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Highlights

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- Through pointing tasks, we study effects of hands synchronicity on users' perceived arm fatigue in a VR environment.
- From two experiments and two free-form observations, we extracted guidelines that should help in designing less fatiguing VR applications.
- Selection of the synchronicity of hands should be made in relation to the task performed.
- Distance covered by the hand and changes in user posture could be used in real-time as indicators of fatigue
- It would be better to favor the use of horizontal directions while interaction in mid-air.

The Effect of Hands Synchronicity on Users Perceived Arms Fatigue in Virtual Reality Environment

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Abstract

The use of virtual reality (VR) system has become more common with the arrival of a new generation of headsets. This increase in accessibility has in turn led to VR being used for applications which require longer sessions, such as video games, artistic expression, rehabilitation, and so on. Taking muscular fatigue in account for the VR applications is therefore becoming essential to ensure a comfort of usage and also to avoid injuries. In addition, usual interactions in these diverse applications are very varied and may require the use of one or two hands, synchronized or not. However, little research has focused on fatigue produced by one and two handed interactions especially during mid-air interaction in VR environment. In this paper, we examine the effect of hands synchronicity and movement direction on the user perceived arm fatigue in VR environment during a simple (one line of targets) and a composite (two lines of targets) pointing tasks performed using both controlled and free hands synchronicity. Our findings indicate that to optimize the relationship between fatigue and efficiency, it seems necessary to **select the synchronicity of hands depending on the performed task**. Furthermore, it is desirable to **permit the users to use the hands synchronicity they prefer**. In addition, **distance covered by the hand and changes in user posture could be used in real-time as indicators of fatigue to trigger changes in the interface, or notifications**.

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Finally, our findings reveal that the directions of movement along the vertical axis and some diagonals are more tiring than those of the horizontal plane, which suggests that it would be better to **favor the use of horizontal directions**.

Keywords: Virtual Reality, Borg CR-10, Arm Fatigue, Hands Synchronicity, Pointing, One-handed Interaction, Two-handed Interaction

1. Introduction

Virtual reality (VR) is increasingly popular, with applications providing information and services in a range of settings that include education, rehabilitation, simulations, tourism, museum, games, etc. There are even some of these applications that have become real commercial successes like *Beat-saber*. The popularity of VR can be attributed to (1) the proliferation of VR headsets that offer high qualities in terms of affordance, comfort and practice and to (2) the use of mid-air gestures (with or without sensors such as, buttons and joysticks) to interact with the virtual 3D environment.

Meanwhile, mid-air gestures are particularly interesting for interacting in a virtual environment because: (i) it is already one of the most widespread means of interaction between humans [1], (ii) mid-air gestures interaction offers a large number of degrees of freedom to users, which allows them to articulate gestures with one or two hands using different hands synchronicity [2, 3, 4] and (iii) mid-air gestures are used in the majority of 3D interaction techniques [5, 6, 7, 8] (*e.g.*, objects selection and manipulation [9, 10], navigation [10], rhythmic path-mimicry or distant path tracking with rhythm [11]).

However, due to the “gorilla-arm effect” [12, 13], interacting through mid-air gestures during a long period of time can affect the perceived arm fatigue which can increase the risk of physical injury and consequently can deteriorate the user experience. In this context, several studies in mid-air gesture and VR have been conducted to assist practitioners in this regard [13, 14, 15]. Researchers have, for example, studied the effect of control-display ratio [15, 16] and the effect of mid-air gesture rhythm [17] on perceived fatigue. Other researchers have reported users preferences in arm position [12, 18, 19, 13] and provided specific insight on how alternative gesture sets should be designed [13] to reduce fatigue. Meanwhile, a set of arm fatigue measures have been introduced to characterize the gorilla-arm effect including subjective ones (like Borg [20], NASA-TLX [21] or Likert ratings)

and quantitative ones like the “Consumed Endurance” metric [13].

Besides, despite the prevalence of these two trends (increased VR device adoption and the use of mid-air gestures in VR) and the fact that some previous studies in AR and VR have raised the presence of a feeling of fatigue that depends on the used hands [22, 16, 17], we do not yet know the effect of hands synchronicity on the users perceived arm fatigue in VR environment. In the context of tactile surface, researchers have studied the efficiency of one- and two-handed interaction with a large horizontal screen [23], shoulder and wrist posture and muscle activity when interacting with the touch pad [24].

In this context, we argue that the effect of hands synchronicity on users perceived arm fatigue is an important factor for VR design that has been little explored so far and, consequently, is little understood. For example, among other fundamental questions, one can for instance ask the following: what hands synchronicity causes a faster increase in perceived arm fatigue in VR and how this increase of fatigue impacts the user behavior and performances? There is also a lack of methodology and models to reliably estimate these factors a priori.

