patterns, potentially allowing for a high information throughput. The aim of the present study was to design and test different encoding schemes to determine the best approach for conveying spatial patterns.

Methods: Encoding schemes with simultaneous (SIM) and sequential pad activation (SEQ) were evaluated, including four SEQ variants designed to potentially facilitate the recognition. In SEQ-col and SEQ-row, the column and row of the activated pad were signified using different frequencies, while SEQ-all and SEQ-all-fast included the activation of all pads where those belonging to the pattern were indicated by changes in frequency (ON pads). The success rate (SR) of the pattern identification and the response time were quantified in 15 participants who recognized 20 patterns delivered through a 3 ×2 pad matrix placed on the lateral torso.

Results: SIM was not a feasible method to present the patterns (median, 15%; IQR, 5%). The SR improved with SEQ (median, 60%; IQR, 20%) and further increased with additional cues, particularly with SEQ-row (median, 78.3%; IQR, 23.3%) and SEQ-all (median, 96.7%; IQR, 5%). Importantly, the stimulation time of SEQ-all could be decreased without a substantial drop in accuracy (SEQ-all-fast: median, 89.2%; IQR, 19.2%).

Conclusions: The spatiotemporal stimulation with sequential activation of all pads (SEQ-all) seems to be the method of choice when conveying tactile messages as spatial patterns. This is an important outcome for increasing the information bandwidth of communication through the tactile channel.

KEYWORDS

encoding schemes, electrotactile stimulation, matrix electrodes, tactile communication, sensory feedback, haptics

1 | INTRODUCTION

The skin is the largest organ in the body providing an extensive area that can be leveraged to convey tactile/haptic information.[1] Tactile interfaces can communicate information to the wearer in an intuitive manner enhancing the surrounding environment while allowing the remaining senses to be fully available for other attentional demands.[2,3] These interfaces can improve operator performance and reduce workload.[4,5] Haptics technology can be used in various application domains from military and space science purposes[6] to assisting sensory deprived users.[7–9] Different methods can be employed to deliver tactile information (e.g., piezoelectric,[10] pneumatic,[11] and hydraulic elements[12]), but the most common approach is to employ vibration motors[13,14] or electrical stimulation.[15,16]

In the latter approach, low-intensity electrical pulses are used to activate skin afferents and elicit tactile sensations. Electrotactile interfaces are power consumption efficient, fast and simple to fabricate, as there are no moving mechanical elements, and they can deliver versatile stimulation patterns through independent modulations of frequency, intensity and spatial location.[17] The utility of tactile interfaces relies upon the ability of the users to discriminate and identify different tactile messages. Electrotactile signals can be rendered through single or multiple channels, and the messages are encoded by modulating the stimulation parameters.[18–20] Tan and collaborators suggested that the encoding methods based on the simultaneous change of multiple parameters elicit better discrimination and identification of different tactile messages.[21] Several studies indicated that the messages encoded by combining spatial and temporal characteristics of the stimuli, e.g., using sequential activation of channels, were more discernable than the messages encoded considering only the spatial location.[22–26] Nevertheless, designing an effective encoding scheme that would allow a high throughput of information via the tactile communication channel is still an open challenge.[1,27]

Electrode matrices integrate multiple conductive pads (stimulation points) of different shapes, sizes and pad configurations. This is an attractive solution to achieve high-bandwidth tactile communication since the messages can be communicated as spatial patterns. Each message can be associated with a specific "shape" (e.g., horizontal or vertical line) produced by activating the corresponding subset of pads in the matrix (e.g., first row or first column of pads). Several patterns can be constructed with only a few spatially arranged pads, and thus, many messages can be conveyed to the user.[1,14,27–29] Despite the large surface of the skin, the most sensitive areas (e.g., hands, inner portion of the legs, or face) are usually impractical for conveying haptic information.[30] In recent years, wearable tactile devices placed on the torso have gained attention.[31] Transmitting information through tactile stimulation delivered to the torso or the base of the neck, results in active body segments (e.g., upper and lower limbs) being fully available for other activities.[2–6,31–34]

Therefore, the present study assessed the participants' aptitude to perceive and recognize tactile messages rendered in the form of spatial patterns using a 3×2 pad matrix placed on the lateral torso. The preliminary results of this study were published as a conference contribution.[35] This work is a part of a larger effort focused on developing a biofeedback system to enhance the situational awareness of first responders (e.g., firefighters, rescuers, paramedics, etc.) in overwhelming situations where other senses are overloaded or partially deprived by the surroundings (e.g., vision blocked by smoke).[36] A specific aim of the present study was to identify, evaluate and quantify the most reliable encoding schemes to convey information to the wearer in the form of electrotactile spatial patterns. The spatial patterns were selected as they provide a uniform approach to encoding many messages (e.g., 64 for a 2×3 matrix). Therefore, an encoding method that allows a reliable recognition of patterns would enable establishing a high-bandwidth communication channel through the skin. This could be used e.g., by a command center to transmit a wide range of "coded" messages to first responders indicating the status of their own body as well as of their environment.[36] In the present study, five encoding methods were designed and tested to determine if the recognition of the patterns can be improved by exploiting the flexibility of electrotactile stimulation (e.g., simultaneous modulation of parameters and sequential activation of channels).

