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# Spatiotemporal Influences on the Recognition of Two-dimensional Vibrotactile Patterns on the Abdomen

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**Abstract**

Spatial and temporal factors are known to highly influence tactile perception, but their role has been largely unexplored in the case of two-dimensional pattern recognition. We investigated whether recognition is facilitated by the spatial and/or temporal separation of pattern elements, or by conditions known to favor perceptual integration, such as the ones eliciting apparent movement. Two-dimensional vibrotactile patterns were presented to the abdomen of novice participants. In Experiment 1, we manipulated the spatial (inter-tactor distance) and temporal (burst duration and inter-burst interval) parameters applied to the tracing mode (sequential activation of pattern elements). In Experiment 2, we compared display modes differing in their level of temporal overlap in the presentation of pattern elements: the static mode (simultaneous activation of pattern elements), the slit-scan mode (pattern revealed line by line), and the tracing mode. The results of both experiments reveal that (a) recognition performance increases with the isolation of pattern elements in space and/or in time, (b) spatial and temporal factors interact in pattern recognition, (c) conditions leading to apparent movement tend to be associated with lower recognition accuracy. These results further our understanding of tactile perception and provide guidance for the design of future vibrotactile communication systems.


*Keywords*: tactile perception, vibrotactile device, pattern recognition, perceptual integration, communication system

Public Significance Statement:

This study reveals that patterns made up of several vibration points are better recognized when pattern elements are clearly isolated in time and space. The feeling of a single point moving continuously along the skin, as if the pattern was manually drawn on the skin, does not appear to favor the recognition of patterns’ shape.

## Spatiotemporal Influences on the Recognition of Two-dimensional Vibrotactile Patterns on the Abdomen

Communicating augmented information through the skin has been a challenge for researchers for about 60 years (Bach-y-Rita, 1972; Geldard, 1957, 1960; see Gallace et al., 2007 and Jones & Sarter, 2008, for reviews). Among the options explored over the years, one way of coding information through tactile devices has been to present patterns in two dimensions (2D) to the surface of the skin, which can reproduce visual forms such as printed characters and geometric shapes (e.g., Arnold & Auvray, 2014; Bach-y-Rita et al., 1969; Linvill & Bliss, 1966; Vincent et al., 2016), or be used to convey various contents such as information relating to the user's context, nearby or distant events, and instructions (e.g., Barralon et al., 2009; Brewster & Brown, 2004; Jones et al., 2009; Schwalk et al., 2015). While a great number of psychophysical studies have been conducted on the perception of 2D tactile patterns in the 70's and 80's (e.g., Bach-y-Rita et al., 1969; Kirman, 1973; White et al., 1970), the subject then progressively fell out of favor despite some unresolved questions and a recent increase of applied studies considering this form of coding. For example, 2D tactile patterns have lately been investigated for patient monitoring by clinicians (Barralon et al., 2006; Ferris & Sarter, 2011), driving assistance (Kim et al., 2006; Schwalk et al., 2015), military communication (e.g., Chapman et al., 2012; Jones et al., 2009; Riddle & Chapman, 2012), body-machine interfaces (Khasnobish et al., 2015), and the initial objective of sensory substitution for visually or hearing-impaired people (e.g., Novich & Eagleman, 2015).

The importance of reviving this subject is twofold. From an applied perspective, tactile devices are likely to be severely limited or ineffective if the psychophysics of tactile perception are not better understood and taken into account (e.g., Cholewiak et al., 2001; Hoffmann et al., 2018; Kirman, 1973; Loomis, 1981, 1990). Beyond the applications considered so far, a better understanding of tactile pattern recognition would also be of benefit to the numerous foreseen applications of tactile devices involving the transmission of abstract information or concepts (see Jones, 2011; Jones & Sarter, 2008 and MacLean, 2008 for in-depth reviews of foreseen applications).

From a fundamental perspective, investigating tactile 2D pattern perception appears to be a fruitful way to extend our understanding of the functioning of the cutaneous sense. It provides an opportunity to connect well-known phenomena in tactile perception, revealed through classical psychophysical paradigms involving unidimensional changes, to responses of participants who are presented with complex patterns of stimulation, composed of sets of vibration points varying in spatial and temporal layouts. Recent technological advances offer new flexibility in the manipulation and control of stimulus parameters which allows questions that were hardly experimentally accessible before to be addressed (e.g., Weisenberger, 2001). In the present article, we propose, on the basis of the main results obtained in the literature on two-dimensional vibrotactile pattern recognition, to investigate how spatial and temporal properties of stimuli interact in this task, with the ultimate goal of both progressing in our understanding of tactile perception and identifying the stimulus structure which allows the most effective tactile pattern recognition.

## Effectiveness of Display Modes

Previous studies on the recognition of two-dimensional vibrotactile patterns have mainly focused on the effectiveness of various modes of pattern generation, differing in how the forms are displayed in space and time. Four main display modes have been used and compared, with the patterns (i) being presented in their entirety at once or partially exposed at a time, and (ii) being either stationary or moving across the stimulation site. Figure 1 presents a simplified illustration of these modes with a 3-by-3 matrix for the letter “T”. In the *static* mode (e.g., Craig, 1980, 1981, 2002; Horner, 1991, 1995; Loomis, 1974, 1980), all tactors making up the pattern were simultaneously turned on and off, thus creating a stationary vibrotactile stimulation. In the *scanned* mode (e.g., Beauchamp et al., 1971; Craig, 1980, 1981, 2002; Loomis, 1974; White et al., 1970), also called the times-square mode (Craig, 1980), the stimulation depicted the displacement of the entire pattern across the array (usually from right to left). In the *slit-scan* mode (e.g., Loomis, 1974, 1980; Craig, 1981), the pattern itself was stationary, but only one portion at a time was exposed through a slit passing across the array (usually from right to left), hence revealing the pattern column by column. Finally, in the *tracing* mode (Shimizu, 1982; Yanagida et al., 2004), also called the drawing mode (Beauchamp et al., 1971), the pattern was gradually traced with the sequential activation of the tactors making up the pattern, as if it was being handwritten.

Several studies have investigated the effects of display mode on pattern recognition (Apkarian-Stielau, & Loomis, 1975; Beauchamp et al., 1971; Craig, 1980, 1981, 2002; Loomis, 1974, 1980; Saida et al., 1982). The technical and experimental features of the main studies conducted on this subject are summarized in Table 1, while similarities and differences in the experimental results are presented below in the text.

With roman letters presented to the fingertip by means of the Optacon[1], Craig (1980, 1981, 2002) repeatedly found that the static mode gave the highest overall recognition performance compared to other display modes. More specifically, he observed that the static mode was as good as or superior to all other modes (including the scanned, slit-scan, and tracing modes) independently of the display time (defined by Craig as the maximum time any element of the pattern was on), and that its superiority was particularly pronounced at brief display times (Craig, 1981). For example, at a display time of 26 ms, recognition accuracy ranged from just over 20% for the scanned mode to 70% for the static mode. At a display time of 400 ms, the differences tended to fade, with 50% of correct recognition for the slit-

[1] The Optacon (optical-to-tactile converter; Linvill, & Bliss, 1966) was designed to convert printed material to vibrotactile patterns for blind people, using an array of tactors contacting the ventral surface of the index finger.

scan mode, about 70% for the tracing mode and the scanned mode, and just over 75% for the static mode. The only case where the static mode was found to be inferior to the scanned mode for the finger (Loomis, 1980) was when the usual letter height of 20 mm (Craig, 1980, 1981) was reduced to 13 mm.

The results obtained for the recognition of patterns presented to other body loci were in singular contrast with the ones obtained for the fingertip. With roman letters presented to the back with the TVSS[2], Loomis (1974) found that the static mode gave the poorest recognition performance (34% of correct responses) compared to the scanned mode (41%) and the slit-scan mode (47%). He concluded that letters are more recognizable when presented sequentially than when presented in their entirety at once, and that, more specifically, the best performance is achieved with presentations that most closely approximate sequential tracing by a single moving point (Loomis, 1974). A study carried out by Beauchamp et al. (1971) conducted with the same device but with the tactile stimulation being generated manually by the experimenter (i.e., with no control of temporal parameters) provides some support for this conclusion, with the tracing mode producing fewer errors than the scanned mode for the recognition of upper-case letters and geometric forms.

Loomis' conclusion is further supported by the high level of recognition accuracy obtained for the tracing mode with vibrotactile displays other than the TVSS. Saida et al. (1982) investigated the recognition of Katakana (Japanese characters) presented to the abdomen. They found that the tracing mode was greatly superior (about 95% of correct responses) to the static mode (20%) and the scanned mode (40%). Shimizu (1982) presented the same set of characters to the palm. Focusing on the tracing mode only, he investigated the effects of the temporal features applied to this mode by testing several burst durations (BD,

[2] The TVSS (Tactile Vision Substitution System; Bach-y-Rita et al., 1969; White, et al., 1970) was designed to transduce complex optical images into tactile stimulation and to be capable of providing a great variety of environmental information.

corresponding to the time of activation of each tactor) and several letter-strokes intervals (corresponding to the delay between the strokes forming the characters), the inter-burst interval (IBI, corresponding to the time interval between successive bursts) being set to 0. With an optimum letter-stroke interval of 80 ms, Shimizu (1982) obtained more than 90% of correct responses for BD of 50 ms and higher. Yanagida et al. (2004) presented alphanumeric characters (digits and upper-case roman letters) to the back using the tracing mode. Because of the low resolution of the display, the position of the tactors forming the letters only roughly corresponded to their visual counterpart. Nevertheless, recognition accuracy reached 87% of correct responses overall.

Finally, Novich & Eagleman (2015, Experiment 1) investigated the recognition of 8-pattern sets following three encoding schemes: spatial encoding (corresponding to the static mode), spatiotemporal encoding (corresponding to the tracing mode), and a single motor encoding (in which participants had to recognize the level of vibration intensity). The authors observed that recognition accuracy tended to remain fairly constant for the single motor mode and the static mode (from 20 to 37%), while it improved with pattern duration for the tracing mode, from about 32% to 67% for pattern durations of 45 ms and 135 ms, respectively. They concluded that patterns encoded in both space and time are a preferred method for encoding information to the skin. Note, however, that the sets of patterns to be recognized were not identical across display mode conditions (see Figure 2A in Novich & Eagleman, 2015).

The results obtained for other body sites than the fingertip tend to indicate that the tracing mode is more effective than the other modes for pattern recognition. However, the variety of spatial and temporal parameters applied to this mode in the different studies hardly allows for optimal stimulation features to be identified (Table 1). For example, even though tactile spatial acuity is known to be highly dependent on body site (e.g., Stevens & Choo, 1996; Weinstein, 1968) and is expected to influence the recognition of tactile patterns (e.g., Cholewiak et al., 2001; Craig, 1981; Jones, 2011; Loomis & Lederman, 1986), the effect of the distance between tactors making up the patterns has not been explored yet. In addition, while the time interval between two points of stimulation has been found to greatly influence tactile discrimination ability (e.g., Boldt et al., 2014; Stronks et al., 2016), the effect of this temporal parameter on pattern recognition has, to our knowledge, never been investigated either. The question of the spatial and temporal parameters applied to display modes thus appears to be of great importance, especially since they are known to largely interact in tactile perception, giving rise to well-studied perceptual phenomena (e.g., Geldard & Sherrick, 1972; Helson & King, 1931; Jones, 1956; Suto, 1952). Among those phenomena, two appear to be of particular interest for the recognition of patterns traced out onto the skin: tactile masking and apparent movement.

**Spatiotemporal Parameters and Perceptual Phenomena**

Masking occurs when separate tactile stimuli are presented close to one another in space and/or time, and affects the ability to discriminate or detect one or more of the stimuli (e.g., Sherrick & Cholewiak, 1986). Kirman (1973) presented two alternative views on the role of masking in tactile pattern perception. The first one is based on the assumption that masking hinders pattern perception. According to this position, called the *isolation hypothesis* by Mahar & Mackenzie (1993), masking should be avoided by separating the vibrations making up the patterns spatially and temporally in order to preserve their individual identities (Kirman, 1973). The second view is based, on the contrary, on the assumption that masking is the manifestation of integrative mechanisms which would facilitate the perception of complex patterns. According to this position, called the *integration hypothesis* by Mahar & Mackenzie (1993), minimizing interactions among stimulus elements would prevent proper perceptual organization.

While several studies using the Optacon have investigated the effects of masking between successive patterns presented in the static mode (e.g., Cholewiak & Collins, 1997; Craig, 1982; Weisenberger & Craig, 1982), the influence of masking between the elements making up the pattern has received less attention, with, to our knowledge, only three studies addressing this issue (Craig, 1982, 1998; Mahar & Mackenzie, 1993). With three tactors contacting different sites on the forearm, Mahar & Mackenzie (1993) delivered six patterns combining strong, medium, and weak amplitudes of vibration. By varying the spatial and temporal separation of the pattern elements, they used a discrimination task in which participants were asked to indicate whether some pairs of patterns were different or not. Their results supported the isolation hypothesis, with a better discrimination performance with increased temporal separation, and with a similar but non-significant trend in the case of spatial separation. Using the Optacon, Craig (1982) presented to the fingertip five upper-case letters that were divided in two halves, with various temporal separations between the onsets of the two halves. Contrary to the results of Mahar & Mackenzie (1993), Craig's results support the integration hypothesis: identification performance improved when the letter halves were presented simultaneously and declined gradually with increasing temporal separations. Enlarging the set of tasks (discrimination and identification tasks favoring the isolation of pattern elements or their perception as a whole) and patterns (upper-case letters or geometric forms), Craig (1998) found a more complex set of results, with the influence of temporal separation between the pattern halves being opposite depending on the sets of measurement. He concluded that the influence of temporal integration on pattern perception appears to depend on pattern shape, pattern elements, and the nature of the task. Some additional assumptions might be made to explain this discrepancy in the results, such as the experience of participants in identifying tactile letters presented in the static mode (i.e., with no delay between the letter halves) and the spatial overlap of pattern elements in one set of measurements (Craig, 1998, Figure 5, p. 894). Yet, further investigations are needed to address the isolation/integration hypotheses.

