Perceptual Limits of Visual-Haptic Simultaneity in Virtual Reality Interactions

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Abstract— **The goal of this work is to establish the range of visual-haptic asynchronies that go unnoticed when touching an object. To perform a psychophysical study, however, we would need asynchronous visual-haptic stimuli, but because the contact of the finger with a real object inevitably creates synchronized haptic feedback, here we employ instead a virtual reproduction of the interaction. Participants immersed in a realistic Virtual Reality environment tapped on a virtual object with their index while viewing a fully articulated representation of their hand. Upon tapping, they received haptic feedback in the form of vibration at their fingertip. After each tap, participants judged whether they perceived the view of the contact and the haptic signal to be synchronous or asynchronous and they also reported which of the two seemed to happen first. Despite the difference between the two judgments, results indicate that none of the 19 participants could reliably detect the asynchrony if haptic feedback was presented less than 50ms after the view of the contact with an object. The asynchrony tolerated for haptic before visual feedback was instead only 15ms. These findings can be used as guidelines for haptic feedback in hand-based interactions in Virtual Reality.**

I. Introduction

The ability to discriminate whether two stimuli are simultaneous is important to determine whether stimuli should be bound together and form a single multisensory perceptual object [1]. Not surprisingly, studying the ability of humans to reliably detect asynchronies and discriminate the temporal order of two stimuli is among the oldest questions in experimental psychology (i.e. [2]). In the seminal work of Hirsh and Sherrick on simultaneity discrimination [3], well-trained participants were presented with simple stimulus pairs composed of audio–visual, visual–tactile, and audio–tactile stimuli and could reliably report stimuli order with about 20ms asynchrony irrespective of the modalities presented. More recent studies suggest that non-experts might not be able to detect such small asynchronies and there might be large differences in performance across the population. For example, it has been shown that naïve participants could only detect asynchronies between a short light and a vibration starting from 35–65ms [4][5]. The stimuli used in these experiments were not coupled with the participant's motion. In a study where participants used a force-feedback joystick to make a cursor hit a line and judged if the collision was simultaneous with the onset of the force produced by the joystick, the threshold for simultaneity perception was 59ms when force came first and 44ms when the cursor hit the line first [6]. In a study employing a touchscreen, it was determined that to ensure for users to perceive feedback to be simultaneous with their touch, haptic signal latency should be at most 50ms, audio latency 70ms, and visual latency 85ms [7].

These results suggest that the limit of simultaneity perception between vision and touch might not be consistent when measured in different scenarios and that results could vary across the population. Empirical evidence suggests that the sensitivity to asynchrony can be influenced by several factors [8]. Attention, for example, can alter the processing time of sensory stimuli. A light had to be presented around 30ms before a tactile stimulus to be perceived as simultaneous, but attention to one of the two stimuli speeds reaction times, consequently affects also temporal order judgments [9], a phenomenon defined "prior entry" [5].

In Virtual Reality, users interact with the environment, i.e., using their hands or through controller devices. The user movement triggers haptic feedback. Results in the literature suggest that the user's movement could be influencing temporal discrimination performance. This effect could be due to spatial discrepancies between the location of the seen contact with the object and where the hand is perceived to be located when the haptic feedback is delivered. Such a discrepancy could improve discrimination performance as sensitivity to the order of stimuli has been shown to improve if the components of the cross-modal stimulus are presented at spatially disparate locations [10][11]. The presence of additional (spatial) cues that could aid the discrimination, but not all results point in the same direction. In one study it has been shown that by using a joystick to control the movement of a stimulus, sensitivity to asynchrony is higher for passive than for active conditions [6]. On the contrary, in another study where participants controlled the movement of a visual stimulus using the position of their finger, it was found that the haptic stimulus would have to lag 20ms more than in the passive case in order to be perceived as simultaneous [12]. The last two studies differ in the way user control movement, a factor that could account for the difference in results, as only in the case of direct active control of one's hand, the sensitivity of the temporal discrimination can improve due to the spatial disparity.

