

Exploring Human Response Times to Combinations of Audio, Haptic, and Visual Stimuli from a Mobile Device

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Abstract—Auditory, haptic, and visual stimuli provide alerts, notifications, and information for a wide variety of applications ranging from virtual reality to wearable and hand-held devices. Response times to these stimuli have been used to assess motor control and design human-computer interaction systems. In this study, we investigate human response times to 26 combinations of auditory, haptic, and visual stimuli at three levels (high, low, and off). We developed an iOS app that presents these stimuli in random intervals and records response times on an iPhone 11. We conducted a user study with 20 participants and found that response time decreased with more types and higher levels of stimuli. The low visual condition had the slowest mean response time (528 ± 105 ms) and the condition with high levels of audio, haptic, and visual stimuli had the fastest mean response time (320 ± 43 ms). This work quantifies response times to multi-modal stimuli, identifies interactions between different stimuli types and levels, and introduces an app-based method that can be widely distributed to measure response time. Understanding the relationship between response time and modalities, as well as user preference towards modalities, will help optimize human-machine interaction.

Index Terms—Response Time, Haptics, Vibration, Auditory, Audio, Visual

I. INTRODUCTION

Auditory, haptic, and visual stimuli are commonly used to provide alerts and notifications in daily life. Response times to these stimuli have been used to characterize human sensorimotor systems [1], measure sleep [2], and design collision avoidance systems [3]. When designing human interfaces, understanding response times to auditory, haptic, and visual stimuli is vital. In some situations, engineers focus on minimizing response time to provide fast alerts for vehicle operators [3]–[5]. In other situations, engineers focus on combining stimuli to elicit responses to constraints in teleoperation or surgical robotic systems [6].

Existing work on quantifying response times is often specific to a particular system and only examines one or two

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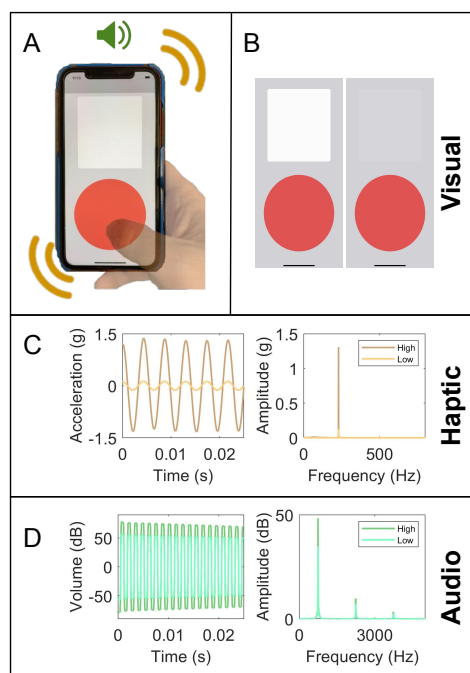


Fig. 1. Smartphone app and stimuli characteristics. We used a custom iOS app (A) to measure response times to 26 combinations of audio, haptic, and visual stimuli at three different intensity levels – off, low, and high. The visual stimulus (B) was a shape with two different transparencies, the haptic stimulus (C) was a vibration at two different intensities, and the audio stimulus (D) was a tone of two different volumes.

types of stimuli. Peon et al. compared response times to audio, visual, and haptic stimuli with a kinesthetic haptic device and found that response time is faster for haptic stimuli, followed by auditory and visual stimuli [7]. Scott et al. also found that subjects responded fastest to haptic stimuli, followed by auditory and visual stimuli, in a driving collision avoidance context [5]. In a similar trucking collision avoidance system, Belz et al. found that a combination of visual and auditory stimuli decreased mean response time, compared to standalone visual or auditory stimuli [3]. Jia et al. found similar results: a combination of visual and auditory stimuli decreases response time and increases accuracy [8]. When a subject is distracted,









	None	Low	High
Audio			
Haptic			
Visual			

Fig. 2. Table of stimuli combinations. Each stimulus is paired with any of the other possible stimuli in the other rows, with the exception of the no audio/no haptic/no visual stimulus condition.

Petermeijer et al. found that auditory and haptic stimuli elicit the fastest response times [4]. Instead of focusing on response times, Hecht et al. focused on human perception of combinations of stimuli. They found that when multiple stimuli are played together, subjects mainly perceive visual stimuli, and are less likely to realize that they also received a haptic or auditory stimulus [9]. While most studies applied haptic stimuli to subjects’ hands, Chan et al. discovered that haptic stimulus location while seated does not affect response times [10].