In this work, we examine the effect of hands synchronicity on users perceived arm fatigue in VR environment and we provide the community with a first understanding of this phenomenon as well as its potential implications for one and two-handed midair interaction in VR environment.

Our contributions are as follows: (1) we conduct an investigation of the user-perceived arm fatigue in VR environment and deliver results in terms of arm fatigue ratings; in doing so, we examine the effect of different hands synchronicity conditions on users’ perceived arm fatigue and performances in a simple pointing task (one line of targets) and a composite pointing task (two lines of targets); (2) we report correlation results between users’ subjective assessments of fatigue and their performance to enable a better understanding of the phenomena involved in the perception of arm fatigue; as a practical result, we report the covered distance and the elapsed time from the beginning of the task as the highest correlators with users’ perceived arm fatigue; (3) we report user preferences for hands synchronicity to reduce the perceived arm fatigue during free-form observations of free hands synchronicity tasks (the simple pointing task and the composite pointing task); (4) we report novel findings on one handed and two-handed performances in VR and on user behavior; (5) finally, we discuss the implications of findings to one and two-handed interaction in VR environment. We hope our results will prove useful to designers and practitioners interested in minimizing the perceived

fatigue in VR environment.

2. Related Work

In this section, we review previous works on methodologies of fatigue measurement, studies to understand muscular fatigue during interactions and the difference between one and two-handed interactions.

2.1. Methodologies to measure muscular fatigue

Three main methodologies have been used to measure the muscular fatigue. A first method is **electromyography** (EMG) and here the portable version called surface electromyography (sEMG). Florimond [25] described the use of sEMG, providing details on the acquisition and processing of EMG signals. They highlighted the importance of monitoring fatigue for the prevention of injury or re-injury during rehabilitation exercises. Cifrek et al. [26] proposed an analysis of how to use sEMG for specifically measuring muscle fatigue and explain in details how muscle fatigue impacts the EMG signal. As it is quickly explained in the Florimond's work [25], the increase of lactates induces the decrease of the muscle fiber conduction velocity (CV) which in turn impacts the EMG signal by lowering frequencies and increasing amplitude.

The second method is **biomechanics**, which is the study of muscular activity mechanics. According to Motti et al. [27] biomechanical analysis could help identify the movements that present a risk of developing musculoskeletal disorders. The use of a biomechanical model to provide an absolute level of fatigue was limited by the fact that it did not take physical condition into account [28]. Hence biomechanics was more adapted to compare the fatigue induced by various movement strategies. Nevertheless, some methods to quantify muscular fatigue have emerged. In HCI, it was explored by Hincapie-Ramos et al. [13]. They propose a new metric, called Consumed Endurance (CE) for measuring fatigue during mid-air interaction. They use a Kinect depth camera to capture the movements of users and particularly the arm joints (shoulder, elbow, wrist, hand tip). With that they compute the center of mass of the arm [29] and determine via a bio-mechanical model and based on endurance time (ET)[30] definition, the user's CE during interaction. To exploit more efficiently the capacity of the Kinect, Jang et al. proposed another measure based on CE called Cumulative Fatigue (CF) [31]. It would correspond to an enhancement of CE which would take the resting

time into account according to them. However, Liu et al. [32] tested the accuracy of the CF model and found that it underestimated fatigue during activity. And they also found that the longer it was used the less accurate it became. Finally another approach of biomechanical feedback is by using marker-based motion capture (mocap), a method which provides much more information as described by Bachynskyi et al. [33].

The last and most common way to gauge how hard users are exercising is to use **questionnaires** and more precisely the **Borg Scale** of Perceived Exertion [20]. This was what Hincapie-Ramos et al. [13] had used to evaluate their own metric. The main advantages of the Borg scale are to take the physical level of users into account, to be inexpensive and simple to set up. There were multiple versions of the scale but one of the latest was the Borg CR-10 Scale of 2010 [34]. This version uses a scale from 0 to 10, respectively “Nothing at all” and “Extremely hard”. Contrary to other approaches, the Borg scale does not provide a continuous measurement of fatigue, and therefore requires periodic evaluation either verbally or using an interface. It has however been thoroughly validated, which led us to select this approach in our experiments.

2.2. Studies to understand muscular fatigue in HCI

Understanding users’ behavior and the effect of new interactive technology configurations on muscular fatigue, from the early stages of design, empowers designers with valuable information to conceive effective and efficient interaction techniques. Several studies have been conducted in the contexts of touch and mid-air interactions.