Another factor that can influence temporal discrimination performance is the degree to which the stimuli to be judged as naturally belonging together. The more stimuli have similar properties, are semantically associated, or are frequently encounter together, the more the perceptual system will try to fuse them into a unified perception, making the discrimination of their temporal order more difficult. In the literature, this has been referred as the *unity assumption* [13]. Making temporal judgments about a visual stimulus representing an anatomically-plausible limb, for example, can reduce discrimination performance. Ide & Hidaka [14] found that a simple drawing of a hand oriented as one's own hand can reduce the precision of visual-tactile temporal order judgments compared to an implausible orientation. This result indicates the tendency of the perceptual system to bind stimuli that belong together, even in the time domain.

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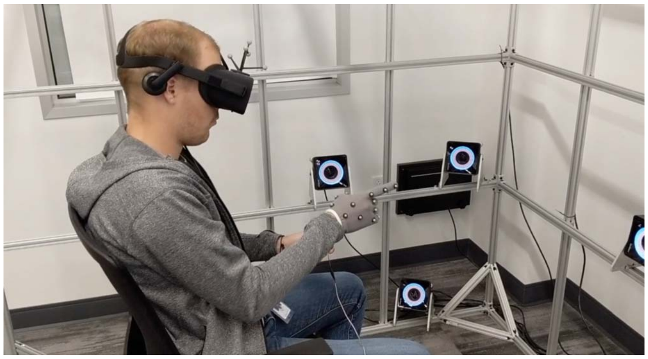

Figure 1: Experimental setup. Participants sat inside a cage to support the cameras, wearing the Oculus Rift headset and a mesh glove with optical markers on the right hand. The glove has a piezoelectric actuator positioned at the index finger to provide the haptic stimulation. Participants hold a remote on the left hand to enter the answers.

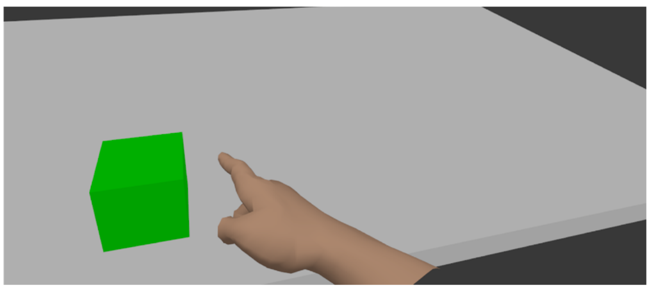

Figure 2: View of the virtual environment from the participant's vantage point. A visible counter kept track of the number of trials.

The motivation for this paper was to characterize what is the limit of visual-haptic perception of simultaneity in a realistic setting. Results in the literature suggest that the conditions in which performance is tested could greatly influence the findings. We thus steered away from simple stimuli in a passive scenario. For the first time, instead, we employed a state-of-the-art Virtual Reality setup with full hand tracking and realistic rendering to measure the perception of simultaneity limits. Because such setup could provide realistic content that could possibly enhance the unity assumption, making asynchronies to be less detectable, we would be able to characterize the limits of perceptual simultaneity in a situation similar to the real world. In addition, to be certain that the task performed by participants does not bias our finding, we ask both about perceived simultaneity and perceived order between the visual and haptic stimuli.

II. Method

A. Participants

Nineteen naïve participants took part in the experiment (mean age=30.7, range=18-46, 12 were females). Participants had normal or corrected-to-normal visual acuity, self-reported normal hearing and somatosensation, and no history of neurological or psychiatric disorder. All participants gave written informed consent before taking part in the experiment, which was conducted according to the protocol approved by Western Institutional Review Board (WIRB). Participants were remunerated for their time.