Previous work is relatively limited in scope, and mainly focuses on the relative response speeds of standalone stimuli. Peon et al. [7], Chan et al. [10], and Scott et al. [5] quantified the relative response times of standalone stimuli, but did not explore combinations of stimuli. Not only did Peon et al. not combine stimuli, but they also did not modulate the visual stimuli in any way [7]. Jia et al. [8] and Belz et al. [3] investigated the interaction of visual and auditory stimuli, but did not consider any combinations with haptic stimuli. While Hecht et al. found that visual stimuli are the most likely to be identified when played in combination with other stimuli, they did not investigate response times [9].

In this work, we aim to understand and quantify the effect that the interactions between auditory, haptic and visual stimuli have on response time. We present our methods using a phone-based system in Section II. In Section III, we discuss our results. In Section IV, we discuss implications of the results, followed by our conclusion and directions for future work in Section V.

II. METHODS

A. Smartphone App

We designed an iOS app (Swift, v5.7.1; XCode v14.1) for an iPhone 11 that presents auditory, visual, and haptic stimuli in randomly-spaced 3-6 s intervals while recording user response times via a button press (Fig. 1). Each stimulus was tested at three levels – off, low, and high. All combinations and levels of these stimuli were tested, except for the case where all stimuli are off (as this would elicit no measurable response) (Fig. 2). The app plays each of these 26 combinations a total of 5 times over a 13-minute duration. Each combination is played once before any repetitions.

The auditory stimulus is a tone (peak frequency at 746 Hz) played at either high (90 dB) or low (65 dB) (Fig. 1). The tone was taken from a pre-recorded soundtrack [11], and

played using the AVF Audio framework (Apple, Inc.) with an “AVAudioPlayer” volume of 0.1 and 0.01. The output volume was measured using a sound meter (Splend Apps) on the Samsung Galaxy S8 at the output of the speaker of an iPhone 11 when the phone volume is on its maximum setting. The haptic stimulus is created using the Core Haptics framework (Apple, Inc.), which can be used to play a discrete pulse by modifying Core Haptics variables of “hapticIntensity” or “hapticSharpness”. The haptic stimulus is either a high amplitude vibration (“hapticIntensity” = 1.0, “hapticSharpness” = 1.0) or low amplitude vibration (“hapticIntensity” = 0.3, “hapticSharpness” = 1.0) that plays for 0.1 s. Both vibrations have a predominant frequency of 230 Hz. The low vibration has an amplitude of 0.12 g, and the high vibration has an amplitude of 1.3 g (Fig. 1). Vibrations were measured using an accelerometer (Analog Devices, EVAL-ADXL354CZ) using a DAQ (National Instruments, NI9220) in Matlab (Mathworks) [12]. The visual stimulus is a white square (4.7 cm × 4.7 cm) that appears against a grey background for 0.5 s. The square appears with either high transparency (“Opacity” = 0.1) or low transparency (“Opacity” = 0.9) (Fig. 1). The values for the levels were chosen based off internal pilot studies such that the low levels would be as small as possible while still perceivable to all subjects and the high levels were as high as possible.

B. User Study

We conducted a user study to measure the response times to the different combinations and levels of auditory, visual, and haptic stimuli by using our app on. Participants were pre-screened, to select only those who were right-handed and over the age of 18. The experimental protocol was approved by our University’s Institutional Review Board, and all participants gave informed consent. Participants were provided a \$15 gift card for one hour of their time.

Upon arrival, participants completed a pre-survey to gather demographic information, report their experience with computer-machine interfaces, and ensure that they met the study requirements. Next, each participant completed three 13-minute blocks of data collection which consisted of 5 trials of each of the 26 audio, visual, and haptic combinations. Therefore, in total, there were 15 response times collected for each stimuli combination and a total of 390 response times per participant.

