Incidental Categorization of Vibrotactile Stimuli

Juan S. Martinez, Lori L. Holt, Charlotte M. Reed, and Hong Z. Tan, *Fellow, IEEE*

***Abstract*—Past research has demonstrated incidental learning of task-irrelevant visual and auditory stimuli. Motivated by the possibility of similar evidence in the tactile domain and potential applications in tactile speech communication systems, we investigated incidental categorization of vibrotactile stimuli through a visuomotor task of shape identification. Two experiments were conducted where participants were exposed to position-based or movement-based vibrotactile stimuli prior to performing a speeded response to one of two targets. The two experiments differed only in the particular sets of such stimuli employed. Unbeknownst to the participants, the vibrotactile stimuli and visual targets were initially correlated perfectly to facilitate the incidental learning of their associations, briefly uncorrelated to check the cost in reaction time, and correlated again to re-establish the initial association. Finally, participants were asked to predict visual targets from novel position-based and movement-based stimuli. The results from both experiments provided evidence of incidental categorization of vibrotactile stimuli. The percent-correct scores and sensitivity indices for the overt categorization of novel stimuli from both experiments were well above chance, indicating generalization of learning. And while both experiments showed an increase in reaction time when the association between vibrotactile stimuli and visual targets was disrupted, this reaction time cost was significant only for the stimuli used in the second experiment. Our finding of incidental categorization in the tactile domain has important implications for the effective acquisition of speech in tactile speech communication systems.**

***Index Terms*—Incidental categorization, incidental learning, vibrotactile stimuli, tactile speech communication.**

I. Introduction

INCIDENTAL learning refers to a form of unintentional learning of properties of task-irrelevant stimuli while performing a different type of primary activity. Examples of incidental learning include the acquisition of vocabulary through reading, learning a new language by moving to the country where the language is spoken, and the development of math concepts (e.g., fraction) through playing musical instruments. It is hypothesized that task-irrelevant stimulus features are processed and learned without being the primary focus of attention, and such learning typically takes place at low (i.e., sensory processing) levels [1]. Incidental learning paradigms such as games can provide a fun and engaging environment and can lead to better outcomes as compared to explicit learning [2].

Incidental learning can be modeled as a form of task-irrelevant perceptual learning and has been demonstrated for both visual and auditory stimuli. Studies of visual incidental learning include motion detection experiments that led to the initial discovery of the phenomenon [3]–[5], and studies on the role of rewards in the incidental detection of sinusoidal-grating orientations [6]. In the auditory domain, speech acquisition is a prime example of incidental learning in our daily lives and many experiments have shown similar effects with non-speech auditory stimuli. For example, incidental learning procedures can effectively train participants to categorize non-speech sounds [7] and to identify difficult non-native speech contrasts [2], [8], [9], to increase sensitivity to auditory formant transitions [10], reinforce associations between novel visual cues and phonetic categories [11], and train young children to categorize audiovisual stimuli [12]. In the above-mentioned studies, the participants were exposed to the visual or auditory stimuli to be learned but were unaware of the correlation of the stimuli with the primary, typically action-based, task. To the best of the authors' knowledge, there have not been systematic studies of incidental learning of vibrotactile stimuli.

A closely-related topic may be passive haptic learning (e.g., piano playing [13], [14], Braille typing [15] and Morse code [16]). However the participants in the passive learning studies were fully aware of the meaning of the vibrotactile stimuli, and therefore the learning effect may have been due to overt attentional shift as opposed to incidental learning. Another similar concept is priming. It typically involves the presentation of an informative stimulus that shares some properties of a target that follows it (e.g., the presentation of a vibration at the left shoulder before a visual target appears on the left side of a screen [17]). Priming effects are usually automatic and effortless. This is not the case in the present study where the tactile stimuli do not share any inherent property with the visual stimuli following them. In some priming studies, the association between the priming and target stimuli was first learned explicitly during a study phase. A test phase then followed to assess the priming effects (e.g., [18]). Such studies are also different from the present study where the association was never explicitly presented to the participants.