B. Setup

Participants sat inside a tracking cage with 17 Prime 17W OptiTrack cameras aimed to track the participant's hand and head (Fig. 1, see [15] for full description of the setup). Motion capture was undertaken at 90 Hz via Motive 1.9.0 software. The participant wore a glove on their right hand (i.e., the hand used for interacting with the VR environment) with 19 fiducial markers glued on the top surface. The position of the markers was reconstructed and then sent to a near real-time hand tracking service which computed a hand pose. The visual rendering of the hand was created using a single low-resolution mesh template representing the shape of a male right hand via a 3D scanner. The mesh was distorted according to the captured hand pose, so that all finger movements could be displayed. Participants wore an Oculus Rift head mounted display with 5 markers so that its position could be captured by the cameras. The precision of hand tracking and rendering was approximately 0.2 mm in all spatial dimensions. A TDK PowerHapt 2.5G piezoelectric actuator encapsulated in a 2mm thick silicone sleeve was positioned on the front side of the fingertip and held in place by the glove. The actuator was driven by an RME Fireface UC card and a DC amplifier.

C. Procedure

Fig. 2 illustrates the virtual environment viewed by the participant in the experiment. In addition to a representation of the right hand, participants could see a cube on a virtual table and the instructions presented vertically at the far end of the table. At each trial, the user moved the right hand toward the virtual cube with a stretched-out index finger, so to make contact with the right side of the cube. A change in color of the cube indicated that the fingertip made contact with the surface. Participants were able to move their finger leftward past the surface and the cube would occlude the portion of the hand inside its volume. Around the time of the contact, a haptic stimulus would be presented. 1000ms after the tap, the cube disappeared, and the subject was required to respond to two questions. The first question was a Simultaneity Judgment (SJ): "Did it feel simultaneous? -> yes/no". Irrespective of the response, the user was asked to perform a Temporal Order Judgment (TOJ): "which stimulus came first -> Box color change / Fingertip vibration". We chose to ask two questions because TOJ and SJ are differently biased measures. Temporal Order Judgment (TOJ) data are better suited to determining the precision of the discrimination but can be biased whereas Simultaneity Judgment (SJ) data have the opposite trend (see[16]). We thus combine the results obtained from the two questions for the best results. After the second response, the cube reappeared at a random location along the direction of the finger movement. If the cube would show up as red, the participant had to move their finger at least 25cm to the right of the cube. Each participant performed 260 trials, each time with a random asynchrony between the change in color and the vibration as indicated below.

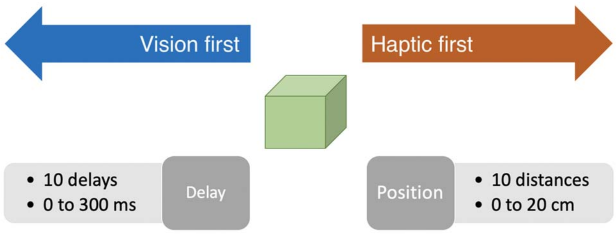

Figure 3: Type of stimuli used in the experiment. The index finger is approaching the cube from the right. Delays are: 10, 15, 21, 31, 45, 66, 97, 141, 206, 300ms. Distances are: 0.5, 0.8, 1.2, 1.9, 3.0, 4.7, 7.3, 11.5, 18.0cm.

D. Stimuli

Participants judged the temporal order of two stimuli: a vibration delivered at the index fingertip (200ms 50Hz vibration) and the visualized contact of the virtual finger with the cube (a change in color of the cube from blue to green). Around the time of contact, but not necessarily synchronous with it, participants experienced a short vibration constituting the haptic feedback. There are three type of asynchrony between the visual and the haptic stimulation in the experiment (Fig. 3):

- Simultaneous stimuli: The haptic stimulation is triggered at the same time as the change in color of the cube, coincidently with the virtual finger reaching the cube. Participants do not receive the stimuli simultaneously as the system has inherent different latencies for each stimulus that have been measured as explained in section II.E below.
- Vision first stimuli (Time delay): The haptic stimulation is triggered at a fixed delay after the visual stimuli (9 delays ranging from 0 to 300ms after the visual stimulus).
- Haptic first stimuli (Position trigger): Haptic stimulation is triggered before the visual stimulus. In this situation, the trigger of the haptic stimuli cannot be based only on time because participants have not yet made contact with the cube. Instead, here we trigger the haptic stimulation at different positions along the trajectory of the finger to the cube (9 perpendicular distances ranging from 20 cm to 0 cm to the right side of the cube). Because the finger movement is not consistent across trials and across participants, this method leads to different temporal asynchronies at every trial.

