Redundant Coding of Simulated Tactile Key Clicks with Audio Signals

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Abstract—The present study examined the efficacy of using audio cues for redundant coding of tactile key clicks simulated with a piezoelectric actuator. The tactile stimuli consisted of six raised cosine pulses at two levels of frequency and three levels of amplitude. An absolute identification experiment was conducted to measure the information transfers associated with the tactile-audio signal set. Results from Condition 1 (C1) provided a baseline measure by employing only the tactile signals. In Conditions 2-4 (C2-C4), supplemental audio signals were used to encode amplitude cues only, frequency cues only, and both amplitude and frequency cues, respectively. The results showed that partial redundant coding of tactile cues with audio signals could increase information transfer, when the cue (amplitude) was not perfectly identifiable with tactile signals alone (C2). When the cue (frequency) was well perceived through tactile signals alone, audio supplemental cues did not improve performance (C3). With redundant coding of both amplitude and frequency cues (C4), audio signals dominated tactile signals. It was also found that increased information transfer was achieved at the cost of increased response time (C2), suggesting increased mental load associated with the processing of multisensory information. Our findings have implications for the design of simulated key-click signals for mobile devices, and the use of multimodal signals for redundant coding of information in general.

1 Introduction

As mobile devices continue to decrease in size, mechanical pop-dome keys are being replaced by visual keyboards where users rely on audio or visual feedback to make key selections. Realizing the need for tactile confirmation of key presses, some devices now mimic key clicks using existing vibration motors for call alert or piezoelectric actuators (e.g., Motorola's ROKR E8 music phone). In earlier studies, the authors have developed a set of distinct signals for simulating key clicks using a piezoelectric actuator [4]. The signals consisted of one or three-cycle raised-cosine pulses differing in amplitude and frequency. They were intended to provide touch feedback of virtual key presses on keyboard-less mobile devices, and at the same time indicate the context of the application (e.g., dialing the phone vs. playing music). Whereas experienced users could almost identify the tactile signals perfectly in an absolute identification experiment, naïve users sometimes made mistakes in identifying the low, mid and high levels of the signal amplitudes. In an effort to make signal identification as accurate and effortless as possible, supplemental audio signals were designed to encode amplitude, frequency or both amplitude and frequency cues to enhance the recognition of tactile signals. It was expected that faster and more accurate responses could be achieved with the audio-tactile signals than with the tactile signals alone.

Our expectation was based on the fact that in our daily lives, we routinely process and react to multisensory stimuli that involve at least two sensory channels: visual and auditory, auditory and tactile, or taste and olfactory. Multimodal mechanisms have been found in all animals with a nervous system [11]. There are many ways information from multiple sources can be organized. In the one extreme (independent coding), each sensory modality carries cues that are unavailable in another sensory modality (e.g., the audio signals contain amplitude cues only and the tactile signals contain frequency cues only). In the other extreme (redundant coding), two sensory modalities can carry the same cues redundantly (e.g., both the audio and tactile signals carry both amplitude and frequency cues). The extent to which independent or redundant coding can improve information transmission depends further on the interactions among the modalities and signals [2]. As far as cue/attribute integration is concerned, some attributes are amodal in the sense that the attribute can be delivered with any sensory modality. There are also cases where the presence of one signal can either inhibit or facilitate the perception of another [9]. All this needs to be taken into account when designing multisensory interaction signals for mobile devices.

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Many researchers have investigated the use of audio-tactile signals in human computer interactions. For example, Chang et al. designed a vibrotactile communication device that magnified remote voice with touch by converting finger pressure into vibrational intensity [3]. Their results showed that by providing either redundant or independent information through tactile gestures, a voice conversation could be improved remotely. Tikka and Laitinen found that the best physical parameter to perceive feedback intensity was the acceleration of stimulus pulse [13]. On the other hand, they also took into account the natural sound generated by a piezoelectric actuator. Participants in the study were asked to rate the intensity under two conditions: one with both haptic and audio stimuli while the other with haptic only. When stimuli were delivered through both channels, participants tended to rate the intensity higher, which indicated that audio signals biased haptic perception. Hoggan et al. have been developing multimodal icons for mobile devices [7][6][8]. For example, in [7], they redundantly encoded three attributes in tactile and audio modalities and investigated the transferability of attributes across the two modalities. The results showed that stimulus attributes trained in one modality can be adopted in the other provided that appropriate matching parameters were used across the two modalities. In [8], they investigated the interactions among vision, touch and sound for congruent design of touch screen widgets. An experiment was conducted to understand if users had preferences in how an audio-tactile signal should be presented visually as a button. They concluded that most users had individual tendencies to relate a specific kind of audio-tactile feedback to a visual representation. Their study aimed at establishing a guideline for crossmodal icon design, but did not focus on how to create a tactilely distinct stimulus set. Ahmaniemi et al. manipulated the amplitude and frequency of an envelope signal to generate virtual texture perception of dynamic audiotactile feedback due to different gestures [1]. The frequency and amplitude of the envelope signal were proportional to the overall angular velocity of the device's motion. Participants were asked to detect when a change in texture occurred. Signal identification performance with audio or audiotactile feedback was found to be better than that with tactile feedback alone.

