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Temporal detection threshold of audio-tactile delays with virtual button

Detjon Brahimaj¹, Mondher Ouari¹, Anis Kaci¹, Frédéric Giraud¹, Christophe Giraud-Audine¹, Betty Semail¹

Abstract—Synchronization of audio-tactile stimuli represents a key feature of multisensory interactions. However, information on stimuli synchronization remains scarce, especially with virtual buttons. This work used a click sensation produced with traveling waves and auditory stimulus (a bip-like sound) related to a virtual click for a psychological experiment. Participants accomplish a click gesture and judge if the two stimuli were synchronous or asynchronous. Delay injection was performed on the audio (haptic first) or the click (audio first). In both sessions, one stimulus follows the other with a delay ranging from 0 – 700 ms. We use weighted and transformed 3-up/1-down staircase procedures to estimate people's sensitivity. We found a threshold of 179 ms and 451 ms for the auditory first and haptic first conditions, respectively. Statistical analysis revealed a significant effect between the two stimuli' order for threshold. Participants' acceptable asynchrony decreased when the delay was on the haptic rather than on the audio. This effect could be due to the natural experience in which the stimuli tend to be first tactile and then sonorous rather than the other way around. Our findings will help designers to create multimodal virtual buttons by managing audio-tactile temporal synchronization.

Index Terms—Surface haptics, Multimodal synchronization, Audio-tactile perception, Ultrasonic vibration, Keyclick, Button click.

I. INTRODUCTION

Traditional push-button user interfaces are now replaced by touchscreens in most commercial devices. This solution offers versatile and customizable ways to design Human Machine Interfaces. However, it requires a high cognitive load, as it relies essentially on visual feedback. To cope with this issue, haptic surfaces [1] offer the possibility to rely less on sight by using the sense of touch in the communication process with the machine.

For example, vibrotactile feedback, which consists of the vibration of the touched surface, has been proven to be effective for typing on a smartphone or a tablet, increasing the performance and reducing typing errors [2] [3]. However, more is needed to address all the perceptual aspects involved when pressing a physical button, such as the force feedback produced on the fingertip.

Different technologies have then been developed to overcome this limitation and therefore not rely only on pure vibrotactile feedback. Tashiro et al. [4] proposed modulating the friction between an ultrasonically vibrating surface and the

finger to recreate the sensation of rapid force changes typical of physical buttons. Similarly, Monnoyer et al. [5] modulated friction via ultrasonic vibration to induce a tactile sensation similar to a keystroke. The authors find that a mechanical detent in the case of a high level of friction followed by a low frictional level was perceived unambiguously by the participants. They also reported a weaker effect when the frictional levels were inverted, suggesting that the keyclick sensation was due to a release of skin stretch stored during the high friction state. This suggests that skin stretch due to lateral forces may play an important role on click perception. Following this idea, more recently, Garcia et al. [6] proposed a method that superimposes two vibrations modes simultaneously (a longitudinal and a transverse mode) on a plate elicited by piezoceramic actuators in order to recreate a keyclick sensation. This superimposition creates an elliptical motion of the plate's particles, which is able to induce a lateral force on the fingertip. The authors also performed a psychophysical study showing that the keyclick haptic feedback was perceived by all their participants [7].

Progressive ultrasonic waves to generate keyclick sensation on an actuated surface has also been proposed [8]. This method consists of a traveling wave based on a predefined force threshold that is reversed when a second force threshold is reached. With this method, the frictional forces produced by the traveling waves can deliver the keyclick sensation when the actuated surface is pressed. The authors performed an interesting comparison of their method with Tashiro's modulation of friction. The results show that both methods are similar in terms of the quality of the sensation.