Between each block of data collection, participants had a 3-minute break. Participants held the phone in their right hand and could rest their arm on a table during the study. The phone had a custom phone case to normalize finger placement across the back of the phone. Participants were also instructed to not touch the phone with their left hand during the experiment and to hold their right thumb over the input button to minimize their response time. Participants were also instructed that the stimuli would occur at random intervals, so they should not try to predict when the stimuli would occur. After the experiment, participants completed a post-survey, in which they ranked their preference and perceived speed for responding to the

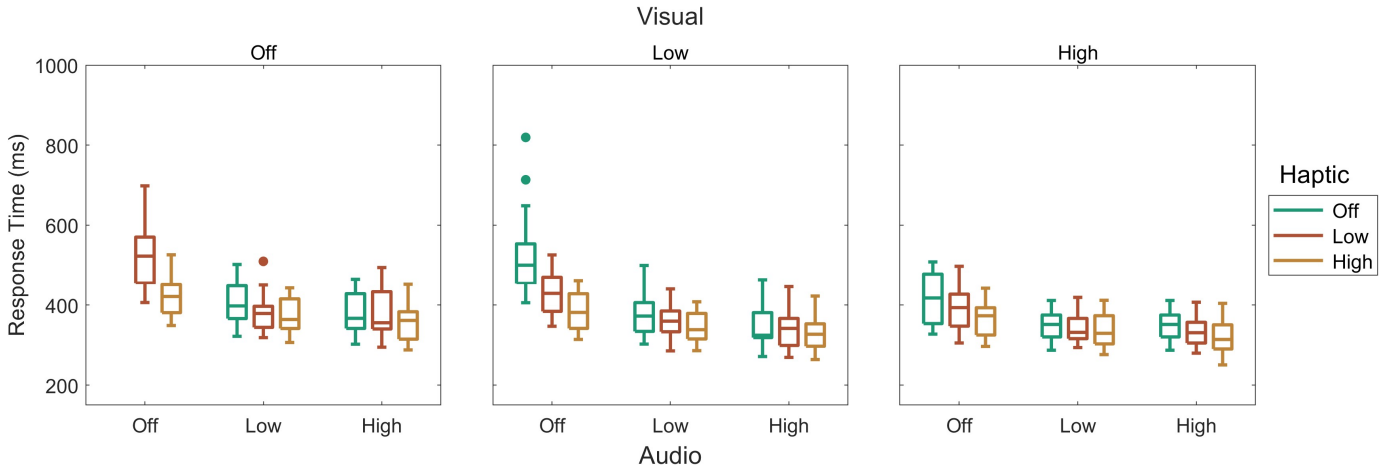


Fig. 3. Boxplots showing the response times for each combination of audio, haptic, and visual stimuli at three levels (off, low, high). Visual levels are denoted by subplots, haptic levels are denoted by color, and audio levels are denoted by x-axis location. The mean response time is the fastest in the condition with high levels of all three stimuli (320 ± 43 ms) and slowest in the low visual condition (528 ± 105 ms).

audio, haptic, and visual stimuli in addition to providing any other feedback about the experiment.

C. Statistical Analysis

Response times were measured as the time between the onset of the visual, haptic, and/or audio stimulus and the onset of the participant’s button press. Response times shorter than 10 ms and greater than 1500 ms were treated as false positives and removed from further analysis. These were removed because they were either faster than humanly possible [13] or were likely a “mis-hit” or accidental tap disconnected from the presented stimulus. If a participant missed any of the stimuli, those individual responses were omitted from the participant’s average for that particular stimulus combination. If a participant missed all the occurrences for a particular stimulus, the participant was removed.

A 3-way repeated measures ANOVA was used to identify main effects or interactions when all three stimuli were played. Three 2-way repeated measures ANOVAs were used to identify main effects or interaction when only two stimuli were played in the absence of the third. Lastly, a 2-way repeated measures ANOVA was used with the stimulus type and stimulus level as main factors for all the data during which only one stimulus is played. Greenhouse-Geisser corrections were applied to within-subjects factors if sphericity was violated. ANOVAs were followed by post-hoc T-tests with Bonferroni corrections. Friedman’s Tests were used to compare results from the survey. R Studio [14] was used for statistical analysis along with the tidyverse package [15]. The significance threshold was set at $p < 0.05$. All plots were created in Matlab (Mathworks).