For touch interaction, researchers have analyzed the impact of the screen orientation on muscular fatigue [35, 36]. Their findings indicated that horizontal configurations are more comfortable than vertical ones as they reduce the risk of damaging muscles [35] and more precisely a screen with an inclination of 22.5 degrees is the least fatiguing for 13 inches (33cm) screens [36]. Kang et al. [37] examined the ideal location of targets on screen. Their findings indicate that targets with which users interact more should be at the bottom of the screen to reduce the perceived fatigue. List et al. [38] studied the size of the touchscreen to reduce the perceived fatigue [38]. Their findings indicate that a 28inches (71cm) screen is probably the best size to optimize fatigue and performances.

During mid-air interaction, Hincapie et al. [13] found that the best design for a text-entry is obtaining by placing the most used letters on the bottom

right for right-handed people. Liu et al [39] found that arm down gestures imply lower arm fatigue [39, 40]. In addition, producing the pointing movement around the wrist whereas the wrist arm can decrease the arm fatigue for certain interaction techniques [12]. Other researchers have examined the effect of control-display ratio (*i.e.* the reduction or amplification of the visual gesture size) on user experience in term or perceived fatigue. Their findings indicate that the amplitude of the real gesture is the factor with the biggest impact on user perceived fatigue [15, 16]. Other studies have investigated the effect of the fatigue on the produced gesture. For example, that the feeling of fatigue decreases the amplitude of elbow positions [41], and the general movement amplitude [14]. Yang et al. [42] found that when performing a repetitive fatiguing pointing task, the coordination of the shoulder and the elbow is degraded by the fatigue. They also found that the trunk accompany the movement when the shoulder and elbow are too fatigued to compensate [43].

2.3. Studies to compare one-handed and two-handed interactions

Differences between hands synchronicity in HCI have been explored in various situations and under many angles.

For touch devices, Huang et al. [23] studied the efficiency of one handed and two handed interaction technique with a large screen. They concluded that the two handed technique was more accurate than the one-handed one. Kin et al. [44] studied performance of marking menu interaction with 1HR (one hand right), 1HL (one hand left), 2HS “Two-Handed Simultaneous movements” and 2HO “Two-Handed Ordered movements”. Their findings indicate that the two handed techniques were slower than the one-handed techniques, but it could be improved by training and developing muscle memories. They also found that that 2HS “was faster than the one-handed designs and performed with reasonable accuracy” and that 2HO “doubled the number of accessible menu items”. Rekik et al. [45] investigated the effect of hands synchronicity (1HR (one hand right), 1HL (one hand left), 2HS “Two-Handed Synchronous movement” and 2HA “Two-Handed Alternated movements”) on attention demand. Their findings indicate that attention demand is lower when using only the dominant hand than when using two hands synchronized movements or two hands alternated movements. Interestingly, they found that two hand synchronized movements produced faster movements than one hand conditions and two hands alternated movements. In an other study [46], they investigated the effect of hands synchronicity

(one hand sequential movement and two hands synchronous movements) on users' perceived gesture difficulty. They found that two hands gestures are faster and are perceived no more difficult to produce than sequential ones.

In VR, Capabianco et al. [3] showed that for some symmetrical tasks the use of bimanual interaction techniques improve significantly user's performances. However, if the task was asymmetric, the user would require training to increase their efficiency, due to the the increased difficulty. In AR, Chaconas and Hollerer [22] found no difference between one and two-handed interaction in term of efficiency and accuracy but the two handed technique was preferred by users. Interestingly, their findings raised a feeling of fatigue related to the used hands.

To the best of our knowledge, our work is the first to investigate the effect of hands synchronicity on the perceived arm fatigue in VR environment.

3. Experiment 1: Controlled Hands Synchronicity in a Simple Pointing Task

We conducted an experiment to compare the perceived arm fatigue and performance between different hands synchronicity during a simple pointing task (a single line of targets to point at sequentially) in a VR environment. We consider that this task may increase the cognitive load, in particular when using two handed conditions, as it requires to sort and plan movements in order to coordinate the two hands. We were also more curious about arm fatigue than absolute speed performance, and we wished to determine what hands synchronicity and what movement direction invokes more fatigue than the others to accomplish the task. Consequently, this task was performed repeatedly during two minutes for each hands synchronicity and movement direction conditions.

3.1. Participants

Ten participants (all males) volunteered to take part in our experiment, aged between 18 and 39 years (mean=26.5, s.d=6). They were right handed. Five participants used frequently mid-air gestures (*e.g.*, wiimote, psmove, kinect, VR controllers ...), four had already used mid-air gestures at least 2 times and the last one had never tried them.