Past research has shown that incidental learning happens when stimuli align with behaviorally-relevant actions and goals in the primary task [1], [19]. An example is the study conducted by Wade & Holt [7] who used a video game to study incidental

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learning of complex auditory stimuli. Their participants engaged in a visuomotor task of shooting four aliens, each appearing from a distinct quadrant of a computer screen. Unbeknownst to participants, each alien was associated with a sound category composed of multiple, variable exemplars. As the task difficulty increased with leveling up in the game, participants were able to use the sound to predict the position of the next alien, thereby demonstrating incidental learning of sound categories. This incidental learning generalized to novel sounds drawn from the categories in an overt post-test in which participants matched sounds to aliens. The multimodal interaction of the game was designed to model characteristics of natural learning environments in which learning is rarely driven by overt instruction. A later study using the same sound categories from [7] modeled characteristics of the videogame in a simplified task, the Systematic Multimodal Associations Reaction Time (SMART) task [20]. In the SMART task, participants see four rectangles in a 1-by-4 grid. On each trial, a visual target appears in one of the four rectangles and the task is to respond rapidly to indicate the target's location by pressing one of four response keys. Prior to each visual target, there are five presentations of auditory stimuli. Unbeknownst to participants, the auditory stimuli belonged to four perceptual categories that map consistently to the four visual locations, respectively. It was expected that as the participant incidentally discovered the category-to-visual location mapping throughout the experiment, the auditory categories would serve to predict the location of the next visual target and reaction time to visual targets would decrease. Moreover, when the consistent category-to-location mapping was disrupted in a block of trials, reaction time to detect the visual targets was expected to increase. Gabay *et al.* observed both patterns of behavior, and found generalization of incidental learning to novel category exemplars in a post-SMART overt categorization task.

We are interested in the incidental *categorization* of vibrotactile stimuli in the context of improving the training strategy for a phonemic-based tactile speech communication system that the authors have developed recently [21], [22]. Incidental categorization can potentially be applied towards a training environment where users learn the association between tactile patterns and the phonemes they represent while engaged in game playing. Based on the SMART task [20], we designed a task of speeded manual response to two visual targets and the association with two categories of vibrotactile stimuli for incidental categorization (see Fig. 1). Two experiments were conducted, with modified vibrotactile stimuli in Exp. 2 based on the results of Exp. 1.

II. General Methods

This section presents methods that are common to both Exp. 1 and Exp. 2. The vibrotactile stimuli differed in the two experiments; thus, these details are provided in the later sections for each of the two experiments (Secs. III-A and IV-A respectively).

A. Participants

A total of 24 participants between 22 and 33 years of age (24 $\pm$ 2.9 years) were recruited for the two experiments.

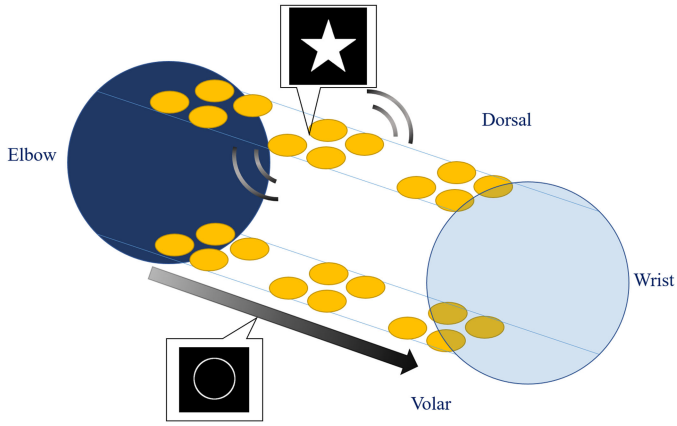


Fig. 1. Illustration of a position-based stimulus (simultaneous vibration of four tactors in the middle of the dorsal forearm) and a movement-based stimulus (apparent motion from elbow to wrist on the volar forearm), and their association with a star and circle, respectively.

Eleven participants (4 females) took part in Exp. 1, and thirteen (7 females) in Exp. 2. All had normal sense of touch by self report. None had prior experience with the vibrotactile stimuli used in the present study. They gave informed consent to the protocol approved by the IRB at Purdue University and received 10 USD as compensation.

