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Research report

Backward and common-onset masking of vibrotactile stimuli

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Abstract

To inform the design of haptic information displays for noisy environments, we investigated two mechanisms for temporal masking of vibrotactile stimuli (backwards and common-onset) using a commodity display. We used a two-channel setup, presenting stimuli to the middle and ring finger of a participant's right hand. The stimuli consisted of 250 Hz sinusoidal waveforms displayed at a fixed amplitude in various combinations of duration (0, 30 or 300 ms) and stimulus onset asynchrony (0 or 30 ms). In anticipation of future embedded applications where signals are deliberately masked but levels cannot be individualized, signals were standardized at conservative (harder to mask) levels. Our results confirm the existence of a statistically significant masking effect for both forms of haptic masking explored, with common-onset exhibiting a significantly larger masking effect than backwards. However, an analysis of confidence in response levels shows no difference between the two successful masking techniques. We discuss mechanisms that could be responsible for these results, which have implications for the design of user interfaces that rely on tactile transmission of information.

Keywords: Tactile; Re-entrant processing; Haptics; Perception

1. Introduction

Take a passing glance at a picture of a snowy field. Your impression is of undulations in the whiteness: shadows, texture, a weathered fence. Then, look at the same picture with a red barn in the middle. Now you see a red barn and a white field: the contrast of the red overwhelms the subtle variations in the white. This is a form of masking in the visual system; the same phenomenon occurs via several mechanisms, including close temporal spacing, in vision and other senses [22].

A common definition for stimulus masking is "the interference of one perceptual stimulus with another causing a decrease or lessening in perceptual effectiveness" [19]. For our purposes, we will consider a stimulus to be masked when interference from another stimulus (differing either in time or location) prevents the recipient from explicitly detecting, identifying or localizing it.

Our own motive for understanding tactile masking is to support perceptual design of an emerging class of user interfaces that convey information through touch, often in multitasking contexts that are filled with distractions. Two perspectives pertain. Sometimes, a designer will wish to avoid inadvertent masking of signals: for example, temporal masking due to "packing" stimuli closely in time in an effort to maximize information transfer [36,10,23]. At other times, the designer might wish to deliberately mask perceivable information-bearing tactile stimuli as a tool to isolate the factors that affect our ability to process tactile patterns sequentially, and their relation to attention and signal detection [24,18,25], or to produce actionable signals that minimize attentional demands.

Our focus is on the latter, and in the study described here we seek practical methods (usable in commodity applications) for masking information-bearing tactile signals.

1.1. Previous work

Our knowledge of tactile single-stimuli perception is exemplified by experiments of Srinivasan, Tan and others which use synthetic stimuli to determine various human capabilities, including pressure, stiffness, position resolution and force magnitude [32,33,36]; while Klatzky et al. have studied texture perception extensively, most recently touching through a stylus [21]. These and other studies lay the foundation upon which we can further explore tactile perception and begin to build a tactile language. However, because of the real-world environment in which this language will be used (full of distractions and

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competing demands on our attention) we also need to understand how tactile signals are masked.

We differentiate the tactile masking studies we will review here along two dimensions: characteristics of the stimulus being masked, and properties of the masking technique itself. These studies typically investigate either stimulus *detection* (a stimulus is perceivable as present or absent) or stimulus *identification* (where the stimulus incorporates some manner of variation in pattern, e.g. spatial layout or rhythm, and is thus capable of delivering information based on its identity). Masking techniques that have been commonly studied include *forward* (masking stimulus precedes target stimulus; attributed to temporal integration), *backward* (masking stimulus follows presentation of target stimulus), and *sandwich* (target stimulus is both preceded and followed by maskers) masking.

Numerous studies have investigated the masking effects of tactile stimuli. Many of these have focused on how masking affects the *detection* of simple vibrotactile stimuli [39,15–17,26]. In these studies, different tracking methods are used to determine detection thresholds for stimuli in the presence of different forms of maskers. Some utilized collocated target and masker stimuli, with the masker being band-limited noise and the target a sinusoidal waveform [16]. Another paradigm utilizes targets and maskers presented at different frequencies, e.g. [39]. These results have provided a foundation for other investigations into masking effects of more complex, information-rich stimuli.

Researchers have also begun to study temporal and spatial masking effects on *identification* of different types of tactual stimulation *patterns* (intended to carry detectable information beyond presence/absence) delivered to various areas of the body, e.g. [5,35]. These investigate the effects of stimulus masking on different vibration patterns presented through an array of tactile displays, and used to convey meanings in a similar fashion to the raised dots used on an electronic Braille display.