The studies discussed above emphasized user preferences under multimodal conditions, as opposed to the design of distinctive tactile feedback signals. In the present study, we were interested in enhancing the perception of tactile key-click signals with audio supplements with the goal to maximize the number of distinctive tactile key-click feedback signals. Therefore, the tactile signals always contained both amplitude and frequency cues. The audio signal either partially or completely encoded the same cues redundantly. Initially, we experimented with encoding only amplitude cues in the audio signals since the amplitude attribute was sometimes not correctly perceived when only tactile signals were presented. Our preliminary data suggested, however, that partial coding of amplitude cues with supplemental audio signals sometimes interfered with the tactile perception of frequency cues. This led to a more systematic investigation of how and to what extent audio cues could be used to supplement tactile cues in order to increase the overall information transfer for key-click signals. The experiment reported here contained four conditions (C1-C4): One baseline condition with tactile signals only (C1), and three audio-tactile conditions with auditory supplements (C2, C3, C4). Under C2 or C3, the supplementary auditory signals contained only amplitude or frequency cues, respectively, in addition to tactile signals. We call C2 and C3 partially-redundant coding schemes. Condition C4 was a completely-redundant coding scheme in which auditory signals with both frequency and amplitude information were delivered concurrently with tactile signals. In addition to estimating information transfers, response time (RT) was also recorded to examine whether certain conditions involved more mental processing (presumably leading to longer RT) than others.

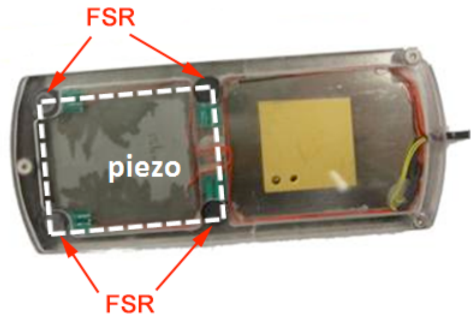
2 METHODS

2.1 Apparatus

The test apparatus resembled a typical mobile phone in its size and appearance (see Fig. 1). A single layer piezoelectric actuator (CTS standard 3203, 4cm L $\times$ 3.5cm W $\times$ 0.2mm H, 147 nF capacitance, occupying the lower half of the apparatus) was affixed to a stainless steel plate that served as the cover of the apparatus. A piece of polycarbonate frame at the same size as the stainless steel plate was attached to the back of the apparatus. Four force sensing resistors (FSRs, from Interlink) were mounted at the corners of the intent keypad area and sandwiched between the polycarbonate frame and a polycarbonate back plate. They were used to trigger a high-voltage input pulse to the piezo whenever the total force exceeded 200g (or equivalently, a resistance of 20kΩ). [1] This value was selected empirically. To emulate the weight of a typical mobile phone, a piece of metal weighing 40g was glued to the upper half of the apparatus (the yellow block in Fig. 1a). The total weight of the apparatus was about 78g. A red dot marked the center of the piezoelectric actuator where the participants were told to press down and feel a virtual key click (see Fig. 1b). Upon detection of a key press through the FSRs, a waveform was sent through a computer sound card to a voltage amplifier with a gain of 100 (Dual Channel High Voltage Precision Power Amplifier, Model 2350, TEGAM Inc., Geneva, OH, USA), and subsequently sent to the piezoelectric actuator to create a virtual click.

A sound card (Creative Sound Blaster SB0100, Creative Resource, Singapore) was used to deliver pre-computed tactile and audio signals. All signals were delivered in stereo mode with the left channel containing tactile signals and the right channel audio signal. The audio signals were transmitted through a stereo headphone.