III. RESULTS

Our user study included 20 participants (13 female, 6 male, 1 non-binary; aged 20-29). None of the users reported familiarity with human-machine interaction devices, neurological conditions, or injuries. Data from a total of 24 participants was collected, but four were removed. Two were removed due to

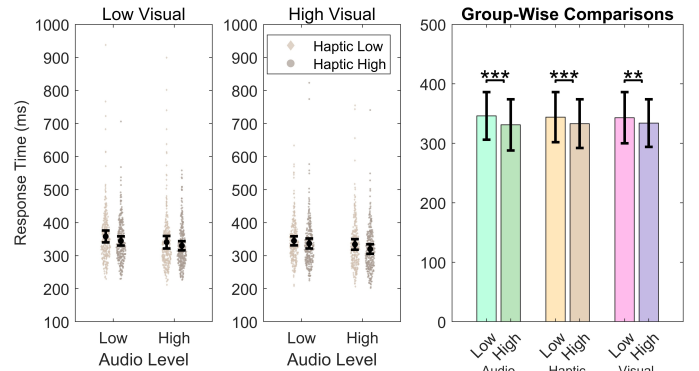


Fig. 4. Scatter plot showing response times for all trials when all stimuli are simultaneously delivered (left). Post-hoc pairwise comparisons comparing the impact of level for each stimulus (right). When all three stimuli are delivered simultaneously, response time is modulated by the level of each stimulus.

excessive missed responses resulting in incomplete data that could not be analyzed, and two were outliers with all data outside the IQR Method of outlier detection [16].

Figure 3 shows boxplots of response times across all 26 conditions. The fastest mean response time recorded for a particular subject was 250 ms, and the slowest was 819 ms. The slowest mean response time occurred for the low visual condition (528 ± 105 ms), and the fastest mean response time occurred for the condition with high levels of all three stimuli (320 ± 43 ms). The overall mean response time across all conditions was (380 ± 52 ms).

A. Three Stimuli Present

Figure 4 displays the mean response time for all conditions in which all stimuli (audio, haptic, and visual) were present with two different levels (high/low). The mean response time was fastest in the condition with high levels of all three stimuli (320 ± 43 s) and slowest in the condition with low levels of all three stimuli (358 ± 43 s). A three-way repeated measures ANOVA with audio, haptic, and visual as independent factors with two levels of each (high/low) revealed a main effect of

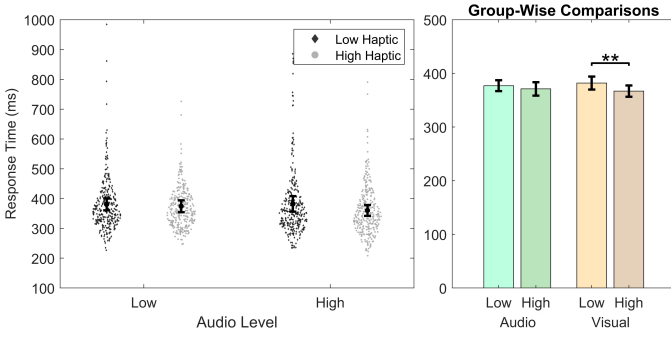


Fig. 5. Scatter plot showing response times for all trials for which audio and haptic stimuli are simultaneously delivered (left). Post-hoc pairwise comparisons comparing the impact of the level of each stimulus (right). When audio and haptic stimuli are simultaneously delivered, the change in response time is only impacted by the level of the haptic stimulus. Changes in the level of the audio stimulus while the haptic stimulus is playing does not impact response time.

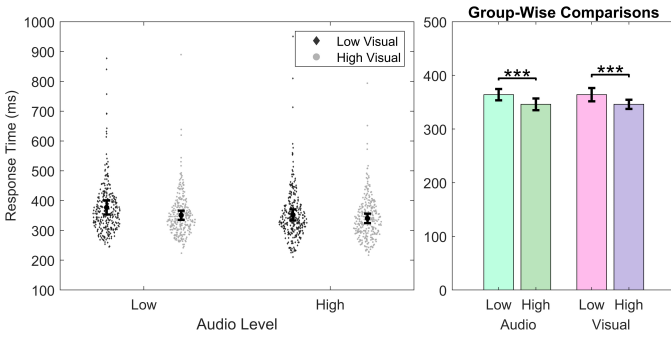


Fig. 6. Scatter plot showing response times for all trials for which audio and visual stimuli are simultaneously delivered (left). Post-hoc pairwise comparisons comparing the impact of the level of each stimulus (right). Both audio and visual stimuli have significant main effects, and when they are simultaneously delivered, the change in response time is dependent on the level of each stimulus.