Aligned with the goal of the experiment reported here, some recent studies using relatively complex stimuli, representing either temporal and spatial patterns have reported several different forms of masking which can occur for the sense of touch [2,28,29,21,35,34]. Of particular relevance is a series of experiments by Tan et al. which targeted temporal masking properties of complex patterns *designed for information transfer* [35]. In this study, stimuli were delivered to the left index finger of three participants who were asked to identify target signals masked by forward, backward, and sandwiched paradigms with stimulus onset asynchronies (SOA) of up to ±640 ms. The SOA is the temporal interval between the onsets of two stimuli. Seven perceptually distinct stimuli composed of one, two or three spectral components (2–4, 30 and 300 Hz) were constructed at each of two signal durations (125 or 250 ms). The masking stimuli were selected from the same stimulus set as the target stimuli. Results show a masking effect (average 70% of correct responses, with performance increasing with SOA) for the different types of masking. For these complex stimuli, participants often confused characteristics of the masker with those of the target; and there was considerable variation in individual performance.

Craig performed a series of experiments investigating the ability of participants to localize a tactile pattern presented at one of several locations on their left index finger, in the presence of a second tactile masking pattern [4]. The target stimulus, generated on a 6×24 array of stimulators, was presented either by itself or in the presence of an extraneous stimulus (masker) that either preceded (200–0 ms SOA) or followed (0–200 ms SOA) the target. The masking stimuli were identical in form to the target stimuli. The localizability of the target was affected by the SOA between the target and masker with masking being strongest (68% correct responses) when the masker followed the stimulus at relatively short SOA's (0–30 ms). In another study [6], Craig and Quian found that the identification of a spatial target pattern presented to one finger may be interfered with by the presentation of a second pattern to either the same or a second finger in both forward and backwards masking paradigms.

Evans observed the strongest masking effects at target durations under 100 ms [11]. Both Tan et al. [35] and Craig and Evans [5] found that degree of masking was influenced by the complexity of the stimuli employed; participants were able to identify simpler spatial patterns more accurately. Tan used long complex stimuli and longer SOA's (>125 ms) in order to accommodate low-frequency spectral content, and observed lower and less consistent masking effects. However, Tan's study also showed that percent correct scores were highest with the simplest target patterns (those that contained one spectral component).

Di Lollo and Enns have shown an application of another form of masking for visual stimuli, called *common-onset* or *object substitution* masking [8], where the masking stimulus is presented simultaneously with a clearly visible target stimulus but the surrounding masker remains after the target stimulus has been removed. In vision, this form of masking can be considered to be the result of two separate masking mechanisms: *camouflage masking* (or noise masking) which refers to a degradation in the representation of a target stimulus through the addition of noise from the mask, and *interruption masking* (backward masking (BWM)) which occurs when the mask appears before the target has been fully processed and represents a competition for higher level processes involved in object recognition. The term *object substitution* is used to describe the latter category because the mask appears to do more than interrupt the perceptual process and instead seems to become the new focus of object recognition mechanisms.

Di Lollo and Enns offer a theory of how common-onset masking (COM) works for vision [7,9]: they suggest that object substitution occurs whenever there is a mismatch between the re-entrant visual representation (in their experiments, the participant's representation of the target) and the ongoing lower-level activity produced by current sensory input (the persistent masker). In the case of tactile stimuli applied to two fingers, the re-entrant representation theory would play out as follows. Initially, two signals (one from each stimulus) are sent through the nervous system to the homunculus in the somatosensory cortex, where a representation of the skin and other senses is stored. The prefrontal cortex, responsible for consciousness, requests a re-entrant confirmation of one of the response hypotheses (finger 1, 2 or both) from the homunculus. By this time, the stimulation

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is present in only one finger and this mismatching information is transferred back to the prefrontal cortex. Using a similar form of common-onset masking in vision, researchers have been able to effectively mask otherwise clearly visible stimuli [7–9].

1.2. Objectives and overview

The goal of our research was to investigate the masking characteristics (backwards and common-onset) of simple vibrotactile stimuli presented to the fingertips using commercially available, relatively inexpensive transducers and stimuli presented at standardized levels, with the longer-term goal of integrating this type of transducer and stimuli into existing and new interfaces for tactile communication, e.g. in mobile devices. Simple yet information-rich stimuli can be useful for communicating navigational cues and event notification signals in these devices. However, it is imperative to first understand how these stimuli interact with one another when presented in tight spatial and temporal proximity. Furthermore, our larger goal of non-intrusive threshold or sub-threshold level communication requires optimizing methods for deliberately masking these stimuli effectively and consistently, yet without recourse to lengthy and sometimes complex individualization processes. This experiment was designed with the latter purpose in mind.