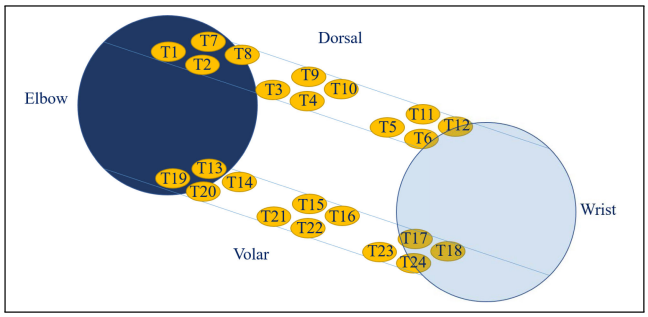
B. Apparatus

A phonemic-based tactile display consisting of an array of 4-by-6 tactors was used in the present study (see Fig. 2 for the tactor-array numbering scheme). The tactors (Tectonic Elements, Model TEAX13C02-8/RH) were connected to the outputs of 24 Class D audio amplifiers that received their inputs from a MOTU 24Ao audio interface. The MOTU device was connected through a USB port to a PC, and performed synchronous digital-to-analog conversions of 24 independently-programmed waveforms. The participants wore the tactile display on their left forearms, with tactors T1-T12 on the dorsal side and the rest on the volar side (Fig. 2). Further details about the hardware can be found in [21].

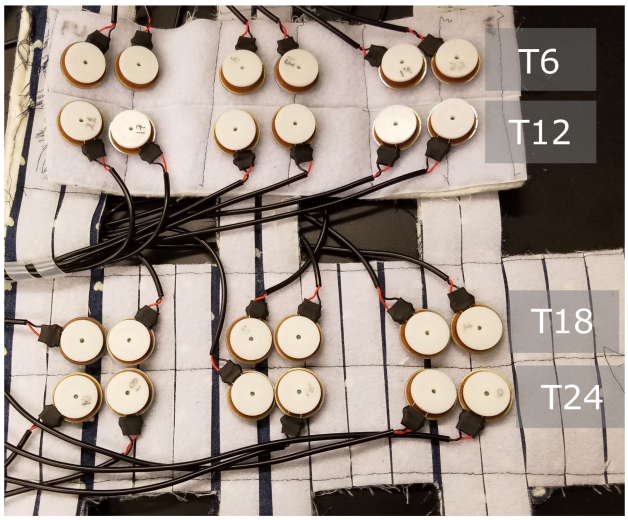
C. Experiment Design

We designed the experiments after the SMART task [20]. Two visual targets (see Fig. 3) were used that occupied roughly $9.07^\circ \times 9.07^\circ$ in the center of a computer screen. We eliminated the location cues of the visual targets to prevent participants from associating tactor locations on the forearm with visual target locations. Due to the fact that our vibrotactile stimuli lasted longer (400 ms) than the auditory stimuli in Gabay *et al.* (250 ms), three vibrotactile stimuli were presented to the forearm prior to the appearance of each visual target. Two categories of vibrotactile stimuli, position based and movement based, were created to map to the visual targets of a star and a circle, respectively (see Fig. 1). The stimuli will be further described in Sec. III-A for Exp.1 and Sec. IV-A for Exp.2.

As illustrated in Fig. 4, trials were organized in blocks as in the SMART task [20]. The familiarization block (blue) allowed the participants to get used to the structure of each trial: fixate



(a) Tactor distribution and numbering on the forearm.



(b) Photo of the tactile display as a two-piece gauntlet.

Fig. 2. Illustration of the tactile display. (a) Tactor distribution and numbering when worn on the left forearm. The tactor array forms 2 rows of 6 tactors in the longitudinal direction on the dorsal side of the forearm, and 2 rows of 6 tactors on the volar side. (b) Photo of the tactor array as a two-piece gauntlet. The participant placed the left forearm on the bottom gauntlet piece first. The top piece was then wrapped around the forearm and placed on the dorsal side, and attached to the bottom piece with Velcro straps. The rightmost tactor labels illustrate the correspondence with the illustration in (a).