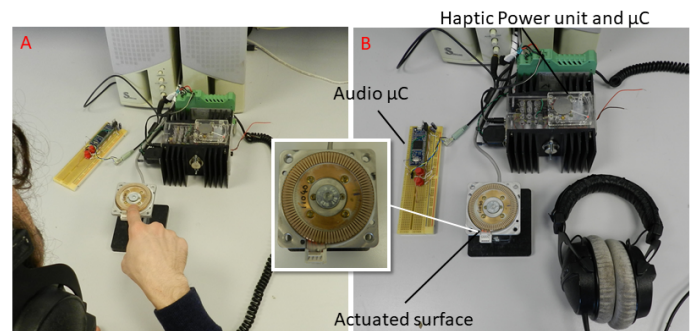


Fig. 1. A) Participant during the experiment. B) System composed of the actuated surface (USR60), the haptic power unit with the microcontroller, and the microcontroller used for the auditory feedback.

However, Geurguiev's method is promising for all those applications where a press is performed and users do not per-

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form any lateral movement of the finger. Indeed, we decided to use their method for our haptic feedback. Even if new different methods now exist for push-button generation that does not rely purely on vibrotactile feedback, the haptic modality alone, however, can not resemble the sensation of a physical button. A physical button is intrinsically bi-modal considering the haptic feedback produced by the pressing gesture and the associated click sound it emits, and it has been shown that both haptic and auditory contribute to the perceived tactile strength [9]. Therefore, it is important to employ this bi-modal relationship in virtual buttons to improve how they are perceived by the user.

Investigating this bi-modal relationship, Kaneko et al. [10] proposed a pseudo-haptic method to vary the sensation of heaviness while participants were performing a click by modulating the auditory feedback. Their result suggests that by presenting a low-frequency pure tone in response to the user clicking a button, they were able to increase the heaviness sensation. This pseudo-haptic effect is simple to implement but still, it can improve the way we perceive a virtual button.

Among different factors related to the integration of multi-modal information, temporal aspects represent a key element for perception. Indeed, the processing time for the modalities can be different, and the perception can be affected if they are not precisely synchronized. As the asynchronies between two modalities increase, the sense of realism or user comfort decreases [11], while simultaneous stimuli give rise to better performances as reported by [12]. The latency between modalities can limit the quality, effectiveness, and interactivity of virtual buttons.

To shed light on this interaction, many works have explored the perceived simultaneity of audio-tactile stimuli in different contexts. Fujisaki et al. [13] investigated temporal resolution of synchronous perception for different modality pairings where stimuli were: a light blob, a white noise, and a vibration on the index finger. The authors reported the audio-tactile superiority in temporal resolution over visio-tactile and audio-visual combinations. Occelli et al. [14] have reviewed prior works describing the results of behavioral studies investigating temporal resolution between hearing and touch. The author highlighted the increased interest in the field and the need for more investigation into audio-tactile temporal perception. Hence, understanding the temporal perceptual aspects of audio-tactile interactions is important when designing multimodal experiences.

In this context, Hao et al. [15] investigated the simultaneous perception of audio-tactile stimuli during voluntary movement with a temporal order paradigm. For this study, participants were moving their index fingers from left to right and were not in the condition of touching virtual button. Their results show that voluntary movement affects the point of subjective simultaneity (PSS) but does not influence the just noticeable difference (JND). This result is important as we are interested in temporal aspect of audio-tactile interactions and voluntary movement is intrinsically related to the action of pushing a button.

While various research has investigated the perceptual tactile aspect of virtual buttons, less has been done concerning

the auditory stimulus and virtual buttons. A relevant work on virtual buttons was performed by Kaaresoja et al. [16]. The authors have investigated touch simultaneity with audio, tactile or visual feedback. During their experiment, the authors varied the latency of the feedback (tactile, audio or visual) with respect to the moment participant was touching a virtual button simulator but not receiving any type of tactile feedback. The authors found that the latency should be lower than 50 ms for tactile, 70 ms for audio, and 85 ms for visual feedback. Even if relevant, this study is in unimodal condition as only one feedback at a time was presented and therefore does not give insight into temporal simultaneity of the audio-tactile interaction that is of our interest. It is, therefore, essential to conduct this type of study in the specific case of virtual button clicks with auditory feedback. Indeed, to our best knowledge, no research has been conducted on temporal aspects related to virtual buttons in the audio-tactile bi-modal condition.