The second phenomenon of interest is apparent movement (also called the cutaneous Phi or Beta phenomenon): successive tactile stimuli can, under certain conditions of spatial and temporal proximity, yield the impression of a continuous movement along the skin. Numerous studies have investigated the optimum spatiotemporal parameters eliciting apparent movement (e.g., Burtt, 1917; Cholewiak & Collins, 2000; Kirman, 1974, 1983; Sherrick & Rogers, 1966), but even if it has been suggested that apparent movement would favor pattern recognition (e.g., Cholewiak & Collins, 2000; Kirman, 1973, 1974), this hypothesis has never been tested. This question is deeply related to the one of perceptual integration raised by Kirman (1973) who proposed that "the proper temporal and spatial conditions for tactile apparent movement between successive stimuli are those required for tactile spatiotemporal integration" (p. 70), an approach he pointed up to be "quite the opposite of the recommendations […] that successive stimuli […] be maximally separated in space and time to avoid masking and other forms of mutual interference" (p. 70).

## The Present Study

We investigated how spatial and temporal stimulus properties jointly influence the recognition of 2D vibrotactile patterns presented to the abdomen. The abdomen constitutes an interesting site of stimulation which is almost unexplored in the literature dedicated to tactile pattern recognition (see Saida et al., 1982, and Scadden, 1973, for two exceptions). From a functional point of view, the abdomen (and more generally the trunk) allows the fingers and the hands, which are the body parts usually involved in haptic exploration and manipulation of objects in our surroundings, to be free for other tasks. This body site also has the advantage of being relatively stable compared to the limbs, which might be of particular importance when the tactile device is designed to assist users who are likely to move in their environment (e.g., Faugloire & Lejeune, 2014). From a sensory point of view, the lower spatial resolution of the trunk (e.g., Weinstein, 1968) compared to the finger or the palm is well compensated by the larger area this body site offers for tactile stimulation (Tan et al., 2003; Gallace et al., 2007). Finally, the only study that has compared tactile pattern recognition on the abdomen and on the back with the TVSS showed that recognition accuracy and latency were significantly better on the abdomen (Scadden, 1973).

In Experiment 1, we asked participants to recognize vibrotactile patterns (straight and broken lines) presented to the abdomen in the tracing mode, while the distance between tactors, burst duration and inter-burst intervals were manipulated to induce various levels of apparent movement and masking. In order to evaluate whether recognition performance was related to the perception of apparent movement, participants were also asked to rate how much the stimulation felt like a single point moving continuously along the skin. In Experiment 2, we compared three display modes differing in their level of temporal overlap in the presentation of pattern elements, namely the tracing mode, the static mode, and the slit-scan mode, for the recognition of eight vibrotactile patterns (upper-case letters and geometric forms) presented to the abdomen. For the two sequential modes (the tracing mode and the slit-scan mode), we further tested two time intervals: one known to induce apparent movement, with a temporal overlap of successive vibrations, and the other generating the perception of discrete vibrations, with a silent delay between successive vibrations.

According to the integration hypothesis (Kirman, 1973; Mahar & Mackenzie, 1993), it can be expected for both experiments that conditions minimizing the interaction between pattern elements, that is, separating patterns elements in space and time, would lead to poor performance in pattern recognition. On the contrary, according to the isolation hypothesis, recognition accuracy is expected to improve with the isolation of pattern elements through large distances between tactors, long time intervals between vibrations, and/or sequential display modes.

While several previous studies used larger sets of tactile patterns than we did in the present experiments (see Table 1, fourth column), it was always at the cost of only including participants that were either already well-experienced in tactile pattern recognition (Loomis, 1974; Shimizu, 1982), trained for several hours prior to the experiment (Craig, 2002; Loomis, 1974, 1980; Saida et al., 1982), or even selected on the basis of their good performance in a preliminary session (Craig, 1980, 1981) (see Table 1, last column). Here, we were interested in the ability to recognize tactile patterns in participants who were completely inexperienced with vibrotactile devices and who were only given a few minutes of familiarization. The number of patterns they were asked to recognize had to be limited accordingly. Besides concerns in terms of pure research, our choice was also motivated by the fact that the need of an important amount of practice is likely to be a brake on the generalization of a device.

**Experiment 1**

The shapes presented in Experiment 1 were two straight and two broken lines (forming an angle of 120°) containing five tactors, presented in the longitudinal and transverse axes of the abdomen (Figure 2). Three distances between tactors were tested: 9.5, 16.5, and 28.5 mm. For comparison, the mean two-point threshold distances measured by Eskildsen et al. (1969) for pairs of vibrotactile stimuli on the lateral back, near the scapula, were 10.15 mm for successive 1-s stimuli (inter-burst intervals of 1 s) and 11.36 mm for simultaneous 2-s stimuli. Recently, Jóhannesson et al. (2017) estimated the spatial acuity of the center area of the back to be lower than 13 mm with a relative localization task and eccentric rotating mass (ERM) motors with in-plane vibrations (also called coin cell motors). With the same task and the same body site, the results obtained by Hoffmann et al. (2018) with successive 200-ms stimuli (SOA = 250 ms) confirmed this order of magnitude and indicated that vibrotactile discrimination accuracy is even higher with cylindrical ERM motors placed parallel to the skin[3].

We tested twelve pairs of temporal parameters by combining three burst durations (BD = 100, 200, or 400 ms) and four inter-burst intervals (IBI = -100, 0, 200, or 400 ms). Since the rapidity of information transfer is an important criterion in the efficiency of tactile communication systems, only values of 400 ms and below were explored in the present experiment. In order to examine whether and how recognition accuracy relates to apparent movement, we also asked participants to rate the degree to which they felt one single vibration moving across their skin (as opposed to distinct vibratory events). The ranges of temporal parameters used in the present experiment were comparable to those used in studies on apparent movement (e.g., Kirman, 1983; Sherrick & Rogers, 1966).

## Method

### *Participants*

Ten participants (four women, six men) took part in the experiment. Their mean age was 22.20 years (range: 20 – 31) and their mean body mass index (BMI) was 23.13 kg/m² (range: 19.31 – 29.32). None of them reported having any sense of touch disorders and all of them were participating in an experiment with a vibrotactile device for the first time. Each participant signed an informed consent statement after receiving oral and written descriptions of the procedure.

### *Apparatus*

Figure 3 illustrates the setup used in this experiment. The tactile device (CAYLAR, Villebon-sur-Yvette, France) consisted of an embedded microcomputer, a battery, and a set

[3] With the same tactors and the same body site as Hoffmann et al. (2018) but with a different task (a "vibrotactile two-tacton resolution" task inspired from the two-point discrimination task) and shorter stimuli (60 ms), Novich and Eagleman (2015, Experiment 2) reported that accuracy was only higher than chance at a tactor distance of 40 mm and estimated vibrotactile spatial resolution to be about 60 mm. Possible explanations for the discrepancy in the results between studies can be found in Hoffmann et al. (2018).

of 80 tactors connected to independent wires of 60 cm. The tactors were small cylindrical eccentric rotating mass (ERM) motors (length of 20 mm and diameter of 4 mm). Their measured vibration frequency was 170.6 Hz (± 5.6) on average, and their mean rise time was 17.8 ms (± 0.5) from command to 20% of vibrating amplitude and 32.2 ms (± 2.2) from command to 80%. ERM motors are easily available and affordable (e.g., Choi & Kuchenbecker, 2013; van Erp & Self, 2008), which is a major criterion for most applications of vibrotactile displays (e.g., Jones & Sarter, 2008; van Erp & Self, 2008). They have been used in most recent studies involving 2D tactile pattern recognition (e.g., Barralon et al., 2009; Jones et al., 2009; Kim et al., 2006; Novich & Eagleman, 2015; Schwalk et al., 2015; Yanagida & al., 2004) and more largely for other applications. The device was connected to a PC unit that was used to trigger the vibrotactile patterns and to record participants' responses.

Twenty-three tactors were set perpendicularly to the skin, using a 14.5 × 14.5 cm pad with predefined holes that was cut out of an anatomic anti-slip gel pad (Clothing Sportswear Outdoor, Ekkia, Haguenau, France). The pad was fixed with Velcro to an elastic abdominal belt (Dynabelt®, Thuasne, Levallois-Perret, France), as shown in Figure 3A. The belt was fastened around the participant's waist (Figure 3B) so that the pad was horizontally centered on the abdomen and extended from above the navel to below the lower extremity of the sternum. The contact area of each tactor on the skin was 12.57 mm². The microcomputer, the battery, and the unused tactors were placed in a hip bag. Participants stood with their feet a comfortable distance apart. They wore muffler headphones that covered the ears to prevent them from using auditory cues produced by the tactors. They also held a keypad labeled with drawings of the four possible shapes which could be displayed at each trial to enter their response (Figure 3C). The predefined holes in the gel pad were organized in staggered rows, with an even center-to-center radial spacing of 9.5 mm. Following this spatial layout, the tactors were inserted into the gel pad to form a straight line and a broken line (angle of 120°)

presented either horizontally or vertically (Figure 2). Three center-to-center distances between tactors were tested: 9.5, 16.5, and 28.5 mm. In order to obtain all possible combinations between the shapes (straight vs. broken line), orientations (vertical vs. horizontal), and inter-tactor distances, the gel pad was rotated by 90° to display half of the vibrotactile patterns (Figure 2, Position B; see Appendix for details).

***Stimuli***

Vibrotactile patterns were generated by the sequential activation of the five tactors forming the lines, with three burst durations (BDs: 100, 200, or 400 ms) and four inter-burst intervals (IBIs: -100, 0, 200, or 400 ms). It should be noted that for the combination of BD = 100 ms and IBI = -100 ms the resulting patterns were stationary (i.e., simultaneous activation of the tactors) and not sequential.

Since anisotropy in tactile perception is a well-documented phenomenon (e.g., Cody et al., 2008; Essock et al., 1997; Fuchs & Brown 1984; Geldard & Sherrick, 1983; Gibson & Craig, 2005; Green, 1982; Greenspan & Bolanowski, 1996; Hoffmann et al., 2018; Longo, 2020; Le Cornu Knight et al., 2014; Longo & Haggard, 2011; Weber, 1826/1978) which might influence recognition performance, the straight and broken lines were presented in two orientations: along the length of the abdomen (longitudinal axis; vertical patterns) and across its width (transverse axis; horizontal patterns). Transverse lines were traced from left to right and longitudinal lines from top to bottom.

***Procedure***

Before starting the experimental session, each of the 23 tactors was successively activated for 400 ms and participants confirmed that they felt each vibration. Then, participants were presented with a sample of six patterns from the experimental set, which differed in shape, distance between tactors, burst duration, and inter-burst interval. They were asked to recognize each shape, regardless of its size or its temporal features, and to enter their response by pressing one of the four corresponding keys on the keypad they were holding (Figure 3C). No specific instruction was given on the time of response because we did not want participants to favor speed over accuracy. The six patterns were presented a first time, with the experimenter announcing the pattern that was about to be displayed. Then, the patterns were presented a second time with no indication from the experimenter. In this second set of presentations, participants received oral feedback after having given their response on the keypad: the experimenter indicated if the participant's response was right or wrong and, if wrong, which pattern had been displayed. Then, participants launched the next trial by pressing the enter key on the keypad.

After this brief familiarization, which lasted no more than a few minutes, the experimental session began. Participants completed two blocks of trials, one for each position of the gel pad (A and B; Figure 2). The order of the blocks was counterbalanced across participants. At the end of the first block, the experimenter unfastened the abdominal belt, rotated the gel pad 90° either counterclockwise (position A then B) or 90° clockwise (B then A), and fastened the belt again around the waist of the participant. The participant could sit and/or walk during this break.

Within each block, each of the 72 conditions (3 distances × 2 lines × 12 temporal parameters) was repeated three times, resulting in 216 trials per block which were presented in random order. The mode of response was the same as in the familiarization session; however, participants never received feedback about the correctness of their responses. At the last (third) presentation of a given condition, after having given their response, participants were also asked to score the impression of movement elicited by the tactile stimulation from 0 (bursts of vibration felt as being totally independent from one another) to 4 (perception of a single point of stimulation moving continuously). Altogether, the experiment took about 45 minutes to complete.

### ***Data Analysis***

We performed separate analyses of variance (ANOVA) with repeated measures on recognition accuracy, response time and apparent movement scores. The $p$ value levels were corrected for possible deviations from sphericity using the Huynh-Feldt epsilon ($\varepsilon$). When appropriate, we report the uncorrected degrees of freedom, the $\varepsilon$ value, and the $p$ value according to the corrected degrees of freedom.

## **Results**

### ***Recognition Accuracy***

We conducted a Distance (9.5, 16.5, 28.5 mm) × BD (100, 200, 400 ms) × IBI (-100, 0, 200, 400 ms) × Orientation (Horizontal, Vertical) ANOVA with repeated measures on the percentages of correct recognition. The main effects of distance [$F(2, 18) = 97.43$, $p < .001$, $\eta_p^2 = .92$], BD [$F(2, 18) = 12.54$, $p < .001$, $\eta_p^2 = .58$], and IBI [$F(3, 27) = 11.35$, $p < .001$, $\eta_p^2 = .56$], were significant, showing that recognition accuracy increased with these three parameters. Tukey's post hoc analyses revealed that recognition rate significantly increased at each increasing level of distance between tactors ($ps \leq .001$), with a mean of 52.92% ($SE$ = 1.37) for the distance of 9.5 mm, 67.01% ($SE$ = 1.38) for the distance of 16.5 mm, and 73.68% ($SE$ = 2.04) for the distance of 28.5 mm. For BD, Tukey's post hoc analyses showed that recognition rates were significantly higher for 200 ms ($M$ = 65.41%, $SE$ = 1.51) and 400 ms ($M$ = 68.89%, $SE$ = 2.40) than for 100 ms ($M$ = 59.30%, $SE$ = 1.15), $ps \leq .015$. For IBI, Tukey's post hoc analyses revealed significant differences between -100 ms ($M$ = 58.89%, $SE$ = 1.04) and all other time intervals, $ps \leq .044$, and between 0 ms ($M$ = 63.99%, $SE$ = 2.55) and 400 ms ($M$ = 69.26%, $SE$ = 1.67), $ps = .035$. The main effect of orientation was also significant [$F(1, 9) = 27.19$, $p = .001$, $\eta_p^2 = .75$], revealing a better recognition for vertical patterns ($M$ = 70.83%, $SE$ = 1.41) than for horizontal patterns ($M$ = 58.24%, $SE$ = 2.16). There was no significant interaction involving orientation [$Fs \leq 2.55$, $p \geq .11$, $\eta_p^2 \leq .22$].