To the best of our knowledge, we are the first to investigate common-onset masking for fixed amplitude tactile signals presented to separate contra-lateral loci and the first to present a measure of participant certainty in recognizing the test stimuli. The results obtained here have immediate practical applications for the design of tactile interfaces, and also improve our understanding of the underlying perceptual processes involved when decoding these simple vibrotactile signals.

2. Method

2.1. Approach

In this experiment, we compared the degree of masking produced in backwards (BWM) and common-onset (COM) methods relative to unmasked signals (CTRL), with simple vibrotactile stimuli delivered to a participant's finger pads. Two fingers were used (middle and ring), in order to support testing of the COM method using single-frequency targets and maskers. Masking method was manipulated with the presence or absence of a fixed SOA (duration determined in pilot tests), and we considered both performance and subjective response confidence in a three-alternative identification task (signal present on left, right or both fingers).

We had in mind applications that deliberately but minimally mask informative signals in order to reduce cognitive workload while allowing their non-conscious perception. Therefore we designed our stimuli sets to balance the goals of (1) maximizing the effects of masking, (2) producing target stimuli capable of simple information transfer (such as navigation cues) and (3) producing maskers that are minimally intrusive. Given our goal to re-use these signals while we determine the most effective masking methods, we conservatively chose simple (single-frequency sinusoid) stimuli as being generally hardest to mask [35], and then (to minimize intrusiveness) in pilot studies roughly identified minimum effective durations of both target and masker as well as appropriate SOA values. Finally, we chose the middle and index fingers after pilot studies identified them as having similar levels of sensitivity [30] for the chosen stimuli. We employed repeated measures of a target identification task, with both target and masker presented at the same fixed amplitude to both fingers and for every participant. Our choice of method and our signal design reflects our intent to use these signals in later studies to investigate higher level perceptual processes: fixed-level standardized stimuli will allow us to investigate the effectiveness of these information-bearing stimuli as well as how perception of these stimuli relates to confidence levels. This differs from previous work in tactile masking where signal intensities are adjusted for every participant and thresholds for stimulus detection are determined through an adaptive procedure [16].

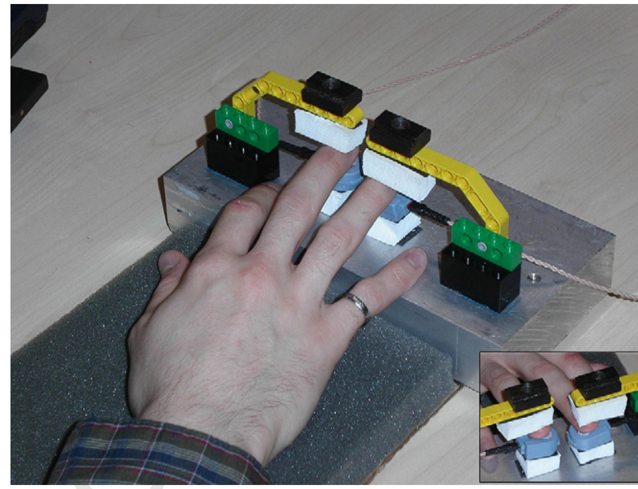

Fig. 1. Tactile display hardware. The participant's middle and ring fingers are pressed against the tactile displays using 30 g weights to maintain a constant pressure.

2.2. Apparatus

Our experiments were carried out using a custom display integrating two Audiological Engineering (www.tactaid.com) tactile displays (visible in Fig. 1). These voice-coil-based transducers, which are used commercially in hearing aids, are capable of producing precisely timed (on/off within 2 ms) waveforms at a useful range of frequencies and amplitudes, with maximum efficiency at 250 Hz; and can be driven directly by a computer's sound card. Tactile displays using similar technology can be found in commercially available mobile phones, PDA's and GPS navigation units.

The design of the apparatus (Fig. 1) was driven by needs for consistent hand position and finger pressure, as well as vibration isolation to prevent crosstalk between the stimulus sites. It utilized two AE displays mounted on a 3 cm thick aluminum plate and insulated with 1 cm thick latex foam rubber commonly used to mechanically isolate sensitive electronic equipment from vibration. The participant's hand rested on another foam pad which was attached to the aluminum plate; weights mounted on articulated plastic arms held his/her fingers against the transducers with a constant pressure of 30 g. User pilot tests confirmed that no crosstalk occurred with this arrangement.

The tactile display was interfaced through the sound card in a 2.5 GHz Pentium 4 computer running Windows XP. Participants wore noise-canceling headphones to block any audible artifacts that the device might produce.