II. EXPERIMENT

In these experiments, we want to access temporal perception within auditory and touch with a virtual button. Pairs of stimuli with different stimulus onset asynchronies (SOAs) were presented to participants. We used a simultaneity judgment (SJ) paradigm where participants had to judge whether auditory and tactile stimuli were synchronous or asynchronous. We want to estimate the threshold and slope of the psychometric function by using a weighted and transformed 3-up/1-down staircase.

A. Participants

We recruited a total of seventeen participants. We excluded two participants due to exclusion criteria (numbness/loss of touch and loss of auditory). Fifteen healthy volunteers participated in these experiments (9 males and 6 females, aged $M = 29,2$ and $SD = 4.00$). 11 participants were right-handed, and four were left-handed. None of the remaining participants exhibit any motor difficulty or loss of sensation in their dominant hand index. Each participant took part in the experiments voluntarily and signed the informed consent before the start of the experiment, and the ethical committee of Lille University approved the experiment.

B. Stimuli and Setup

Tactile: The tactile stimuli were delivered by a haptic device developed by Gueorguiev and al. [8]. The device is based on the stator of an ultrasonic motor (USR60, Shinsei Corporation, Japan). It consists of a bronze disc under which a ring of 16 piezoelectric actuators is glued. Half of these actuators are arranged to excite a transverse mode, with a resonance frequency of 40 kHz and a wavelength of $\lambda = 21$ mm. The remaining actuators, positioned with a spatial shift of $\lambda/4$, excite a doublet of the previous mode. The excitation of both vibration modes, with a temporal phase shift of $\pi/2$, generates a traveling wave. Changing the sign of the phase shift inverts the direction of the traveling wave, while the cancellation of the phase shift results in a stationary wave. To generate the keyclick sensation using our haptic device, we modulate

the traveling wave depending on a force sensor applied in the USR60. Indeed, when the produced finger-pushing force reaches a predefined threshold of $f_{th} = 0.25\text{ N}$, we produce the traveling wave in a direction (Fig. 2.B1). Then, after a predefined time-delay $\tau = 10\text{ ms}$, we reverse the direction of the wave (Fig. 2.B2). Finally, the change of direction of the traveling wave gives the keyclick sensation by a lateral force produced on the fingertip [8]. From the moment the force threshold was reached to the moment the reversed travelling wave is stopped, our haptic signal duration is 40 ms .

Auditory: Auditory stimuli are delivered to participants through a pair of headphones. The selected stimulus is a pure tone with 0.5 kHz frequency and 100 ms duration (see Fig. 2). For the volume level, we selected 30% in loudness concerning its maximum. We choose a low-frequency pure tone because, as suggested by [10], this can increase the perception of heaviness, making the click sensation more similar to classical buttons. In addition to the pure tone, a white noise sound is played constantly in the background (low intensity/low volume) to prevent participants from hearing any audible noise produced by the tactile device. The white noise is chosen because we wanted to compare the auditory stimuli with the tactile stimuli without the aid of the audible noise coming from the actuated surface.