2 | METHODS

2.1 | Participants

The experiment was conducted on fifteen naïve participants (11-M and 4-F; mean age 30.13 years; mean height: 1.76 m; mean weight: 78.27 kg; mean BMI: 25.35 kg/m^2). The participants have not had previous experience with the electrotactile system and pattern identification. The protocol was approved by the Ethics Committee of Region Nordjylland (VN-20190036) and performed according to the Helsinki declaration. All participants gave their written informed consent.

2.2 | Experimental setup

A custom-made surface electrode (SIXTHSENSE ALPHA electrode, Tecnalia Serbia, Serbia) was manufactured by screen-printing of conductive Ag/AgCl and dielectric biomedical inks on a commercial PET substrate. The electrode consisted of 8 cathodes: 6 circle-shaped and 2 rectangular with rounded corners: each of them was surrounded by an anode forming 8 concentric cathode–anode pairs (Figure 1). The center of the electrode (midpoint between pads 3 and 4) was placed on the right, lateral side of the torso in the midpoint along the line connecting the armpit and the iliac crest at the hip. Prior to positioning the electrode, the skin area was cleaned with alcohol swabs. The electrode and placement used in the present experiment were proposed previously[17] based on the feedback from the end-users (first responders) as the most convenient choice considering the envisioned application demands, i.e., providing tactile feedback to a fully equipped first responder (e.g., equipment carried on the back and front, special clothing and wearable sensors, etc.).

The electrotactile stimulation was delivered using a multichannel stimulator (MaxSens, Tecnalia, Spain) controlled wirelessly by a host computer through the 3 × 2 pad matrix (i.e., 6 active pads—pad1, top-back; pad2, top-front; pad3, middle-back; pad4, middle-front; pad5, bottom-back; pad6, bottom-front), via a switching circuitry. The large pads (top and bottom) were not used (Figure 1). The stimulator generated current-controlled, biphasic and symmetric pulses with a pulse duration set to 400 µs. The stimulation parameters were modulated according to the encoding methods that were tested in the present study (see Encoding Methods section).

2.3 | Sensation and discomfort thresholds

The sensation (ST) and discomfort thresholds (DT) were determined for each pad using the method of limits.[37] The stimulation frequency was set to 25 Hz. The ST was obtained by increasing the pulse amplitude in 100 µA-steps starting from 500 µA until the participant verbally reported that they felt the stimulus. The DT was determined using a similar procedure; starting from ST the pulse amplitude was increased in 200 µA-steps until the participant reported that the evoked sensation was perceived as uncomfortable. In case the participants did not report an uncomfortable sensation, the maximum intensity was set to 9.5 mA (stimulator maximum).

The stimulation intensity for each pad was set to the midpoint value between ST and DT. To avoid differences in saliency, the intensities were equalized by fine-tuning the pad amplitudes around this value until a similar perception across the pads was evoked.

2.4 | Encoding methods

Five methods were designed to convey spatial patterns. These included simultaneous, as well as sequential activation of the pads forming the pattern (ON pads). The simultaneous activation minimizes the message duration

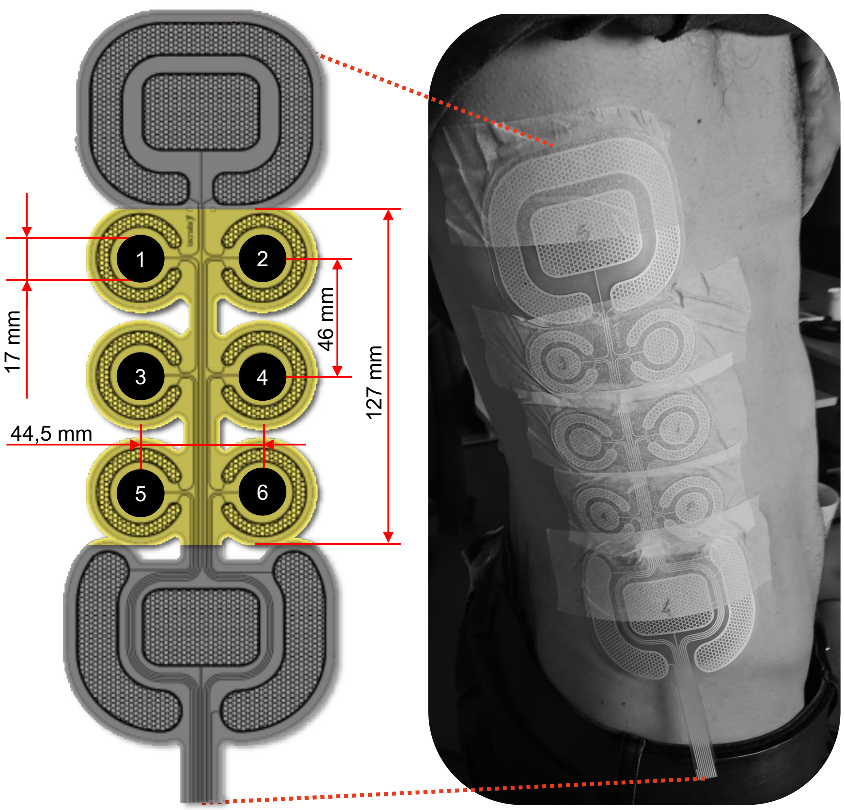


FIGURE 1 The electrode and positioning. The electrode was placed on the right lateral side of the torso, along the line connecting the armpit and the iliac crest at the hip. The 3 × 2 pads matrix (highlighted) was used in this study. [Color figure can be viewed at wileyonlinelibrary.com]