2.3. Experiment task and instructions

In both the pilot and main experiments, we used a three-alternative forced-choice performance task followed by a two-alternative forced-choice subjective task. Participants were read instructions from a script before the beginning of the experiment. They were told that every trial would consist of a single stimulus presentation after which they would be asked to respond with one of three options: stimulus present on middle finger (answering "left"), stimulus present on ring finger (answering "right") or stimulus felt on both fingers (answering "both"). The participants responded by using the left hand to press a key on the computer keyboard with overlays showing "left", "right" or "both". After responding by identifying the stimulus presented, participants were asked to rate the level of confidence in their response by answering "certain" or "uncertain" (again using a keyboard overlay).

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2.4. Stimuli

We used in-phase sinusoidal stimuli with identical amplitudes presented at 250 Hz. Human tactile sensitivity is highest around 250 Hz. The simplicity of the stimuli and the presentation frequency was chosen to give the most conservative results for intentional masking [30]. Throughout the experiment, we presented stimulus pairs consisting of various combinations of three durations and two stimulus onset asynchrony levels (including zero for COM) to the participant's middle and/or ring finger.

In a series of pilots, we determined an appropriate range of stimulus duration and levels. In the first of these pilots, we adjusted stimulus amplitude using an adaptive procedure [37] so that, when presented randomly to either the middle (referred to hereafter and to participants as "left") or ring ("right") finger of the right hand, participants could accurately identify the target finger for stimuli with durations of 10–500 ms 95% of the time. This resulted in a stimulus amplitude of 10 Db above threshold. We used this fixed amplitude for both target and masker for every participant in the experiment.

For all our comparisons, we elected to use three stimulus durations: long (masking), short (target) or none (for use in control (CTRL) trials). For this study, we first chose a target (short signal) duration of 30 ms (the shortest reliably perceived when unmasked; 10–50 ms were tested). A masker (long signal) of 300 ms was then chosen for minimum length in effective masking of the chosen target signal (150–500 ms tested). We note that these thresholds are to some extent specific to the apparatus as well as the experimental setup used.

SOA differentiates BWM from COM (zero SOA), which are otherwise identical. We used an SOA of 30 ms for BWM, because it demonstrated the most effective masking of the 10–50 ms range explored in pilot studies (masking level began to drop as 50 ms was approached). These SOA values are consistent with prior work on tactile pattern masking [4].

Fig. 2 is a graphical representation of the stimuli pairs used, grouped as control, in which only one stimulus was applied, common-onset masking and backward masking.

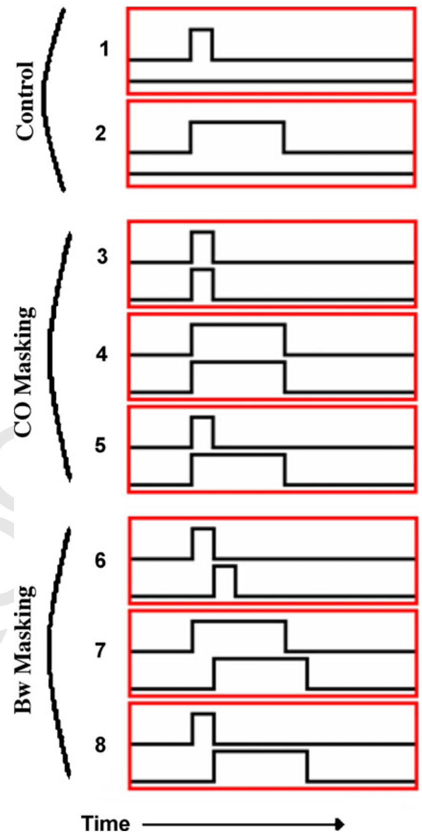

Fig. 2. The eight stimuli types employed. Each box represents the stimuli presented to the middle or "left" (upper) and ring "right" (lower line) finger for a different kind of trial; mirrors of all except symmetric stimulus pairs 3–4 were also used. Short pulses are 30 ms, long pulses are 300 ms, and a flat line indicates no stimulus delivered to that finger. SOA's are either 0 or 30 ms.

2.5. Experiment design

Masking presence and type (the latter dictated by SOA) were the independent variables for this study. As illustrated in Fig. 2, single-finger trials (CTRL) were used as controls. COM (common-onset) trials were those where two stimuli of any length were initiated with zero SOA. Backwards masking trials were those where two stimuli of any length were initiated with 30 ms SOA.

Participants were instructed to respond "left" or "right" if any stimulus (short or long) was noted on *only* the left/middle or right/ring finger, respectively; and "both" if stimuli were detected on both fingers. Thus, "both" indicates successful identification of a target stimulus despite presence of a masker.

A total of 18 trials were delivered in a single repetition: eight types with six mirrored (stimuli 1, 2, 5, 6, 7 and 8), and two extra balancing applications of the control pairs 1 and 2 and their mirrors. The latter ensured that every repetition had an equal number of "left", "right" and "both" correct responses and was intended to minimize response bias. For each participant, 10 full repetitions were conducted, and trial order was randomized within repetitions (a different random order for each repetition and participant).