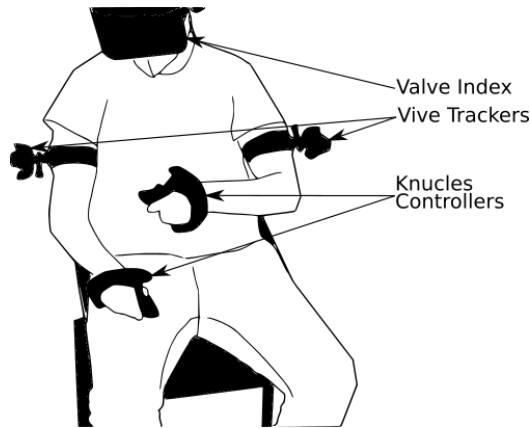


Figure 1: Full equipped seated participant with the Valve Index HMD, the two Knuckles and the two HTC Vive Trackers.

3.2. Apparatus

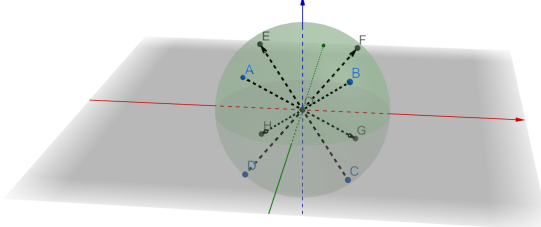
The experiment was conducted on the Valve Index HMD with SteamVR 2.0 sensors. Participants sat just in front of a virtual desk (56 cm high). They interacted with the virtual environment using the Valve Index knuckles. They were also equipped with Vive trackers on each arm to track elbows and shoulders, as shown in Figure 1. Only the hands positions were used in this study, arm positions were kept for further analysis. Noticeably, the Knuckles are attached to the hands and therefore do not require users to maintain a constant grip force. This could potentially attenuate the effect of hand muscle fatigue from the perceived arm fatigue.

The experiment was implemented on Unity. We recorded positions and rotations of the HMD (head), knuckles (hands and associated points corresponding to wrist and fingers' tips), trackers (and positions of associated points corresponding to elbows and shoulders) at a frequency of 90Hz.

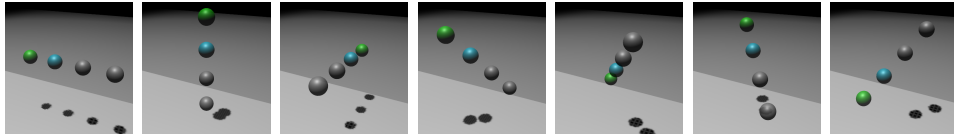
3.3. Design

Independent measures are analyzed using a $4 \times 7 \times 8$ repeated measures within-subjects analysis of variance for the factors: *hands synchronicity*, *direction* and *periods of time*.

For *hands synchronicity*, we tested four different conditions covering the used hands and their synchronicity to accomplish the sequential pointing task: (1) *1HR*: right-handed sequential movements, (2) *1HL*: left-handed



(a) In green the anteroposterior axis, in red the transverse axis, in blue the longitudinal axis and in dark gray the diagonals axes.



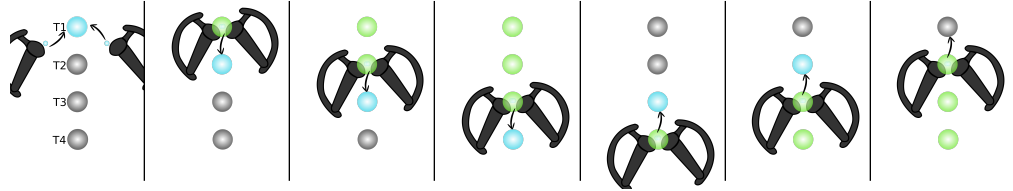
(b) Accordingly to Unity coordinate system (i.e. Y-up and Left-handed), from left to right: $\vec{X} : (1, 0, 0)$, $\vec{Y} : (0, 1, 0)$, $\vec{Z} : (0, 0, 1)$, $\vec{AG} : (-1, 1, -1)$, $\vec{BH} : (-1, -1, 1)$, $\vec{CE} : (-1, 1, 1)$, $\vec{DF} : (-1, -1, -1)$

Figure 2: The 7 directions used in our experiments. With in (a) a schematic representation and in (b) a representation of what can see the user.

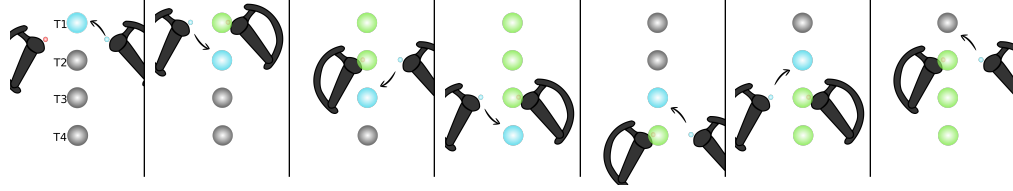
sequential movements, (3) *2HT*: two-handed together movements and (4) *2HO*: two-handed, ordered movements.