[1]The latency between the detection of a $>$ 200g force by the FSR and the onset of the audio/tactile signals was less than 1 *ms* using a PC. In real applications where the latency is limited by firmware, the latency can be significantly longer (e.g., $<$ 40 *ms* in ROKR E8).



(a) Back

(b) Front

Fig. 1. Back and front views of the test apparatus

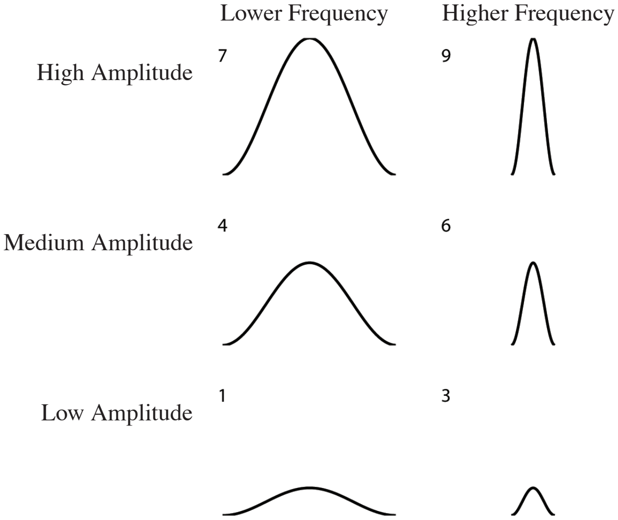
2.2 Participants

Twelve participants (PT1-PT12, age 23-43, 4 females, all right-handed except for PT11) were recruited for the experiment. PT1-PT3 were experienced with haptic experiments. All participants had an educational background in electrical and computer engineering which facilitated the interpretation of the graphic response code used in the experiments (see below). The participants were compensated for completing the experiment except for PT1-PT3 who were research staff.

2.3 Stimuli

From earlier experiments [4], a total of six key-click stimuli consisting of raised cosine pulses were designed and optimized. There were three (peak to peak) amplitude values: 40 V (A1), 120 V (A2) and 200 V (A3). There were two frequency values: 125 Hz (F1; 24 *ms* long consisting of three pulses) and 500 Hz (F2; 2 *ms* long consisting of one pulse). The stimuli differed in three attributes: signal amplitude, number of pulses and frequency. It was found that increasing either the amplitude or the number of pulses led to an increase in the perceived intensity of the stimuli, but the participants could not distinguish whether an increase in perceived intensity was due to a larger amplitude or more pulses [4]. Therefore, even though three physical parameters were used in generating the six tactile signals, there were only two distinct perceptual dimensions: perceived intensity and perceived crispness of the clicks. There was some indication that the two perceptual dimensions were not independent, in the sense that a signal at the higher frequency was perceived to be of higher intensity as compared to a signal at the lower frequency with the same amplitude and number of pulses [4]. In order to achieve similar levels of perceived intensities associated with the lower and higher-frequency signals, we always used three pulses with the lower frequency and one pulse with the higher frequency. (A detailed discussion of perceptual independence is beyond the scope of this article. Interested readers may read [2].) Graphically, the six stimuli are shown in Table 1. Since the number of pulses was totally correlated with the frequency parameter, and the sole purpose of using multiple pulses at the lower frequency was to increase the perceived intensity of low-frequency signals, we will from now on discussing the tactile stimuli as having two *independent* parameters: amplitude (leading to perceived intensity) and frequency (leading to perceived crispness). Therefore, in Table 1, we

Table 1. Graphic icons for the six tactile stimuli. The correspondence between signal number and stimulus parameters are as follows: S1=(A1,F1), S3=(A1,F2), S4=(A2,F1), S6=(A2,F2), S7=(A3,F1) and S9=(A3,F2).



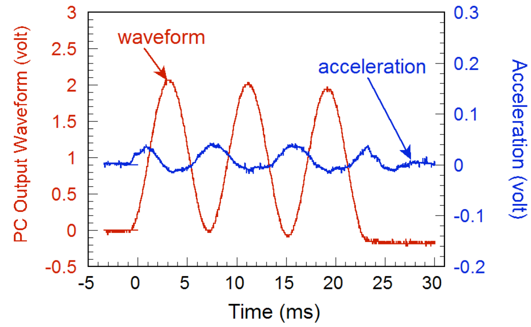


Fig. 2. Acceleration profile of S7. Shown are the PC output waveform and the acceleration measured near the piezoelectric actuator.