3. Results

3.1. Participants

Eleven university students, five female and six male, participated in the experiment. All were 22–27 years of age, right handed and were paid $10 in cash for a 35-min session. All participants reported normal tactual function.

3.2. Identification performance

We obtained a measure of masking performance in the form of overall rate of correct responses for each of the eight stimuli configurations tested (from 14 distinct pairs, including mirrors). Each bar in Fig. 3 was obtained by counting the correct responses out of 10 repetitions for all 11 participants and dividing this number by the total number of presentations of that particular stimulus. The error bars represent the standard deviation of this average. The graphic pairs below each bar specify the stimulus parameters for the middle (left graphic) and ring (right graphic) fingers: absent, short and long black regions indicate stimulus durations of 0, 30 or 300 ms, respectively, and a black region atop a short white region indicates a 30 ms delay. For example, in Fig. 3, stimulus 7 represents the presentation of a long stimuli applied to the middle finger and a long (300 ms) delayed (30 ms) stimuli applied to the ring finger (backwards masking of the middle finger) along with its mirror, i.e. backwards masking of the ring finger. A correct response to these stimuli would be "both".

A single-factor, 3-level analysis of variance (ANOVA) confirmed a statistically significant effect on identification performance of masking type ($p < 0.001$, $F = 22.459$), when all observations for each of the three masking types (CTRL, COM, BWM) are grouped. Common-onset masking produced the greatest rate of erroneous responses, i.e. the most effective masking, with the ANOVA comparisons showing significant differences between COM and BWM ($p = 0.041$, $F = 22.459$),

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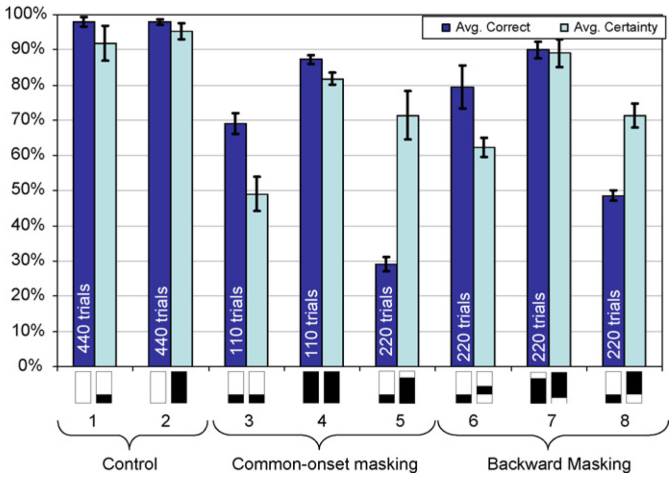

Fig. 3. Overall percentage identification performance and confidence levels, by stimulus type. The stimulus number matches Fig. 2. The number of trials represented by each pair of bars is shown on each bar. Lower performance values indicate a stronger masking effect. Stimuli 1, 2, 5, 6, 7 and 8 were mirrored; stimuli 1, 2 and their mirrors were applied twice for overall left/right balance. See Section 3.2 for further description of this figure.

and between both of the masking types and the control trials ($p < 0.001$, $F = 22.459$).

We analyzed incorrect responses to determine whether errors were due to overlooking a masked target. We found that nearly 100% of incorrect responses indeed involved missing the short (target) stimulus: in these cases, the response to a masked trial was the longer stimulus, rather than either 'Both', the correct response, or the short stimulus, a different possible incorrect response. Thus together with the observation of near-perfect responses for both long and short unmasked single-finger stimuli, we can conclude that an error is equivalent to a successfully masked target. The types of error and error rates for each of the stimuli are presented in Table 1. Visual inspection of individual identification performance data indicated that although there are differences in overall task performance amongst participants as evidenced in the standard deviation bars for Fig. 3, trends across stimuli pairs are consistent for all participants.

We note that there was a difference in performance within the mirrored stimuli for both COM and BWM, observable in Table 1 and most evident for stimuli 5 and 8. However, this difference was not statistically significant ($p < 0.199$ for COM and $p < 0.307$ for BWM) and we thus continued to group these stimuli in the larger analysis. We believe this was due to a difference in tactile acuity between the middle and ring fingers. Our stimuli were presented at a standardized level and were not balanced for possible differences in perceptual sensitivity between middle and ring fingers, because of our goal of testing worst-case "plug and play" use. From Table 1, we observe that while the target stimulus was in general masked more effectively for COM than BWM for the same mirrors of stimuli 5 and 8 (lower percent correct rates), the ring finger was more sensitive (the short target stimuli noted more often with a "both" response for both the BWM as well as the COM stimuli.