For *direction*, which in this experiment is the sequence of movement directions, we consider seven cases: $\vec{X} : (1, 0, 0)$ or transverse axis, $\vec{Y} : (0, 1, 0)$ or longitudinal axis or vertical direction, $\vec{Z} : (0, 0, 1)$ or anteroposterior axis, $\vec{AG} : (-1, 1, -1)$ (corresponding to a movement between right knee and left shoulder), $\vec{BH} : (-1, -1, 1)$ (corresponding to a movement between left knee and right shoulder), $\vec{CE} : (-1, 1, 1)$ (corresponding to a movement between right side of pelvis and around a location in front of left shoulder and above left knee, it corresponds to the maximal extension we will demand for the right hand), $\vec{DF} : (-1, -1, -1)$ (corresponding to a movement between left side of pelvis and around a location in front of right shoulder and above right knee, it correspond to the maximal extension we will demand for the left hand) (refer to figure 2). The different directions are placed on a sphere where the center is placed at 44 cm of the bust of the participant and a height of 70 cm and the diameter of this sphere is 50 cm. We based these values on the mean dimensions of the male human body [47, 48].

For *time*, we consider eight successive time periods: 0-15, 15-30, 30-45, 45-60, 60-75, 75-90, 90-105 and 105-120 seconds. These represent periods during which we measured participants performance and at the end of which



(a) The sequence of target to follow for 1HR, 1HL and 2HT conditions. For the 1HR (respectively 1HL) condition, participant only had to use the right hand (respectively left hand) to validate the target.



(b) The sequence of target to follow for 2HO condition. Participant had to use the active controller to validate the target (the blue one). For 2HO condition, participant had to use the right hand for the first Target (T1), then left hand for T2, then right hand for T3, then left hand for T4, then right hand for T3, then left hand for T2 to complete a trial.

Figure 3: The two types of sequences for the target selection task with the different hand conditions.

participants are reminded by a beep sound to estimate their current fatigue level using the Borg CR-10 scale.

3.4. Procedure & Task

One day before starting the main experiment, participants were instructed to complete an effort task, similar to the isometric exercise proposed by Jang et al. [31], so that they could familiarize themselves with the Borg scale. In addition, participants worn two bracelets of 2.5 kg on each forearm. Two targets of 20 cm were displayed in front of participants so that they have to bend their arm to reach them. Participants were instructed to keep their hands inside the targets for as long as they could without feeling pain. Every 15 seconds a beep was played, to which participants had to reply by giving their level of fatigue following the Borg scale, which was reminded to them multiple times. To fix the period of time, we were first inspired by the methodology of Jang et al. [31] in which the participants were asked to report their current Borg rating every 20 seconds, during each trial. However, as in our experiments, participants used a VR headset, we wondered whether we need or not to shorten this period of time. Consequently, we run preliminary tests with three external users who were asked to rate their fatigue each time

they felt a difference. These preliminary tests confirmed that the period of time should be shorten to 15 seconds.

Participants were instructed to sit on a chair while wearing the virtual reality headset. Participants were, then, instructed to point at spherical targets of 5 cm of diameter as quickly and accurately as possible. Each trial consisted of a sequence of six targets with a *start target* and an *end target*. As shown in Figure 3, participants had to point a sequence of four aligned targets (t1-t2-t3-t4) sequentially in the following order t1, then t2, t3, t4, t3 and finally t2 to complete the trial. Each trial began after the start target (t1) was successfully selected and ended with the selection of the end target (t2). At the beginning of a trial, the start target is active and blue while the remainder targets were inactive and gray.

When one hand is needed to validate the target, if the good hand is inside the target to select, the target turns green and if the wrong hand is inside, the target blinks red and the trial is reinitialized. When two hands are needed to validate the target, if both hands are in the target it turns green, if one hand is inside the target it turns to yellow until the second hand comes inside too, if the hand is withdrawn before the other one is inside the target the trial is reinitialized. If the target is validated and turns green, the next target to select becomes active and turns to blue. Reinitialized trials are counted as errors. After selecting and validating the first four targets (t1-t4) – *i.e.*, the participants reached the end of the line – t1, t2 turns to gray while t3 turns to blue and became active.

Participants were instructed to perform the task using their right hand in *1HR* condition and the left one for *1HL* (cf. figure 3a). By following the same sequence of targets (3a), we instructed participants to use their two hands simultaneously to select one target at a time. For the *2HO* two hands alternated movements condition, participants were instructed to select targets sequentially while alternating hands (cf. figure 3b), always starting with the dominant hand.