E. Delay measurement

To measure the end-to-end delay of the VR system, we needed to simultaneously capture all information about events in the real and virtual world (as laid out by [17]). To do this, we placed a wooden cube at the same position and orientation of the virtual cube. We tapped the wooden cube and recorded the tap using a microphone positioned next to it. The contact of the virtual cube triggered the change in color and the haptic stimulus. We put a photodiode in front of the rift screen to record the change in color and a second microphone in contact with the tactor to record the vibration. The three sensors (two microphones and one photodiode) were attached to three channels of an audio-card to assure simultaneous recording. A total of 23 taps were recorded. The results show 71±11ms delay between physical tap and visual tap (contact of the finger and change in the virtual color) and 100±12ms delay between physical tap and haptic stimulation. Based on the results, there is an intrinsic 29±7ms asynchrony between the visual stimulus and the haptic stimulus. This means that generating simultaneous stimuli actually leads to a haptic stimulus occurring on average 29ms after the user's finger makes contact with the cube. We thus subtract 29ms from the commanded asynchronies in all results of the psychophysical experiment.

F. Data analysis

Participants performed two tasks, they judged simultaneity and temporal order. We fitted the response data, i.e. binary values (0: asynchronous, 1: synchronous), with a function obtained from the difference of two cumulative Gaussian distributions by varying the mean and standard deviation of each one. To find the best fitting function, we implemented the cross-entropy optimization approach. The loss function is the sum of the cross-entropy of all samples [18]. From the fitted function, illustrated in Fig. 4, we extracted the Point of Subjective Simultaneity (PSS) and Threshold of Simultaneity Detection (TSD_{VH}, TSD_{HV}), whose difference is termed Window of simultaneity (WS). Note that the Point of Subjective Simultaneity (PSS) does not necessarily coincide with the Point of objective simultaneity (POS), the value with "Zero" asynchrony. There might be an offset between participants' simultaneity (PSS identified by the maximum point on the black curve in Fig. 4) and actual POS.

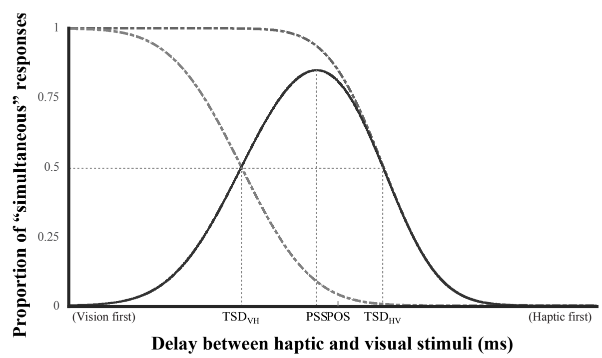

Figure 4: Function fitted to the proportion of "simultaneous" responses plotted as a function of asynchrony. The two points where the proportion of simultaneous responses drop below 50% are defined to be the thresholds for simultaneity detection (TSD).