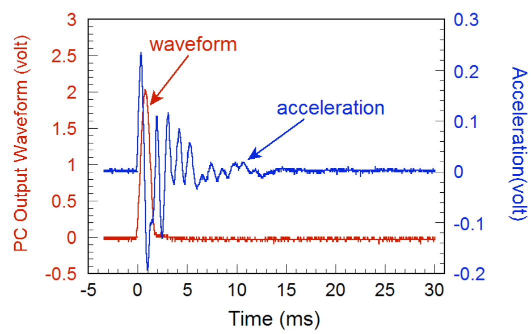


Fig. 3. Acceleration profile of S9. Shown are the PC output waveform and the measured acceleration.

did not draw multiple pulses for signals at the lower frequency, as we wanted the participants to focus on perceived intensity and crispness for the identification of tactile signals. None of the participants noticed the multiple pulses used at the lower frequency during the experiment. The six signals were labeled with numbers such that the stimulus number corresponded to the key on a numerical keypad that was used for identifying a particular signal. For example, the tactile stimulus consisting of (A1, F1) was identified by pressing the #1 key on the numerical keypad. Since the participants were electrical and computer engineering majors, it was easy for them to associate the tactile stimuli with the graphic icons shown in Table 1.

The audio signals were designed to redundantly encode the amplitude and frequency cues to supplement the six tactile stimuli described above. In C4, two audio frequencies, 150 and 4000 Hz, were selected for the 125 and 500 Hz tactile frequency levels, respectively. The audio frequencies were selected by playing pure tones at different frequencies and subjectively match the audio pitch to the perceived crispness of the tactile stimuli. The durations of the audio signals matched the durations of the tactile stimuli as measured by an accelerometer (8794A, Kistler, Winterthur, Switzerland) on the surface of the test apparatus near the center of the piezoelectric actuator. . The acceleration profiles of S7 (A3, F1) and S9 (A3, F2) are shown in Figs. 2 and 3, respectively. The duration of measured acceleration was about 25 *ms* for S7 and 10 *ms* for S9. Whereas the durations of the PC output waveform and the measured acceleration were similar for S7 (Fig. 2), the proximal stimuli for S9 lasted much longer than that of the 2-*ms* PC output waveform (Fig. 3). Therefore, the duration of the audio signals was set to 26.6 *ms* (4 cycles) for the 150 Hz tone, and 10 *ms* (40 cycles) for the 4000 Hz tone. Finally, the amplitudes of the audio signals were subjectively matched with a method of adjustment [5] so that the loudness of audio signals matched pairwise at the low, medium and high amplitudes. Sound pressure levels for the audio signals were measured by a 01dB Solo Sound level meter (SOLO SLM, 01dB-Metravib, Limonest, France). A B&K Sound Level Calibrator at 94 dB SPL was used. Each audio signal was measured five times under instantaneous mode to retrieve the average and standard deviation. The sound pressure levels in terms of A-weighted values for the six audio signals are summarized in Table 2.

When the audio signals were used to partially encode amplitude information alone (C2), the frequency of the audio tone was fixed at 750 Hz with a duration of 13.3 *ms* (10 cycles). The amplitudes of audio signals corresponding to S3, S6 and S9 were used to encode the

Table 2. A-weighted sound intensity values for the audio stimulus set used in C4. Units are in dB(A).

	Left Channel		Right Channel	
Signal	AVG	STD	AVG	STD
#1	54.46	0.66	55.10	0.54
#4	65.78	0.55	62.88	0.35
#7	76.24	0.42	73.80	0.54
#3	68.08	0.30	66.62	0.37
#6	80.96	0.38	79.52	0.29
#9	93.88	0.44	92.2	0.41

Table 3. Summary of the four experimental conditions

C1	Tactile Only
C2	Tactile + Audio Amplitude Cues
C3	Tactile + Audio Frequency Cues
C4	Tactile + Audio Amplitude and Frequency Cues

three intensity levels. When the audio signals were used to partially encode frequency information alone (C3), the amplitude of the audio signal corresponding to S6 was always used with either a 150 Hz tone or a 4000 Hz tone.