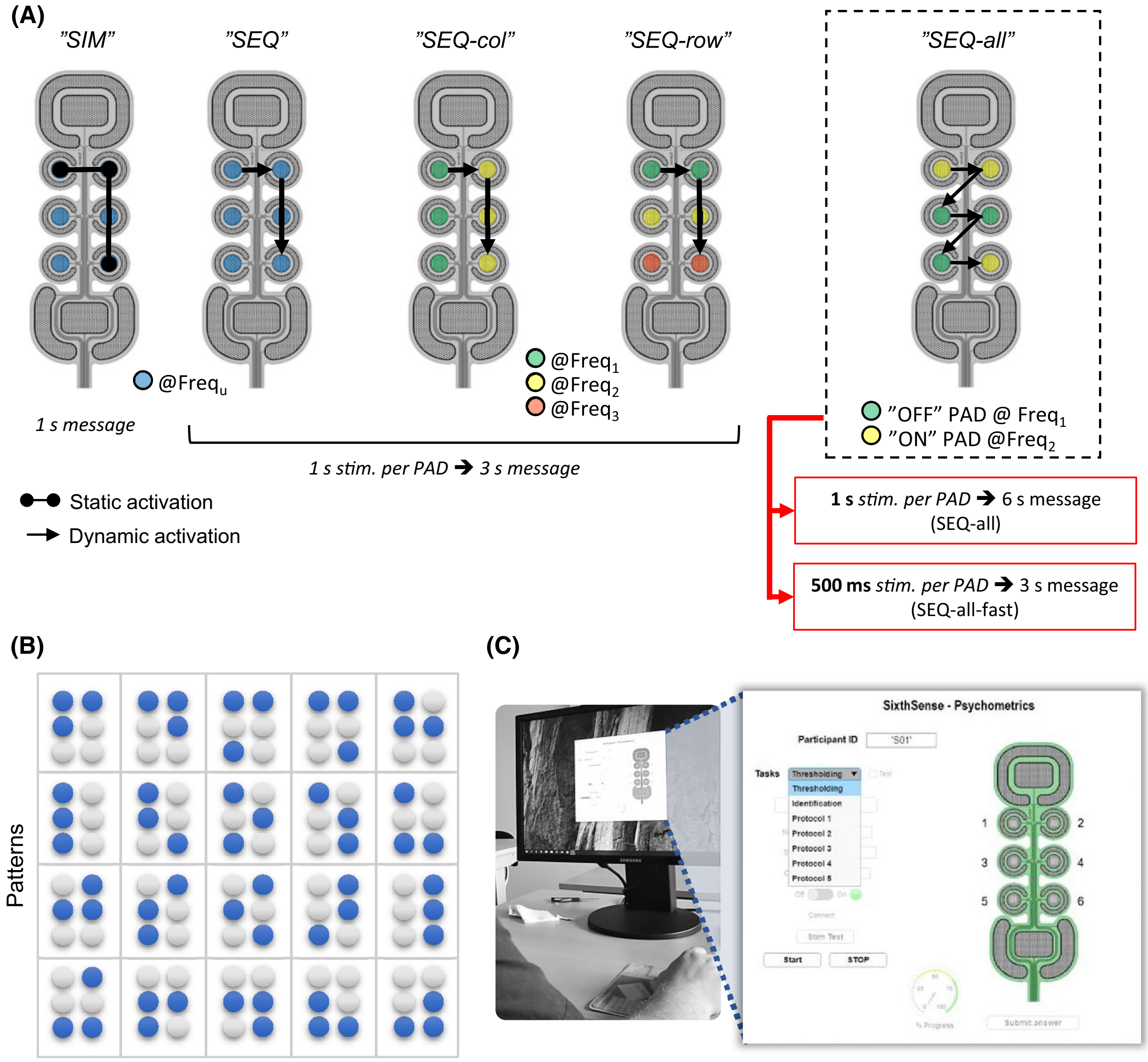


FIGURE 2 Experimental protocol. (A) the figure depicts the five encoding methods (SIM, SEQ, SEQ-col, SEQ-row, SEQ-all/SEQ-all-fast). (B) the schematics shows the twenty spatial patterns used in the experiment, where the active ON pads are indicated in blue. (C) the figure depicts the GUI which the participants used to indicate the ON pads. [Color figure can be viewed at wileyonlinelibrary.com]

(stimulation time) while the sequential activation might facilitate the recognition of the patterns. The proposed encoding methods included additional "cues" based on frequency modulation to possibly enhance the spatial identification of the pads, for instance by sectorizing them into columns and rows. The following encoding methods were implemented:

1. *Simultaneous stimulation ("SIM")*: The pads comprising the spatial pattern (ON pads) were activated simultaneously at a fixed frequency of 50 Hz for 1 s (Figure 2A-SIM).
2. *Sequential stimulation at a fixed frequency ("SEQ")*: The ON pads were activated sequentially for 1 s at a fixed stimulation frequency of 50 Hz (Figure 2A-SEQ).
3. *Sequential stimulation varying the column frequency ("SEQ-col")*: The ON pads were activated sequentially for 1 s at a frequency determined by the column to which the pad belonged (25 Hz for the back and 50 Hz for the front column, Figure 2A-SEQ-col).
4. *Sequential stimulation varying the row frequency ("SEQ-row")*: The ON pads were activated sequentially for 1 s at a frequency determined by the row to which the pad belonged (25, 50 and 150 Hz for the top, middle and bottom rows, respectively, Figure 2A-SEQ-row).
5. *Sequential stimulation with activation of all pads ("SEQ-all")*: All pads of the matrix were activated sequentially for 1 s. The ON pads were activated at the frequency of 50 Hz, while the frequency of the OFF pads was 25 Hz.