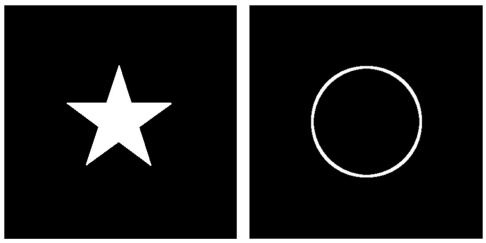


Fig. 3. Visual targets in the modified SMART task: a star and a circle.

on a cross at the center of the computer screen, feel three vibrotactile stimuli on the forearm, detect a visual target, and respond quickly by pressing a key. During this block, each category of vibrotactile stimuli was equally likely to be presented before a star or a circle. During all the incidental categorization blocks (green), the position-based vibrotactile stimuli always preceded a star and the movement-based stimuli always preceded a circle. The mapping was not employed (i.e., the correspondence between vibrotactile stimuli and visual targets was

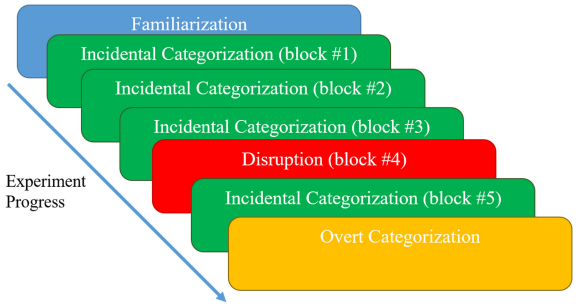


Fig. 4. Experimental blocks modeled after the SMART task [20].

randomized) in the disruption block (red) and re-established in block #5. Finally, during the overt categorization block (yellow), no visual targets were presented. The participants were asked to *predict* the visual shape after feeling three repetitions of a novel vibrotactile stimulus by pressing a key on a computer keyboard that is covered with the image of a star or a circle. The overt categorization block was unexpected by the participants as they had not been informed about this task until just before it was conducted. With this design, blocks #1-3 allowed the participants to incidentally learn the vibrotactile-visual mapping. Increased response times were expected in block #4. After the mapping was restored in block #5, the participants were explicitly tested for categorization of novel vibrotactile stimuli in the last block.

D. Procedures

Prior to the experiments, detection thresholds for vibrations at 300 Hz and 60 Hz were measured for all participants using a a three-interval, two-alternative, one-up two-down adaptive forced-choice procedure with trial-by-trial correct-answer feedback [23]. The detection thresholds at 150 Hz and 210 Hz (used in creating novel stimuli for overt categorization) were derived from the threshold data found in Bolanowski *et al.* [24] as follows. The participant's detection threshold at 300 Hz was compared to that at 300 Hz in Figure 1 of Bolanowski *et al.* [24] and the difference Δ was computed. The thresholds at 150 Hz and 210 Hz in Figure 1 were then shifted by the same Δ and used to estimate the participant's thresholds at these two frequencies, respectively. The relative intensities of all tactors were then calibrated at 300 Hz using the method of adjustment. Interested readers may refer to Sec. IV-D of Reed *et al.* [21] for details. Participants wore noise cancelling earmuffs during the experiments to block any possible auditory cues.

At the beginning of each experiment, the participants received a written instruction sheet about the task. They were asked to respond to the visual targets *as quickly and accurately as possible* using two keys covered with the images of a star and a circle. They were told that each visual target was proceeded by three vibrotactile patterns delivered to their left forearm, and they should not ignore the tactile stimuli. During a pilot test, one participant thought the vibrotactile stimuli were distractors and did his best to ignore them. We therefore found it necessary to instruct the participants not to ignore the tactile signals. We did not reveal why the vibrotactile stimuli were used, nor their

association with visual targets. The tactile signals were separated by a 200-ms gap. The visual target appeared immediately after the offset of the third tactile stimulus and remained on the screen until a response key was pressed.

There were 16 trials in the familiarization block, 60 trials (2 vibrotactile categories × 6 stimuli/category × 5 repetitions/stimulus) in each of the incidental categorization blocks, 24 trials (2 vibrotactile categories × 6 stimuli/category × 2 repetitions) in the disruption block, and 50 trials (2 vibrotactile categories × 5 novel stimuli/category × 5 repetitions) in the overt categorization block. The stimuli per category in each experimental block are described later in Sec. III-A for Exp.1 and Sec. IV-A for Exp.2.

There were fewer number of trials (24) in block #4 to avoid completely erasing the learning in blocks #1-3. No correct-answer feedback was available to the participant during any part of the experiment. Trials in which the key with the wrong image was pressed or the response time was over 1.5 s were repeated at the end of blocks #1-5. Error trials ranged 0-8 trials per block. Data from error trials were discarded. The participant could take a break between blocks and the experiment lasted about 1 hour for each participant.