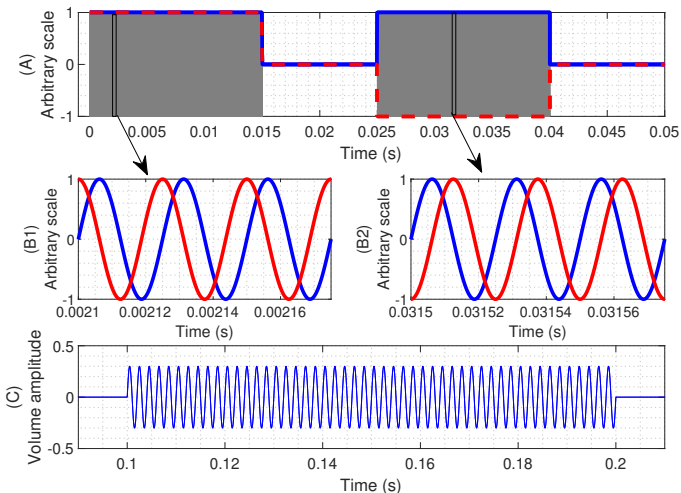


Fig. 2. A) Haptic signal used for the keyclick generation. It is composed of the superposition of two stationary waves depicted with their amplitude reference in blue and red colors. Once the force threshold is reached (time = 0), the travelling wave is switched on (0 to 15 ms) by a step increase in the amplitude vibration and the two waves are shifted by $+90^\circ$ as depicted in B1. After 10 ms the direction of the travelling wave is reversed performing a -90° phase shift (25 ms to 40 ms) as depicted in B2. B1 and B2 shows a zoom of the two ultrasonic waves and their phase shift. C) Recorded waveform and timing of the audio signal used as auditory feedback.

Setup: Our system comprises two microcontrollers (STM32F4) handling one stimulus each. The microcontroller (μC) dedicated to the tactile stimuli was in charge of producing both the traveling wave and the change of direction of the wave. Moreover, the audio stimulus was triggered when the threshold force was reached (haptic first - HF). In the case

of audio first (AF), an internal timer was set to provide the desired delay on the keyclick after the audio stimuli.

The second μC was in charge of audio delivery. In the case of AF, the short burst was delivered as soon as the μC was triggered. In contrast, in the HF case, an internal timer was responsible for providing the audio feedback with the desired delay after the tactile stimuli.

In order to allow a good synchronization between the stimuli, we performed a different test on both HF and AF conditions. The measurements revealed an internal mean latency of $100\text{ }\mu\text{s}$ over the multiple tests. Such value is acceptable for the type of experiment, as it allows a low latency synchronization between the stimuli.

C. Method

Two experiments were conducted to measure the point of subjective simultaneity of auditory-tactile and to estimate the psychometric function. In the first experiment (HF), the haptic stimulus was always presented before the audio stimulus, while in the second one (AF), audio was always delivered before the haptic stimulus. In both experiments, the second stimulus followed the first one with a stimulus-onset asynchrony (SOA) ranging from 0 to 1000 ms with a fixed step size of 15 ms.

Each participant underwent both experiments, and we alternated the order to avoid bias due to the presentation order.

A weighted and transformed 3-up/1-down staircase was employed to present the delay at each trial. The calculation of the targeting level can be obtained by using the following formulas:

$$P_{down} = p^N, \quad P_{up} = 1 - p^N \quad (1)$$

where p_{up} and p_{down} are the probabilities of responses leading to the staircase going up or down, p is the target fraction correct level, and N is the number of correct responses necessary to go down. In our case, N is set to 2. Considering the equilibrium condition for convergence

$$S_{down}P_{down} = S_{up}P_{up} \quad (2)$$

where S_{up} and S_{down} are the up and down step sizes, and by substituting (1) in (2), we obtain:

$$S_{up}/S_{down} = p^N/(1 - p^N) \quad (3)$$

With a 3-up/1-down algorithm, the upward step size is three times bigger than the downward step size, leading to $S_{up}/S_{down} = 3$, targeting $p = 0.866$. Hence, our weighted and transformed 3-up/1-down staircase targets the 86.6% perceptual threshold [17].

D. Procedure

In both experiments, participants sat comfortably in a chair in front of the device, and the experiment took place in a quiet room. After reading and signing the informed consent form, we allowed participants to try the device and familiarize themselves with the haptic feedback by performing some keyclick. Before starting the experiment (either the first or the second), we presented to participants the stimuli with