In the experiment phase, the four hands synchronicity conditions were presented in a balanced order across participants. Each hand condition was evaluated on a different day. For each, participants completed a 14 minutes pointing task. Each direction is evaluated using a 2 minutes session, separated by a pause (as long as needed) so that participants can rest. Our software application presented the 7 directions in a randomized order – for a total of 224 periods of time of 15 s (4 hands synchronicity \times 7 directions \times 8 periods of time of 15 s).

After each period of time, a sonic beep was played to remind participants to rate their perceived right and left arms fatigue accordingly to Borg CR-10 ratings [13, 20]. The Borg scale provides a ratio-scale measure of physical exertion which values are matched to verbal anchors. Borg CR-10 values range from 0 to 10, where 0 corresponds to “*nothing at all*”, 0.5 to “*extremely low*”, 1 to “*very low*”, 2 to “*low*”, 3 to “*moderate*”, 5 to “*hard*”, 7 to “*very hard*” and 10 to “*extremely hard*” (Maximal).

If participants had not finished the trial in progress before the end of a 15 s period, the trial was counted for the next 15 s. If the 2 minutes ended while a trial was not yet finished, this trial was not considered. At the end of each direction and each hand condition, participants were asked to explain their assessment of fatigue, *i.e.*, what they found less fatiguing for each condition. On average, the experiment lasted 120 minutes, split in four sessions over four consecutive days.

4. Results for Experiment 1 - Controlled

Our results include the level of agreement between participants in terms of perceived fatigue, performance measures, and qualitative observations.

4.1. Consensus between users on the perceived fatigue

We are interested in this section in the level of agreement between participants in terms of their perceived fatigue during the sequential pointing task in a virtual environment. In particular, we analyzed the perceived right arm fatigue and left arm fatigue. To this end, we report and analyze 4480 (2 (right and left arm fatigue) \times 2240 = 4 (hands synchronicity) \times 7 (directions) \times 8 (time periods) \times 10 (participants)) individual ratings of absolute fatigue collected from 10 participants.

We ran a Shapiro-Wilk normality test [49] for the measures of left arm and right arm fatigue which showed that the data was not normal ($.66 < W < .95$ and $p < .0001$). Thus, we used an aligned-rank transform (with ARTool [50, 51] to be able to perform ANOVAs on non-parametric data. We then followed with ART-Contrast for post-hoc tests and used Tukey tests for significant main effects and interactions. We used this analysis methodology for the user performance results and for the second experiment results, since none of our measurements was normal. In the following, we report significant results.

4.1.1. Right Arm fatigue

Overall, we found a moderate degree of agreement between participants' responses, as reflected by Kendall's coefficient of concordance² when rating their right arm fatigue ($W=.523$, $\chi^2(224)=1072$, $p<.0001$) during the experiment. However, Kendall's coefficients remained above .50, which shows large Cohen effect sizes³. These findings indicate that the level of right arm fatigue is perceived by people in a consistent manner, which justifies further investigation.

The level of agreement also remained moderate when we ran the analysis for *1HR*, *2HO* and *2HT* conditions ($.479<W<.584$) with, and without surprise, participants were perfectly in agreement when rating *1HL* ($W=1$). The degree of consensus between participants, stayed moderate when we ran the analysis for each movement direction ($.537<W<.611$). When calculating agreement for each period of time condition, we found that the bigger the period of time, the higher the degree of consensus between participants, with Kendall's W coefficients varying from .378 to .616.

There were statistically significant main effects of *hand* ($F_{3,2.5e+08} = 273.12$, $p < .0001$), *direction* ($F_{6,3.4e+07} = 13.84$, $p < .0001$) and *time* ($F_{7,2.2e+08} = 99.16$, $p < .0001$) on *right arm fatigue* with *hand* \times *direction* ($F_{27,4.1e+07} = 3.72$, $p < .0001$), *hand* \times *time* ($F_{31,2.0e+08} = 18.87$, $p < .0001$) and *direction* \times *time* ($F_{55,3.9e+07} = 1.72$, $p = .0009$) interactions.

Post-hoc tests revealed that *1HR* was rated more fatiguing than *1HL* and *2HO* consistently over all directions and than *2HT* for all direction except \overrightarrow{BH} ($p<.05$). We also found that *1HL* was rated less fatiguing than *2HT* and *2HO* for respectively each direction and \overrightarrow{AG} , \overrightarrow{CE} , \overrightarrow{Y} and \overrightarrow{Z} ($p<.05$). Additionally, on the direction \overrightarrow{BH} , *2HT* was more fatiguing than *2HO* and for the *2HO*, the direction \overrightarrow{Y} was rated more fatiguing than \overrightarrow{BH} ($p<.05$).

We also found that *1HR* was rated more fatiguing than *1HL*, *2HO* and *2HT* from respectively, 45 s-120 s, 60 s-120 s and 75 s-120 s of the exercise

²Kendall's coefficient of concordance is a normalization of the statistic of the Friedman test used to assess continuity of judgment among multiple individuals. W takes values in $[0 \dots 1]$, where 0 denotes no agreement at all and 1 perfect agreement [52].