audio ($F(1, 19) = 28.1, p = 4.07 \times 10^{-5}, \eta_p^2 = 0.597$), haptic ($F(1, 19) = 23.8, p = 1.05 \times 10^{-4}, \eta_p^2 = 0.556$), and visual ($F(1, 19) = 9.01, p = 7.00 \times 10^{-3}, \eta_p^2 = 0.322$) stimuli on response time. These main effects were not qualified by any interactions between audio and haptic stimuli ($F(1, 19) = 0.155, p = 6.98 \times 10^{-1}, \eta_p^2 = 0.008$), audio and visual stimuli ($F(1, 19) = 0.129, p = 7.23 \times 10^{-1}, \eta_p^2 = 0.007$), haptic and visual stimuli ($F(1, 19) = 0.039, p = 8.45 \times 10^{-1}, \eta_p^2 = 0.002$), or all three stimuli ($F(1, 19) = 2.559, p = 1.26 \times 10^{-1}, \eta_p^2 = 0.119$). Post-hoc pairwise comparisons showed that a higher levels of audio ($p = 4.07 \times 10^{-5}$), haptic ($p = 1.05 \times 10^{-4}$), or visual ($p = 7.33 \times 10^{-3}$) stimulus result in a faster response time. The significant main effects and post-hoc comparisons mean that when all three stimuli are delivered, the response time will change depending on the strength of each stimulus.

B. Two Stimuli Present

We conducted three separate 2-way repeated measures ANOVAs to understand the main effects and interaction effects of audio, haptic, and visual stimuli when only two of the three are present. When only two stimuli are present, response time

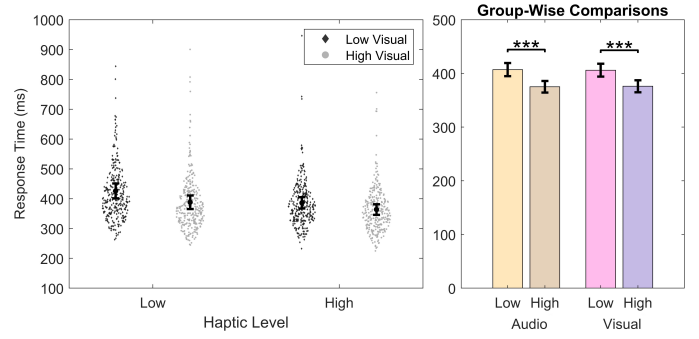


Fig. 7. Scatter plot showing response times for all trials for which haptic and visual stimuli are simultaneously delivered (left). Post-hoc pairwise comparisons comparing the impact of the level of each stimulus (right). Both haptic and visual stimuli have significant main effects, and when they are simultaneously delivered, the change in response time is dependent on the level of each stimulus.

is the fastest with high levels of audio and haptic stimuli (341 ± 42 ms) and the slowest in the condition with low levels of haptic and visual stimuli (426 ± 53 ms).

1) *Audio and Haptic*: Figure 5 shows the response time of all trials for all subjects for all combinations of audio and haptic stimuli at two levels (high/low) in the absence of visual stimuli. A two-way repeated measures ANOVA with stimulus types as independent factors (audio/haptic) with two levels (high/low) revealed a main effect of haptic ($F(1, 19) = 11.0, p = 4.00 \times 10^{-5}, \eta_p^2 = 0.367$), but not audio ($F(1, 19) = 0.801, p = 0.382, \eta_p^2 = 0.040$) stimuli on response time. These main effects were not qualified by any interactions between audio and haptic stimuli ($F(1, 19) = 3.28, p = 0.086, \eta_p^2 = 0.147$). Post-hoc pairwise comparisons showed that a high haptic stimulus resulted in a faster response time ($p = 0.003$). This means that when audio and haptic stimuli are simultaneously delivered, the change in response time depends on the strength of only the haptic stimulus, and not the strength of the audio stimulus.

