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Selective and Divided Attention for Vibrotactile Stimuli on Both Arms

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***Abstract*— The present study investigates how reliably one can selectively attend to vibrotactile stimuli, as well as what characteristics of the attended and unattended stimuli affect attention. Participants wore one tactile display on the forearm and another on the opposite upper arm. They were trained to identify nine stimuli varying in location and frequency and tested on stimulus identification under various conditions: attending to one arm when only one arm was stimulated, selectively attending to one arm when both were stimulated, or attending to both arms when both were stimulated. The results demonstrate 92% accuracy for the single-arm stimulated conditions, 82% accuracy for the selective attention conditions, and a significantly lower accuracy of 50% when attending to both arms. Accuracy was higher for the slightly delayed stimulus when selectively attending. Estimates of information transfer indicate that participants can selectively attend to three locations and two frequencies with high accuracy when attending to a single arm. About 24 combinations of stimulus alternatives on the left and right arms could be reliably identified when attending to both arms.**

Fig. 1. Photo of a participant wearing one tactile display on the upper left arm and the other on the right forearm. The computer screen shows a diagram of tactors on the attended arm(s), with three buttons representing the three frequency conditions at each location. The participant selected the response by clicking on the button corresponding to the location and frequency combination with the right hand.

I. INTRODUCTION

In everyday life, we are capable of orienting our attention toward certain targets while ignoring others. When reading a book, we can focus on the words on the page and tune out other sights and sounds. At a cocktail party, we can isolate the voice of a single person with whom we are making conversation. Selective attention refers to this ability to focus on certain sources of information while ignoring others [1].

The degree to which we can selectively attend varies. Cherry (1953) demonstrated the strength of selective attention in the audio domain in a dichotic listening experiment, in which participants listened to two different streams of continuous speech, one in each ear. Participants demonstrated an ability to repeat either of the two messages as they played with ease but could describe little about the unattended message [2]. These experiments demonstrated that unattended auditory messages may be filtered out to some degree based on spatial location or pitch [3]. However, Moray (1959) found that participants could identify hearing their own names in the unattended message [4]. Likewise, Treisman (1960) switched the messages between ears and found that participants sometimes repeated one or two words from the unattended ear when the switch occurred [5]. Johansen-Berg and Lloyd (2000) also reviewed evidence that the degree to which irrelevant tactile stimuli are processed before filtering depends on the context [6]. These findings indicate that unattended information may be attenuated rather than blocked completely prior to central processing [7]. Lavie (1995) [8] and Spence and Gallace (2007) [9] also proposed that the locus of selection within the sequence of processing may be a function of perceptual load. Our ability to selectively attend appears to depend on a variety of factors, including context, familiarity, and perceptual load.

The ability to selectively attend to haptic stimuli has also been investigated. In a study of reaction times when shifting attention between body sites, Lakatos and Shepard (1997) found that participants could report whether an air puff occurred at the specific site with very high accuracy when four sites were stimulated simultaneously [10]. Gomez-Ramirez et al. (2016) reviewed evidence of selective attention in the tactile domain, suggesting that stimuli at attended locations (or with attended features) are enhanced and stimuli at unattended locations (or with unattended features) are suppressed [11]. It would be useful to know whether this ability depends on the specific features of the stimuli – such as location, frequency, duration, movement, or rhythm.