(Figure 2A-SEQ-all). While the total duration of the stimulation per pattern was 3 s for SEQ, SEQ-col and SEQ-row, the stimulation lasted 6 s for *SEQ-all*.

6. *Sequential stimulation with shorter activation of all pads ("SEQ-all-fast")*: This encoding method was similar as *SEQ-all* but the stimulation per pad was shortened to 0.5 s so that the total duration of the pattern was 3 s, i.e., equal to SEQ, SEQ-col and SEQ-row.

The sequential activation of the pads was delivered following the same top-down direction, i.e., from the top-back (pad 1) to the bottom-front (pad 6) of the pad matrix (Figure 1). The hypothesis was that SEQ approach will lead to better performances (i.e., higher success rates and lower reaction times) compared to SIM, and that additional cues (SEQ-row and col) will improve the performance further. SEQ-all might lead to overall best result as all the patterns are presented uniformly, but the tradeoff is the increased duration of the message. SEQ-all-fast was therefore introduced to test if the message time can be decreased without a significant loss in performance.

2.5 | Experimental procedure

The participants received a verbal explanation of the experimental procedure. The electrode was then positioned and the participants were asked to sit comfortably on a chair in front of a screen. Afterward, ST and DT were determined and the stimulation intensity was set for each pad. Three stimulation frequencies were presented to the participants (25, 50, and 150 Hz) by randomly activating single pads until they were confident in recognizing the frequencies.

The experiment consisted of a single session divided into three main phases:

Single pad recognition - Familiarization training: 1-s long stimulation bursts were sequentially delivered to the participant through each of the 6 pads in the matrix. The participant received feedback through a custom-made GUI indicating which pad was active. This procedure was repeated three times per pad (i.e., $3 \times 6 = 18$ stimuli in total). The aim was to familiarize the participants with the sensation and allow them to associate the perceived location on the skin with the pad in the matrix shown on the screen.

Single pad recognition - Reinforcement training: 1-s long stimulation bursts were delivered to the participant through a randomly selected pad. The participant had to indicate which pad was active using the custom-made GUI, which then provided feedback on the correct answer. The procedure consisted of three blocks of 6 stimuli where each pad was activated once. The participants repeated the procedure until they could recognize active pads with an accuracy higher than 80% (i.e., at least 15/18 correct answers). After this, the assumption was that they could identify single pads in the matrix reliably.

The familiarization and reinforcement phases were conducted so that participants could learn to identify individual pads rather than a set of specific patterns. The aim was to train a "spatial alphabet" that can be leveraged to recognize any "word" (pattern) that is delivered, rather than a limited set of specifically trained patterns. This is in line with the goal of facilitating high-bandwidth communication using electrotactile stimulation. Furthermore, this procedure makes training time independent of the number of patterns that need to be discriminated in the validation phase.

Spatial pattern recognition - Validation: All the encoding methods were tested. The order of the methods was randomized across participants. First, verbal instruction was given to the participants explaining the method along with a brief familiarization period, during which a few patterns were delivered to the participant using the tested encoding scheme. Twenty spatial patterns comprising different combinations of 3 active pads were selected (Figure 2B). The test included three blocks and, in each block, all patterns were delivered in a pseudorandom order. After the stimulation for a single pattern finished, the participant indicated the ON pads on the custom-made GUI (Figure 2C). In this test, no feedback on the correct answer was given to the participant. A 5–8 seconds pause was introduced between patterns, and a longer 3–5 min break was introduced between the blocks. Note that the participants only knew that the patterns comprised 3 pads.

2.6 | Data analysis and statistics

The main outcome measure was the success rate (SR) in identifying the spatial patterns. The identification was deemed successful if the participant correctly recognized all ON pads belonging to the pattern. For all successful identifications, the decision time was recorded as the time between the end of the stimulation and the participant submitting their answer. Averaged decision time across trials was computed per method and participant. For methods SEQ-col and SEQ-row, the SR in identifying frequencies (i.e., the correct column and row, respectively) were analyzed regardless of the correctness of the overall answer. The latter was performed to rule out frequency identification of the stimuli as a confounding factor for pattern identification.

The first five participants performed all methods except SEQ-all-fast. After these first tests, it became obvious

TABLE 1 Means and standard deviations (SD) for the detection and discomfort threshold intensities for each of the stimulation pads and ratio between the thresholds

		ST [mA]	DT [mA]	DT/ST
Back side	*PAD 1* (top)	1.693 (0.771)	5.967 (2.656)	4.082 (2.506)
	PAD 3 (middle)	1.527 (0.548)	5.780 (2.917)	4.112 (2.370)
	PAD 5 (bottom)	1.520 (0.391)	5.927 (2.301)	4.135 (1.809)
Front side	*PAD 2* (top)	1.373 (0.359)	5.347 (2.116)	4.330 (2.420)
	PAD 4 (middle)	1.527 (0.573)	5.367 (2.226)	3.860 (1.835)
	PAD 6 (bottom)	1.333 (0.318)	5.400 (2.683)	4.167 (1.990)

that the SIM method was not a feasible approach to convey the electrotactile patterns. The SR (median (IQR)) for these participants was only 15 (5)% with SIM compared to 66.7 (15)% for SEQ and 88.3 (31.7)% for SEQ-row (see Ref. [35] for detailed results). Therefore, the SIM method was discontinued and replaced by SEQ-all-fast. Consequently, the SIM method was excluded from the statistical analysis.