2.4 Procedures

As described earlier, there were four conditions in the main experiment. In C1, the participants received only the tactile stimuli. In C2-C4, the participants could feel the tactile signals and hear the audio signals at the same time. The same six tactile stimuli were used in all four conditions. In C2, the audio signals provided only amplitude cues. In C3, the audio signals delivered only frequency cues. In C4, the audio signals encoded both amplitude and frequency cues. A summary of the four experimental conditions is provided in Table 3.

At the beginning of the experiment, the participants were given an instruction sheet that explained the experimental procedures. The participants were told to press down on the test apparatus in order to trigger a key-click feedback signal. They were aware of the nature of the audio signals presented during C2-C4. All participants completed C1 first. The order of C2-C4 was randomized for each participant. Each participant attended two 60-90 min experimental sessions, and two conditions were administered per experimental session. Under all four conditions, the participants were instructed to identify the stimuli based on what was *felt*. In other words, the participants were told to focus on the feel of the signals and to use supplemental audio signals to aid their *tactile* identification of key-click signals in C2-C4. Each condition started with a training session. The participant could choose any of the six signals pertaining to the experimental condition by pressing the corresponding number on the numeric keypad. Training was terminated by the participant whenever s/he was ready. During the main experiment, one of the six signals was randomly selected on each trial with equal a priori probability. A total of 250 trials, divided into five 50-trial runs, were collected per condition. The total number of times each signal was presented over the 250 trials was similar but not necessarily the same. Under C1, the participants were asked to wear earplugs and a noise-cancelling earphone in order to block any sound made by the test apparatus. Under C2-C4, the participants wore a stereo headphone to hear the audio signals. In addition to the responses made by the participants, response times (RTs) were also recorded although the participants were not under any time pressure. Trial-by-trial correct-answer feedback was provided throughout the experiment. The graphic icons listed in Table 1 were shown to the participants at all times. The participants could take a break between experimental runs.

At the end of the second experimental session, an audio-only condition was briefly administered for all participants. The experimenter randomly selected one of the six audio signals used in C4 and ask the participant to identify it. The purpose of this follow-up test was to ascertain to what extent the audio signals used in C4 provided completely redundant information. In other words, we wanted to know if the six audio signals could be correctly identified in the absence of any tactile stimuli.

2.5 Data Analysis

A 6-by-6 stimulus-response confusion matrix was formed to summarize all the trials for each condition and each participant. Information transfers and conditional information transfers for amplitude and frequency were calculated. Average RT was also calculated using only the trials with correct responses. Information transfer was calculated using the equation below:

$$IT_{est} = \sum_{j=1}^{k}\sum_{i=1}^{k}\left(\frac{n_{ij}}{n}\right)\log_2\left(\frac{n_{ij}\cdot n}{n_i\cdot n_j}\right) \quad (1)$$

where i and j are the indices for the ith stimulus and jth response, respectively; n_{ij} the number of times the ith stimulus was presented and the jth response was called; n_i the sum of n_{ij} over all j values (i.e., the total number of times the ith stimulus is presented); n_j the sum of n_{ij} over all i values (i.e., the total number of times the jth response is called); n the total number of trials, and k the number of stimulus alternatives. The quantity IT_{est} measures the amount of information transmitted from the stimuli to the responses. A related quantity, $2^{IT_{est}}$, is an abstraction number. It is interpreted as the number of items that can be correctly identified.

Conditional information transfers were calculated by first collapsing the confusion matrices along either amplitude or frequency. When IT_{Amp} was calculated, the trials where the stimuli and responses had the same amplitude values (regardless of frequency values) were combined into one cell. The matrices for computing IT_{Freq} were constructed in a similar way. The equation shown above was then used on the new matrices. These partial or conditional information transfers indicate the amount of information transmitted through one variable in a multisensory multi-attribute stimulus set [10]. Readers interested in further details regarding data analysis can consult [4] and [12].