In accordance with our expectation of an interdependence between spatial and temporal properties of stimulation, the analysis also revealed significant interactions between distance and BD [$F(4, 36) = 4.03$, $p = .008$, $\eta_p^2 = .31$], distance and IBI [$F(6, 54) = 2.44$, $p = .037$, $\eta_p^2 = .21$], and BD and IBI [$F(6, 54) = 3.54$, $p = .005$, $\eta_p^2 = .28$]. These results are best explained by the significant Distance × BD × IBI interaction [$F(12, 108) = 3.05$, $p = 0.001$, $\eta_p^2 = 0.25$] (Figure 4, top panels) we describe next. For the distance of 9.5 mm, temporal parameters had virtually no influence on recognition rate. Tukey's post hoc analyses only revealed one difference between BD/IBI combinations for this distance, with a significantly higher recognition rate for 200/-100 than for 100/-100 ($p = .036$). For the distance of 16.5 mm, 100/-100 led to significantly poorer recognition than 6 other combinations (100/400, 200/400, and all combinations with BDs of 400 ms; $ps \leq .036$) and 400/200 led to better recognition than 3 other combinations (100/-100, 100/0, and 200/-100; $ps \leq .036$). The influence of temporal parameters on recognition rate was more pronounced for the distance of 28.5 mm. For this distance, 100/-100 was the combination leading to the worst recognition rate, with a mean value being lower than that of the 9 other combinations (all others but 100/0 and 200/-100; $ps \leq .002$). 100/0 was the second BD/IBI combination to lead to the lowest recognition performance, with an accuracy lower than that of the 8 other combinations (all others but 100/-100, 100/200, and 200/-100; $ps \leq .019$). The other differences for this distance were 200/-100 leading to lower performance than that of the four other combinations (100/400, 200/400, 400/-100, and 400/200; $ps \leq .005$).

An interesting way to visualize the mutual influence of spatial and temporal stimulation features on recognition accuracy is to express the time interval between successive bursts in terms of Stimulus Onset Asynchrony (SOA; corresponding to the time interval between the onset of two successive bursts) rather than IBI (corresponding to the time interval between the termination of one burst and the onset of the next burst). Switching the abscissa from IBI (top panels of Figure 4) to SOA (obtained by simply adding BD to IBI; bottom panels of Figure 4) seems to better express the nature of the interactions between spatial (distance) and temporal (BD, IBI) parameters on recognition accuracy. In fact, the three curves which were found to diverge in the top panels of Figure 4 turn into a single continuous curve, seemingly independent of BD, in the bottom panels. The resulting curves exhibit an incremental influence of SOA on recognition accuracy, whose magnitude (slope) appears to be contingent on the distance between tactors: the higher the distance, the greater the influence of SOA on recognition accuracy.

***Recognition Time***

As an indicator of the difficulty of pattern recognition, we calculated recognition time by subtracting the total duration of pattern presentation (ranging from 0.1 s for 100/-100 to 3.6 s for 400/400) from response time (i.e., the delay between launching the tactile pattern and participant's response on the keypad). We conducted a Distance × BD × IBI × Orientation ANOVA with repeated measures on recognition time. The main effect of orientation was significant [$F(1, 9) = 10.32$, $p = .01$, $\eta_p^2 = .53$], revealing a faster recognition for vertical patterns ($M = 1.28$ s, $SE = 0.06$) than for horizontal patterns ($M = 1.41$ s, $SE = 0.05$). The main effect of distance was also significant [$F(2, 18) = 57.88$, $\varepsilon = .69$, $p < .001$, $\eta_p^2 = .87$]. Tukey's post hoc analyses revealed that recognition time significantly decreased at each level of distance between tactors ($ps \leq .001$), with a mean of 1.56 s ($SE = 0.06$) for the distance of 9.5 mm, 1.32 s ($SE = 0.05$) for the distance of 16.5 mm, and 1.15 s ($SE = 0.05$) for the distance of 28.5 mm.

The main effects of BD [$F(2, 18) = 65.68$, $p < .001$, $\eta_p^2 = .88$] and IBI [$F(3, 27) = 14.40$, $\varepsilon = .92$, $p < .001$, $\eta_p^2 = .62$] were significant, showing that recognition time decreased as BD and IBI increased. Tukey's post hoc analyses showed that recognition time decreased at each level of BD ($ps \leq .001$), with a mean of 1.59 s ($SE = 0.05$) for the BD of 100 ms, 1.26

s (*SE* = 0.06) for the BD of 200 ms, and 1.15 s (*SE* = 0.06) for the BD of 400 ms. For IBI, Tukey's post hoc analyses revealed significant differences between -100 ms (*M* = 1.53 s, *SE* = 0.05) and all other time intervals, $ps \leq .001$, which were comprised between 1.25 s (*SE* = 0.06) for IBI = 400 ms and 1.32 s (*SE* = 0.06) for IBI = 0 ms.

Finally, the ANOVA revealed a significant BD × IBI interaction [$F(6, 54) = 8.50$, $p < .001$, $\eta_p^2 = .49$], indicating that the influence of IBI on recognition time decreased as BD increased (Figure 5, left panel). Tukey's post hoc analyses comparing recognition times across IBIs for a given BD revealed that, for the BD of 100 ms, the IBI of -100 ms led to slower recognition than all the other IBIs ($ps \leq .001$); for the BD of 200 ms, the IBI of -100 ms led to slower recognition than the IBI of 400 ms ($p = .023$); as for the BD of 400 ms, there was no significant difference across IBIs ($ps = 1$). The conversion of IBI into SOA (Figure 5, right panel) shows once again that this parameter seems to capture in one single variable the effects of temporal parameters on pattern recognition. The ANOVA revealed no other significant interaction [$Fs \leq 2.23$, $p \geq .14$, $\eta_p^2 \leq .20$].

***Apparent Movement Scores***

We conducted a Distance × BD × IBI × Orientation ANOVA with repeated measures on apparent movement scores. The main effects of distance and orientation were not significant [$Fs \leq 1.12$, $p \geq .33$, $\eta p^2 \leq .11$]. The main effects of BD [$F(2, 18) = 9.05$, $p = .002$, $\eta_p^2 = .50$] and IBI [$F(3, 27) = 82.13$, $\varepsilon = .42$, $p < .001$, $\eta_p^2 = .90$] were significant, showing that the impression of movement tended to decrease as these temporal parameters increased. The interaction between BD and IBI was also significant [$F(6, 54) = 6.76$, $\varepsilon = .75$, $p < .001$, $\eta_p^2 = .43$] (Figure 6). Tukey's post hoc analyses comparing apparent movement scores across IBIs for a given BD revealed a significant decrease in perceived continuity for each increase of IBI ($ps \leq .001$), except for BDs of 200 ms and 400 ms for which no difference was found between the IBIs of – 100 ms and 0 ms ($ps = 1$). It should be noted that contrary to recognition accuracy and recognition time, IBI (left panel of Figure 6) seems to better capture the influence of stimulation's temporal properties on apparent movement scores than SOA (right panel of Figure 6).

The interaction between distance and IBI was also significant [$F(6, 54) = 3.77$, $\varepsilon = .75$, $p = .013$, $\eta_p^2 = 0.30$]. Tukey's post hoc analyses revealed that apparent movement scores tended to be similar across the three distances for each IBI (ps $\geq .07$), except for the IBI of 200 ms whose scores were found to be significantly lower for the distance of 28.5 mm than for the distance of 9.5 mm ($p < .001$). The ANOVA revealed no other significant interaction [$Fs \leq 2.50$, $p \geq .06$, $\eta_p^2 \leq .22$].

We evaluated the relation between apparent movement scores and recognition accuracy for the three distances between tactors (Figure 7). The correlation was not significant for the distance of 9.5 mm [$r(10) = -.31$, $p = .32$], but we found significant negative correlations for the distances of 16.5 mm [$r(10) = -.623$, $p = .030$] and 28.5 mm [$r(10) = -.659$, $p = .020$], which showed that, as apparent movement scores increased, recognition accuracy decreased for these two distances.

**Discussion**

Experiment 1 demonstrates that the recognition of vibrotactile patterns presented in the tracing mode is highly influenced by spatial and temporal characteristics of stimuli as well as by interactions among them. The results show that this influence overall supports the isolation hypothesis (Mahar & Mackenzie, 1993). In fact, the farther apart the pattern elements were in space (inter-tactor distance) and/or in time (expressed either in terms of IBI or SOA), thereby reducing the amount of masking, the better the recognition performance was, for both accuracy and recognition time.

This result does not disprove the integration hypothesis in itself, because the optimum level of masking for the purpose of pattern perception may lie somewhere between the point where no masking occurs and the point of maximum masking (Mahar & Mackenzie, 1993). However, if we cannot ensure that our larger inter-tactor distance (28.5 mm) entirely ruled out spatial masking effects (see the General discussion), the highest inter-burst intervals we tested (200 and 400 ms, corresponding to SOAs ranging from 300 to 800 ms) were way beyond the range in which temporal masking effects are usually observed (e.g., Craig, 1983, 1998; Evans & Craig, 1986; Gescheider et al., 1989). In addition, contrary to what has been suggested or implicitly assumed previously (e.g., Cholewiak & Collins, 2000; Kirman, 1974) in line with the integration hypothesis, the perception of apparent movement was not positively correlated to pattern recognition. We observed that recognition accuracy was either not related to apparent movement scores (for the inter-tactor distances of 9.5 mm) or tended to decrease as apparent movement scores increased (for the inter-tactor distance of 16.5 and 28.5 mm). This result is consistent with the fact that apparent movement scores were found to decrease with higher burst duration and time intervals between vibratory bursts (in line with Cholewiak & Collins, 2000; Kirman, 1974, 1983; Sherrick & Rogers, 1966) while, on the contrary, recognition performance improved with these temporal parameters. The interactions between spatial and temporal parameters, as well as the question of the variable which better captures the influence of stimulation's temporal properties (IBI vs. SOA), will be discussed in the General discussion section.

An additional result is that pattern orientation on the abdomen had an effect on recognition performance, with better recognition accuracy and shorter recognition time in the longitudinal orientation than in the transverse orientation. This result relates to tactile anisotropy, a well-documented effect that has been investigated mainly in the upper limb. Since Weber (1826/1978) has found that tactile sensitivity as measured by the two-point threshold was greater in the transverse orientation than in the longitudinal orientation for the upper arm and the forearm, several studies have reported congruent results in spatial perception with various measures for the arm (e.g., Cody et al., 2008; Geldard & Sherrick, 1983; Gibson & Craig, 2005; Green, 1982; Le Cornu Knight et al., 2014), the posterior surface of the hand (Cody et al., 2008; Longo & Haggard, 2011), the wrist (Cody et al., 2008), and the calf of the leg (Fuchs & Brown, 1984). For these body loci, acuity and perceived distance between tactile stimuli were greater in the transverse axis than in the longitudinal axis. The few studies that have investigated anisotropy on the torso led to diverging results. Using pressure stimuli, Fuchs and Brown (1984) observed an anisotropic effect on the lateral mid-back that was reversed compared to other body sites, with a greater two-point acuity in the longitudinal axis than in the transverse axis. Also using pressure stimuli, Green (1982) and recently Longo et al. (2019) observed no anisotropy in perceived distance on the abdomen. Finally, Hoffmann et al. (2018) assessed vibrotactile spatial acuity in the center area of the back with three different tactor types and observed an anisotropic effect similar to what has been found for the limbs, with higher spatial acuity for horizontal than for vertical stimulus presentation. Given that the present study was not designed to specifically address the question of anisotropy, we will not further discuss the differences in the results across studies or the possible explanatory factors that have been proposed to account for this effect in the literature (e.g., Essock et al., 1997; Gibson & Craig, 2005; Greenspan & Bolanowski, 1996). However, the asymmetry that we observed in pattern perception reveals that contrary to what has been found for distance perception with pressure stimuli (Green, 1982; Longo et al., 2019), anisotropy in vibrotactile perception turns out to exist on the abdomen and would deserve to be further investigated in future research.

## Experiment 2

Previous studies led to diverging results concerning the superiority of the static mode and the tracing mode for the recognition of 2D tactile patterns. The tracing mode was proposed (Loomis, 1974, 1980) and found as leading to the best performance in pattern recognition for the back (Beauchamp et al., 1971; Novich & Eagleman, 2015) and the abdomen (Saida et al., 1982), whereas the static mode was found as leading to the best performance for the fingertip (Craig, 1980, 1981, 2002). In addition, the three studies which have compared the tracing mode to other modes for the torso do not allow a firm statement about its superiority for this body site, either because there was no standardization of stimulus parameters across trials (Beauchamp et al., 1971), because the total durations of pattern presentation were unusually long and different between display modes (from 9.4 s for the static mode to 35.4 s for the scanned mode; Saida et al., 1982), or because the sets of patterns were not identical across the display modes tested (Novich & Eagleman, 2015).

Experiment 2 was dedicated to the comparison between the static mode and the tracing mode for the recognition of eight vibrotactile patterns (upper-case letters and geometric forms) presented to the abdomen of novice participants. We also examined the slit-scan mode (Figure 1), as an intermediate between a full presentation of the pattern at once (static mode) and a completely successive activation of each tactor making up the pattern (tracing mode). The display modes we tested thus induced three levels of temporal overlap in the presentation of pattern elements, allowing further evaluation of the isolation/integration hypotheses. In order to enhance the precision of the analysis, we tested two different time intervals for the sequential modes. The first corresponded to a temporal overlap of successive vibrations known to induce apparent movement. The second was chosen from the highest recognition rates observed in Experiment 1 and corresponded to a silent delay between successive vibrations, isolating pattern elements in time.

## Method

### *Participants*

Twelve participants (six women, six men) took part in the experiment. Their mean age was 24.25 years (range: 20 – 36) and their mean BMI was 22.27 kg/m² (range: 19.05 –

24.90). None of them reported having any sense of touch disorders and all of them experienced the use of a vibrotactile display for the first time. Each participant signed an informed consent statement after receiving oral and written descriptions of the procedure.

***Apparatus and Stimuli***

The setup was similar to Experiment 1 (Figure 3) with the following differences. Twenty-two tactors were inserted into the gel pad to form eight patterns: a triangle, a hexagon, a diamond, a converging double arrow, a V, a W, an X, and a Y (Figure 8, top panel). The participants held a keypad labeled with drawings of the eight patterns to enter their responses.