3.3. Response confidence

The confidence participants reported in their responses, regardless of actual performance, is shown in Fig. 3: responses of '1' (confident) are counted and normalized to the total number of trials. Confidence is similar for both types of masking (67.4 and 74.2% for COM and BWM, respectively), and lower than for the unmasked control trials (93.5%); a single-factor, 3-level ANOVA confirms a statistically significant effect of masking type on confidence ($p < 0.005$, $F = 8.764$). Post-hoc comparisons indicate a difference between both masking methods and the control stimuli ($p < 0.001$, $F = 8.764$), but not between COM and BWM.

Table 1
Error rates and stimulus ~~confusion~~ matrix Q5

Stimulus type	Stim #	Middle finger		Ring finger		% Correct	Response distribution (%)			Conf Level (%)
		Delay	Duration	Delay	Duration		Middle	Ring	Both	
Control	1	0	0	0	30	98.6	0	**99**	1	91.8
	2	0	0	0	300	97.7	0	**98**	2	94.5
	1	0	30	0	0	97.3	**97**	0	3%	91.8
	2	0	300	0	0	98.2	**98**	0	1%	95.9
Common-onset Masking	3	0	30	0	30	69.1	25	5	**69**	49.1
	5	0	30	0	300	21.8	0	78	**22**	71.8
	5	0	300	0	30	36.4	64	0	**36**	70.9
	4	0	300	0	300	87.3	10	3	**87**	81.8
Backward Masking	6	0	30	30	30	75.5	2	23	**75**	59.1
	8	0	30	30	300	33.6	4	63	**34**	70.9
	7	0	300	30	300	89.1	5	6	**89**	88.2
	6	30	30	0	30	83.6	10	6	**84**	65.5
	8	30	300	0	30	63.6	35	1	**64**	71.8
	7	30	300	0	300	90.9	5	5	**91**	90.0

Response distribution values indicate the % of participants who provided each of the possible responses; *% Correct* simply repeats the distribution value that was in fact the correct answer. Most bars in Fig. 2 are the average of the two rows of this table which represent mirrors of the same stimuli.
This table shows how the errors were distributed for each of the stimuli types (as described in Fig. 2) used in the study. Q6

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There are two notable observations to be made of the confidence results. First, the lowest level of confidence (49.1%) was accorded to the simultaneous presentation of two short signals to both fingers (COM stimulus 3) and substantially lagged actual performance (69.1%). Secondly, confidence levels for COM stimulus 5 and BWM stimulus 8 (in both cases, masking of a short target) were identical (71.4%). Actual performance levels for those stimuli (21.8, 36.4 for the two mirrors of COM 5 and 33.6, 63.6 for BWM 8) were much lower than confidence levels in these instances. Taken together, these two observations suggest that while the masker's length (30 ms vs. 300 ms) did not substantially change performance, it *did* substantially change confidence in performance. That is, participants had high confidence that only one signal was present, when in fact both ~~were.~~

4. Discussion

4.1. Masking performance

The results obtained indicate that some form of masking is possible under the selected conditions and with the hardware tested. Both of our base stimuli (30 and 300 ms) could be accurately (98.0%) identified when presented in isolation, but identification performance dropped to 31–87% when combined with a masker in some form. A review of individual participants results (not presented) shows that while differences exist, individuals exhibit the same general pattern of performance across stimuli (i.e. a graph like Fig. 3 has roughly the same shape for every participant, but at slightly different amplitudes).

In their general trend, our results are consistent with previous work in the areas of haptic and vibrotactile backward masking and visual common-onset masking, where a decreased level of target identification accuracy is induced by the introduction of a masking stimulus presented contiguously (temporally and spatially) to the target stimulus. However, differences in our methodology and type of stimuli offer new and more fine-grained insights with respect to overall masking results obtained. We will first develop these by comparing our BWM results with previous studies that employed a similar methodology to ours, and then proceed to look closely at new comparisons possible within our own data.

4.1.1. Type of errors and stimulus complexity

Evans [11] reported 20–65% overall error rates under backward masking at SOA in the range of 26–106 ms; of these, 20–30% were attributed to the use of the masker as response (the remainder of errors were random). In contrast, our results for both BWM and COM stimuli show nearly 100% of errors (out of overall error rates of 49–90% for our three BWM stimulus variants) being made by using the masker as the response (Table 1). We believe that the increased specificity in type of error which we found (as opposed to differences in overall error rate, which are harder to compare given differences in setup) is due to the simplicity of the stimuli used here (only three possible cases: left, right or both) as well as the masking paradigm employed. In our design, a successfully masked stimulus was one where the participants respond with the masker.