The statistical tests were performed using IBM SPSS Statistics 27.0 (SPSS Inc., USA). A p-value <0.05 was established as a threshold for statistical significance. The data were analyzed using generalized linear mixed models (GLMMs). Since the data were non-normally distributed (assessed with the Shapiro–Wilk test), the models used a gamma distribution and a log link function. All models controlled for the within-participants variation by considering a random intercept and random slopes. A scaled identity covariance structure was used, in which variances are constant and no correlation was assumed between the elements. The sequential Sidak test was employed for the correction of multiple comparisons.

The ST and DT were analyzed using a GLMM for each intensity with *Column* (Front and Back), *Row* (Top, Middle and Bottom) and their interaction as fixed factors, including the intercept. The degree of freedom parameter was determined using the residual method, since the data were balanced, with 100 iterations and a criterion for convergence of $1{\cdot}10^{-6}$.

The SR and decision-time were analyzed using a GLMM for each variable, with *Method* (*SEQ*, *SEQ-col*, *SEQ-row*, *SEQ-all* and *SEQ-all-fast*) as a fixed factor, including the intercept. The degree of freedom parameter was determined with the Satterthwaite method, since the data were unbalanced, with 100 iterations and a criterion for convergence of $1{\cdot}10^{-6}$.

Ten participants completed the SEQ-all-fast method, while all fifteen participants completed SEQ, SEQ-col, SEQ-row and SEQ-all. The GLMMs for the SR and decision-time were performed with five missing values (i.e., 6.7% of the total dataset), corresponding to the five participants that did not perform the *SEQ-all-fast* method.

For the frequency identification rates, a non-parametric Wilcoxon test was applied to compare the SR between SEQ-col and SEQ-row, since the data were non-normally distributed (Shapiro–Wilk test).

3 | RESULTS

3.1 | Sensation and discomfort thresholds

There was no effect of Row (GLMM: $F_{(2,84)} = 0.446$, $p = 0.641$) in ST, however, a weak effect of *Column* was found (GLMM: $F_{(1,84)} = 4.167$, $p = 0.044$). Specifically, the skin area at the back (i.e., pads 1–3-5, estimated group mean (SE): 1.509 (0.108) mA) was slightly less sensitive (adjusted Sidak: pair-wise t = 2.020, $p = 0.047$) compared to the skin area at the front (i.e., pads 2–4-6, estimated group mean (SE): 1.381 (0.099) mA). No interaction effects were observed (GLMM: $F_{(2,84)} = 1.216$, $p = 0.302$). There was no effect of *Row* (GLMM: $F_{(2,84)} = 0.313$, $p = 0.732$) nor *Column* (GLMM: $F_{(1,84)} = 3.691$, $p = 0.058$) in DT, and no interaction effects were found (GLMM: $F_{(2,84)} = 0.509$, $p = 0.603$). The average ST and DT across participants are reported in Table 1.

3.2 | Success rates and decision-time

All participants successfully completed the *training* phases of the experiment. In the *reinforcement training* phase, the participants performed on average 3.2 ± 2.1 blocks (range: 1–9) to reach an SR higher than 80% in identifying individual pads.

As mentioned, only five participants performed the *Spatial pattern recognition* phase using the SIM method. The participants consistently reported an overall blurred sensation, and resulting difficulty in recognizing the spatial patterns.

Figure 3A summarizes the results achieved with different encoding methods. There was a strong effect of *Method* on the SR (GLMM: $F_{(4,54)} = 22.828$, $p < 0.001$).