2) *Audio and Visual*: Figure 6 shows the response times for all combinations of audio and visual stimuli at two levels (high/low) in the absence of haptic stimuli. A two-way repeated measures ANOVA with audio and visual stimuli as independent factors with two levels (high/low) revealed a main effect of audio ($F(1, 19) = 20.1, p = 2.54 \times 10^{-4}, \eta_p^2 = 0.514$) and visual ($F(1, 19) = 13.4, p = 0.002, \eta_p^2 = 0.415$) stimuli on response time. These main effects were not qualified by any interaction between audio and visual stimuli ($F(1, 19) = 3.97, p = 0.061, \eta_p^2 = 0.173$). Post-hoc pairwise comparisons showed that a high audio stimulus ($p = 7.53 \times 10^{-5}$) and a high visual stimulus ($p = 2.09 \times 10^{-4}$) resulted in faster response times, meaning that when both are played, the level of each one can influence response time.

3) *Haptic and visual*: Figure 7 shows the response times for all combinations of haptic and visual stimuli at two levels (high/low) in the absence of audio stimuli. A two-way repeated measures ANOVA with haptic and visual stimuli as independent variables with two levels (high/low) revealed a main effect of haptic stimuli ($F(1, 19) = 34.8, p =$

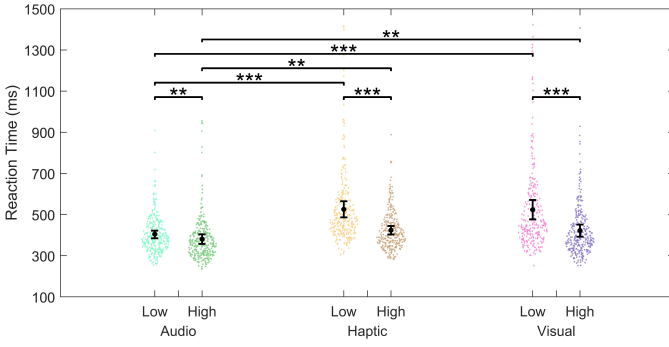


Fig. 8. Response times from single stimuli. There were significant differences between the response times for the high and low levels for each stimulus. The low haptic and visual stimuli had slower response times than the low audio stimulus, and the high haptic and visual stimuli had slower response times to the high audio stimulus.

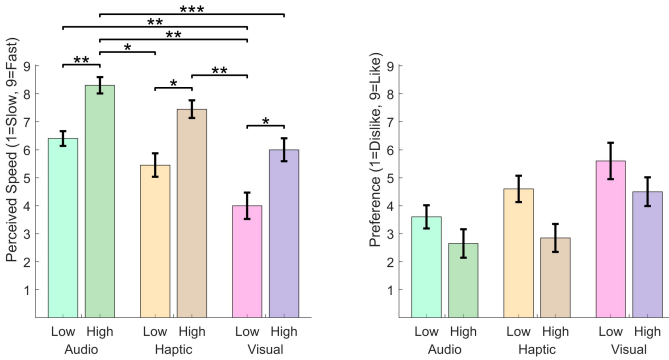


Fig. 9. Participant Survey Responses. Participants were asked how fast they responded to different stimuli (left), and reported that they responded fastest to the high audio stimulus and slowest to the low visual stimulus. Participants were asked to rate each stimulus based on preference (right), and reported that the low visual stimulus was most favored, while the high audio stimulus was least favored.

1.11×10^{-5} , $\eta_p^2 = 0.647$) and visual stimuli ($F(1, 19) = 49.0$, $p = 1.11 \times 10^{-6}$, $\eta_p^2 = 0.721$) on response time. These main effects were not qualified by an interaction between haptic and visual stimuli ($F(1, 19) = 2.28$, $p = 0.148$, $\eta_p^2 = 0.107$). Post-hoc pairwise comparisons showed that a high haptic stimulus ($p = 4.55 \times 10^{-7}$) and a high visual stimulus ($p = 2.28 \times 10^{-7}$) resulted in faster response times, meaning that when both are played, the level of each one can influence response time.

C. One Stimulus Present

Figure 8 shows the response times audio, haptic, and visual stimuli when they are displayed independently at high and low levels. Participants had the shortest response time for the high audio stimulus (405 ± 50 ms) and longest response time for the low visual stimulus (528 ± 105 ms). A two-way repeated measures ANOVA was conducted with type of stimuli (audio, haptic, or visual) and level of stimuli (high/low) as independent factors. The two-way repeated measures ANOVA revealed a main effect of stimulus type ($F(1.33, 25.3) = 24.1$, $p = 1.18 \times 10^{-5}$, $\eta_p^2 = 0.559$) and stimulus level ($F(1, 19) = 59.7$, $p = 2.79 \times 10^{-7}$, $\eta_p^2 = 0.759$) on response time. These main effects were qualified by an interaction between stimulus

type and level ($F(1.65, 31.3) = 12.5$, $p = 2.26 \times 10^{-4}$, $\eta_p^2 = 0.398$).