Knowing what information an operator can selectively attend could inform the design of haptic displays in which multiple haptic stimuli are presented at once and information is encoded in the features of those stimuli (see [9] for a review by Spence and Gallace). In some situations, such tactile information displays may even be preferable to audio or visual displays. For instance, in recent years, telerobotic solutions for explosive ordnance disposal (EOD) have gained traction as a way to reduce an EOD technician's time-on-target. Haptic feedback could offer technicians the ability to "feel" the pressure of the robotic end effector on its target, or

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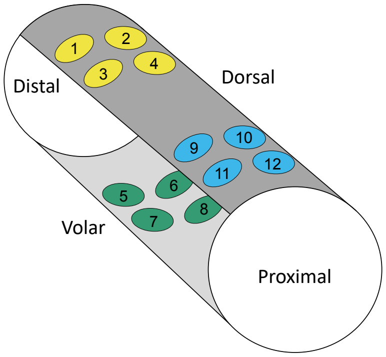

Fig. 2. Illustration of a single tactile display with tactors numbered from 1 to 12

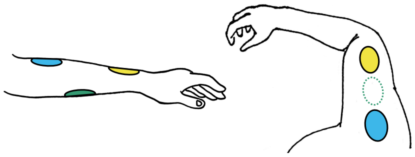

Fig. 3. Tactor placement on the forearm and upper arm. The dotted line indicates the triceps on the underside of the upper arm. The dot colors correspond to those of the tactors at the same locations in Fig. 2.

even convey the material properties of an unknown object. This information would be uniquely suited to a tactile or multimodal display, especially when the operator's vision is obscured. It could be advantageous for an operator to receive multiple simultaneous streams of information on different parts of the body and selectively attend to each, just as one can selectively attend to a panel on a screen or to a particular conversation. Designing such a tactile display would require knowing how much information the operator can selectively attend to and reliably identify at a given time.

The purpose of the present study is to investigate if participants can selectively attend to and reliably identify simultaneous haptic signals on the left and right arms, as in Fig. 1. Additionally, we hope to determine what characteristics of attended and unattended signals may cause confusion.

II. METHODS

A. Participants

Ten participants (7 females) ages 19 to 27 (23±2.9 years) completed the experiment. Six had participated in a tactile perception experiment before. All were right handed. All participants gave informed consent to the IRB-approved protocol and were compensated 10 USD per hour. An eleventh participant was recruited for the experiment but withdrew in the middle of the training; his data was not analyzed. In total, the 10 participants spent 43 experiment hours.

B. Apparatus

Two identical tactile displays were used, each comprised of an array of 12 tactors (Tectonic Elements, Model TEAX13C02-8/RH), as illustrated in Fig. 2. Participants wore one display on the forearm and one on the opposite upper arm. The decision to place the displays on opposite body halves was motivated by dichotic listening experiments, in which two different streams of speech are delivered simultaneously to opposite ears [2]. An additional motivator was that masking effects are much less prevalent when stimuli are presented contralaterally as opposed to ipsilaterally [12]. Non-symmetric body sites – one upper and one lower arm – were chosen to avoid confusion of mirror-image locations [13], [14]. When worn on the forearm (or upper arm), tactors 1−4 and 9−12 were placed on the dorsal side (or the biceps) with 5−8 on the volar side (or the triceps), as shown in Fig. 1 and 3. Cushions were placed under the wrists and elbows to avoid putting pressure on the tactors on the volar forearm, and participants wore noise-cancelling headphones.

Waveforms were generated in MATLAB using the playrec utility [15]. They were sent to a 24-channel MOTU 24Ao audio device for synchronous digital-to-analog conversion and passed through 12 class D stereo audio amplifiers before being delivered to the arms via the two 12-tactor arrays. Further details about this process and the tactile display hardware can be found in Sec. II. of [16].

C. Stimuli

Our goal was to design stimuli that the participants would be able to identify with high accuracy after a brief training period. This motivated the use of multiple perceptual dimensions [17], [18], namely location on the tactor array, frequency, and body site. That such a goal was attainable has been demonstrated by Reed et al. (2019), whose participants were trained to identify 39 vibrotactile stimuli representing phonemes of the English language and achieved a mean phoneme recognition rate of 86% [16]. Of the 39 phonemic stimuli used in the study by Reed et al. several pairs of stimuli were identical except for location or frequency.