In the same study, Evans reported that for backward masking, percent correct scores indicated that when stimuli were masked, participants were able to identify simpler spatial patterns more accurately. Similarly, Tan et al.'s [35] percent correct scores were highest with target patterns that contained one spectral component, and lowest with those that were more complex (containing three spectral components). In the experiment reported here, every stimulus was composed of a single spectral component and carried 1.5 bits of information (participants could answer left, right or both). We therefore hypothesize that the masking effect would be stronger if we were to employ more complex stimuli.

4.1.2. Other potential mechanisms: temporal integration

Temporal integration is often cited as an explanation for decreased levels of accuracy in stimulus recognition when stimuli are presented closely in time [3,12]. These studies suggest that target identification may be disrupted because the target and non-target form a composite pattern through temporal integration. For example, in vision, if two semicircles (one left and one right) are target and masker, respectively, then integration would result in perception of a full circle composite.

We believe it is unlikely that the incidence of masking observed in our study is a result of temporal integration: this would imply that the target and masker form a composite percept that is the temporal and/or spatial sum of both signals. Our hypothesis is that with our paradigm, temporal integration would work against any of the masking techniques used and would in fact improve stimulus identification accuracy: temporal integration of a short stimulus presented to one finger and a longer stimulus presented to another finger would form a composite percept. Based on findings in vision (where, for example, "–" and "|" are integrated and perceived as "+"), the composite percept is most likely to be that of *both* fingers being stimulated, i.e. the expected correct response [27].

4.1.3. Common-onset masking as compared to backwards masking

To the best of our knowledge, this is the first study to investigate tactile common-onset masking using standardized stimuli levels presented to separate but contiguous loci as represented by stimulus pair 5; and one of a few studies which assess any form of tactile COM [16,40]. Di Lollo et al. [7], investigated this form of masking for visual stimuli (which are not typically standardized by individual); our study was designed to mimic their setup while using tactile stimuli. In vision, the masker takes the form of four dots presented simultaneously and surrounding but not touching a target shape. The target can appear in one of eight possible locations on a screen. The dots remain for a period of time after a brief presentation of the target shape. Participants are unable to identify a target shape within the dots and report only the presence of the dots. In our study, a short tactile stimulus is presented simultaneously with a second stimulus which remains present after the short stimulus has ended. The target can be presented to the middle finger, the ring finger or

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both loci simultaneously. Participants are unable to perceive the short stimulus and report only the long one.

In the present study, we found that COM provided the most effective masking overall. In particular, COM stimulus 5 produced a participant response accuracy of 29.1% correct as compared to 48.6% for BWM stimulus 8, whereas confidence levels were similar. Our data are consistent with the view that this difference in performance is the result of a combination of two different masking mechanisms similar to those observed in vision. Both COM and BWM can in theory be subject~~ed~~ to the backwards (interruption) mechanism of masking (which Enns found to be strongest at 0 < SOA < 100 ms for vision) [8]; but COM ~~additionally~~ may be affected by camouflage (or noise) masking, which is strongest at SOA's ∼ 0 [38,14,1,16,26]. These time estimates could plausibly be used as a first crude approximation of durations required for tactile signal processing if we assume that they involve a substantial cognitive component, as is believed to be the case for visual pattern processing.

This theory is substantiated by the observation that COM stimulus pairs 3 and 4, which unlike the other COM stimuli should *not* be subject to backwards masking as the two stimuli were of the same length, resulted in 69 and 88% correct responses for the 30 and 300 ms duration stimuli, respectively. This represents about 40 and 12% masking relative to unmasked signals, and is comparable to the masking performance difference of 19.5% observed between stimulus pairs 5 (camouflage plus backwards masking) and 8 (backwards masking alone). Thus, we can posit an additive effect of these two mechanisms.

Another possible contributor to the observed difference between COM and BWM is that our backward-masked stimuli might have generated a salient sensation of motion on the fingers of the participants, due to the (30 ms) delay between the onset of the target and masking signals. The presence of this sensation of motion was reported by two of the participants for some of the trials. Previous work has shown an increased sensitivity to perception of motion for vision [13] but to the best of our knowledge, this increased sensitivity has not been investigated for the sense of touch. Further research is required to follow up on this possibility.

From a high-level theoretical standpoint, our results might be explained by the proposed existence of the same type of higher level perceptual processes that have been recently explored in vision, i.e. re-entrant processing of the target stimulus [7]. This theory states that perception of an object (or stimulus) is the result of a series of hypothesis-confirmation stages: when a stimulus is first detected, a hypothesis is built as to what the stimulus is. This hypothesis is later confirmed or modified based on subsequent gathering of information. The theory of re-entrant processing is controversial, and temporal estimates of loop confirmation duration are scarce (10–13 ms has been proposed [31,20]); however it does provide an attractive explanation of what we have observed. In the case of stimulus 5 (COM, short target and long masker), the initial hypothesis is that there is one stimulus being presented to each finger. This hypothesis is later rejected when the data available at a subsequent time (after the short target has terminated) points to a single stimulus being present. In this way, after an initial stimulation ascends through the perceptual system, an iterative-loop system acts to reduce noise to establish the most plausible perceptual interpretation.