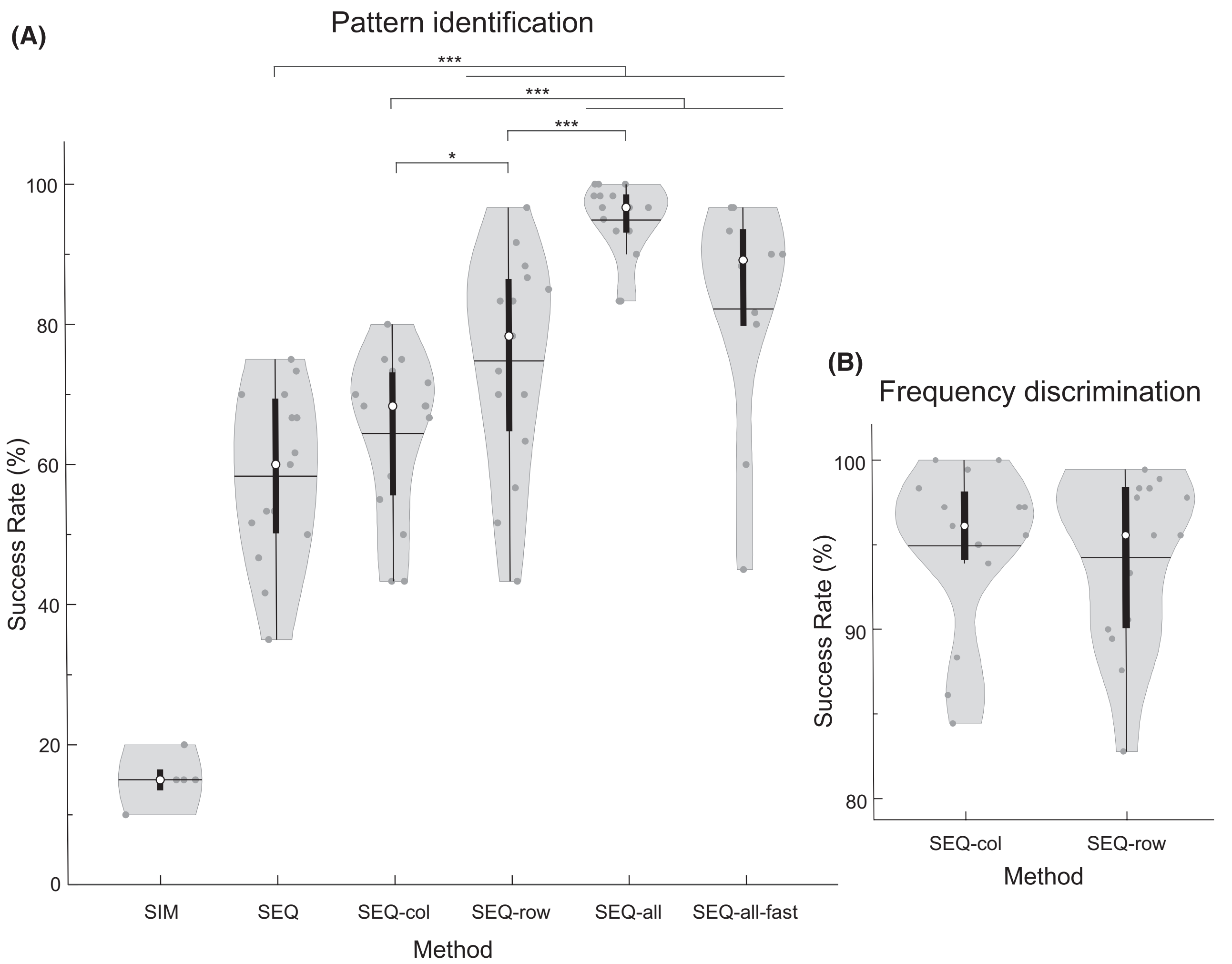


FIGURE 3 Identification of spatial patterns and frequency discrimination. The violin-plots represent the percent success rate (SR) in (A) identifying the spatial patterns across the tested methods and (B) discriminating the frequencies associated to the columns and rows in SEQ-col and SEQ-row. The middle vertical bar represents the interquartile range, the empty dot on the bar is the median and the horizontal line is the mean. Whiskers indicate 1.5 times the interquartile range. The outer shape represents the distribution of the observations while the dots inside the shape are the individual values.

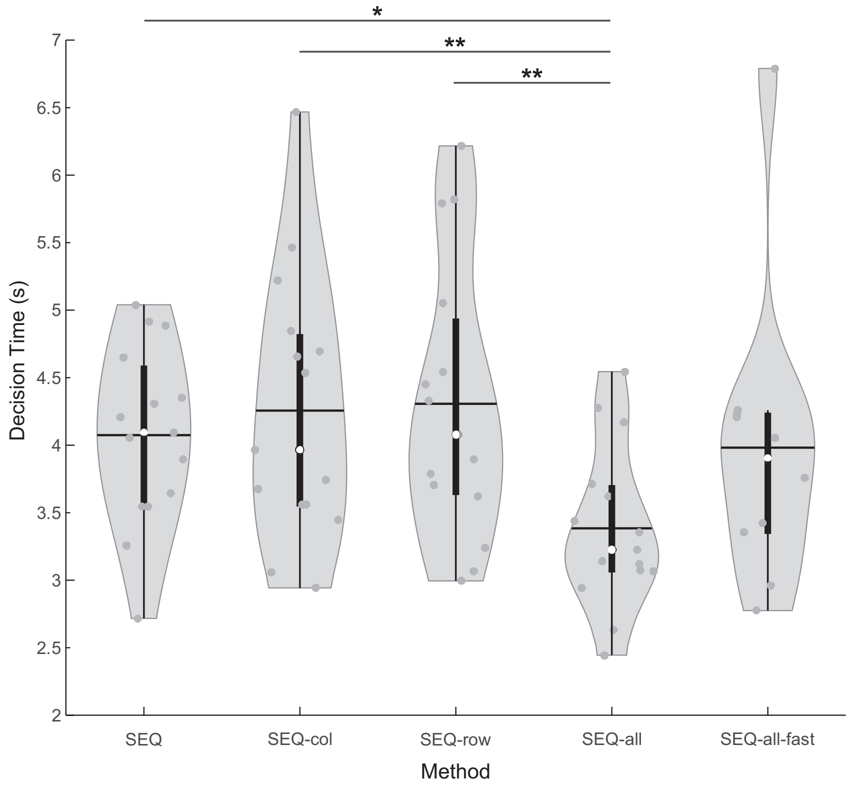
Post hoc analysis (adjusted Sidak) revealed that the SR achieved with *SEQ* was lower compared to *SEQ-row* ($t = -4.499$, $p < 0.001$), *SEQ-all* ($t = -8.536$, $p < 0.001$) and *SEQ-all-fast* ($t = -5.622$, $p < 0.001$). The results for *SEQ-col* were similar to *SEQ*, and the performance was not significantly different ($t = 1.847$, $p = 0.122$) while *SEQ-col* performed worse than *SEQ-row* ($t = -2.723$, $p = 0.035$), *SEQ-all* ($t = -7.033$, $p < 0.001$) and *SEQ-all-fast* ($t = -4.242$, $p < 0.001$). Furthermore, the results for *SEQ-row* did not greatly differ when compared with the performance achieved with *SEQ-all-fast* ($t = -2.022$, $p = 0.122$); however, the SR achieved with *SEQ-row* was worse compared to *SEQ-all* ($t = -4.585$, $p < 0.001$). Finally, the analysis did not show a strong effect when the performance of *SEQ-all-fast* and *SEQ-all* were compared ($t = -2.079$, $p = 0.122$).