The present study used nine vibrotactile stimulus alternatives that were the combination of three locations and three frequency components at each of the two body sites tested: the upper arm and forearm. When the display was worn on the forearm, stimuli were presented near the dorsal wrist, at the volar mid-forearm, or near the dorsal elbow area. When the display was worn on the upper arm, stimuli were presented to the distal biceps, triceps, or proximal biceps area, as shown in Fig. 3. The three frequency components used were 300 Hz only, 300 Hz with 60 Hz amplitude modulation (modulation index = 1), and 60 Hz only. All signals were 300 ms in duration and presented at 25 dB SL (sensation level; dB above respective detection threshold) per tactor. The detection thresholds for 60-Hz and 300-Hz stimuli were measured for each participant and used to calculate the corresponding signal amplitudes. Waveforms were presented simultaneously via four tactors at each location to boost the perceived intensity per location [19]. A 10-ms Hanning window on/off ramp was applied to smooth and ensure zero amplitude at the onset and offset of each stimulus.

When stimuli were presented to both arms, a non-zero SOA (signal onset asynchrony) was employed between the stimuli delivered to the left and right arms. This was motivated by prior research indicating that SOA can improve information transmission [20]. A pilot test was conducted on the first author to determine the SOA values. It was found that at 0 ms, the stimuli felt simultaneous; at 25 ms, the stimuli did not feel simultaneous but order judgement was difficult; and at 50 ms, the order of the two stimuli could be perceived clearly. These values were consistent with previous studies of intramodal asynchrony for tactile stimuli (e.g., [21]). Therefore, three SOA values of 0 ms, 25 ms, and 50 ms were employed with equal *a priori* probability. The delayed signal was equally likely to be applied to either arm.

D. Experimental Conditions

There were five experimental conditions depending on which arm was stimulated and which arm the participants were asked to pay attention to:

- (L, L): left arm stimulated, left arm attended
- (R, R): right arm stimulated, right arm attended
- (LR, L): both arms stimulated, left arm attended
- (LR, R): both arms stimulated, right arm attended
- (LR, LR): both arms stimulated, both arms attended

The two single arm conditions, (L, L) and (R, R), were considered baseline measurements against which the two selective attention conditions, (LR, L) and (LR, R), and the divided attention condition, (LR, LR) could be compared. The (LR, L) and (LR, R) conditions required the participants to selectively attend to either the left or the right arm, respectively, and report the signal felt. The (LR, LR) condition required participants to divide their attention by paying attention to both arms and responding to both stimuli. Half of the participants were randomly assigned to one configuration (left forearm, right upper arm) and the remaining half to the other configuration (left upper arm, right forearm).

E. Procedure

1) Threshold Measurements: Prior to the experiment, each participant's absolute detection thresholds for 300 Hz and 60 Hz stimuli were determined using a three-interval, two-alternative, one-up two-down adaptive method with trial-by-trial correct answer feedback [22]. Tactor #4 in Fig. 2 was used for all threshold estimates. As expected from the literature (e.g., [23]), the participants were more sensitive to the 300-Hz stimulus than the 60-Hz stimulus. The average thresholds across the ten participants were -39.6 ± 6.3 dB and -32.4 ± 6.3 dB relative to the maximum system output for the 300-Hz and 60-Hz stimuli, respectively.

2) Tactor Intensity Equalization: The method of adjustment was used to adjust the perceived intensity of the other 23 tactors across both displays to equal that of the reference tactor #4. A 400-ms 300-Hz vibration with a fixed amplitude at 10 dB below the maximum system output was sent to tactor #4. The participant adjusted the amplitude of the same vibration sent to one of the 23 tactors until the perceived intensity felt the same as that of tactor #4. The intensity adjustment was performed on each of the 23 tactors. The detection thresholds and tactor-intensity adjustments per participant were used to calculate the amplitude of the stimuli at 25 dB SL per tactor for the participant.