At the end of the experiment, a short debriefing session was conducted in which participants were asked about their strategy for solving the overt categorization task, any perceived association between the tactile stimuli and visual targets, and their description of the possible categories of tactile stimuli.

E. Data Analysis

Reaction times (RTs) were recorded from the onset of a visual target to the corresponding key press for all trials in blocks #1-5. To normalize the RTs across participants, the mean RT averaged over all incidental categorization blocks (#1, 2, 3, 5) for each participant was subtracted from the individual RT data points for the same participant. The de-meaned RTs were then averaged across all participants in the same experimental block. The process of de-meaning reduced the variations in the absolute size of RTs due to individual differences, and also allowed us to focus on the *change* in RTs from block to block. Of particular interest was the *RT cost*, calculated as the difference in RTs between block #3 and block #4, which was not affected by the de-meaning process. We hypothesized that participants would respond slower in block #4 because they were likely confused by the sudden lack of predictable vibrotactile-visual association in block #4. This increase in RT reflects the disruption of the incidental categorization established in blocks #1-3.

To assess the performance of participants in the overt categorization block, a two-by-two stimulus-response matrix was caculated for each participant where the rows were for the novel position-based and movement-based vibrotactile stimuli, respectively, and the columns for the stars and circles, respectively. From individual matrices, the percent-correct scores and sensitivity indices [23] were calculated. A high percent-correct score indicated the generalization of the mapping between position-based and movement-based vibrotactile stimuli and stars and circles, respectively. A low score also provided evidence of generalized incidental learning, except that the participant accidentally switched the mapping; i.e., position-based stimuli were associated with circles, and movement-based stimuli with stars. A medium score close to 50% indicated a lack of categorization of the two types of vibrotactile stimuli. The sensitivity index d' is related to the percent-correct score but is not confounded by response biases. The stimulus level at which $d' = 1$ is typically defined as the just noticeable difference [23]. Therefore a d' value greater than 1 indicates strong evidence of the ability to discriminate the two types of vibrotactile stimuli, hence success in overt categorization.

TABLE I
POSITION-BASED VIBROTACTILE STIMULI USED IN EXP. 1

Experimental Block	Signal Label	Tactors Activated	Frequency (Hz)
Blocks #1 to #5	Pos01	T1, T2, T7, T8	60
	Pos02	T3, T4, T9, T10	60
	Pos03	T5, T6, T11, T12	60
	Pos04	T13, T14, T19, T20	300
	Pos05	T15, T16, T21, T22	300
	Pos06	T17, T18, T23, T24	300
Overt Categorization	Pos07	T2, T3, T8, T9	150
	Pos08	T4, T5, T10, T11	150
	Pos09	T14, T15, T20, T21	150
	Pos10	T16, T17, T22, T23	210
	Pos11	T6, T12, T18, T24	210

III. EXPERIMENT 1

A. Vibrotactile Stimuli

As mentioned earlier, two categories of vibrotactile stimuli that corresponded to the two visual targets of star and circle were designed in this experiment: *position-based* and *movement-based*. Position-based stimuli consisted of the simultaneous vibrations of four closely situated tactors at one location on the forearm, and were associated with the star. Movement-based stimuli consisted of the successive onset of vibrations with sufficient temporal overlap that resulted in the apparent motion illusion [25], [26] along the length of the forearm, and were assigned to the circle. These two categories were motivated by the tactile coding of English phonemes described in Reed *et al.* [21] where consonants were represented by position-based vibrotactile stimuli on the forearm and vowels by movement-based signals. This coding strategy proved to be very effective: consonant-vowel confusion errors were only 3.2% of 1,560 trials collected from 10 participants in a phoneme identification experiment [21]. It was therefore expected that the position vs. movement distinction in the vibrotactile stimuli used in the present study could be learned incidentally by the participants.

Following the strategy of Gabay *et al.* [20], we designed six position-based (Pos01 to Pos06) and six movement-based (Mov01 to Mov06) vibrotactile stimuli for the incidental categorization and disruption blocks, and five novel stimuli per category (Pos07 to Pos11 and Mov07 to Mov11) for the overt categorization block. Table I shows the 11 position-based vibrotactile stimuli in terms of the simultaneously activated tactors (see labels in Fig. 2a) and the frequencies of vibration.