The SR on the identification of frequencies for *SEQ-row* and *SEQ-col* are shown in Figure 3B. The Wilcoxon test did not show an effect of *Method* on SR ($Z = 0.142$; $p = 0.887$) when using *SEQ-col* (median, 96.1%; IQR, 4.4%) and *SEQ-row* (median, 95.6%; IQR, 8.3%).

The decision-time across encoding methods is shown in Figure 4. There was a strong effect of the *Method* on the decision-time (GLMM: $F_{(4,52)} = 5.904$, $p < 0.001$). The decision time was shorter (adjusted Sidak) in *SEQ-all* compared to *SEQ* ($t = -3.270$, $p = 0.015$), *SEQ-col* ($t = -3.847$, $p = 0.003$), and *SEQ-row* ($t = -4.053$, $p = 0.002$). However, the analysis did not show any difference when *SEQ-all* and *SEQ-all-fast* were compared (adjusted Sidak, $t = -2.479$, $p = 0.109$). No further relevant effects were found.

Table S1 presents descriptive statistics and pairwise differences for the SR and decision-time across encoding methods.

FIGURE 4 Decision times when responding to the electrotactile spatial patterns. The violin-plots represent the time the participant needed to identify the correct messages. The middle vertical bar represents the interquartile range, the empty dot on the bar is the median and the horizontal line denotes the mean. Whiskers describe 1.5 times the interquartile range. The outer shape represents the distribution of the observations while the dots inside the shape are the individual values.



4 | DISCUSSION

This study aimed to identify, evaluate and quantify the most reliable encoding schemes to convey spatial patterns to the lateral torso of the body using electrotactile stimulation through a 3 × 2 pad matrix. For that purpose, five encoding schemes were designed to convey 20 spatial patterns. The encoding schemes were conceptualized based on two different stimulation approaches, named static or spatial (i.e., simultaneous stimulation of the ON pads—SIM), and dynamic or spatiotemporal (i.e., sequential activation of the ON pads—SEQ). Moreover, several SEQ encoding schemes were designed to include further modulations of the stimulus characteristics, such as frequency cues (SEQ-col and SEQ-row) and temporal modulation (SEQ-all and SEQ-all-fast). The participants' SR in identifying the ON pads that formed the patterns and their reaction times were measured for each encoding scheme. The present study demonstrated that the SIM encoding scheme was not suitable for delivering tactile messages. However, the sequential activation of the pads (SEQ) seems a promising approach to conveying patterns. This approach improves the recognition rate, especially when using SEQ-all, however, at the expense of a longer time for message delivery.

The reason for the poor SR of the SIM encoding approach was that the simultaneous activation of the pads elicited a blurred sensation, as reported by the participants, from which it was difficult to localize the pads. The median SR increased when the patterns were presented using the dynamic, spatiotemporal encoding approaches, ranging from 60% (SEQ) to >95% (SEQ-all). The finding that SEQ is better than SIM is in line with the results reported by Novich and Eagleman[22] and reaffirmed by Hu and collaborators[23] who concluded that the spatiotemporal encoding substantially improved the SR.

The better recognition of the spatial patterns using a spatiotemporal approach reflects a fundamental result from psychometric tests, showing that the perception of spatiotemporal stimuli seems to be generally better than simultaneous, spatial stimuli. Plaisier and collaborators[24] used eight vibrotactile motors at the lower back and reported that the distance between the stimulation sites was perceived as shorter when the stimuli were presented simultaneously compared to sequentially, concluding that the distance perception was more precise for sequential stimulation. Schlereth and collaborators[25] reported lower two-point discrimination thresholds when sequential stimuli were applied. Additionally, Boldt and collaborators[26] indicated that introducing a delay between consecutive stimuli positively influenced the tactile spatial discrimination ability.

The present study provided further insights into the spatiotemporal approach (SEQ) by testing four variations of this method: SEQ-row, SEQ-col, SEQ-all and SEQ-all-fast. The findings showed that adding an extra dimension to the encoding scheme, by enhancing the spatial encoding parameters with frequency modulation, further improved the performance; however, this strategy was successful only when the frequency was modulated across rows (SEQ vs. SEQ-row). These observations agree with the notion promoted by Tan and collaborators[21] and reinforced by Boldt and co-workers[26] that higher dimensionality of stimuli generally improves discrimination and identification of patterns. In the present work, by signaling each row of the pad matrix with different frequencies, the discrimination task was simplified. Presumably, by recognizing the frequency, the participants could identify one dimension of the matrix, e.g., the first row, and then, they could choose between fewer options along the second dimension of the matrix, i.e., back or front. In this regard, the SIM scheme could have also included additional frequency cues. This was though technically not possible with the setup used in the present study, as the frequency was a global stimulation parameter (common to all channels activated concurrently). However, it is unlikely that this would have substantially changed the performance due to the overall blurred sensations reported when multiple pads were activated concurrently. Although different frequency cues could have produced differences in saliency, the sensations elicited by the pads activated at different frequencies would still superpose, likely making the localization of pads difficult.