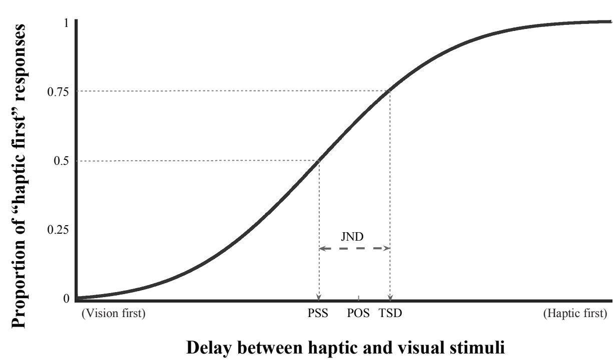

Figure 5: Cumulative Gaussian function fitted to the responses in the temporal order judgment trials. The 50% point identifies the point of subjective simultaneity (PSS), the asynchrony at which there are equal number of responses for the two stimuli. The 75% point identifies the threshold for simultaneity detection (TSD). The difference in asynchrony between the TSD and PSS is defined as the Just Noticeable Difference (JND), the change in asynchrony from PSS necessary to lead to 3/4 correct responses.

We fitted the Temporal Order Judgment data with a cumulative Gaussian by changing the mean and standard deviation using a Generalized Linear Model regression. From the fitted function, shown in Fig. 5, we derive the Point of Subjective Simultaneity (PSS) and Just Noticeable Difference (JND).

III. RESULTS

A. Simultaneity Judgments

The data in all graphs have been corrected considering the asynchrony between the channels (29ms) measured as explained above. We first look at the responses for the judgment of simultaneity. The distribution of responses is shown in Fig. 6 together with the fit performed on the data across all participants. The results of the fit performed on each participant (Tab. 1) indicate that the average delay of haptics at which perceived simultaneity is maximal (PSS) is 11ms, the threshold for a majority of asynchronous responses with vision first (TS_{VH}) is 118ms and the threshold for more asynchronous responses with haptic first (TS_{HV}) is 77ms, with a window (WS) of 195ms. A negative PSS in Fig. 6 and Tab. 1 means that the haptic stimulus should occur 11ms after the visual stimulus for participants to report the two as being most simultaneous. This is logical, as participants accept haptic stimuli to be coming after visual contact rather than *vice versa*, as in real life is possible to predict and thus anticipate the time of contact from the visual information.

B. Temporal Order Judgments

We then look at the responses for the judgment of order. The distribution of responses is shown in Fig. 7 together with the fit performed on the data across all participants. On the fit performed on each participant (Tab. 2), the equally often choice of the two stimuli (PSS) is achieved on average with 40ms delay between vision and touch, whereas the change in asynchrony that leads to a 75% of responses (JND) is 100ms, which corresponds to a threshold of simultaneity detection (TSD) of 60ms (-40ms+100ms) for haptic first stimuli and 140ms for visual first stimuli (-40ms–100ms). The PSS is shifted in the same direction of the value obtained with Simultaneity Judgments (SJ), but the magnitude is higher with Temporal Order Judgments (TOJ), whereas JND is smaller than WS.

C. Correlation between the two types of judgment

We performed a correlation analysis of the results obtained from each of the participants' fit with the two tasks (SJ and TOJ). We find that the two tasks lead to correlated PSS values ($r=0.41$, $t(17)=1.89$, $p=0.038$, one tailed) whereas the correlation between the Window of Simultaneity (WS) and the JND does not reach statistical significance ($r=0.34$, $t(17)=1.50$, $p=0.076$, one tailed). We also tested whether there is a relation between accuracy and precision in the responses by correlating the absolute value of PSS and WS for the SJ task ($r=0.57$, $t(17)=2.82$, $p=0.012$, two tailed) and the absolute PSS and JND for the TOJ task ($r=0.27$, $t(17)=1.16$, $p=0.26$, two tailed).

D. Cumulative analysis

To summarize the results obtained with the individual-fitted functions and visualize the distribution across participants, we order the values obtained by subtracting (and adding) the JND in the Temporal Order Judgment (TOJ) data from the PSS obtained in the Simultaneity Judgment (SJ) data. These values are shown in Fig. 8 and highlight a large variability across participants. Results indicate that for some participants, an asynchrony of more than 250ms was not detectable. On the other hand, none of the participants could reliably detect the asynchrony if haptic feedback was presented less than 50ms after the view of the contact with an object and 20ms if the vibration was delivered before the contact.