3 Results

Table 4 shows the stimulus-response confusion matrices with data pooled from all participants under the same condition. The six tactile stimuli are labeled S1, S3, S4, S6, S7 and S9, in order to be consistent with the labels shown in Table 1. The six response labels are marked R1, R3, R4, R6, R7 and R9, with R1 being the correct response for S1, R2 for S2, etc. The highlighted cells indicate the correct responses. It can be observed from all four confusion matrices that the participants generally did well, with the majority of trials falling into the shaded correct-response cells. In Table 4(a) where only tactile stimuli were presented, most of the mistakes were associated with confusion of signal amplitude: (S7, R4)=117, (S9, R6)=92, (S4, R7)=76, (S1, R4)=71, and (S6, R3)=66. This was consistent with our earlier findings that participants made more mistakes identifying the amplitude of the signals than the frequency [4]. In Table 4(b) where audio signals supplemented amplitude information, identification mistakes due to confusion of signal amplitude were significantly reduced. However, we observed an increase in frequency confusion from C1 to C2, especially in the following cells: (S7, R9)=64, (S3, R1)=63, (S6, R4)=41, and (S9, R7)=33. This was consistent with the anecdotal report that the audio amplitude signals made it difficult for the participants to pay attention to the crispness (frequency) of the tactile stimuli. In Table 4(c) where audio signals supplemented frequency information, there was no significant improvement of frequency identification, but in some cases amplitude confusion increased as compared to Table 4(a); for example, (S4, R7)=138, (S6, R9)=101, (S3, R6)=100. Finally, in Table 4(d) where the audio signals redundantly coded both amplitude and frequency information, the numbers in off-diagonal cells (i.e., mistakes) decreased significantly as compared to Table 4(a), indicating that the participants benefited from the redundant cues.

Estimated ITs and conditional ITs are summarized in Table 5 along with percent-correct scores and reaction times for each participant and each experimental condition. Several observations can be made from the information transfer results. First, IT_{est} was the highest in C4, followed by C2, then C1/C3 with very similar values. A post-hoc Tukey test confirmed that IT_{est} formed three groups: C1 and C3 (mean 1.80 and 1.74 bits, respectively), C2 (mean 2.04 bits) and C4 (mean 2.37 bits). This is graphically presented in Figure 4(a) where data points in the same statistical group are shaded in the same fashion.

Second, IT_{Amp}, the conditional IT for amplitude, was found to be higher in C2 and C4 when audio amplitude cues were available than that in C1 and C3 when only amplitude information was presented. A post-hoc Tukey test confirmed two groups: C2 and C4 (mean 1.34

Table 4. Pooled confusion matrices for the four conditions

	R1	R3	R4	R6	R7	R9
S1	400	12	71	5	2	0
S3	5	474	0	18	0	7
S4	31	3	409	1	76	3
S6	4	66	2	347	0	63
S7	6	1	117	5	377	5
S9	1	10	3	92	0	384

(a) C1 (tactile only)

	R1	R3	R4	R6	R7	R9
S1	438	23	25	2	0	0
S3	63	440	2	8	0	0
S4	14	1	438	16	7	0
S6	9	32	41	416	0	2
S7	0	0	7	2	435	64
S9	0	0	0	16	33	466

(b) C2 (tactile + audio amp)

	R1	R3	R4	R6	R7	R9
S1	411	2	59	0	8	0
S3	1	428	0	100	0	4
S4	55	0	348	3	138	0
S6	1	23	2	361	0	101
S7	5	0	108	3	343	1
S9	0	2	1	93	5	394

(c) C3 (tactile + audio freq)

	R1	R3	R4	R6	R7	R9
S1	466	2	37	0	0	0
S3	1	474	0	2	0	0
S4	5	0	427	2	16	0
S6	0	15	2	483	0	5
S7	0	0	17	0	509	2
S9	0	0	0	10	2	523

(d) C4 (tactile + audio amp & freq)

and 1.38 bits, respectively) and C1 and C3 (mean 0.86 and 0.76 bits, respecitvely), as shown in Figure 4(b).

Third, IT_{Freq}, the conditional IT for frequency, was found to be the lowest in C2, where audio signals contained only amplitude but not frequency cues, as compared to those in the other three experimental conditions. As stated earlier, frequency information was generally well received through the tactile stimuli alone, but the audio amplitude cue in C2 appeared to have interfered with the tactile perception of frequency information. The same trend was observed in percent-correct scores. A subsequent Tukey test confirmed that IT_{Freq} in C2 (mean 0.65 bits) was significantly different from those in C1, C3 and C4 (mean 0.90, 0.95 and 0.97 bits, respectively), as shown in Figure 4(c). Anecdotal reports suggested that in C2, the participants gradually learned to focus on the crispness of the tactile stimuli first, and then to incorporate the audio amplitude information into their judgment of key-click intensity.