TABLE II
MOVEMENT-BASED VIBROTACTILE STIMULI USED IN EXP. 1

Signal Label	Forearm Surface	Direction	Spatial Extent	Frequency (Hz)
Mov01	Dorsal	E→W	1/2	60
Mov02	Volar	E→W	1/2	60
Mov03	Volar	W→E	1/2	60
Mov04	Volar Dorsal	E→W W→E	1 1	300
Mov05	Dorsal Volar	W→E E→W	1 1	300
Mov06	Dorsal Volar	E→W W→E	1 1	300
Mov07	Volar	W→E	1	150
Mov08	Dorsal	E→W	1	150
Mov09	Volar Dorsal	W→E E→W	1/2 1/2	150
Mov10	Volar Dorsal	E→W W→E	1/2 1/2	210
Mov11	Dorsal	E→W W→E	1 1	210

The four tactors used in each position-based vibrotactile stimuli were always located next to each other on the forearm. The set of position-based signals employed in the incidental categorization and disruption blocks varied in frequency of vibration (60 Hz or 300 Hz), the surface of the arm that was stimulated (dorsal or volar), and the location along the forearm (near the elbow, center, or wrist). These changes in location and frequency in signals Pos01-Pos06 were used in an attempt to enhance incidental categorization (see [20]). Signals Pos07-Pos11 were also position-based, but their locations and frequencies (150 Hz or 210 Hz) were different from those used in signals Pos01-Pos06. They were novel in the sense that the participants had not felt any vibrotactile stimuli at these locations and frequencies prior to the overt categorization block. The extent to which the participants could predict the star from signals Pos07-Pos11 would serve as evidence that the incidental categorization of signals Pos01-Pos06 in blocks #1-5 was generalizable.

A qualitative description of the movement-based stimuli is provided in Table II. The six stimuli used in the incidental categorization and disruption blocks (Mov01-Mov06) varied in the surface of the arm (dorsal or volar), direction of movement (Elbow to Wrist or vice versa), spatial extent (fraction of forearm length), and frequency of vibration (60 Hz or 300 Hz). The five novel stimuli used in the overt categorization task (Mov07-Mov11) were at two new frequencies (150 Hz or 210 Hz) and involved different movement patterns. Some of the signals require two rows of description for Forearm Surface and Direction. For example, Mov04 moved on the volar forearm from the elbow to the wrist, and continued on the dorsal forearm from the wrist to the elbow. The 11 movement-based vibrotactile stimuli simulated smooth movements on the skin surface using the apparent motion illusion [25] and the sequential tactor activation timing parameters recommended in Israr & Poupyrev [26]. A complete description of the 11 movement-based signals can be found at https://juansmartinez.github.io/IncidentalExpVibrotactileDesign/.

For both the position-based and movement-based vibrotactile stimuli, the total duration for each signal was always 400 ms. A 5-ms Hanning window was used at the onset and offset of each tactor to ensure smooth transitions. The tactile patterns were presented with a roving intensity level in the range 11-23 dB SL (sensation level; dB above detection threshold) for position-based stimuli, and 14-26 dB SL for movement-based stimuli.

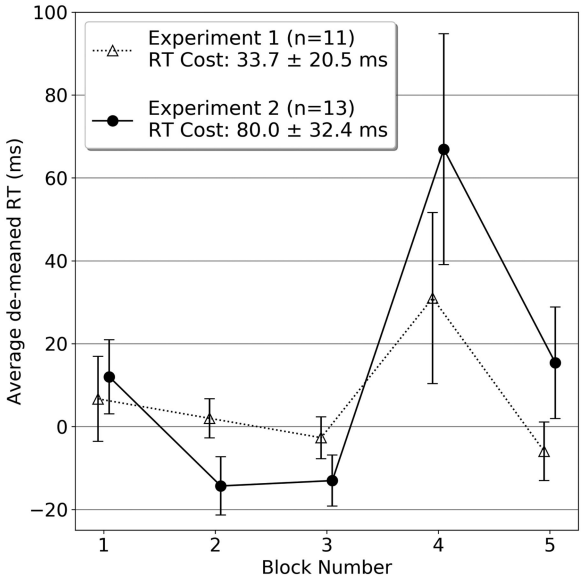


Fig. 5. Averaged de-meaned RT's for both experiments. Error bars denote standard errors for every experiment. Data points have been slightly offset horizontally to avoid overlapping. The RT Cost for every experiment was computed as $\overline{RT}_{block4} - \overline{RT}_{block3}$ and is reported along with its corresponding standard error.