From the results of Experiment 1, we retained the distance of 28.5 mm between tactors, which gave the best recognition accuracy and the shortest response time. Note that because of the pre-defined configuration of the gel pad, the size of the tail of the Y-shape (distance between the two lower tactors), which was equal to 33 mm, is an exception.

The patterns were made up of four to seven tactors and were generated in three modes, differing in their level of temporal overlap in the presentation of pattern elements (Figure 8, bottom panel). In the static mode, all the tactors making up the pattern were activated simultaneously. In the slit-scan mode, the tactors making up the pattern were activated row by row, from top to bottom. In the tracing mode, the tactors making up the pattern were activated successively, following the same order as in handwriting.

For the two sequential modes (i.e., the slit-scan mode and the tracing mode), we fixed BD at 400 ms, which gave the best recognition accuracy and the shorter recognition time in Experiment 1. We varied the continuity of pattern presentation by testing two time intervals between vibrations: an SOA of 300 ms (IBI = -100 ms), yielding an uninterrupted, continuous presentation of successive vibrations (with 100 ms of overlap between vibrations), and an SOA of 600 ms (IBI = 200 ms), in which the vibrations followed each other in a discrete manner (with 200-ms pauses in between). As the tactors were all activated at once in the static mode, the temporal parameter was varied by means of burst duration, with a value of 400 ms (i.e., equal to the burst duration used in the sequential modes) and a longer duration, equal to 1 s. In fact, test trials conducted with higher values of BD (until 4 s) for the static mode showed no performance improvement compared to 1 s. For comparison, Craig (1980, 1981) tested durations inferior or equal to 400 ms for the static mode on the fingertip, and Loomis (1974, 1980) used a duration of 1.5 s for the static mode on the back.

***Procedure***

Prior to the start of the experimental session, each of the 22 tactors was successively activated for 400 ms and participants confirmed that they felt each vibration. Participants then completed three blocks of trials corresponding to the three modes of pattern generation: static, scanned, and tracing modes. The order of the blocks was counterbalanced across participants.

At the beginning of each block, participants were familiarized with the stimuli and the task. During the first phase of familiarization, the eight patterns were presented in the mode corresponding to the block. The experimenter announced the pattern that was about to be displayed and launched the tactile pattern twice for each temporal parameter (SOA = 300 ms or 600 ms for the tracing and the slit-scan modes; BD = 400 ms or 1 s for the static mode). During the second phase of familiarization, the experimenter did not announce the patterns. Participants were asked to recognize them and to enter their response by pressing one of the eight corresponding keys on the keypad. This second phase of familiarization consisted of 32 randomized trials (8 patterns presented in the mode corresponding to the block × 2 temporal parameters × 2 trials) and lasted about 5 minutes. Feedback was provided after each trial of this familiarization phase: the experimenter indicated if the participant’s response was right or wrong and, if wrong, which pattern had been displayed.

Participants then completed 48 randomized experimental trials (8 patterns presented in the mode corresponding to the block × 2 temporal parameters × 3 trials). The mode of response was the same as in the second phase of familiarization, but participants received no feedback about the exactness of their response. Participants launched the next trial themselves by pressing the enter key on the keypad.

After the completion of a block, participants were invited to take a short break during which they could sit down. Altogether, the experiment took about 55 minutes to complete.

### *Data Analysis*

Since the static mode implies no delay between the vibrations, the two levels of temporal parameters for this mode were based on burst duration, whereas they were based on SOA for the slit-scan mode and the tracing mode. To account for this asymmetry, we compared the influence of temporal parameters on recognition accuracy and recognition time with independent *t* tests for each display mode and then compared display modes across temporal parameters using one-way analyses of variance (ANOVAs). Since each data set was used twice, a Holm-Bonferroni correction was applied to control for Type I error: the lowest *p* value resulting from the *t* test and the ANOVA had then to be less than .025 to reach significance. In the ANOVAs, the *p* value levels were corrected for possible deviations from sphericity using the Huynh-Feldt epsilon (ε). When appropriate, we report the uncorrected degrees of freedom, the ε value, and the *p* value according to the corrected degrees of freedom.

## Results

### *Confusion Matrix*

Table 2 shows the confusion matrix for the three display modes. The percentage of responses was computed over the two levels of temporal parameters, giving a total of 72 responses (3 trials × 2 temporal parameters × 12 participants) for each pattern in a given display mode. With eight patterns to recognize, the probability to give a correct answer by responding at random was equal to 12.5%.

The confusion matrix reveals that the static mode yielded poor levels of performance, with a percentage of correct responses ranging from 18.1% (for the triangle and the V) to 43.1% (for the W). The hexagon was quite often confounded with the V (25% of responses), the diamond with the Y (29.2% of responses), and conversely, the Y with the diamond (27.8% of responses). Recognition accuracy was better but still modest for the slit-scan mode (see the ANOVA on recognition accuracy below for statistical significance), with a percentage of correct responses ranging from 36.1% (for the X) to 63.9% (for the triangle). The V was quite often confounded with the Y (26.4% of responses) and the W with the V (31.9% of responses). Better recognition rates were achieved in the tracing mode, with a percentage of correct responses ranging from 52.8% (for the triangle) to 81.9% (for the hexagon). The triangle was quite often confounded with the hexagon (23.6% of responses) in this mode.

***Recognition accuracy***

Mean recognition accuracies for the three display modes and their corresponding temporal parameters are presented in Figure 9. The independent *t* tests comparing the two levels of temporal parameter for each display mode revealed a significant effect of SOA for the tracing mode [$t(11) = -3.27$, $p = .007$, $d = 0.94$] and the slit-scan mode [$t(11) = -2.20$, $p = .050$, $d = 0.64$], indicating that recognition accuracy was higher for the larger SOA (600 ms) than for the shorter one (300 ms). For the static mode, no difference in recognition accuracy was found between the burst durations of 400 ms and 1000 ms [$t(11) = -0.84$, $p = .42$, $d = 0.24$].

The display modes were compared with a one-way repeated measures ANOVA conducted on recognition accuracy values averaged across the two levels of temporal parameter. The ANOVA revealed a significant effect of display mode [$F(2, 22) = 40.76$, $p < .001$, $\eta_p^2 = .79$]. Tukey's post hoc analyses indicated that recognition accuracy was significantly higher for the tracing mode ($M = 68.29\%$, $SE = 5.91$) than for the two other display modes [$ps \leq .016$], and that the slit-scan mode ($M = 54.13\%$, $SE = 6.42$) led to significantly better recognition performance than the static mode ($M = 26.75\%$, $SE = 1.99$) [$p < .001$].

It is interesting to note that, while recognition accuracy was homogeneously low across participants for the static mode, inter-individual differences were much higher in the slit-scan mode and in the tracing mode. This can be seen from the confidence intervals (error bars in Figure 9) as well as from the standard error values presented earlier, but this inter-individual variability in performance for the sequential modes is even more manifest when we compare the best and worst individual performances in the different conditions. Individual recognition rates ranged from 8.33% to 41.67% in the static mode, from 8% to 88% in the slit-scan mode, and from 25% to 100% in the tracing mode. The recognition task appeared to be particularly difficult for one of the participants, who obtained three of the four lowest individual recognition rates in the sequential modes and who never exceeded 29% of correct answers in any of the conditions. Conversely, some participants appeared to be particularly successful, especially when the SOA of 600 ms was applied to the tracing mode: in this condition, three participants reached individual recognition rates of 96% and higher.

***Recognition Time***

As an indicator of the difficulty of pattern recognition, we analyzed recognition time, i.e., the delay between the end of pattern presentation and the participant's response on the keypad. The *t* test conducted for the slit-scan mode revealed a significant effect of SOA on recognition time [$t(11) = 2.93$, $p = .014$, $d = 0.84$], the SOA of 600 ms leading to a shorter recognition time ($M = 2.85$ s, $SE = 0.32$) than the SOA of 300 ms ($M = 3.45$ s, $SE = 0.35$).

The other *t* tests revealed no significant effect of SOA for the tracing mode [$t(11) = 1.07$, $p = .31$, $d = 0.31$] and no significant effect of BD for the static mode [$t(11) = -0.14$, $p = .89$, $d = 0.04$]. The one-way repeated measures ANOVA conducted on recognition time values averaged across temporal parameters revealed no significant effect of display mode [$F(2, 22) = 3.36$, $\varepsilon = .63$, $p = .081$, $\eta_p^2 = 0.23$].

**Control Experiment**

Experiment 2 showed that recognition accuracy was the highest in the tracing mode, intermediate in the slit-scan mode, and the lowest in the static mode. However, we cannot exclude the possibility that this ordering of display modes might be influenced by the fact that the duration of pattern presentation differed between modes. In fact, the temporal parameters we tested in Experiment 2 induced pattern durations which were equal to 400 ms or 1 s for the static mode (pattern duration being equal to BD in this mode), to 1 s or 1.6 s for the slit-scan mode (corresponding to three steps in pattern presentation - Figure 8 - with SOAs of 300 ms and 600 ms, respectively), and which ranged from 1.6 s to 2.2 s (SOA = 300 ms) and from 2.8 s to 4 s (SOA = 600 ms) for the tracing mode. To exclude the potential confounding effect of pattern duration on recognition accuracy, we conducted a control experiment testing a large set of pattern durations for the static mode and the slit-scan mode. This new set of pattern durations included (*i*) the temporal parameters already tested in Experiment 2 for each mode (400 ms and 1 s for the static mode; 1 s and 1.6 s for the slit-scan mode), as a basis of comparison, and (*ii*) pattern durations equivalent to those tested in Experiment 2 for the tracing mode (1.9 s and 3.4 s in average for the SOAs of 300 ms and 600 ms, respectively).

Twelve participants (six women and six men from 23 to 43 years; BMI from 19.15 to 25.95 kg/m²) took part in this control experiment. Seven of them had participated in Experiment 2, which provided an important baseline for the comparison between studies. The apparatus and the eight two-dimensional patterns were similar to Experiment 2. Participants completed two blocks of trials corresponding to the static mode and the slit-scan mode. The order of the blocks was counterbalanced across participants. As in Experiment 2, two phases of familiarization were completed for the five novice participants at the beginning of each block. For the seven participants who took part in Experiment 2, the number of familiarization trials was reduced by half. For the static mode, five pattern durations were tested by manipulating burst duration: 200 ms, 400 ms, 1 s, 1.9 s, and 3.4 s. For the slit-scan mode, burst duration was fixed at 400 ms and four pattern durations were tested by manipulating the delay between vibrations: 1 s (SOA = 300 ms; IBI = -100 ms), 1.6 s (SOA = 600 ms; IBI = 200 ms), 1.9 s (SOA = 750 ms; IBI = 350 ms), and 3.4 s (SOA = 1.5 s; IBI = 1.1 s).

For the static mode, mean recognition rates ranged from 18.1% for the pattern duration of 200 ms to 25.7% for the pattern duration of 1 s for the group of twelve participants. A one-way ANOVA (5 pattern durations) with repeated measures revealed no significant effect of pattern duration on recognition accuracy for this mode [$F(4, 44) = 1.73$, $p = .16$, $\eta_p^2 = .14$]. The same analysis conducted for the slit-scan mode revealed a significant effect of pattern duration [$F(3, 33) = 14.16$, $p < .001$, $\eta_p^2 = .56$] which, as revealed by Tukey's post hoc analyses, was due to a lower recognition rate for the pattern duration of 1 s ($M$ = 38.53%, $SE$ = 4.45) than for all other pattern durations ($ps \leq .003$). Recognition rates for pattern durations of 1.6, 1.9 and 3.4 s were equal to 51.74% ($SE$ = 4.49), 51.04% ($SE$ = 5.60) and 59.7% ($SE$ = 4.51) respectively, and did not significantly differ from each other ($ps \geq .058$). The first analysis demonstrates that recognition accuracy in the static mode does not improve with longer pattern durations and appears to be quite insensitive to temporal parameters. The second analysis indicates a significant influence of pattern duration on recognition accuracy for the slit-scan mode, but performance levels remained lower to the ones we observed for the tracing mode in Experiment 2, both for the shorter temporal parameter (*M* = 60.11%, *SE* = 8.13) and for the longer one (*M* = 74.40%, *SE* = 5.33).

To further verify that the ordering of display modes observed in Experiment 2 was unchanged when comparing equivalent pattern durations, we analyzed the results of the seven participants who took part in both Experiment 2 and the control experiment (Figure 10). First, it should be noted that participants' recognition rates in identical conditions (same mode, same pattern duration) were very similar for the two experiments, with the mean of individual differences across the group ranging from 0 to 4.8%. This consistency in the results enabled us to conduct a Mode (static, slit-scan, tracing) × Pattern duration (1.9 s, 3.4s) ANOVA on recognition accuracy, with repeated measures on both factors. The main effect of mode was significant [$F(2, 12) = 48.53$, $p < .001$, $\eta_p^2 = .89$] and confirmed that the ordering of display modes observed in Experiment 2 was not due to pattern duration. Tukey's post-hoc analyses revealed that recognition accuracy was significantly higher for the tracing mode (*M* = 67.26%, *SE* = 6.4) than for the two other display modes [$ps \leq .026$], and that the slit-scan mode (*M* = 52.68%, *SE* = 6.15) led to significantly better recognition than the static mode (*M* = 21.13%, *SE* = 2.86) [$p < .001$]. The main effect of pattern duration was also significant [$F(1,6) = 19.30$, $p = .005$, $\eta_p^2 = .76$], showing that recognition accuracy was higher for the pattern duration of 3.4 s (*M* = 51.19%, *SE* = 4.41) than for the pattern duration of 1.9 s (*M* = 42.86%, *SE* = 4.97). The interaction Mode × Pattern duration was not significant [$F(2, 12) = 2.14$, $p = .16$, $\eta_p^2 = .26$].