Finally, a Tukey test indicated that the RT in C2 (mean 1.56 s) is significantly different from those in C1, C3 and C4 (mean 1.34, 1.36 and 1.21 s, respectively). This suggested that although providing amplitude information through the auditory channel enhanced the participants' ability to identify the key click signals, especially the intensity levels, it also cost the participants more time in order to process that information.

Post-experiment debriefings with the participants revealed that since the frequency information was clearly conveyed through the tactile stimuli alone, most participants ignored the audio signals in C3 and focused on the tactile stimuli instead. In C4, most participants felt that the audio signals dominated their perception, and their identification decisions were mostly based on the audio, not the tactile, stimuli.

4 Conclusions

In the present study, we studied the extent to which audio signals could be used to enhance tactile identification of simulated key-click signals. A previously-designed 6-alternative tactile stimulus set that varied in both amplitude and frequency was used with supplemental audio signals. It was found that information transfer for the tactile signals alone was 1.80 bits, corresponding to roughly 3.5 perfectly identifiable key-click signals. When the audio signals supplemented the tactile signals with redundant amplitude information, the information transfer increased to 2.04 bits (4.1 items). When audio signals with supplemental frequency information was used, however, the information transfer remained about 1.74 bits (3.3 items), presumably because the frequency information was well conveyed through the tactile signals already. Finally, when the audio signals redundantly encoded both amplitude and

Table 5. Summary of individual results for the four conditions (PT = participant, IT = information transfer in bits, PC = percent correct in %, RT = reaction time in s)

PT	IT_{est}	IT_{Amp}	IT_{Freq}	PC	RT
1	**2.19**	1.20	0.97	92	1.27
2	**2.03**	1.02	0.93	86	1.26
3	**2.31**	1.31	1.00	94	1.46
4	**2.00**	1.03	0.96	86	1.60
5	**1.78**	0.78	1.00	79	1.23
6	**0.88**	0.18	0.64	50	1.34
7	**1.64**	0.81	0.75	79	1.33
8	**2.06**	1.06	1.00	88	1.49
9	**1.71**	0.81	0.84	77	1.54
10	**1.64**	0.71	0.86	76	1.55
11	**1.90**	0.90	1.00	83	1.03
12	**1.43**	0.47	0.87	66	0.98
Avg	**1.80**	0.86	0.90	79.67	1.34
Std	**0.38**	0.31	0.12	12.09	0.20

(a) C1 (tactile only)

PT	IT_{est}	IT_{Amp}	IT_{Freq}	PC	RT
1	**2.45**	1.53	0.90	98	1.36
2	**2.22**	1.32	0.84	93	1.28
3	**2.01**	1.43	0.51	88	1.84
4	**2.32**	1.46	0.84	96	1.60
5	**2.26**	1.42	0.79	94	1.59
6	**1.36**	1.25	0.06	58	1.69
7	**1.83**	1.39	0.41	83	1.15
8	**2.29**	1.37	0.87	96	1.75
9	**2.02**	1.30	0.68	89	1.77
10	**1.77**	1.26	0.41	82	1.80
11	**2.11**	1.29	0.79	92	1.15
12	**1.85**	1.11	0.66	85	1.69
Avg	**2.04**	1.34	0.65	87.83	1.56
Std	**0.30**	0.11	0.25	10.77	0.25

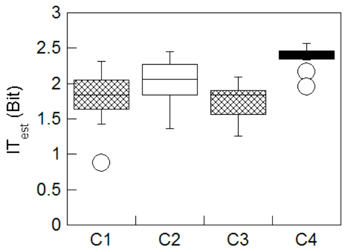
(b) C2 (tactile + audio amp)

PT	IT_{est}	IT_{Amp}	IT_{Freq}	PC	RT
1	**1.93**	0.93	1.00	84	1.46
2	**2.09**	1.14	0.93	88	1.26
3	**1.89**	0.94	0.93	85	1.50
4	**1.83**	0.83	0.94	79	1.47
5	**1.74**	0.76	0.93	78	1.23
6	**1.26**	0.26	0.96	52	1.30
7	**1.59**	0.64	0.87	73	0.97
8	**1.90**	0.93	0.96	83	1.84
9	**1.54**	0.55	0.96	68	1.67
10	**1.84**	0.84	0.96	82	1.35
11	**1.90**	0.91	0.96	84	1.26
12	**1.42**	0.38	0.97	58	0.98
AVG	**1.74**	0.76	0.95	76.17	1.36
STD	**0.24**	0.26	0.03	11.38	0.25