Because of the significant interaction, the effect of the level of stimulus on response time was analyzed for each type of stimulus using post-hoc pairwise comparisons with Bonferroni correction. These tests found that a higher haptic stimulus resulted in a faster response time than a lower haptic stimulus ($p = 1.50 \times 10^{-7}$), a higher audio stimulus resulted in a faster response time than a lower audio stimulus ($p = 0.008$), and a higher visual stimulus resulted in a faster response time than a lower visual stimulus ($p = 2.06 \times 10^{-5}$).

Lastly, the effect of the type of stimulus on response time was analyzed for each level of stimulus. Post-hoc pairwise comparisons with Bonferroni correction showed a significant difference between the low audio and low haptic stimulus ($p = 4.62 \times 10^{-7}$) and the low audio and low visual stimulus ($p = 1.01 \times 10^{-5}$). There was no significant difference between the low haptic and low visual stimulus.

Post-hoc testing also showed significant differences between the high audio and high haptic stimulus ($p = 2.79 \times 10^{-5}$) and the high audio and high visual stimulus ($p = 0.005$). There was no significant difference between the high haptic and high visual stimulus.

D. Survey Results

Participants were asked to fill out a short survey after the experiment to measure their perceived response time, preferred stimulus, and strategies for completing the experiment.

1) *Perceived Response Time*: Participants were asked to rate their response time on a 9-point Likert scale from 1 (slow) to 9 (fast) for each of the individual stimuli (high audio, low audio, high haptic, low haptic, high visual, low visual). Figure 9 shows the reported participant speed for the six individual stimuli. A Friedman's Test was used to identify the effect of stimulus level (low/high) and type (audio/haptic/visual) on perceived response time. There was a significant effect of stimulus type on perceived response time ($\chi^2(2) = 36.2$, $p = 1.37 \times 10^{-10}$) and a significant effect of stimulus level on perceived response time ($\chi^2(1) = 37.4$, $p = 9.56 \times 10^{-10}$). Wilcoxon Signed-Rank Tests with Bonferroni corrections were used to compare perceived speed, and the adjusted p-values from those tests are shown in Table I. Participants reported that they believe that they performed fastest for the high audio, and slowest for the low visual stimulus. Participants also reported that they had faster response times for higher stimuli.

2) *Preference*: Participants were asked to rate their preference on a 9-point Likert scale from 1 (dislike) to 9 (like) for each of the individual stimuli (high audio, low audio, high haptic, low haptic, high visual, low visual). Figure 9 shows the mean preference of each stimulus. A Friedman's Test was used to identify the effect of stimulus level (low/high) and type (audio/haptic/visual) on preference. There was a significant effect of stimulus type on preference ($\chi^2(2) = 14.2$, $p = 8.32 \times 10^{-4}$) and a significant effect of stimulus level on perceived response time ($\chi^2(1) = 13.2$, $p = 2.76 \times 10^{-4}$). Wilcoxon Signed-Rank Tests with Bonferroni Correction showed no

TABLE I
PAIRWISE COMPARISONS FOR PERCEIVED SPEED

		Audio		Haptic		Visual	
		Low	High	Low	High	Low	High
Audio	Low		0.009	0.269	0.064	0.006	1.000
	High			0.015	0.383	0.002	0.001
Haptic	Low				0.011	0.238	1.000
	High					0.004	0.111
Visual	Low						0.033
	High						

significant differences between any pairings of stimuli. Participants reported that they preferred the low visual stimulus the most and the high audio the least. Across all stimulus types, participants reported higher preference for the lower stimulus level.

IV. DISCUSSION

This study found that a low visual stimulus resulted in the slowest mean response time (528 ± 105 ms), and a combination of audio, haptic, and visual stimuli at high levels resulted in the fastest mean response time (320 ± 43 ms). Our results show that when played individually, haptic and visual stimuli had similar response times, with audio being faster. This is different from Chan et al. [10] who used a different setup and found that a haptic stimulus was the fastest (385 ms), followed by audio (493 ms), then visual (517 ms). Peon et al. [7] also found that vibrations had a faster response time than audio, which is different compared to our setup.