4.2. Confidence and its relation to masking

To the best of our knowledge, this is the first study to report confidence in responses to masked vibrotactile stimuli. It is important to look at confidence levels in relation to performance levels for the different stimuli utilized. A high level of confidence indicates that the participants were certain about their interpretation of the stimuli being presented; when combined with a high error rate (low % correct responses); it implies that masking that went beyond "confusing" participants to convincing them of the error case. Conversely, a low confidence level indicates that the participants felt they were unable to clearly perceive the stimuli, and might be paired with either a high but uncertain actual performance or genuinely confused, low performance.

Confidence levels for stimuli 1, 2 (no masking) and 4, 7 (two long stimuli) closely match their performance levels (difference < 5%). These stimuli were correctly identified on 80–95% of the trials. Confidence is always slightly lower than the high identification performance for these stimuli, but it is perhaps unjustified to make such precise comparisons of subjective and objective parameters such as these. Instead, we will use these confidence levels and their relation to respective performance levels as baselines for relative comparisons below.

Stimuli 3 and 6 (COM and BWM versions, respectively of short stimuli on both fingers) both exhibit a performance/confidence disparity of about 20%, as compared to <5% above. This means that participants were correctly identifying the stimuli (70–80% accuracy) significantly more often than they believed (49–62% confidence levels, with lowest confidence for COM stimulus 3).

Confidence levels are equal (71%) amongst the two stimuli that show the strongest masking effects: 5 (COM) and 8 (BWM), both involving a short target and long masker. For both of these stimuli, confidence levels were considerably higher than performance levels. The COM stimulus was correctly identified only 29% of the time and the BWM stimulus was identified 49% of the time (chance = 33%). This suggests that participants were confident that they had perceived and interpreted the stimuli correctly more often than they did, with disparities of 42% (COM) and 22% (BWM). The higher confidence/performance values as compared to stimulus pairs 3 and 6 are very likely due to the difference in length of masker; 5 and 8 have a long masker which dominates the target more effectively than that of 3 and 6. However, the target in both cases is clearly detectable when alone.

From the standpoint of designing information-bearing signals that will be intentionally masked from conscious perception at periods of high cognitive workload, we can speculate that high confidence-performance disparities are positive: the goal here would be to achieve high correct identification performance, without a conscious awareness of the target information having been received. Conversely, however, uncertainty about perception might contribute to cognitive load at the same time that

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attentive processing of the unmasked signal has been averted. However, further work is required to substantiate such theories.

5. Conclusions

To the best of our knowledge, this is the first report of an investigation of the effects of common-onset masking of vibrotactile stimuli presented to separate but contiguous locations using fixed amplitude stimuli, and the first report of participant confidence levels when identifying the masked vibrotactile stimuli. Most of the existing work on haptic and vibrotactile masking has focused on testing different forms of forward and backward masking techniques and to the best of our knowledge, none have reported participant confidence.

Specific contributions of the present study include observations that for synthetic vibrotactile signals, (a) common-onset masking (exemplified as simultaneous presentation of a short target with a longer masker) shows the strongest masking effect among the set of masking techniques tested, (b) backward masking presents lower, yet significant, masking levels and (c) confidence levels for participant responses are affected equally by backward and common-onset masking. We propose that the performance differences we have observed between COM and BWM may be explained by an additive effect of two complementary masking mechanisms similar to those which have been observed in visual signal processing. Meanwhile, the pattern of confidence levels we observed suggest that if we intend to deliberately mask stimuli yet maintain confidence levels as high as possible (for the purpose of participant comfort while automatically processing information-bearing signals which are deliberately “hidden” from conscious processes) we should consider using common-onset masking.

The stimulus design and masking paradigms presented comprise an innovative method for investigating the masking characteristics of simple vibrotactile patterns. The use of simple information-bearing stimuli has allowed a better understanding of the underlying processes that occur when identifying masked stimuli. Although common-onset masking has been explored for the sense of vision, our work has not only applied similar techniques to the sense of touch but has also opened up the possibility of further investigating possible commonalities between high-level visual and haptic perceptual processes when stimuli are masked.

The experimental method and analysis techniques developed can be used both to determine tactile communication bandwidth when using multiple vibrotactile displays for interactive devices (to maximize communication ratios) as well as to further study tactile perceptual processes.

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