**Discussion**

In Experiment 2, we selected a distance between tactors (28.5 mm) which favored the separation of pattern elements in space and we manipulated the temporal separation in the presentation of these elements, either through the temporal overlap induced by the display modes and/or through the delay between successive vibrations (SOA/IBI). The first important result to emerge was that the tracing mode led to the best recognition accuracy whereas the static mode led to the worst. These results are opposed to those obtained for the fingertip (Craig, 1981), but confirm and enlarge the results reported for the back (Beauchamp et al., 1971; Novich & Eagleman, 2015) and the abdomen (Saida et al., 1982). In particular, we demonstrated a progressive increase in recognition accuracy with the three levels of temporal overlap we tested, performance being the lowest when pattern elements were all displayed simultaneously (static mode), intermediate when patterns were displayed group of elements by group of elements (slit-scan mode), and the highest when the elements were displayed one after the other (tracing mode). In addition, we controlled for factors that were potentially confounding in previous studies by using the same set of patterns for every display mode condition, and by controlling for the influence of pattern duration on the ordering of display modes in a control experiment.

In line with this result, Experiment 2 also revealed the influence of temporal separation between the steps of pattern presentation. Increasing SOA from 300 ms (IBI = -100 ms) to 600 ms (IBI = 200 ms) for the slit-scan and the tracing modes significantly improved recognition accuracy. The interest of this result is twofold. First, to our knowledge, this is the first evaluation (and demonstration) of the influence of the delay applied to the slit-scan mode and the tracing mode on the recognition of vibrotactile patterns. In previous studies, inter-burst interval was set to 0 ms (i.e., SOA was equal to BD; see Table 1), which, according to the present results, does not appear to be the optimal choice. Second, in accordance with what has been observed with apparent movement judgments in Experiment 1, this result further suggests that the continuity of tracing does not benefit recognition performance compared to the isolation of pattern elements in time. For burst durations that are higher than 100 ms, apparent movement was found to be elicited when successive bursts partially overlap (e.g., Kirman, 1974; Niwa et al., 2009; Sherrick & Rogers, 1966; Shimizu, 1989). For example, Sherrick and Rogers (1966) observed that for a burst duration of 400 ms, the optimum SOA for best apparent movement was 246 ms, a value which is very close to the shorter temporal interval (SOA = 300 ms) we tested in Experiment 2. Therefore, the lower recognition rates observed for the SOA of 300 ms compared to the SOA of 600 ms confirm the findings of Experiment 1 that temporal parameters eliciting apparent movement do not favor pattern recognition. Together with the fact that recognition rates improved with the sequentiality of display modes, this result is a new element to support the isolation hypothesis.

## General Discussion

The present study investigated the influence of spatial and temporal factors in the presentation of two-dimensional tactile patterns in order to test whether the spatial and/or temporal proximity of pattern elements would help or hinder pattern recognition. According to the integration hypothesis, conditions leading to an optimal interaction between pattern elements, such as the ones eliciting apparent movement, are expected to favor pattern recognition through proper perceptual integration. On the contrary, according to the isolation hypothesis, separating pattern elements in time and space is expected to favor recognition by avoiding masking effects. The results overall support the isolation hypothesis. Focusing on the tracing mode, Experiment 1 demonstrated that the farther apart the pattern elements were presented in space (inter-tactor distance) and/or in time (either expressed in terms of IBI or SOA), the better the performance was, both in terms of recognition accuracy and of recognition time. In particular, apparent movement, i.e., the perception of a continuous displacement of the stimulation on the skin, was found to be associated with a decrease in recognition performance for the larger distances. Experiment 2 showed that recognition accuracy increased with the sequentiality of display modes, performance being the lowest for the static mode, intermediate for the slit-scan mode, and the highest for the tracing mode. The results also confirmed the findings of Experiment 1 that recognition performance is improved when patterns are displayed in a discrete (long SOA, positive IBI) rather than in a continuous (short SOA, negative IBI) manner.

**Masking, Sequentiality, and Spatial Acuity**

The poor performance in pattern recognition that we observed when pattern elements were close in space and time suggests the presence of masking effects, which probably reveal the limits in spatial and temporal acuity of the skin. The results of our experiments enlarge the conclusions drawn from studies on the influence of display mode on 2D pattern recognition for the abdomen (Saida et al. 1981) and the back (Loomis, 1974; Novich & Eagleman, 2015) and from the only study we know of which has tested the integration/isolation hypotheses for another body site than the fingertip (Mahar & Mackenzie, 1993). By contrast, they are in contradiction with the results obtained for the fingertip (Craig, 1981, 1982, 1998; Epstein et al., 1989; Loomis, 1980). Loomis & Lederman (1986) have already pointed out this discrepancy between body sites and hypothesized that “there should be an advantage of sequential presentation only when cutaneous spatial resolution is limiting recognition performance” (p. 31.15). Loomis’ results (1980) support this idea, showing that the slit-scan mode yielded slightly better recognition performance than the static mode when the letters presented to the finger were smaller (13 mm high) than the size commonly used with the Optacon (20 mm).

Firmly accepting or rejecting the hypothesis that sequential presentation (scanning and a fortiori tracing) is superior to the static mode only when the cutaneous spatial resolution limits recognition performance is difficult. In fact, because of a variety of tasks (e.g., two-point discrimination, point localization, grating orientation, gap detection), types of contact (touch, vibrations, electrical pulses), and temporal stimulation parameters (simultaneous or sequential stimuli), there is no consensual measure of tactile spatial resolution (e.g., Bruns et al., 2014; Boldt et al., 2014; Hoffman et al., 2018; Jóhannesson et al., 2017; Johnson & Phillips, 1981). The distance of 28.5 mm between the tactors that we tested in Experiment 2 is two to three times higher than most measurements of vibrotactile spatial acuity available for the torso in the literature (Eskildsen et al., 1969; Jóhannesson et al., 2017; Hoffman et al., 2018; see the introduction of Experiment 1 for the presentation of tasks, stimuli, and threshold values). However, it is well below the spatial resolution of 6 cm estimated by Novich & Eagleman (2015, Experiment 2; see Footnote 3). The validity of the assumption by Loomis & Lederman (1986) thus remains an open question. It would be interesting to further increase the distance between the tactors in order to evaluate if the ordering of the display modes would change. This procedure could also contribute to testing whether recognition performance can be further increased by varying this parameter.

**Apparent Movement and Temporal Integration**

While the tracing mode led to the best recognition performance regardless of temporal parameters in Experiment 2, the continuity of tracing, which might be considered to be the characteristic attribute of the tracing mode according to such descriptions as “finger writing on the back” (Loomis, 1974, 1981; Loomis & Lederman, 1986), was on the contrary detrimental to recognition performance (Experiments 1 and 2). Good apparent movement, that is, the feeling of a stimulus moving smoothly along the skin, has been considered to be the expression of perceptual integration (Kirman, 1973) and has been proposed or assumed to favor the recognition of spatiotemporal tactile patterns (e.g., Cholewiak & Collins, 2000; Kirman, 1973, 1974). In Experiment 1, we found no correlation between the judgments of apparent movement and recognition accuracy for the shorter distance between tactors (9.5 mm). For the distances of 16.5 mm and 28.5 mm, we found a negative correlation, in other words, recognition accuracy decreased as apparent movement scores increased. In Experiment 2, we tested two temporal intervals, one with an overlap of 100 ms between successive vibrations, known to elicit apparent movement when used in conjunction with a BD of 400 ms (e.g., Kirman, 1974; Niwa et al., 2009; Sherrick & Rogers, 1966; Shimizu, 1989), and another with a delay of 200 ms between successive burst, known to produce the feeling of distinct, independent vibrations (e.g., Cholewiak & Collins, 2000). In accordance with the results of Experiment 1, recognition accuracy was found to be better for the latter (SOA of 600 ms; IBI = 200 ms) than for the former (SOA of 300 ms; IBI = -100 ms). To our knowledge, the only author who reported a comparable effect is Bice (1969), who found that the subjective reports rating the clearness of apparent movement correlated poorly with the recognition of the direction of displacement of successive vibrations. In line with the isolation hypothesis, the present result confirms and enlarges this observation: the full benefits of the tracing mode in terms of pattern recognition are likely to be obtained for sufficient temporal intervals between successive vibrations, that is, delays that do not elicit apparent movement but the feeling of independent vibrations.

The temporal interval between vibrations can be expressed in terms of IBI or SOA. In Experiment 1, we observed that SOA appeared to synthesize the influence of BD and IBI on recognition accuracy and recognition time (Figures 4 and 5). This result is congruent with previous studies (e.g., Craig, 1983, 1985) which have found that SOA is the critical dimension for temporal tactile masking. It follows that reducing BD to reduce the amount of temporal masking is unlikely to be very successful if SOA is left unaltered (Craig, 1983, 1985). This statement, formulated by Craig for masking effects between successive patterns, seems to be also applicable to masking effects between successive pattern elements, as demonstrated in Experiment 1 (Figure 4, bottom panel).

On the contrary, we observed that IBI might be a better candidate than SOA to capture the influence of temporal parameters on the perception of apparent movement (Experiment 1, Figure 6). While most studies on tactile apparent movement have manipulated SOA and not

IBI, some results (Kirman, 1974; Cholewiak & Collins, 2000) indicate that our observation might deserve further research.

**Interaction of Spatiotemporal Parameters**

Previous studies have shown the important interdependence of spatial and temporal factors on the perception of tactile stimuli, such as in the sensory saltation phenomenon (e.g., Geldard & Sherrick, 1972), the Tau effect (e.g., Helson & King, 1931), the Kappa effect (e.g., Suto, 1952), or the judgment of the overall extent produced by pairs of vibrotactile stimuli (Cholewiak, 1999). To our knowledge, the present study is the first to test and demonstrate that such an interaction between space and time exists for the recognition of 2D vibrotactile patterns.

In fact, Experiment 1 revealed that the influence of the temporal parameters applied to the tracing mode increased with inter-tactor distance. Temporal parameters had virtually no influence on recognition accuracy for the distance of 9.5 mm (likely to be inferior to the vibrotactile spatial resolution of the torso; e.g., Eskildsen et al., 1969; Jóhannesson et al., 2017; Hoffman et al., 2018). For the inter-tactor distance of 16.5 mm, recognition accuracy increased with temporal parameters; such influence was even more pronounced for the inter-tactor distance of 28.5 mm. It is interesting to note that a medium value of one parameter was in part compensated by a high value of the other parameter. For example, increasing inter-tactor distance improved recognition accuracy for a given combination of temporal parameters (Figure 4). Conversely, the medium inter-tactor distance of 16.5 mm was compensated by longer temporal parameters, to yield levels of recognition accuracy comparable to those obtained for the inter-tactor distance of 28.5 mm. In other words, the results of Experiment 1 suggest that, if specific constraints related to the context of use require limiting the size of the display or the presentation time of the pattern, this limitation could be compensated by increasing the other, less constrained, parameter. Again, it would be interesting to test higher distances between tactors in order to evaluate the extent to which temporal parameters could be reduced while obtaining a satisfying level of pattern recognition. In fact, the tracing mode has the disadvantage of requiring a long presentation time, and reducing this time to a minimum might be of major importance for many contexts of use. In this line of reasoning, testing higher values of temporal parameters so as to examine the extent to which spatial parameters could be reduced, could also be interesting from a theoretical point of view, although it may be less relevant from an applied perspective.

Psychophysical research on tactile perception usually distinguishes between spatial and temporal resolution of the skin (e.g., Johnson & Phillips, 1981; Sherrick & Cholewiak, 1986; Lederman & Klatzky, 2009). The present results and others on spatiotemporal illusions (e.g., Geldard & Sherrick, 1972; Helson & King, 1931; Jones, 1956; Suto, 1952) support the idea that separate measures might not be well adapted to predict recognition performance for tactile patterns involving both spatial (more than one point of stimulation) and temporal components (inherently present with the duration of contact or of vibration, and, when several are present, with the delay between stimulation points). In these most frequent cases, it might be necessary to refer to the spatiotemporal resolution of the skin, without separating the spatial and temporal dimensions (cf. Boldt et al., 2014).

**Absolute Level of Performance in Pattern Recognition with the Tracing Mode**

With a set of eight patterns in Experiment 2, the group of participants reached a mean percentage of correct responses of 62.2% (95% CI [48.5, 75.8]) for the SOA of 300 ms and 74.4% for the SOA of 600 ms (95% CI [60.8, 88.1]) in the tracing mode. These absolute levels of performance are comparable to the best recognition rate (67%) reported by Novich & Eagleman (2015) for the back, with the same number of patterns and the same display mode. However, they appear to be moderate in comparison to the best recognition rates obtained with the tracing mode in other previous studies (87% for the back, Yanagida et al., 2004; 90% for the palm, Shimizu, 1982; 95% for the abdomen, Saida et al., 1982), especially given the large sets of patterns used in these experiments (see the fourth column of Table 1).

One explanation might be linked to the procedure. In Experiment 2, the two temporal parameters applied to one display mode were mixed into each block of trials. Jumping from one temporal parameter to the other within the same block might have complicated the task, as stated by one of the participants. However, we think that a major factor explaining this lower performance is the fact that, contrary to previous experiments, we deliberately chose to test participants who were total novices in the use of vibrotactile displays. Outside the laboratory, the need for an important amount of practice is likely to discourage potential users and thus hinder the effective use of a device. The initial level of performance is therefore a crucial reference to define the optimal manner in how to present vibrotactile patterns. We can see from the last column of Table 1 that, when it was reported, the experience of participants with vibrotactile displays appeared to be substantial (from several hours to several months) in most previous studies. These differences in participants' experience are likely to explain, at least in part, the differences in performance between studies. They also encourage future work to examine the evolution of performance with practice in a longitudinal manner, in order to evaluate the rate at which recognition accuracy increases, as well as when and at which level performance reaches a ceiling. This question could be addressed in conjunction to the one of inter-individual differences in the ability to recognize tactile patterns. While the influence of display mode and temporal parameters appeared to be very similar across participants, Experiment 2 revealed large differences in individual recognition rates that are in line with previous results obtained with the Optacon (Cholewiak & Collins, 1997; Epstein et al., 1989). It would be interesting to examine if these inter-individual differences in performance persist or fade with learning, and if they imply different learning profiles.