During the incidental categorization and disruption blocks, the three tactile patterns on each trial were randomly selected from the same category (position-based or movement-based). The three vibrotactile stimuli were always different from each other, as past research has shown that a higher within-category variability benefits generalized learning [20]. The stimuli presented on the same trial always contained signals on both the volar and dorsal sides of the forearm, in an effort to discourage participants from associating vibrotactile stimuli to visual targets based on the dorsal-volar distinction. During the overt categorization block, the same novel tactile stimulus was presented three times.

B. Results

The de-meaned average RT results for Exp. 1 are shown in Fig. 5 as open triangles. The de-meaned averages varied from -6.0 ms to 31.0 ms across blocks. There appears to be a slight decreasing trend from the first to the third incidental categorization block, an apparent increase in RT in the disruption block, and a drop in the last incidental categorization block (#5). The average RT cost was 33.7 ms ($\pm$20.5 std.err.). However, a repeated measures analysis of variance (ANOVA) did not reveal a significant effect of block ($F(4, 40) = 1.58, p = 0.198$). Furthermore, a one-tailed paired t-test did not indicate any statistically significant difference between the RTs for blocks #3 and #4 ($t(10) = 1.64, p = 0.066$), confirming the lack of a significant RT cost. A comparison of the RTs in blocks #3 and #5

TABLE III
POSITION-BASED VIBROTACTILE STIMULI USED IN EXP. 2

Experimental Block	Signal Label	Tactors Activated	Frequency (Hz)
Blocks #1 to #5	Pos12	T1, T7	60
	Pos13	T3, T9	60
	Pos14	T5, T11	60
	Pos15	T2, T8	300
	Pos16	T4, T10	300
	Pos17	T6, T12	300
Overt Categorization	Pos18	T2, T3	150
	Pos19	T4, T5	150
	Pos20	T9, T10	150
	Pos21	T7, T8	210
	Pos22	T11, T12	210

showed no significant difference either ($t(10) = 0.50, p = 0.631$). The average percent-correct score in the overt categorization task was 67.8% ($\pm$7.3 std.err.), which was significantly higher than 50% ($t(10) = 2.32, p = 0.021$). The average $|\,\mathrm{d}'\,|$ was 1.7 ($\pm$0.4 std.err.), confirming generalized categorization of the novel vibrotactile stimuli.

During the debriefing after the experiment, six of the eleven participants correctly described the association of position-based vibrotactile stimuli with stars and movement-based stimuli with circles. One participant was unsure of the mapping. Four participants indicated that they associated the dorsal/volar positions of the vibrotactile stimuli with the two visual targets, despite the fact that the three vibrotactile stimuli preceding the visual targets always contained both dorsal and volar stimuli. Since we had designed a vibrotactile-visual mapping based on features other than the dorsal/volar sides of the forearm, it was likely that the four participants were confused on most of the trials. Nonetheless, it was understandable that the dorsal/volar distinction was used in the incidental categorization of the vibrotactile stimuli. Therefore, the experiment was repeated with a modified design of vibrotactile stimuli that removed the dorsal/volar distinction.

IV. EXPERIMENT 2

Encouraged by the results of Exp. 1 that provided initial evidence of incidental categorization of vibrotactile stimuli, we re-designed the vibrotactile signals in Exp. 2 to avoid using the volar forearm. Thirteen new participants were tested using the same apparatus as in Exp. 1, with a slight modification to the procedure. Instead of presenting three *different* vibrotactile stimuli prior to each visual target in blocks #1 to 5, the same tactile stimulus was presented three times to eliminate any possibility of confusing three successive position-based stimuli as a movement-based stimulus.

A. Vibrotactile Stimuli

The position-based and movement-based vibrotactile stimuli were redesigned so that only the dorsal side of the forearm was stimulated. Table III shows the tactors activated for the 11 position-based stimuli in Exp. 2 (Pos12 to Pos22). The movement-based stimuli in Exp. 2 (Mov12 to Mov22) involved redesigned movement patterns as compared to those in Table II but shared the same frequency assignments. Due to limited space, a complete listing can again be found at https://juansmartinez.github.io/IncidentalExpVibrotactileDesign/.