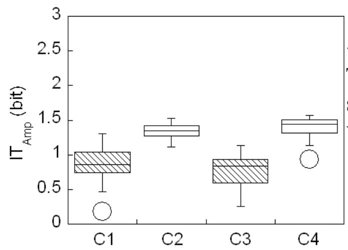
(c) C3 (tactile + audio freq)

PT	IT_{est}	IT_{Amp}	IT_{Freq}	PC	RT
1	**2.43**	1.42	1.00	97	1.35
2	**2.48**	1.47	1.00	98	1.15
3	**2.45**	1.46	0.98	98	1.22
4	**2.33**	1.28	1.00	95	1.38
5	**2.42**	1.42	1.00	98	1.23
6	**2.44**	1.49	0.93	98	1.08
7	**2.47**	1.52	0.93	98	0.88
8	**2.57**	1.57	1.00	100	1.42
9	**2.37**	1.53	0.83	97	1.68
10	**2.17**	1.13	1.00	92	1.23
11	**2.38**	1.36	1.00	97	1.10
12	**1.95**	0.93	0.96	85	0.84
AVG	**2.37**	1.38	0.97	96.08	1.21
STD	**0.16**	0.19	0.05	4.01	0.23

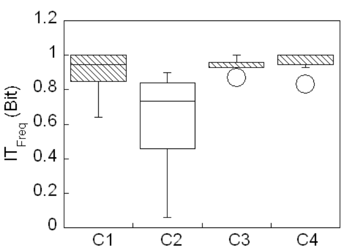
(d) C4 (tactile + audio amp & freq)



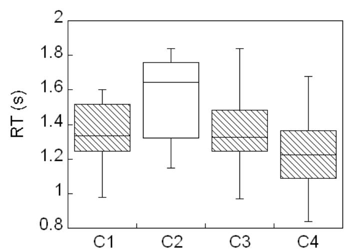
(a) IT_{est}



(b) IT_{Amp}



(c) IT_{Freq}



(d) RT

Fig. 4. Summary box plots for information transfer (IT_{est}), conditional information transfer (IT_{Amp} and IT_{Freq}), and response time (RT) under the four experimental conditions. Data in the same Tukey group are shaded in the same fashion. The open circles indicate outliers.

frequency information, the information transfer reached a maximum of 2.37 bits (5.2 items).

Our results have implications for the design of multisensory signals in mobile devices. First, we have demonstrated that with one piezoelectric actuator, 3 to 5 distinctive types of key clicks can be simulated. The distinctive key clicks can be used to provide contextual information for a mobile user, so that the virtual keys feel different in a phone-dialing mode than in a music-playing mode. Given the limited number of applications a mobile user routinely engages in, 3 to 5 key-click types are likely sufficient for most mobile devices. Second, we have shown that audio supplemental signals can be useful for disambiguating tactile signals, such as the intensity of key-click signals. Completely redundant coding (C4) resulted in a larger increase in overall performance than partially redundant coding (C2 or C3).

However, multisensory redundant coding should only be used if a single sensory-modality stimulus set cannot be identified perfectly. In our present study, the frequency information was conveyed well through the tactile sensory channel alone. Therefore, no performance gain was observed by providing audio signals with supplemental frequency information (compare C3 to C1). On the other hand, the amplitude information was not perceived perfectly through the tactile signals alone. As a result, audio signals with supplemental frequency information improved identification performance (compare C2 to C1). We hasten to point out that the observed performance increase in C2 was achieved at the cost of increased RT, indicating that the integration of the tactile and audio signals used in the present study required additional processing time.

Compared to many studies that investigated the use of multisensory signals in mobile devices from the perspective of user preferences [6] [8] [13] [7], the present study focused on the development of perfectly-identifiable multisensory key-click signals. Our results demonstrate some advantage of using multisensory signals over single modality signals, especially if redundant coding of an otherwise ambiguous cue (e.g., amplitude) is provided through an additional sensory channel. At the same time, our results also indicate that multisensory signals should be designed judicious in order to maximize the integrality and compatibility of redundant coding of the same information through multiple channels, and to minimize undesirable side-effects such as increased response time.

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