3) Training: Participants were introduced to the nine stimuli during a brief training. They were told that Signal 1 is a high-frequency vibration which may feel smooth, high-pitched, and penetrating; Signal 3 is a low-frequency vibration which may feel rough, heavy, and diffused; and Signal 2 is a combination of Signals 1 and 3. Participants were allowed to feel the stimuli or test themselves with trial-by-trial correct answer feedback on either arm using a MATLAB interface. Once a participant reported feeling comfortable identifying all nine stimuli, they were given a test without feedback. Both the (L, L) and (R, R) conditions were tested once in a 50-trial run. For each trial, one of the nine stimuli was randomly selected with equal *a priori* probability. Participants were required to reach 85% correct to proceed to the main experiment; else, they were given additional training time before attempting the test again. Participants spent an average of 30 ± 23 minutes on training.

4) Main Experiment: An absolute-identification experiment was conducted in a total of five sessions on five separate days. At the beginning of each day, participants were once again given the opportunity to freely play the stimuli and test themselves with feedback. Then, each of the five conditions was tested once in a 100-trial run without any feedback. For each trial, one of the nine stimuli was randomly selected with equal *a priori* probability. There was a 500-ms pause between receipt of the participant's response and presentation of the stimulus for the next trial. The order of the five runs was randomized for each participant. In total, each participant completed 2500 trials (5 conditions × 100 trials/day per condition × 5 days). The 500 trials per condition per participant was greater than the $5K^2 = 405$ trials ($K = 9$ stimulus alternatives) needed to obtain an unbiased estimate of information transfer (IT) [24].

F. Data Analysis

For each run, a stimulus-response confusion matrix was generated with rows representing attended stimuli and columns representing responses. For the four conditions in which participants attended to a single arm, nine stimulus alternatives were presented, and therefore a 9×9 confusion matrix was generated. For the (LR, LR) condition, each pair of stimuli for the left and right arms was considered a unique stimulus, and an 81×81 matrix was generated. A percent-correct score (pc) was calculated for each run. The pc scores for the same condition were then averaged over the five sessions for each participant and across all participants.

An information transfer (IT) value associated with each of the five conditions was also calculated. For each participant and condition, the five 9×9 confusion matrices corresponding to five runs of that condition were combined, and IT was computed for the pooled matrix. IT values for each condition were then averaged across all participants.

While pc scores decrease with increasing number of stimulus alternatives in an absolute-identification experiment, IT estimates reach a plateau called *channel capacity* [18], [25]. It is therefore a more succinct and invariant measure of identification performance. A related quantity, 2^{IT}, is inter-

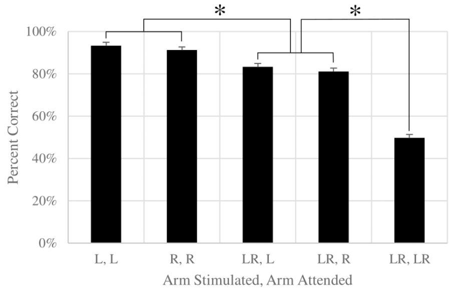

Fig. 4. Average pc scores by condition, across all runs and all participants. Error bars indicate standard error. Asterisks indicate statistical significance.

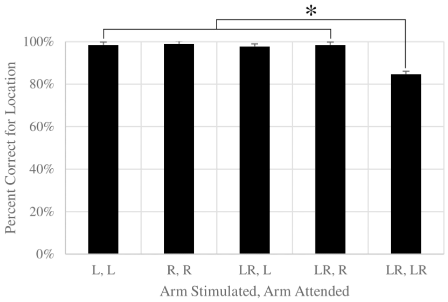

Fig. 5. Average pc scores for location information only by condition. Error bars indicate standard error. Asterisks indicate statistical significance.