Other methodological specificities might explain the differences in absolute levels of recognition. For example, Saida et al. (1982), who obtained the best level of recognition accuracy (95%) of all the studies, presented each pattern 3 times in a row before recognition, which is likely to have significantly favored recognition accuracy. Another, non-exclusive, explanation is that, beyond inter-tactor distance, the number of tactors defining the pattern and/or the overall size of the pattern also influence their recognition. In Saida et al. (1982), each stroke composing the character could be formed by as much as 10 tactors and the size of patterns could be as much as 13.5 cm horizontally and vertically. In Experiment 2, each stroke was formed by no more than two or three tactors and the size of patterns did not exceed 8.55 cm horizontally and 5.78 cm vertically. This analysis questions the influence of both the density of tactors making up the patterns and the overall pattern size. In particular, one might wonder whether increasing the number of tactors defining the 2D pattern would favor recognition, even if the distance between tactors is reduced. Moreover, as mentioned earlier, one might wonder if increasing the overall size of the patterns would also increase recognition accuracy, and if the answer to this question depends on inter-tactor distance.

**Practical implications**

The present results can be used to draw some guidelines for designers interested in conveying information through 2D vibrotactile patterns. Note that, as discussed above, these guidelines are valid for the abdomen, in the range of spatial and temporal parameters we investigated, and with cylindrical ERM motors set perpendicularly to the skin[4].

Firstly, pattern elements should be activated sequentially (using slit-scan or tracing modes) rather than together at once (static mode), the best recognition rates being expected when only one tactor vibrates at a time (tracing mode). Secondly, pattern elements should be

[4] Given that tactor type and shape were found to influence tactile acuity (e.g., Hoffman et al., 2018), it would be interesting to investigate whether the use of other kinds of tactors, such as coin ERM motors or linear resonant actuators, the latter being known to produce vibrations along a single axis and have shorter rise time compared to ERM motors, would affect the pattern of results.

separated in space (large inter-tactor distance) and/or time (long SOA, inducing the perception of independent vibrations rather than continuous stimulation). In our study, novice participants who were familiarized with only two presentations of each pattern reached a recognition rate as high as 74.4% of correct responses with an inter-tactor distance of 28.5 mm and a SOA of 600 ms, which were the highest values we tested. Thirdly, spatial and temporal parameters interact in such a way that, if one parameter has to be constrained by the context of use, recognition performance might be maintained by increasing the other parameter. Hence, if pattern duration had to be restricted, inter-tactor distance could be increased to compensate for the reduced SOA, and conversely, SOA could be increased if the size of the device had to be minimized (with the limit of the floor effect we observed for the inter-tactor distance of 9.5 mm, for which SOA has no impact on recognition performance).

## Conclusion

The present study has demonstrated the great influence of spatial and temporal factors, as well as their interaction, on the recognition of 2D vibrotactile patterns. From a fundamental point of view, the results offer important insights that we have discussed in light of well-known perceptual phenomena, such as masking, apparent movement, and perceptual integration. From an applied point of view, our study provides some directions to guide the conception of vibrotactile patterns that should be valuable in the expanding scientific and technical literature on vibrotactile displays. In our opinion, two main challenges still have to be faced so that 2D vibrotactile patterns can be used as an effective way of conveying information. The first one is to reach an absolute level of recognition that ensures the reliability of the communication system. The second one is to find the optimum trade-off between presentation speed and recognition accuracy. Some of the leads we proposed for future investigation, such as testing larger distances between pattern elements, greater overall sizes of patterns, and different densities of tactors, might help to both overcome these difficulties and to further extend our understanding of tactile perception.

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**Table 1**

*Summary of the Main Previous Studies on the Recognition of Two-Dimensional Vibrotactile Patterns*

| Study | Device | Site | Set of patterns | Inter-tactor distance | Display modes | Temporal parameters | Participants: number and experience |
|---|---|---|---|---|---|---|---|
| Craig (1981) | Optacon: 6-by-24 matrix of piezoelectric beam actuators<br>*f* = 230 Hz | Finger | 26 upper-case roman letters | Transversal: 2.4 mm<br>Longitudinal: 1.17 mm | *6 modes including static, scanned, slit-scan, and tracing* | *Display time[a]: from 4.3 ms to 400 ms* | N = 3 + 4 (two sets of measurements)<br>Participants selected for their good performance |
| Loomis (1974) | TVSS: 20-by-20 matrix of solenoid actuators<br>*f* = 60 Hz<br>Ø = 1 mm | Back | 26 upper-case roman letters | 12 mm<br>(in both rows and columns) | *4 modes including static, scanned, and slit-scan* | Static mode: PD = 1.5 s<br>Scanned: PD = 1.7 to 2.0 s<br>Slit-scan: PD ≈ 1 s | N = 7 including 3 blind<br>Blind participants: more than 100h of practice<br>Others: trained for 6h |
| Saida et al. (1982) | 10-by-10 matrix of solenoid actuators<br>*f* = 50 Hz<br>Ø = 2 mm | Abdomen | 46 Katakana (Japanese characters) | 15 mm<br>(in both rows and columns) | *3 modes : static, scanned, and tracing* | Static: PD = 300 ms × 8 repetitions (1-s intervals) = 9.4 s<br>Scanned: PD = 6.8 to 9.8 sec. × 3 repetitions (1-s intervals) = 26.4 to 35.4 s<br>Tracing : PD = 1.5 to 6.6 sec × 3 repetitions (1-s intervals) = 10.5 to 25.8 s | N = 8 including 4 blind<br>Blind participants: more than 3h of practice<br>Others: no information |
| Shimizu (1982) | 7-by-9 matrix of solenoid actuators<br>*f* = 80 Hz<br>Ø = 2 mm | Palm | 46 Katakana (Japanese characters) | 7 mm<br>(in both rows and columns) | Tracing mode | *4 BD: 25, 50, 100 and 200 ms*<br>*5 letter-strokes intervals[b]: 0, 40, 80, 160 and 320 ms*<br>IBI = 0 ms | N = 4 experienced subjects (participation in tactile experiments for over 10 months) |
| Yanagida et al. (2004) | 3-by-3 matrix of coin ERM motors<br>*f* = 69 Hz<br>Ø = 18 mm | Back | 34 alphanumeric characters | 60 mm<br>(in both rows and columns) | Tracing mode | BD = 500 ms<br>IBI = 0 ms | N = 10 among which several members of the laboratory |
| Novich & Eagleman (2015, Experiment 1) | 3-by-3 matrix of cylindric ERM motors<br>*f* = 340 Hz (static and tracing modes); *f* = 70 to 340 Hz (single motor mode)<br>Ø = 8.8 mm (× 24.9 mm) | Mid-lower back | Sets of 8 patterns which differed between display modes | 25 mm<br>(in both rows and columns) | *3 modes: static, tracing, and single motor mode (different levels of vibration intensity)* | *3 PD: 45, 90, and 135 ms* (for the tracing mode, these PD were obtained with BD of 15, 30 and 45 ms with IBI = 0 ms) | N = 10 including 7 novices, 2 with participation in a previous experiment with the device, and 1 with moderate experience |

*Note*. Italics indicate the manipulated conditions. ERM = eccentric rotating mass; *f* = vibration frequency; Ø = diameter; PD = pattern duration; BD = burst duration; IBI= Inter-burst interval.

[a]Maximum time any element of the pattern was on. [b]Delay between the strokes forming the character.

**Table 2**

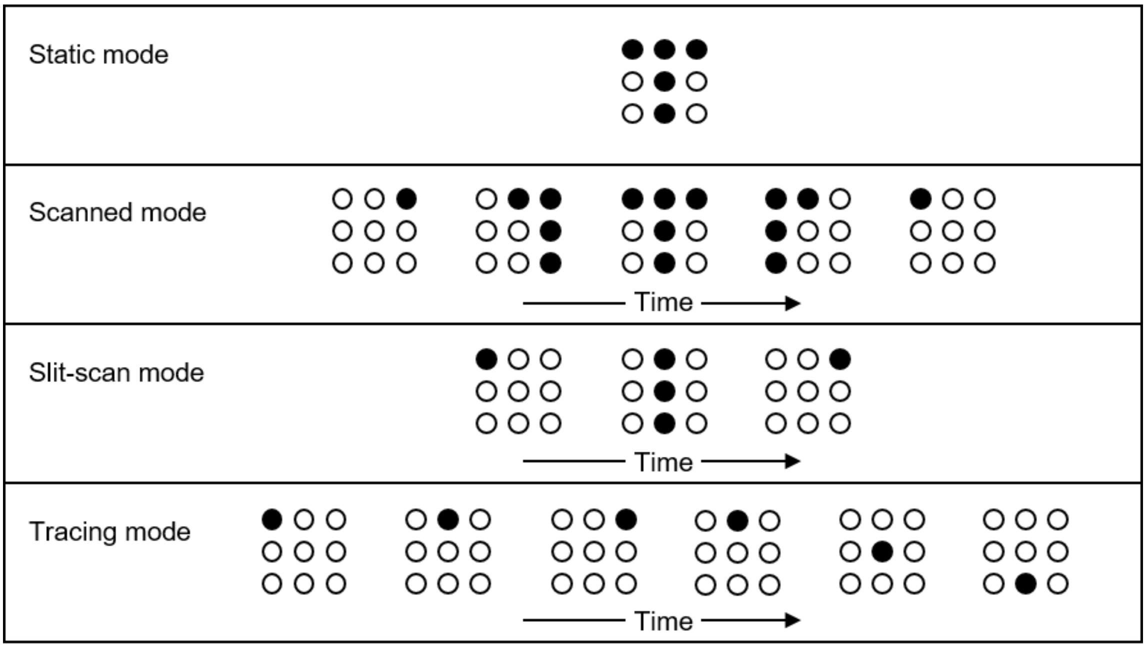
*Stimulus/Response Confusion Matrix from Experiment 2*

| Vibrotactile Pattern | | Response (in percentage) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Tri | Hex | Dia | Dbl | V | W | X | Y |
| Static Mode | Tri | 18.1 | 15.3 | 6.9 | 16.7 | 16.7 | 12.5 | 6.9 | 6.9 |
| | Hex | 9.7 | 19.4 | 9.7 | 11.1 | 25.0 | 9.7 | 6.9 | 8.3 |
| | Dia | 4.2 | 6.9 | 38.9 | 1.4 | 8.3 | 1.4 | 9.7 | 29.2 |
| | Dbl | 11.1 | 16.7 | 8.3 | 20.8 | 16.7 | 13.9 | 12.5 | 0.0 |
| | V | 12.5 | 13.9 | 5.6 | 16.7 | 18.1 | 9.7 | 13.9 | 9.7 |
| | W | 1.4 | 8.3 | 2.8 | 20.8 | 20.8 | 43.1 | 2.8 | 0.0 |
| | X | 4.2 | 11.1 | 19.4 | 5.6 | 15.3 | 5.6 | 20.8 | 18.1 |
| | Y | 5.6 | 5.6 | 27.8 | 2.8 | 8.3 | 0.0 | 15.3 | 34.7 |
| Slit-scan Mode | Tri | 63.9 | 6.9 | 1.4 | 6.9 | 1.4 | 2.8 | 15.3 | 1.4 |
| | Hex | 5.6 | 50.0 | 5.6 | 11.1 | 9.7 | 9.7 | 8.3 | 0.0 |
| | Dia | 4.2 | 4.2 | 59.7 | 2.8 | 4.2 | 0.0 | 4.2 | 20.8 |
| | Dbl | 1.4 | 5.6 | 0.0 | 62.5 | 2.8 | 4.2 | 22.2 | 1.4 |
| | V | 1.4 | 5.6 | 4.2 | 2.8 | 51.4 | 4.2 | 4.2 | 26.4 |
| | W | 1.4 | 4.2 | 1.4 | 9.7 | 31.9 | 45.8 | 4.2 | 1.4 |
| | X | 8.3 | 8.3 | 12.5 | 8.3 | 12.5 | 1.4 | 36.1 | 12.5 |
| | Y | 1.4 | 1.4 | 19.4 | 0.0 | 6.9 | 1.4 | 6.9 | 62.5 |
| Tracing Mode | Tri | 52.8 | 23.6 | 1.4 | 9.7 | 0.0 | 6.9 | 5.6 | 0.0 |
| | Hex | 8.3 | 81.9 | 1.4 | 5.6 | 0.0 | 0.0 | 2.8 | 0.0 |
| | Dia | 2.8 | 12.5 | 58.3 | 0.0 | 4.2 | 1.4 | 9.7 | 11.1 |
| | Dbl | 5.6 | 1.4 | 0.0 | 73.6 | 0.0 | 11.1 | 6.9 | 1.4 |
| | V | 0.0 | 0.0 | 11.1 | 1.4 | 72.2 | 6.9 | 4.2 | 4.2 |
| | W | 0.0 | 1.4 | 1.4 | 6.9 | 9.7 | 79.2 | 1.4 | 0.0 |
| | X | 1.4 | 5.6 | 1.4 | 8.3 | 4.2 | 2.8 | 65.3 | 11.1 |
| | Y | 4.2 | 0.0 | 13.9 | 1.4 | 2.8 | 1.4 | 13.9 | 62.5 |

*Note.* Tri = triangle; Hex = hexagon; Dia = diamond; Dbl = converging double arrow; V, W, X and Y designate the corresponding letter patterns. The cells containing the correct responses are highlighted with a frame. Cells are shaded depending on the percentage of correct responses: light grey for values ranging between 25% and 50%, medium grey for values ranging between 50% and 75%, and dark grey for values ranging between 75% and 100%.