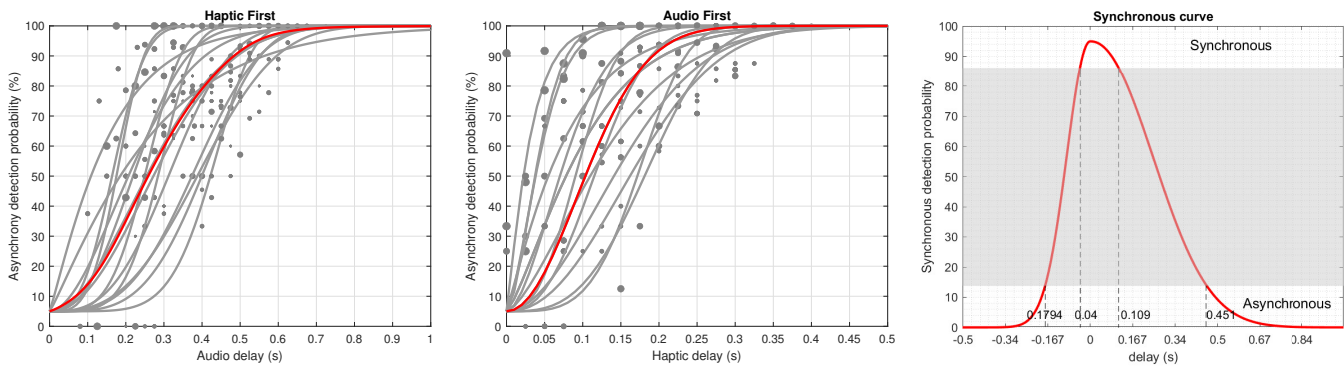


Fig. 3. **Left, Center**) Asynchronous discrimination performance in the haptic first and audio first condition . Individual estimated curves are plotted in light grey and data (grey dots) are plotted as the proportion of trials in which the two stimuli were judged as asynchronous as a function of the audio delay. The dimension of the dots is related to the occurrence of the associated delay. The psychometric curve constructed with the most likely parameter's value (medians) is represented in red and a higher value corresponds to a higher probability of asynchronous. **Right**) Synchronous curve obtained applying eq. 5. Negative delay values indicate AF condition and positive values indicate HF condition. High/low values indicate high/low probability to feel the stimuli as synchronous.

different SOAs: 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 *ms*. This step was performed to ensure a good understanding of the experiment by participants.

Participants then performed a forced-choice task where, at each trial, they were asked to accomplish a click gesture with the index finger of their dominant hand. Each keyclick was performed only once. After pressing the actuated surface, they had to report whether they perceived the tactile and auditory stimuli to be synchronous or not synchronous before moving to the next trial.

All the participants performed a total of 100 trials for each experiment. The minimum number of reversal points we achieved with this number of trials during the experiments were 21 ($M=30.3$, $STD=4.68$) and 26 ($M=32.2$, $STD=4.23$) for HF and AF, respectively. This number ensures a good estimation of the parameters as we run a pretrial test in order to choose the initial value of the staircase to be close to the expected estimated threshold [18]. We chose a random values between 300 *ms* and 400 *ms* for HF condition and a random values between 100 *ms* and 250 *ms* for the AF condition.

E. Data Analyses

The psychophysical curve was estimated with the weighted and transformed 3-up/1-down staircase. We estimate the threshold and slope of each participant in both experiments separately.

A standard function to predict the psychometric function for a forced-choice experiment is the so-called Weibull cumulative distribution function, defined as follows:

$$W(x) = 1 - (1 - g)e^{-\frac{k \cdot x^s}{t^s}}, \text{ with } k = -\log\left(\frac{1 - a}{1 - g}\right)^{\frac{1}{s}} \quad (4)$$

where g is the chance performance, i.e., the expected performance to be achieved by chance (0.05 in our case). t represents the threshold, s the slope of the psychometric function, and a is the performance level or targeted threshold performance (86.6%).

The density function predicts the probability that the subject will answer that the two stimuli were asynchronous. Considering a trial i , with a delay x_i , the probability for the subject

to answer asynchronous (P_a) or synchronous (P_s) could be written as:

$$P_a = W(x_i) \text{ or } P_s = 1 - W(x_i) \quad (5)$$

Where $W(x_i)$ represents the Weibull for a given delay x_i . We can then define the probability of observing the whole experiment by the log-likelihood function, an efficient method for estimating the parameters of the psychometric curve [18] (known as Fisher's maximum-likelihood procedure). The function is defined as:

$$h_i \log(W(x_i)) + (1 - h_i) \log(1 - W(x_i)) \quad (6)$$

Where h_i is the subject's answer (1 or 0 if asynchronous or synchronous).