preted as the number of equally-likely stimulus alternatives that a participant can identify correctly. Given a stimulus-response confusion matrix, an IT is estimated as:

$$IT = \sum_{i=1}^{K} \sum_{j=1}^{K} \left(\frac{n_{ij}}{n}\right) \log_2 \left(\frac{n_{ij} \cdot n}{n_i \cdot n_j}\right), \tag{1}$$

where K is the number of stimulus alternatives, n_{ij} is the number of times stimulus i was presented and response j was recorded (i.e., an entry in the confusion matrix), $n_i = \sum_{j=1}^{K} n_{ij}$ and $n_j = \sum_{i=1}^{K} n_{ij}$ are the sums of rows and columns, respectively, and $n = \sum_{i=1}^{k} \sum_{j=1}^{K} n_{ij}$ is the total number of trials [18].

To determine how well participants selectively attended to location or frequency information alone, the original stimulus-response confusion matrices were collapsed to contain location or frequency information only [26]. For the (L, L), (R, R), (LR, L), and (LR, R) conditions, each 9×9 matrix was collapsed to a 3×3 matrix of location (or frequency) information by pooling stimuli and responses for corresponding locations (or frequencies) across all three frequencies (or locations). For the (LR, LR) condition, each 81×81 confusion matrix was collapsed to a 9×9 matrix of L/R location combinations (or L/R frequency combinations). The pc scores and IT estimates for location or frequency information alone were calculated from the collapsed matrices.

To measure the effect of delay based on the three SOA categories of interest – simultaneous presentation of L/R stimuli, unattended stimulus presented first (by either 25 or 50 ms), and attended stimulus presented first (by either 25 or 50 ms) – a pc score was calculated for each run using only the trials within each of the three SOA categories. Trials with an SOA of 25 ms and 50 ms within the same category were combined. This analysis involved only the two selective attention conditions – (LR, L) and (LR, L).

Several repeated-measures analysis of variance (ANOVA) were conducted with pc scores as the dependent variable. To account for the binomial distribution of the pc score where the variance is dependent on the mean [27], each pc score was adjusted using the arcsine transformation $2\arcsin\sqrt{pc}$ prior to the statistical analyses. First, a one-way repeated-measures ANOVA was performed with experimental condition as the independent variable to determine if the five conditions yielded significantly different overall pc scores. Second, the same ANOVA was run using the transformed pc scores from the collapsed matrices to determine if the accuracy for location alone or frequency alone depended on the experimental conditions. Finally, a repeated measures, two-way ANOVA with factors SOA category (simultaneous, unattended stimuli first, attended stimuli first) and selective attention condition [(LR, L), (LR, R)] was conducted to examine whether either factor had a significant effect on the participants' performance. A significance level of $\alpha = 0.05$ was used for all statistical analysis.

III. RESULTS

Average pc scores by condition across all runs and all participants are shown in Fig. 4. There is a slight decreasing trend in average pc scores from the single arm conditions, (L, L) and (R, R) ($avg = 92\%$), to the selective attention conditions, (LR, L) and (LR, R) ($avg = 82\%$). There is a steeper decrease in pc between those four conditions and the (LR, LR) condition (50%). A repeated measures ANOVA confirmed that experimental condition has a significant effect on pc scores ($F(4, 236) = 189.27$, $p < 0.0001$). A *post hoc* Tukey test revealed three groups as indicated by the asterisks in Fig. 4. All five average pc scores were significantly higher than the chance level for their respective conditions [1.2% for (LR, LR); 11.1% for all other conditions.]

Average pc scores for location are shown in Fig. 5. There is a slight decreasing trend from the four conditions (L, L), (R, R), (LR, L), and (LR, R) ($avg = 98\%$) to the (LR, LR) condition (85%). A repeated measures ANOVA confirmed that condition has a significant effect on pc score for location ($F(4, 236) = 99.38, p < 0.0001$). A *post hoc* Tukey test revealed two groups as indicated by the asterisk in Fig. 5. All five average pc scores for location information were significantly higher than the respective chance levels [11.1% for (LR, LR); 33.3% for all other conditions.]