**Figure 1**

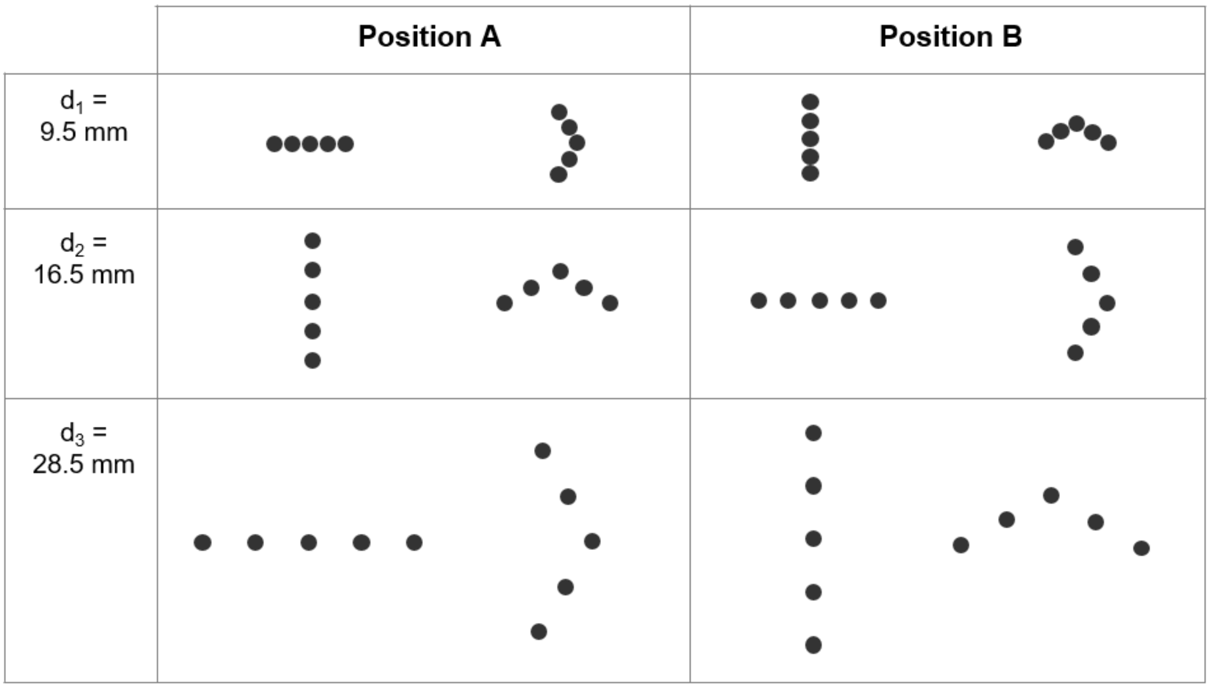
*Schematic Representation of the Four Main Display Modes Tested in the Literature on Tactile Pattern Recognition*




*Note*. Each frame represents the pattern of stimulation at a given moment in time, with the tactor(s) being activated depicted in black and the inactive tactors depicted in white. The frames must be read from left (first activation in time) to right (last activation in time, i.e., end of pattern presentation). The duration of each frame and the time interval between two frames vary depending on the studies (see Table 1).

**Figure 2**

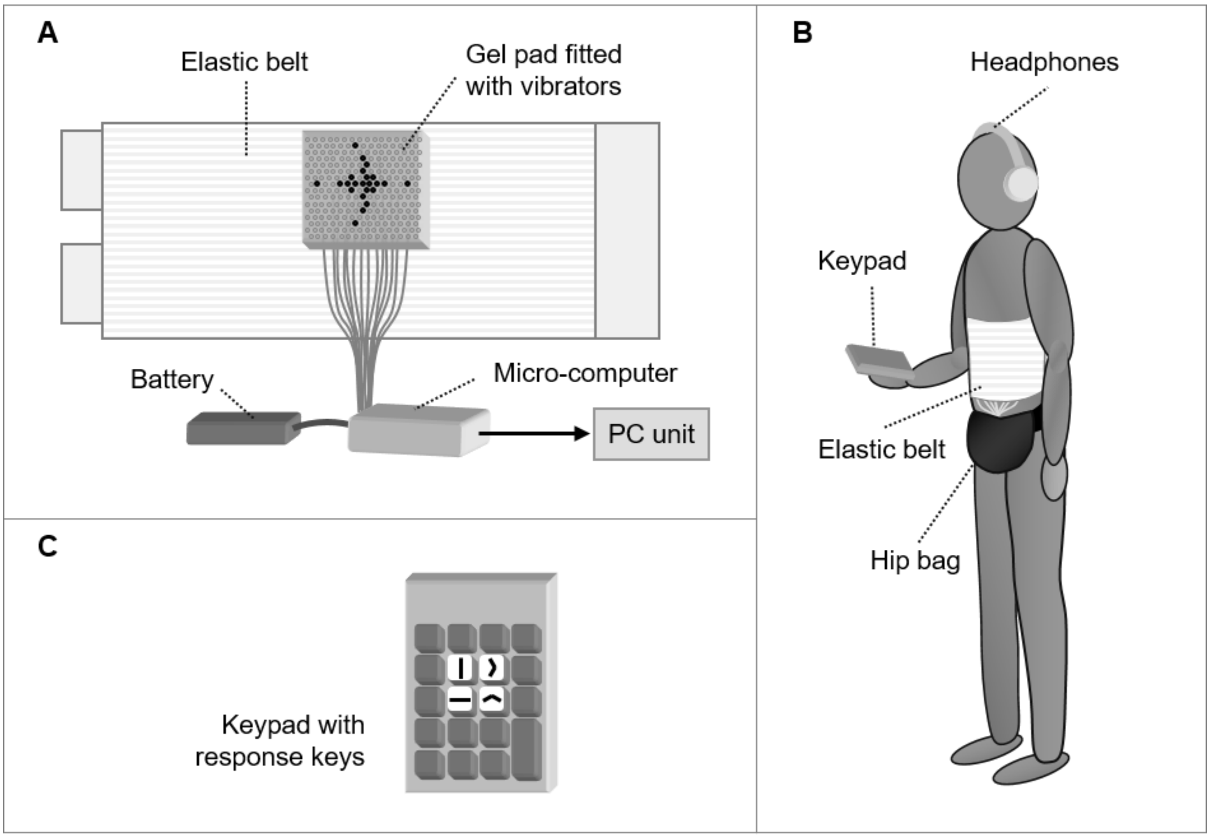
*Location of Tactors and Resulting Patterns for the Two Positions of the Gel Pad in Experiment 1*




*Note*. Patterns are shown for Position A (left panel) and B (right panel: the pad was rotated 90° counterclockwise compared to position A). Successions of five vibrations defined straight and broken lines with three distances between tactors: 9.5 mm ($d_1$), 16.5 mm ($d_2$), and 28.5 mm ($d_3$).

**Figure 3**

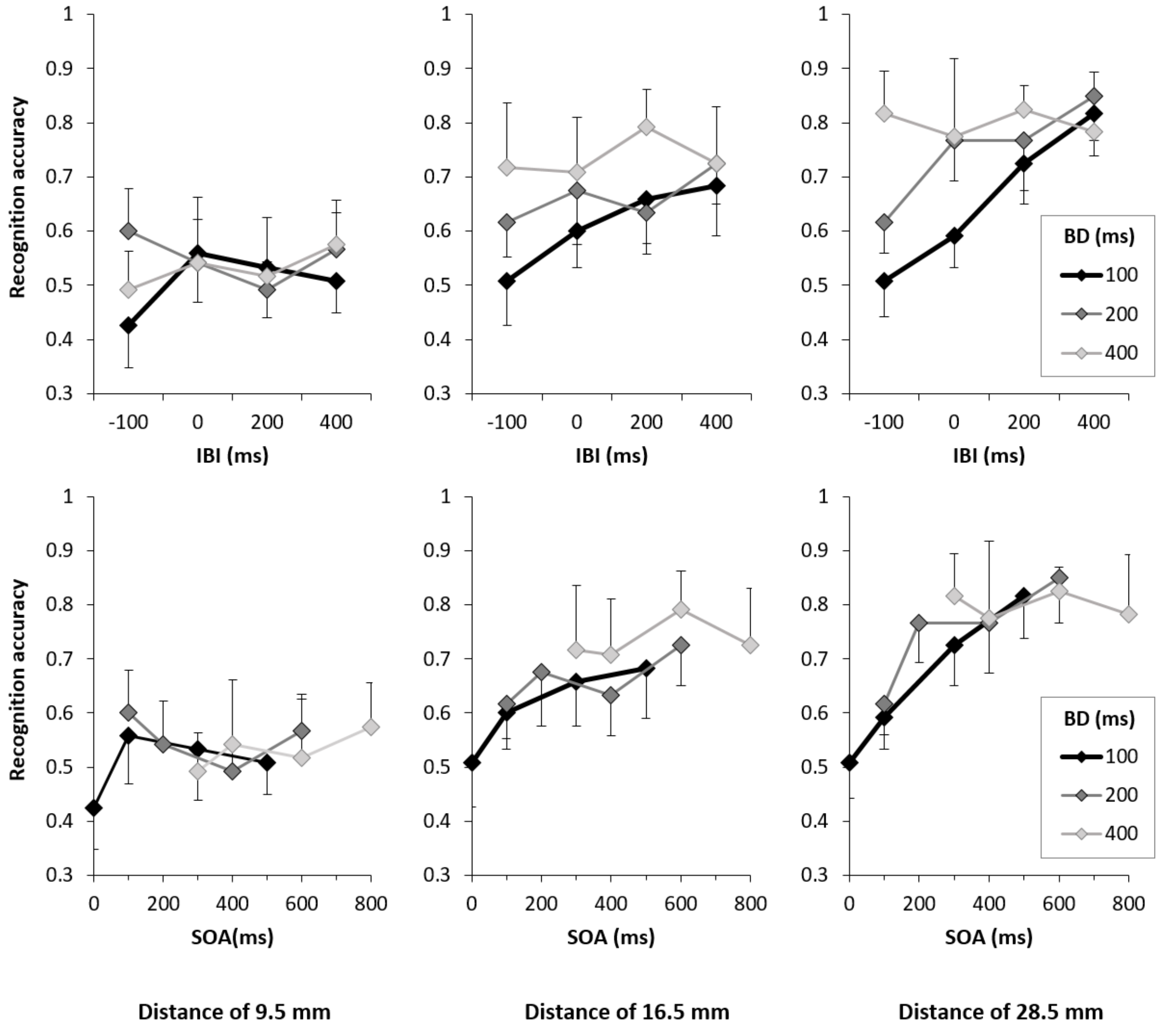
*Schematic View of the Setup Used in Experiment 1*




*Note*. Panel A: Apparatus. Panel B: Equipment. Panel C: Response keypad.

**Figure 4**

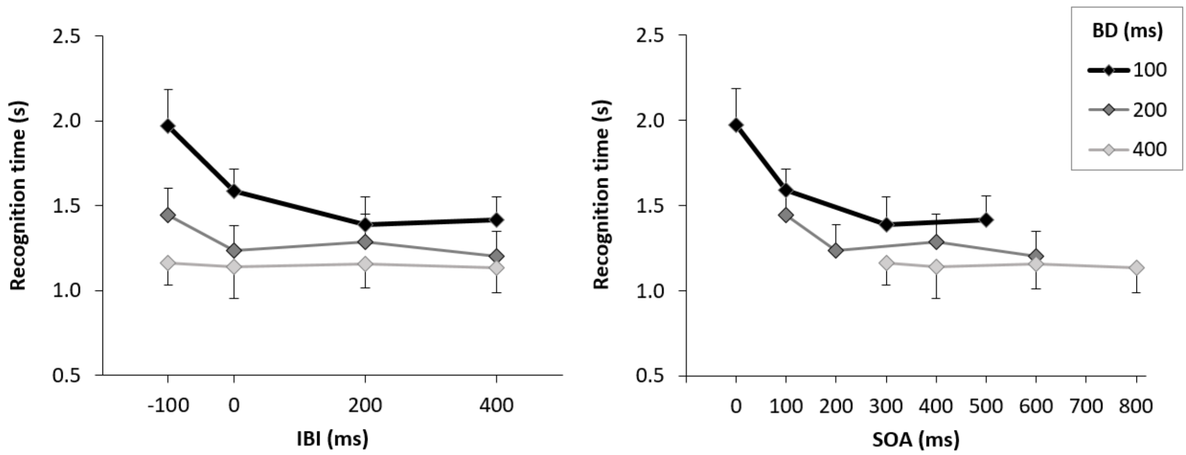
*Mean Values of Recognition Accuracy Depending on Spatial and Temporal Parameters*




*Note*. Mean values of recognition accuracy (proportion of correct answers) are shown depending on the delay between successive vibrations (abscissa), burst duration (BD, represented by the different curves), and distance between tactors (left, middle, and right charts for the distances of 9.5, 16.5 and 28.5 mm, respectively). In the top panels, the delay between the vibrations is expressed in terms of inter-burst interval (IBI). The bottom panels plot the same data, but the delay between the vibrations is expressed in terms of stimulus onset synchrony (SOA). The error bars represent 95% confidence intervals.

**Figure 5**

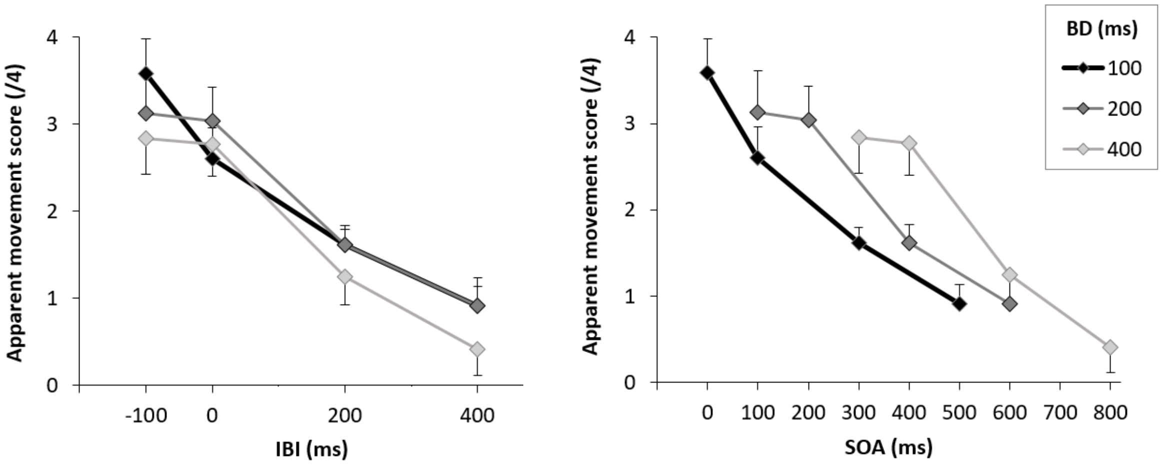
*Mean Values of Recognition Time Depending on Temporal Parameter*




*Note*. Mean values of recognition time are shown for the three burst durations (BD) as a function of the time interval between successive vibrations expressed in terms of inter-burst interval (IBI, left panel) and stimulus onset asynchrony (SOA, right panel). The error bars represent 95% confidence intervals.