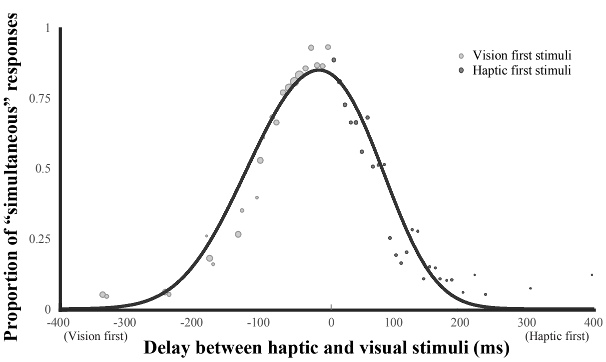

Figure 6: Proportion of "simultaneous" responses obtained in the Simultaneity Judgment across participants plotted as a function of delay between the stimuli. The data is binned so that the diameter of the points represents the number of trials in each bin. The fit with a single function obtained by the difference of two cumulative Gaussians is shown across participants for illustrative purposes. The delays include system latency measured in section II.E.

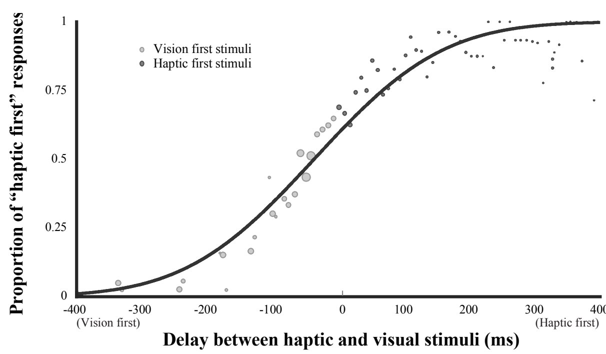

Figure 7: Proportion of "vibration first" responses obtained in the Temporal Order Judgments across participants plotted as a function of delay between the stimuli. The diameter of the points represents the number of trials. The data pooled across participants is fitted with a unique cumulative Gaussian function for illustrative purposes. The delays include system latency measured in section II.E.

TABLE 1

	PSS	TSD_{VH}	TSD_{HV}	WS
Mean	-10.6	-117.9	76.6	194.5
S.E.M.	4.6	13.2	8.3	16.0

TABLE 2

	PSS	TSD	JND
Mean	-39.7	60.2	99.8
S.E.M.	12.3	17.6	13.6

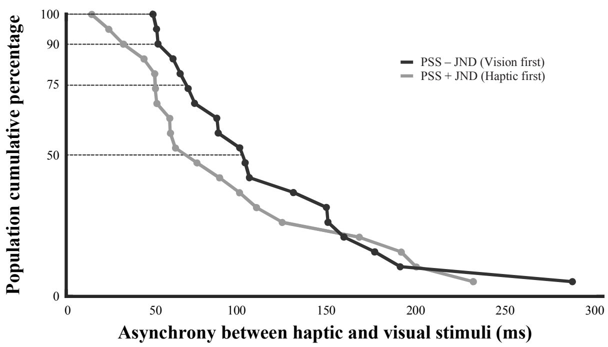

Figure 8: Cumulative analysis of the threshold for judging most stimuli to be asynchronous. The values are obtained by combining PSS obtained from simultaneity judgment (SJ) data and JND obtained with temporal order judgment (TOJ) data. Each participant's data is represented as a horizontal pair of points on the two lines.

IV. Discussion

In this paper, we addressed the perceptual limits of visual-haptic simultaneity in a realistic VR interaction. The average asynchronies required across participant for simultaneity discrimination with the two tasks (Tab. 1 and Tab. 2) are much larger than the ones recorded with non-VR experiments, especially if compared to simple stimuli in passive cases [3][4][5] but still almost twice the ones recorded with dynamic interactions in 2D interfaces [6][7]. We posit that this finding is likely due to the realistic appearance and interactivity of the VR environment employed, factors that have favored cognitive processes like multisensory integration and the unity assumption [13], which should fuse signals into a unique percept making discrimination more difficult. Increasing the realism of the scenario seem thus to have a beneficial effect as it could be making asynchronies to be overall less noticeable.