A chi-square χ^2 goodness of fit test was also performed. This test can be used to determine whether our observed frequency distribution deviates significantly from the hypothesized Weibull distribution (4). The test confirmed the hypothesized distribution and didn't show any significant deviation.

Model parameters (threshold t and slope s) were then estimated by maximizing the log-likelihood equation.

All the data analysis was performed in MATLAB 2022b with the appropriate toolboxes [19].

III. RESULTS

For each subject, we calculated the probability of the stimuli being felt as asynchronous as a function of the SOAs. We then estimated the best-fitting psychometric function for each individual by maximizing the log-likelihood function, as explained in the preview section. In Figure 4, we show the best-fitting threshold value for each participant and both HF (red) and AF (blue) conditions. After visual inspection, the PFs appeared to match well the collected data. The PFs are illustrated in Figure 3 by the curves plotted in light grey for the HF and AF conditions, respectively.

For the AF condition, the median value of threshold and slope calculated were respectively 179.4 *ms* ($IQR = 0.231 - 0.134$) and 1.755 ($IQR = 2.4353 - 1.3485$). We used these

values to construct the best-fitting psychometric curve depicted in Figure 3.

On the other hand, for the HF condition, the median value of threshold and slope calculated were respectively 451.0 ms ($IQR = 0.50874 - 0.334$) and 2.962 ($IQR = 3.8044 - 1.992$). We illustrate the best-fitting using these parameters in Figure 3.

The threshold values of 179.4 ms and 451.0 ms for the AF and HF condition, respectively, represent the delay that with 86.6% probability, will make the audio-tactile stimuli be felt asynchronous. On the contrary, the synchronous curve depicted in Fig. 3, obtained by applying equation 5, gives information on the simultaneity perception of audio-tactile stimuli. Here the threshold values are 40 ms and 109 ms for AF and HF conditions, respectively. These threshold values represent the delay that will make the audio-tactile stimuli felt as synchronous, with an 86.6% probability (i.e., with an 14.4% probability of the two stimuli felt as asynchronous).

Generally, threshold values in the AF condition tend to be lower than in the HF condition as illustrated in Fig. 4. Furthermore, we compared the estimated thresholds in the HF condition with those estimated in the AF condition. By performing an ANOVA (Figure 5), we found that for both threshold and slope, there was a statistically significant difference ($p = 6.39 \times 10^{-8}$ for threshold and $p = 0.0167$ for slope) between the two conditions. Therefore, highlighting an asymmetry between the conditions and the tendency of individuals to be more sensible to asynchrony in the condition where delays were injected in the haptic stimuli. Furthermore, our results also show a larger variance for both threshold and slope in HF condition with respect to AF.

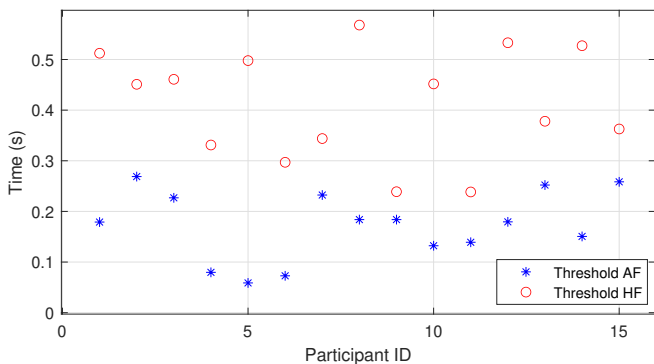


Fig. 4. Best estimated threshold parameters for each participant and both haptic first (red circles) and audio first (blue stars) conditions.

IV. DISCUSSION

In this study, we evaluated the temporal sensitivity of synchrony perception for audio-tactile stimuli with virtual buttons. We estimated threshold parameters where injection of delay was performed in the auditory stimuli preceded by the tactile stimuli and vice versa. We estimated the most likely parameter value (threshold and slope), and our results show that temporal sensitivity was different in the two conditions (HF, AF). Our analysis shows a statistically significant difference in threshold and slope between the two conditions.