**Figure 6**

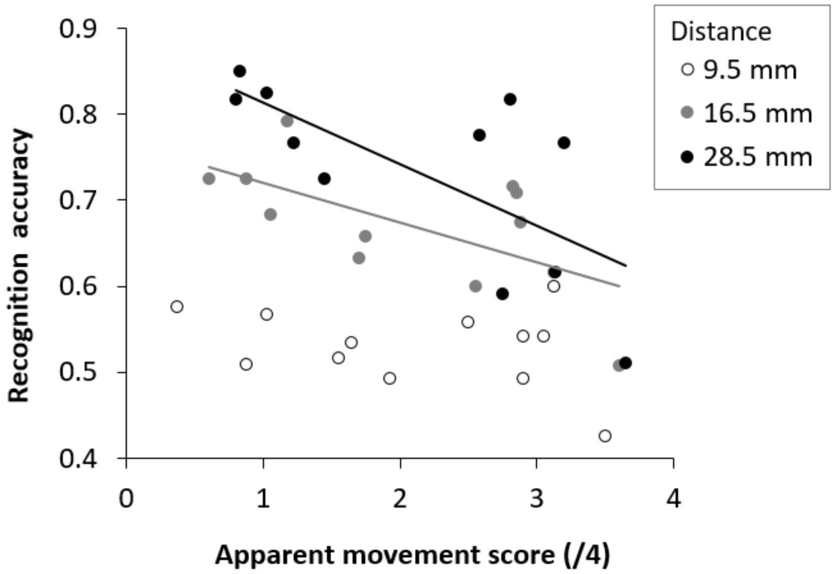
*Mean Values of Apparent Movement Scores Depending on Temporal Parameters*




*Note*. Mean values of apparent movement scores are shown for the three burst durations (BD) as a function of the time interval between successive bursts expressed in terms of inter-burst interval (IBI, left panel) and stimulus onset asynchrony (SOA, right panel). The error bars represent 95% confidence intervals.

**Figure 7**

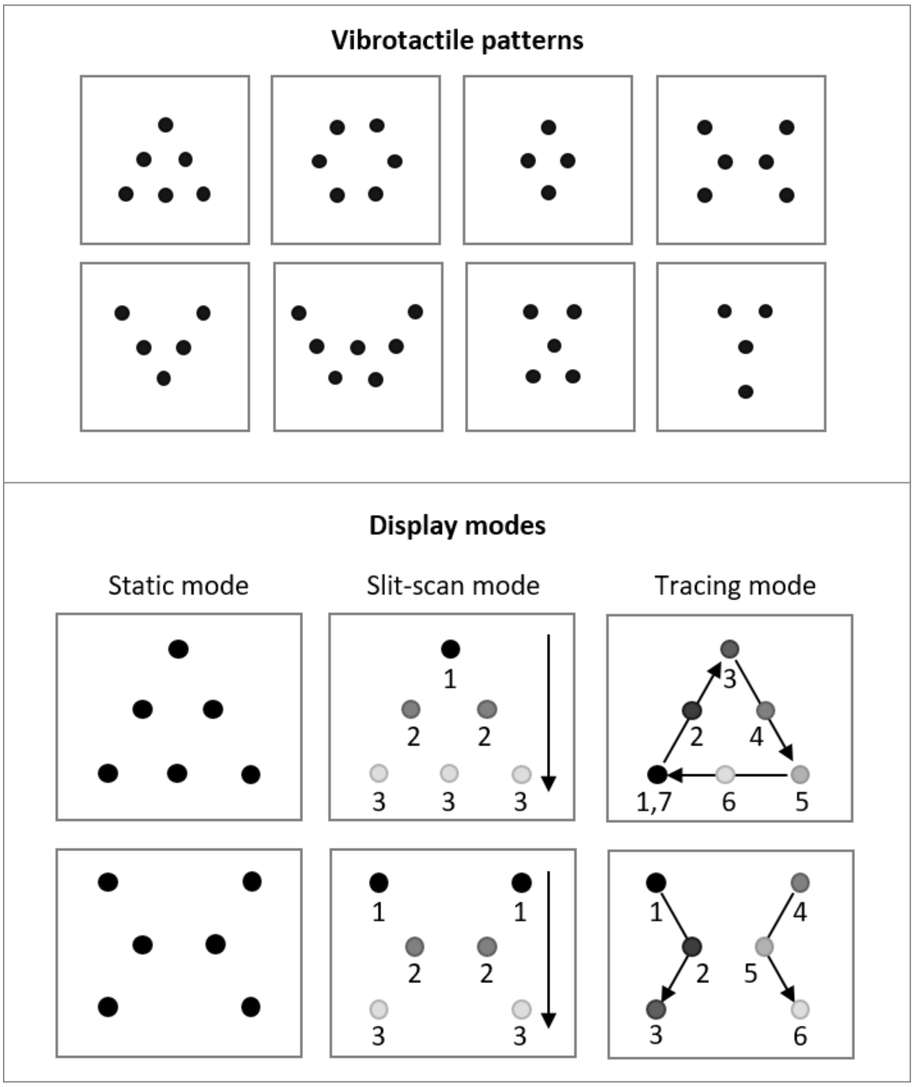
*Scatter Plot of Recognition Accuracy as a Function of Apparent Movement Scores*




*Note*. Recognition accuracy is plotted as a function of continuity scores (from 0, vibrations felt as being totally independent, to 4, perception of a single stimulus moving continuously) for the three distances between tactors (9.5, 16.5 and 28.5 mm, represented by white, grey and black dots, respectively). Each point indicates the mean value of the group of 12 participants for one BD/IBI combination. Regression lines are plotted for the significant correlations (in grey and in black for the distances of 16.5 and 28.5 mm, respectively).

**Figure 8**

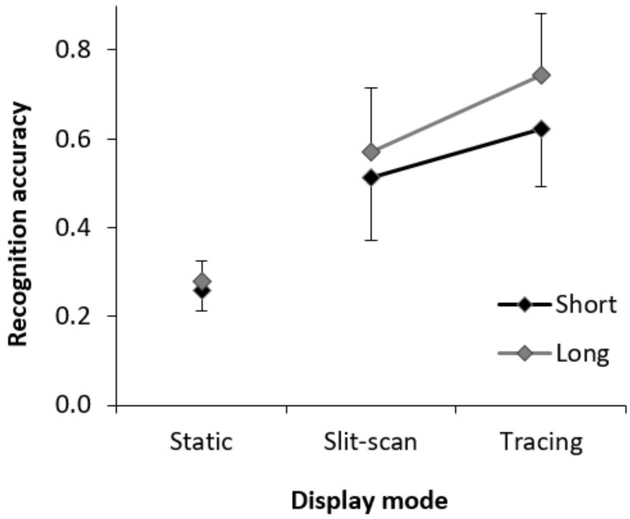
*Vibrotactile Patterns and Display Modes of Experiment 2*




*Note*. Top panel: The eight patterns that participants were asked to recognize (triangle, hexagon, diamond, converging double arrow, V, W, X and Y). Bottom panel: Illustration of the three display modes (static, slit-scan and tracing) for the triangle and the converging double arrow. The numbers indicate the activation order of the tactors.

**Figure 9**

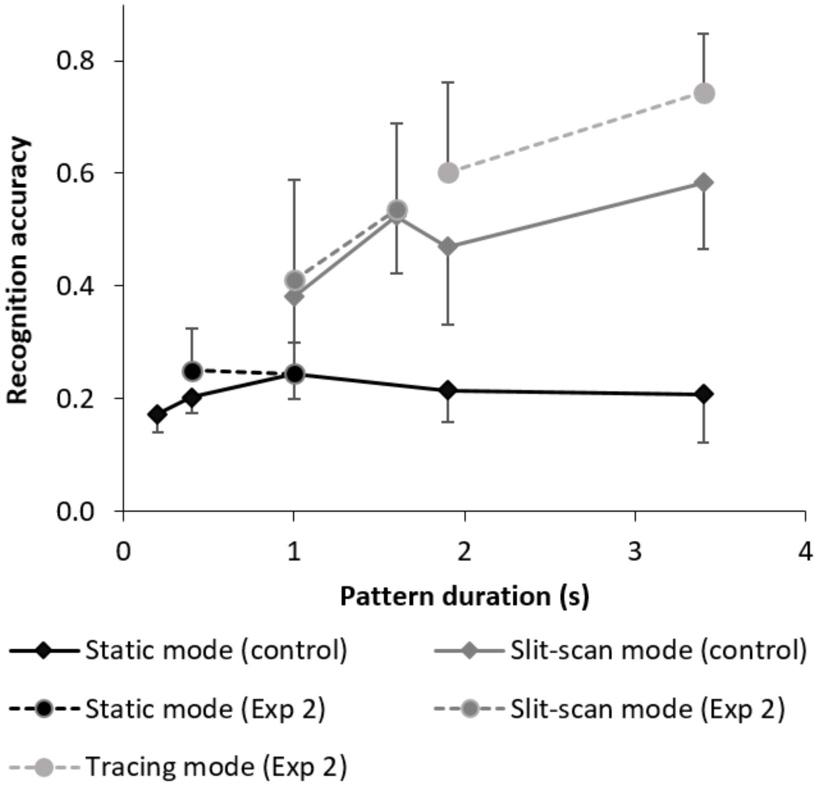
*Mean Values of Recognition Accuracy for the Three Display Modes and Their Corresponding Temporal Parameters*




*Note*. Mean values of recognition accuracy (percentage of correct answers) are shown for the three display modes and their corresponding temporal parameters. For the static mode, the temporal parameters corresponded to BD = 400 ms (short parameter) and BD = 1000 ms (long parameter). For the slit-scan mode and the tracing mode, the temporal parameters corresponded to SOA = 300 ms (short parameter) and SOA = 600 ms (long parameter); BD was fixed at 400 ms for these two modes. The error bars represent 95% confidence intervals.

**Figure 10**

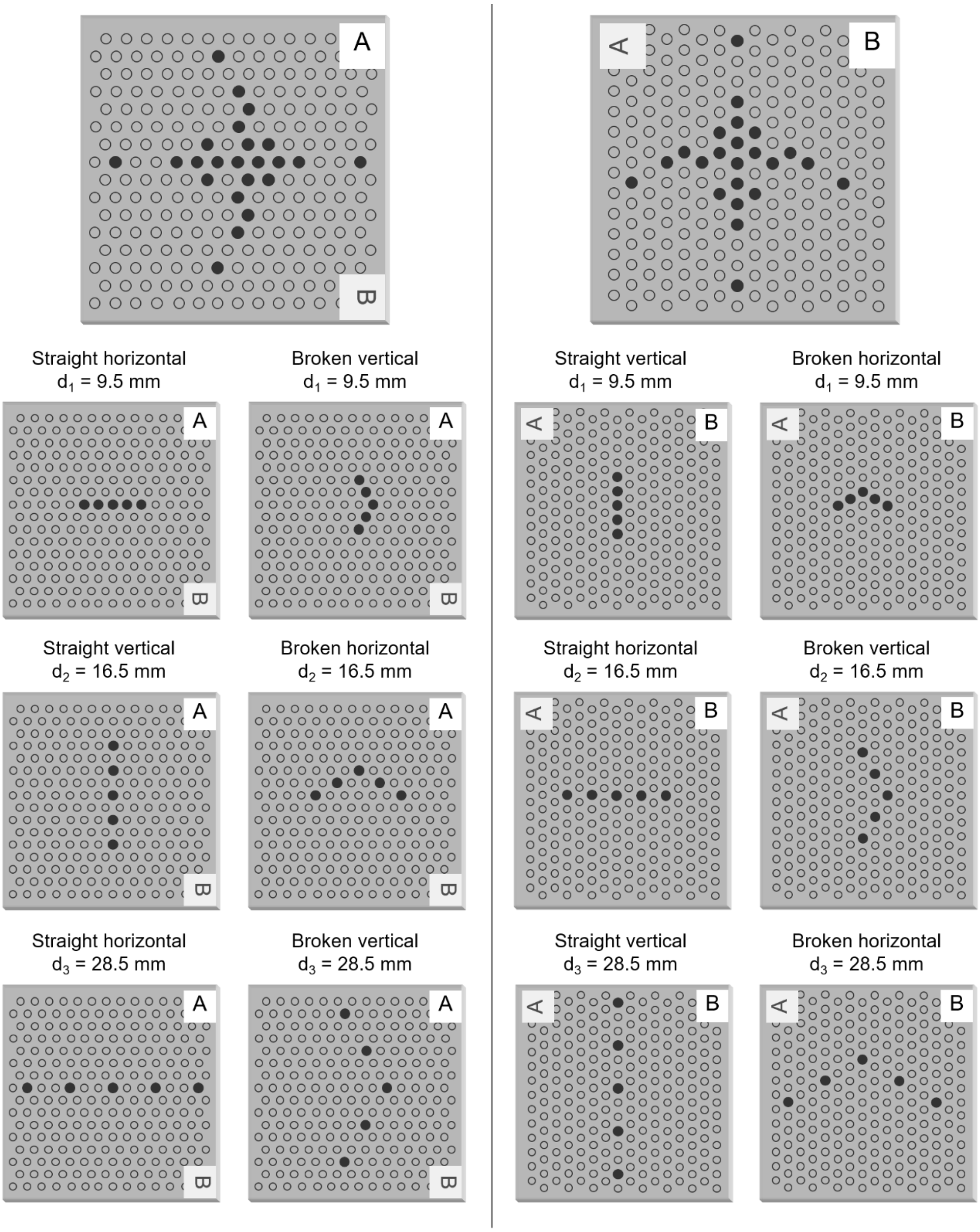
*Mean Values of Recognition Accuracy as a Function of Pattern Duration (N = 7)*




*Note*. Mean values of recognition accuracy (percentage of correct answers) are shown as a function of pattern duration for the group of seven participants who took part both in Experiment 2 (Exp 2) and the control experiment (control). The error bars represent 95% confidence intervals.

## Appendix

## Location of Tactors and Resulting Patterns for the Two Orientations of the Gel Pad in Experiment 1




Orientation A (left panel) and B (right panel: the pad was rotated 90° counterclockwise compared to orientation A). Successions of five vibrations defined straight and broken lines with three distances between tactors: 9.5 mm ($d_1$, distance of one hole from its closest radial neighbors), 16.5 mm ($d_{2,}$ distance between every other row of holes), and 28.5 mm ($d_{3,}$ distance obtained by skipping two holes separated by 9.5 mm). Transverse lines were traced from left to right and longitudinal lines from top to bottom with three burst durations (100, 200, or 400 ms) and four inter-burst intervals (-100, 0, 200, or 400 ms).