The row frequency variation (SEQ-row) was significantly more effective than the column variation (SEQ-col). The participants identified the frequencies in both methods with similar success rates (Figure 3B) despite they differentiated between 2 (SEQ-col) versus 3 (SEQ-row) frequencies. Therefore, the recognition of the frequencies seemed to be an overall simple task and the participants could identify the column or row equally well. Nevertheless, the performance improved by ~10% when additional information was applied along the vertical (SEQ-row) compared to the horizontal axis (SEQ-col). Participants were better at recognizing ON pads horizontally (i.e., back or front column) rather than vertically (i.e., top, medium or bottom row). This is likely due to the lower number of "horizontal" options compared to the "vertical" options (i.e., choosing between 2 vs. 3 pads). The literature suggests though that it could be due to a more general trend. Hoffmann and collaborators[38] reported a higher tactile acuity along the horizontal axis at the lower back skin area using vibrotactile stimulation. Comparable findings were reported by Jouybari and co-workers[32] for vibrotactile stimulations but not for focal forces where participants performed better in identifying stimuli aligned horizontally compared to vertically at the top back area of the torso. Similarly to the present findings, Štrbac and colleagues[17] reported less confusion between the spatial identification of the electrodes along the horizontal axis compared to the vertical axis, when using electrotactile stimulation at the lateral torso.

The highest performance was achieved with SEQ-all approach, which significantly outperformed all other methods except SEQ-all-fast. The encoding scheme that included a combination of spatiotemporal sweeps and frequency modulations was therefore highly effective in conveying spatial patterns, resulting in a median SR of ~96%. Moreover, the participants responded with the correct pattern faster compared to the other encoding schemes (reaction time ~ 3.4 s). During the SEQ-all approach, all pads were sequentially swept, presumably allowing the participants to easily recreate the electrode grid by noting the ON pads based on the change in frequency. Instead of guessing the spatial location of the pads, the participants could count the activations and thus reconstruct the pattern without performing explicit spatial discrimination. However, this approach entails a compromise between the identification rate and the message delivering time; activating all pads to reveal the ones that are ON requires more time compared to presenting only the ON pads. The maximal rate at which messages can be conveyed is reduced compared to other methods. However, the effective information bandwidth depends not only on the message transmission rate but also on the SR in their recognition, and therefore, the effective bandwidth that can be achieved with each of the tested methods needs to be investigated in future work. Nevertheless, the present study provides an encouraging result. Namely, when the stimulation time per pad was reduced to half (SEQ-all-fast), the decrease in SR was not statistically significant. However, SEQ-all still appears to be somewhat better than SEQ-all-fast, as when the two methods are compared to other approaches (SEQ, SEQ-row and SEQ-col), the comparisons were statistically significant in more cases for the former method. Overall, this study suggests that the encoding scheme with sequential activation of all pads of the matrix is indeed an excellent strategy to convey tactile information using spatial patterns. Importantly, this approach is rather flexible as the time of pad activation can be regulated to control the trade-off between the recognition SR and the message delivery time. This trade-off will be further explored in future work.

Finally, the pads facing the front of the torso presented a slightly higher sensitivity (lower ST) compared to those facing the back. Since the positioning of the electrode was in the mid-point between the two main sensitive areas at the torso, i.e., the spine and the navel,[39] no significant difference in sensation thresholds was expected. However, previous studies investigating spatial acuity have found differences between the dorsal and ventral portions of the torso, where the latter was more accurate and sensitive.[40] Although the present observation is in line with those studies, to the best of the authors' knowledge, there are no previous studies assessing the psychophysical response to electrical stimulation delivered to this particular skin area. Interestingly, the DT seemed to be approximately 4 × ST, consistent across all pads. These observations may be important regarding the usability of this skin area for wearable haptic devices, especially those that rely on intensity modulation to convey information.

5 | CONCLUSIONS

The present study suggested that the sequential activation of the pads, leveraging the spatiotemporal stimulation profiles, is the most convenient method to convey electrotactile feedback. Adding an extra dimension to the encoding scheme, namely, frequency modulation, further improved the participants' performance. Finally, as shown with the SEQ-all and SEQ-all-fast, a combined, spatiotemporal plus frequency modulation scheme, in which all pads were sequentially activated, seemed to be the best method to achieve a high success rate in recognizing tactile messages in the form of spatial patterns.

AUTHOR CONTRIBUTIONS

Fabricio A. Jure, Erika G. Spaich and Strahinja Došen contributed to the study design, data collection, analysis and interpretation, article drafting, and revisions. Jovana Malešević and Miloš Kostić contributed to the concept development and data interpretation. Matija Štrbac contributed to the concept development, data interpretation, and manuscript revisions. All the authors read and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ORCID

Fabricio A. Jure https://orcid.org/0000-0003-1204-963X
Erika G. Spaich https://orcid.org/0000-0003-1275-4064
Jovana Malešević https://orcid.org/0000-0002-4487-9999
Miloš Kostić https://orcid.org/0000-0003-1299-4252
Matija Štrbac https://orcid.org/0000-0002-6831-1943
Strahinja Došen https://orcid.org/0000-0003-3035-147X

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