B. Results

The de-meaned average RT results for Exp. 2 are shown in Fig. 5 as filled circles. The de-meaned averages varied from -14.3 ms to 66.9 ms. A repeated measures ANOVA revealed a significant effect of block ($F(4, 48) = 4.47, p = 0.004$). The RT data decreased significantly from the first to the second incidental categorization block ($t(12) = 2.59, p = 0.012$), and remained roughly the same in the third block. There appears to be a larger increase in RT in the disruption block as compared to the Exp. 1 data, and a similar drop in RT in the last incidental categorization block (#5). The average RT cost was 80.0 ms ($\pm$32.4 std.err.). A one-tailed paired t-test confirmed a statistically significant difference between RTs for blocks #3 and #4 ($t(12) = 2.47, p = 0.015$). However, the RT results for blocks #3 and #5 were not significantly different ($t(12) = -1.69, p = 0.116$), suggesting the recovery of previously-established vibrotactile-visual associations after the disruption in block #4.

From the overt categorization block, four of the thirteen participants had percent-correct scores that were significantly below 50% ($t(49) \leq -2.36, p \leq 0.011$), indicating that they were able to categorize the vibrotactile stimuli but flipped the vibrotactile-visual mapping. Before further analysis, the scores of these four participants were subtracted from 100% to obtain the equivalent percent-correct scores had they used the correct mapping. The resulting average percent-correct scores from all thirteen participants, 77.4% ($\pm$5.8 std.err.), was significantly above 50% ($t(12) = 4.52, p < 0.001$). The average $|\,\mathrm{d}'\,|$ was 2.1 ($\pm$0.3 std.err.). With the modified vibrotactile stimuli, both the percent-correct scores and the d′ values increased as compared to those in Exp. 1.

During debriefing, ten of the thirteen participants were able to accurately describe the two vibrotactile categories. Seven were able to identify the correct tactile-visual association and three inverted the mapping. The remaining three participants were uncertain about the vibrotactile-visual associations, although at least one of them produced RT data that clearly followed the same trends as those in Fig. 5. As expected, no participant reported any categorization based on the dorsal/volar distinction of stimulation locations.

V. DISCUSSION

The results of the present study are likely the first indications of incidental categorization of vibrotactile stimuli. With the revised vibrotactile stimuli in Exp. 2, the participants were able to incidentally categorize them by associating position-based vibrotactile stimuli with stars and movement-based stimuli with circles, even though they had not felt these vibrotactile stimuli before and were not told about the vibrotactile-visual mapping. The significant drop in RTs from the first to the second incidental categorization block suggested that the participants learned the vibrotactile-visual association within the first block of 60 trials and were able to achieve faster RTs in the

second block by predicting visual targets from the vibrotactile stimuli preceding them. The RT cost of 80 ms was statistically significant and twice as large as the 38 ms found in Exp. 1 of Gabay *et al.* [20]. This increase in RT in the disruption block indicated that the participants were probably surprised during the trials where the learned vibrotactile-visual mapping was invalid, leading to an increase in their response time. Yet the RTs returned to baseline as soon as the mapping was restored in the incidental categorization block following the disruption block. Further evidence of incidental categorization came from the overt categorization block where the participants successfully predicted visual targets from vibrotactile stimuli at a performance level that was significantly above chance, and they did so with novel vibrotactile stimuli they had not felt before. We note that some participants inverted the vibrotactile-visual mapping, but still demonstrated overt categorization with percent-correct scores that were significantly below chance.

Our finding that vibrotactile stimuli can be incidentally categorized opens the door to interesting future explorations on this fertile research topic. For example, previous studies have emphasized the multimodal nature of incidental categorization such as that occurring in natural language acquisition [7]. Our finding provides another sensory modality for future studies of incidental categorization. Recently, Lim, Fiez & Holt [19] showed that the striatum contributes to the incidental acquisition of sound categories in an fMRI study, expanding earlier findings that implicated this brain region in overt categorization. It will be interesting to expand such studies to include tactile stimuli, to investigate how cortical-striatal networks contribute to vibrotactile categorization. Finally, our finding can be applied to the acquisition of speech through tactile speech communication systems. We will devise a more natural approach to learning the vowel vs. consonant distinction on a phonemic-based tactile speech communication system [21] that encodes vowels with movement-based stimuli and consonants with position-based stimuli.

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