Unlike prior studies that test only a subset of stimuli types or levels [3]–[5], [7]–[10], [17], we tested 26 combinations of three stimuli types (audio/haptic/visual) across two intensity levels (high/low). In addition to confirming that a greater number of stimulus types decreases response time [17], we also show that this multi-modal trend follows alongside different stimulus levels, by showing that both level and type of stimulus have main effects for modulating response time across most combinations of conditions. This supports evidence that the activation of more sensory modalities with higher intensities may activate a larger neural network for faster processing [17], [18]. The time to recognize audio-visual signals can happen in as little as 45 ms with a processing time of up to 200 ms [13]. Combined with the time to physically input a response, the full response times in our study match others, with a range from around 200 ms to 1,000 ms [7], [17], [19].

Peon et al. [7], evaluated how standard deviations changed with different types of stimuli. We wanted to further evaluate this relationship, so we averaged the response times and standard deviations across all subjects for each of the 26 conditions and plotted this relationship in Figure 10. We found that larger mean response times correspond to larger standard deviations in response time ($R^2 = 0.827$). This could be because weaker stimuli that have slower response times require more cognitive attention or processing, leading to more variability between trials and subjects.

Our survey results showed that participants favored visual stimuli over auditory stimuli and they perceived that they re-

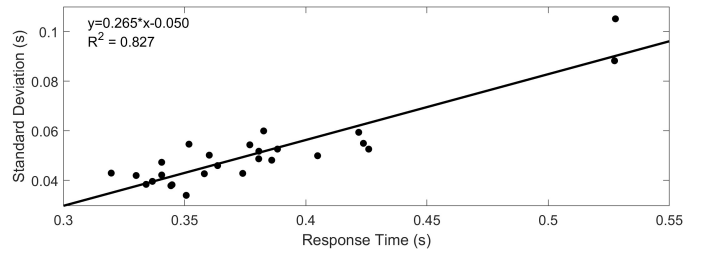


Fig. 10. Relationship between mean response time and standard deviation, grouped by stimulus combination. Combinations with higher mean response times have higher variability in response time.

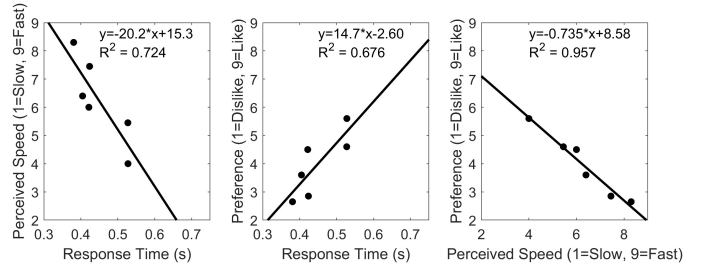


Fig. 11. Relationship between perceived speed and response time (left), preference and response time (middle), and preference and perceived speed (right). The mean response time perceived by participants was related to their actual response time, and participants had a stronger preference towards stimuli with higher response times. Participants had a stronger preference for stimuli to which they felt they responded slower.

sponded fastest to audio stimuli. In Fig. 11, we plotted a linear fit between perceived speed and actual response time averaged for each of the 6 conditions for which only a single stimulus is played and found that there was a strong relationship ($R^2 = 0.724$). We also found strong relationships between stimuli preference and response time ($R^2 = 0.676$), in addition to stimuli preference and perceived speed ($R^2 = 0.957$). These relationships may exist because more predominant stimuli elicit annoyance and a heightened sense of urgency, promoting a faster response [20]. This also shows that there is a trade-off between response time and stimuli preference that designers of haptic and mobile haptic devices should consider.

V. CONCLUSION

Our study tested 26 combinations of audio, haptic, and visual stimuli at two levels and showed that response time decreases with higher levels of stimuli and more types of stimuli. Our results show that combinations of stimuli affect response times and that people may have a preference for certain stimuli over others.

In the future, we will broadly distribute our app to measure response time in different populations. In-lab research has shown that factors like education and age impact response time [10], and we would like to further extend this to examine how other factors like physical activity, technology use, socioeconomic status, gender, geography, sleep, and race impacts response time.

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