³Kendall's W coefficient is related to the average of $\binom{n}{2}$ Spearman rank correlation coefficients between pairs of the n rankings [52] (p. 276). Therefore, we use Cohen's suggested limits of .10, .30, and .50 for interpreting the magnitude of the effect size [53].

($p < .05$). In addition when using *1HR*, the 75 s period of time was rated more fatiguing than the three first periods of time (15 s-45 s), and 90 s, 105 s and 120 s were more fatiguing than the four first periods of time (15 s-60 s) ($p < .05$). We also found that *1HL* was rated less fatiguing than *2HT* and *2HO* for the five last periods of time (60 s-120 s) ($p < .05$). Besides, we found that, when using *2HO*, 75 s, 90 s-105 s and 120 s periods of time were rated more fatiguing than respectively the first period of time (15 s), the three first periods of time (15 s-45 s), and the four first periods of time (15 s-60 s) ($p < .05$). When using *2HT*, 60 s and 120 s periods of time were rated more fatiguing than respectively the first period of time (15 s), the four first periods of time (15 s-60 s) and 75 s, 90 s, 105 s were rated more fatiguing than the three first periods of time (15 s-45 s) ($p < .05$).

4.1.2. Left Arm fatigue

Similarly to right arm fatigue, we found a moderate degree of consensus between participants' assessments of left arm fatigue ($W = .511$, $\chi^2(224) = 1042$, $p < .0001$). When calculating agreement for each hands synchronicity condition, Kendall's W coefficients stayed above .5 ($.513 < W < .69$) with a very high level for *1HR* ($W = .921$). The degree of consensus between participants, stayed moderate when we ran the analysis for each movement direction ($.515 < W < .6$). Additionally, we found that the bigger the period of time, the higher degree of consensus between participant with Kendall's W coefficients ranging from .38 to .675.

Repeated-measures ANOVA revealed a statistically significant effect of *hand* ($F_{3,2.1e+08} = 219.08$, $p < .0001$), *direction* ($F_{6,4.0e+07} = 16.57$, $p < .0001$) and *time* ($F_{7,2.2e+08} = 100.36$, $p < .0001$) on *left arm fatigue* with *hand* \times *direction* ($F_{27,5.8e+07} = 5.45$, $p < .0001$), *hand* \times *time* ($F_{31,1.8e+08} = 16.74$, $p < .0001$) and *direction* \times *time* ($F_{55,4.5e+07} = 2.00$, $p < .0001$) interactions.

Post-hoc tests revealed that *1HL* was rated more fatiguing than *1HR*, *2HT* and *2HO* respectively, for all directions, for \overrightarrow{CE} and for all directions except \overrightarrow{AG} , \overrightarrow{BH} ($p < .05$). Additionally, for the *1HL* hands synchronicity, the direction \overrightarrow{CE} was rated more fatiguing than \overrightarrow{AG} , \overrightarrow{BH} , \overrightarrow{X} and \overrightarrow{Z} . We also found that *1HR* was rated less fatiguing than *2HT* and *2HO* for respectively each direction and \overrightarrow{AG} , \overrightarrow{BH} and \overrightarrow{Y} ($p < .05$). In addition, *2HT* was rated more fatiguing than *2HO* on the directions \overrightarrow{CE} , \overrightarrow{DF} , \overrightarrow{Z} and for the *2HT* condition, the direction \overrightarrow{Y} was rated more fatiguing than \overrightarrow{AG} ($p < .05$).

1HL was rated more fatiguing than *1HR* and *2HO* respectively, for 60 s-

120 s and 75 s-120 s periods of time ($p < .05$). In addition when using *1HL* or *2HT*, 60 s and 75 s period of time were rated more fatiguing than respectively the first period of time (15 s) and the three first periods of time (15 s-45 s), and 90 s, 105 s and 120 s were more fatiguing than the four first periods of time (15 s-60 s) ($p < .05$). We also found that *1HR* was rated less fatiguing than *2HT* and *2HO* for respectively the five last periods of time (60 s-120 s) and the four last (75 s-120 s) ($p < .05$). Besides, when using *2HO*, 75 s, 90 s and 105 s-120 s periods of time were rated more fatiguing than respectively the two first periods of time (15 s-30 s), the three first periods of time (15 s-45 s) and the four first periods of time (15 s-60 s) ($p < .05$).

4.2. User Performances

In this section, we report the results for the dependent measures *trial time* and *number of trials*.

4.2.1. Trial time

Trial time is measured as the interval between the first target selection and the last target selection in the sequence of the six targets.