Average pc scores for frequency are shown in Fig. 6. Just as with the overall pc scores, there is a slight decreasing trend from the single arm conditions, (L, L) (95%) and (R, R) (92%), to the selective attention conditions, (LR, L) and (LR, R) ($avg = 84\%$). Of the 139 erroneous responses in the selective attention conditions, 65% matched the frequency of the unattended stimulus. There is a steeper decrease between those four conditions and the (LR, LR) condition (57%). A repeated measures ANOVA confirmed that condition has a

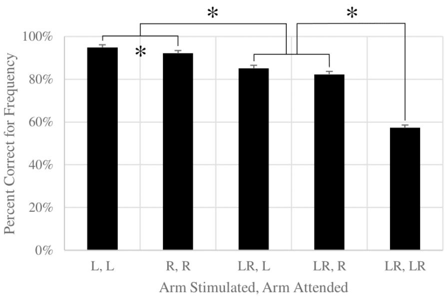

Fig. 6. Average pc scores for frequency information only by condition. Error bars indicate standard error. Asterisks indicate statistical significance.

TABLE I

AVERAGE IT AND 2^{IT} VALUES BY CONDITION

	(L, L)	(R, R)	(LR, L)	(LR, R)	(LR, LR)
Overall IT	2.81	2.74	2.40	2.35	4.58
(and 2^{IT})	(7.0)	(6.7)	(5.3)	(5.1)	(23.9)
Location IT	1.47	1.51	1.44	1.48	2.41
(and 2^{IT})	(2.8)	(2.8)	(2.7)	(2.8)	(5.3)
Frequency IT	1.28	1.19	0.88	0.81	1.36
(and 2^{IT})	(2.4)	(2.3)	(1.8)	(1.8)	(2.6)

significant effect on pc score for frequency ($F(4, 236) = 167.97, p < 0.0001$). A *post hoc* Tukey test revealed significant differences among all pairs of conditions except the (LR, L) and (LR, R) conditions. All five average pc scores were significantly higher than the respective chance levels [11.1% for (LR, LR); 33.3% for all other conditions.]

The information transfer for the five experimental conditions are shown in Table I. The IT values in *bits* are calculated from the $9{\times}9$ or $81{\times}81$ stimulus-response confusion matrices (Overall IT) and the collapsed $3{\times}3$ or $9{\times}9$ matrices (Location IT; Frequency IT). Also shown are the corresponding 2^{IT} values indicating the number of equally likely stimulus alternatives that can be correctly identified. For the four conditions where only one arm was attended, the overall IT results show that the participants were able to identify about seven of the nine frequency-location stimulus alternatives when only one arm was stimulated and five of nine alternatives when both arms were stimulated. For the identification of location alone, participants were able to identify almost all three locations. For frequency identification, the participants were able to correctly identify about two of the three stimulus alternatives. For the (LR, LR) condition, participants were able to identify about 24 of the 81 frequency-location combinations, 5 of the 9 location combinations, and less than 3 of the 9 frequency combinations.

A repeated measures, two-way ANOVA with the factors delay and selective attention condition revealed that in addition to the attention condition, delay also has a significant effect on pc scores ($F(2, 285) = 8.10, p = 0.0004$) and that interaction between delay and attention conditions is not significant ($F(2, 285) = 0.09, p = 0.9172$). A *post hoc* Tukey test revealed that the pc scores were not significantly different when the stimuli were presented simultaneously ($avg = 80\%$) compared to when the attended stimulus was presented first ($avg = 82\%$). When the unattended stimulus was presented first, however, the results ($avg = 85\%$) were significantly different from the other two delay conditions.