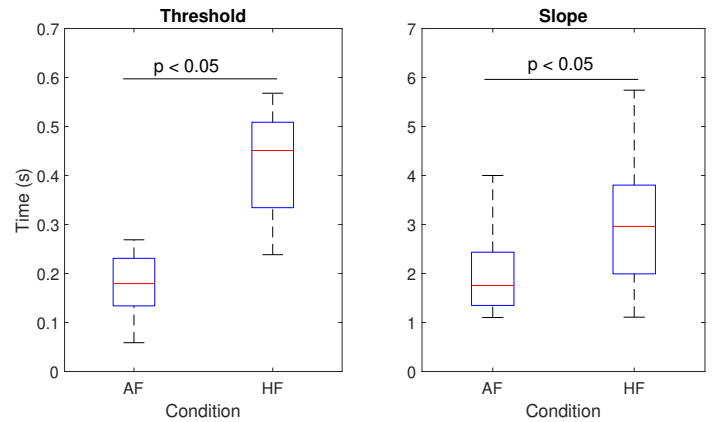


Fig. 5. ANOVA box-plot for threshold and slope for both haptic first and audio first conditions

The results show a tendency of individuals to be more sensitive to delay injection in the haptic modality rather than in the auditory. This difference may be due to our natural experience in our daily life. A multisensory experience is most likely to be felt first by our haptic modality and then followed by auditory. This sensation is true mainly when we perform a click gesture, where a button is first felt tactically and then heard (or followed by another audio event). We believe that this experience we live in our daily lives reinforces our expectation of one stimulus (haptic) followed by another (audio in our case). Therefore, it may create a sensation of discomfort or a negative surprise effect when the stimuli are inverted. Indeed, we think this mechanism is responsible for the higher sensitivity of asynchrony detection (i.e., lower threshold) in the audio first condition.

Guidelines:

- In general, the audio first condition should be avoided, as explained before. A delay ≤ 40 ms will ensure a small probability ($\leq 14.4\%$) of the stimuli to be felt as asynchronous, i.e., a high probability of the stimuli to be felt as synchronous. Suppose for some technical reasons this is not possible. In that case, we suggest designers keep the latency as small as they can and however to not have a delay $\gg 70$ ms that represents the 30% probability of the stimuli to be felt as asynchronous.
- In the haptic first condition, the delay on the audio feedback is larger and allows for less stringent requirements. Designers should pay attention to being as far as possible from the threshold value at 86.6% asynchronous (i.e., delay ≤ 451 ms). In general, a delay value ≤ 109 ms will ensure the stimuli are simultaneous (with a 14.4% probability of being asynchronous or with an 86.6% probability of being felt synchronous). We suggest designers avoid delays $\gg 192$ ms, which represent the 30% probability of the stimuli to be felt as asynchronous.
- Designers should use these guidelines independently of the haptic surfaces or stimulator they want to implement, as we believe this result does not depend on the set-up we have used. However, caution should be paid to the stimuli duration. Suppose the stimuli duration is not similar to ours (100 ms for auditory and 40 ms for haptic). In

that case, a shift in the point of subjective simultaneity may occur, as the authors in [20] reported for audio-visual synchrony perception. We do not know if the shift will occur and in which direction, as this requires further investigation into audio-tactile temporal perception.

V. CONCLUSION

In this study, we performed two experiments (AF and HF) to estimate the most likely parameters for constructing the psychometric function related to audio-tactile asynchrony perception while executing a click gesture with a virtual button.

Synchronicity is a critical element of a multimodal experience. For engineers designing virtual buttons, strictly synchronous modalities are expensive to afford. Fortunately, our results demonstrate that people tolerate significant delay when haptic occurs first and a delay between the stimuli below 109.0 *ms* ensure synchronicity. However, we also show that audio occurring first should be prohibited because people are stringent and intolerant of that condition. If this is not possible, designers should ensure a minimum delay value below 40 *ms*. Therefore, our results have significant consequences on hardware development for virtual buttons.

With this study, we aim to help the community of designers and developers to cast light on some temporal aspects of audio-tactile interaction occurring when performing a keyclick with virtual buttons.

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