The results obtained with simultaneity judgments (Fig. 6 and Tab. 1) suggest that sensitivity to visual-haptic asynchrony differs depending on the order of the stimuli, with higher tolerance for visual-first asynchronies. In some cases, it was found that discrimination performance was independent of stimulus order [6]. We speculate that the realistic VR setting employed in the experiment might have led participants to employ a judgment based on causality. It is unlikely that the haptic feedback, which is due to the contact between the finger and the object could happen before the finger reaches the object. The opposite situation is more likely, for example including the case of interacting with very soft objects.

The significant correlation found between the PSS results obtained with the two tasks is in line with others in the literature (i.e., [16]), suggesting that the two types of judgments access the same internal representation of temporal properties. The lack of correlation between WSs and JNDs could instead be ascribed to the different influence of response biases affecting the tasks across participants. Finally, the correlation between precision and accuracy, significant for Simultaneity Judgments but not significant for Temporal Order Judgments, suggests that TOJs can discriminate between the two across participants.

The results of the detection of asynchrony across the population, summarized in Fig. 8, can be used in two ways: (a) to determine the proportion of individuals in the population that will judge visual-haptic stimuli to be non-simultaneous with a specific value of stimulus asynchrony, or (b) to determine the maximum asynchrony at which a proportion of the population would not judge the stimuli as asynchronous. The graph indicates that participants vary up to one order of magnitude in terms of the ability to discriminate asynchrony. While all of the participants in the population tested did not judge stimuli to be asynchronous if the haptic feedback lagged up to 50ms from the view of the contact and 15ms if the vibration came before the vision, some participants required almost 300ms asynchrony. The figure also indicates that to satisfy 90% of the population, the asynchrony needs to be 52ms and 30ms, for 75% it needs to be 78ms and 55ms. The median values (50% of the population) are 100ms and 68ms.

A possible limitation of the results of this study might be that the current implementation of the VR environment has a delay of 70ms in the rendering of the hand. Previous results, however, have shown that changing such a delay has no influence on perceived visual-haptic simultaneity performance, as participants are able to distinguish between absolute delay and asynchrony [6].

In this study, we choose to display a change in color as the visual stimulus at contact. This element of non-realistic appearance should lead to less multi-sensory integration and make asynchrony more noticeable. Our results suggest low temporal discriminability than in the literature, so it is likely that the non-realistic change in color might not have been relevant or might not have decreased realism after all. Mounting a tactor on a different location rather than the fingertip could have a similar effect of decreasing realism. The delivery of haptic feedback that involves skin compression and force feedback could instead increase realism making asynchrony more difficult to perceive.

A factor affecting the generality of the results is related to the anthropometric parameters of the population that took part in the study. It is renown that perceptual sensitivity -among other factors- depends on the participant's age and gender. Further analysis should clarify how such factors relate to the results. The type of movement performed by participants could also have influenced the results. In the literature, sensitivity was found to depend on movement velocity [6]. Future research will consider this factor.

Finally, an observation that should be made is that the study employed only stimuli from two sensory modalities, and it is not clear how adding a sound would influence (either by increasing or decreasing) the sensitivity to asynchronies.

V. Conclusion

Multisensory stimuli in Virtual Reality are generated in response to the user interactions with separate hardware and software pipelines. As such, sensory signals in different modalities could have different latencies. The detection of the latencies and of the resulting asynchronies can negatively influence user experience. These findings can be used as a guideline for haptic feedback in hand-based interactions in Virtual Reality. The range of simultaneity thresholds across participants could provide guidelines to assess what proportion of the population could detect delays if these values are to be exceeded.

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