IV. DISCUSSION

Participants in the present study demonstrated an ability to selectively attend to vibrotactile stimuli on a certain arm with high accuracy. Performance was near-perfect when selectively attending to location information only. Performance with frequency information was lower; more than half the erroneous frequency responses matched that of the unattended signal, indicating that the frequency of the unattended signal affects the response. This is consistent with the review by Gomez-Ramirez et al. (2016) that most ERP studies of temporal incidence of tactile attention effects suggest feature-based effects (e.g. frequency identification) are observed after spatial selection of stimuli by at least ≈40 ms [11].

The IT results suggest using two rather than three stimulus frequency alternatives to allow participants to achieve high performance when selectively attending. As expected, attending to both arms in the (LR, LR) condition was more challenging, and the drop in performance was significant, albeit well above chance level. Despite the drop, participants could still identify the locations of both stimuli with 85% accuracy on average. Performance was similar between the (L, L) and (R, R) conditions and between the (LR, L) and (LR, R) conditions, except for the small difference between (L, L) and (R, R) when frequency alone was considered.

With the exception of the divided attention (LR, LR) condition, average location IT and frequency IT values summed to within 0.1 bits of the overall IT value for each condition. This indicates the dimensions of location and frequency may be independent or *separable*; that is, participants' performance on responding to location information was unaffected by the frequency information present, and vice versa [26], [28], [29]. The discrepancy between the overall IT for the (LR, LR) condition and the sum of the ITs for location and frequency deserves additional analysis as outlined in Rabinowitz et al. (1987) [26].

The significant increase in performance when the unattended stimulus was presented first compared to other delay conditions was an interesting result. It is well known that sensory effects persist for a brief period when removed from the environment and that information can be extracted from the persisting representation of a stimulus. This has provided evidence for the existence of *sensory memories* that are thought to exist for each sensory modality [1]. Previous studies by Sperling (1960) on the visual domain demonstrated that information persists on the visual sensory-memory store with high capacity, decays within a second, and is susceptible to disruption by subsequent visual stimuli [30]. Durlach & Braida (1969) proposed the concept of *sensory trace* to model the memory noise associated with the first of two sequentially-presented auditory stimuli as a Gaussian function whose variance increases with elapsed time [31]. Bliss (1966) provided evidence of a tactile sensory memory with similar characteristics but less capacity [32]. Therefore, it is possible that participants identified the attended stimulus with higher accuracy when it was the latest stimulus available in tactile sensory memory. It may also be speculated that longer stimulus duration may lead to improved performance, especially for the divided attention (LR, LR) condition.

During the main experiment, participants were not instructed to employ any particular strategy for the (LR, LR) condition. They may have consciously shifted their attention from one arm to another sequentially or attempted to perceive both simultaneously. Anecdotally, several participants reported guessing or using gut instinct during the divided attention task rather than consciously shifting attention from one location to another. It is possible that increasing the duration of the stimuli from 300 ms could improve performance in this condition, regardless of the strategy employed. For example, Gallace et al. (2006) found evidence that there is an attentional limit when multiple simultaneously-presented tactile stimuli at different body sites are presented only briefly. They found that when tactile stimuli were presented repeatedly for 5 s on each trial, numerosity judgements were more accurate than when presentation time was limited to 200 ms [14]. The notion of rapidly-decaying information in the tactile sensory memory agrees with these results. It is possible that longer stimuli durations increase the time during which information is available in the tactile sensory memory, allowing participants to retrieve more information by either shifting their attention across stimuli, or simultaneously identifying characteristics from all stimuli.

To conclude, the present study provides empirical evidence for selective attention of vibrotactile stimuli. Participants achieved near-perfect accuracy to selectively attend to location information. Accuracy for frequency identification was lower, and more than half of the errors matched the frequency of unattended stimuli. Our IT results suggest that six stimulus alternatives (three locations, two frequencies) can be recognized perfectly when attending to one arm. When attending to both arms, about 24 combinations of left/right arm, location, and frequency information can be correctly identified. These results show promise for the utility of vibrotactile displays that present multiple simultaneous signals for information transmission.

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