Repeated-measures ANOVA revealed a significant main effect of *hand* ($F_{3,2.4e+08} = 250.28, p < .0001$), *direction* ($F_{6,3.7e+07} = 15.49, p < .0001$) on *trial time* with *hand* \times *direction* ($F_{27,4.3e+07} = 3.98, p < .0001$) interaction.

Post-hoc tests showed that *2HO* is slower than *1HR* and *1HL* for all directions ($p < .05$). Similarly, we found that *2HT* is slower than *1HR* and *1HL* for respectively all directions and all direction except \overrightarrow{AG} and \overrightarrow{BH} ($p < .05$). We also found that *1HL* and *1HR* is slower than *1HR* and *1HL* for respectively \overrightarrow{DF} and \overrightarrow{CE} ($p < .05$).

When using *1HR*, \overrightarrow{Z} and \overrightarrow{CE} are slower than respectively \overrightarrow{X} and all directions except \overrightarrow{Z} ($p < .05$). For *1HL*, \overrightarrow{DF} is slower than \overrightarrow{CE} , \overrightarrow{X} , \overrightarrow{Y} ($p < .05$). We also found that when using *2HO*, \overrightarrow{AG} is slower than \overrightarrow{X} and \overrightarrow{CE} is slower than \overrightarrow{X} and \overrightarrow{Y} ($p < .05$). For *2HT*, \overrightarrow{Y} is faster than \overrightarrow{CE} and \overrightarrow{DF} ($p < .05$).

4.2.2. Number of trials

Number of trials measured the number of trials performed without errors made inside a period of time of 15 s.

Repeated-measures ANOVA revealed a significant effect of *hand* ($F_{3,2.7e+08} = 307.97, p < .0001$), *direction* ($F_{6,4.2e+07} = 17.57, p < .0001$) and *time* ($F_{7,5.9e+07} = 21.60, p < .0001$) on *number of trials* with *hand* \times *direction* ($F_{27,3.2e+07} = 2.95, p < .0001$) interaction.

Descriptors	Descriptions
Trial Dist Trial Dist R Trial Dist L	Average over a period of 15s of the distances covered, when performing a trial, by respectively both, right and left hand(s).
Period Dist Period Dist R Period Dist L	Distance covered, during a period of 15s, by respectively both, right and left hand(s).
Total Dist Total Dist R Total Dist L	Distance covered, since the start of the task, by respectively both, right and left hand(s).
Trial Time	Average over a period of 15s of the trial completion time.
Total Time	Time spent since the start of the task.

Table 1: Arms movements descriptors employed in this study. NOTE: This set of descriptors were computed from raw data of this experiment which is sampled at 90Hz and then re-sampled on 15s periods

Total	Overall		1HR		1HL		2HT		2HO	
	B. R	B. L	B. R	B. L	B. R	B. L	B. R	B. L	B. R	B. L
Borg (B.)										
Distance	.294	.290	.566	-.058	-.036	.498	.381	.482	.338	.324
Dist R	.482	-.064	.572	-.048	.133	.274	.380	.481	.331	.319
Dist L	-.112	.460	.387	-.140	-.027	.503	.383	.485	.344	.327
Time	.352	.356	.672	-.002	.000	.584	.390	.503	.446	.433

Table 2: Correlation results

Post-hoc tests showed using *1HR* or *1HL* imply more trials than when using *2HT* or *2HO*, consistently over all directions ($p < .05$). We also found that *1HL* and *1HR* imply more trials than *1HR* and *1HL* for respectively \vec{CE} and \vec{DF} ($p < .05$). Besides, tests showed using *2HT* implies more trials than *2HO* for \vec{AG} and \vec{Y} directions ($p < .05$).

When using *1HR*, \vec{CE} implies less trials than all directions except \vec{Z} ($p < .05$). For *1HL*, \vec{DF} implies less trials than \vec{CE} , \vec{X} , \vec{Y} ($p < .05$). We also found that when using *2HO*, \vec{AG} and \vec{CE} imply less trials than \vec{X} ($p < .05$). Finally, for *2HT*, both \vec{CE} and \vec{DF} imply less trials than \vec{AG} and \vec{Y} ($p < .05$).

4.3. Correlations between performances & perceived fatigue

We computed the Spearman Correlation between the different user performances measures and participants self perceived fatigue for the right and

left arm. Essentially, if a correlation exists with one or more measures, then those measures can be considered as an indicator of arm fatigue. The number of trials is specific to our tasks and can not be considered as an indicator for fatigue which is confirmed by Spearman correlation ($-.1 < r < .1$). Conversely, covered distance and time are interesting features to characterize arms movements. We are also interested in capturing the evolution of the arm movement during the experiment. Consequently, we proposed three variations for computing covered distance and two variations for computing time, and we denote these variations by respectively *trial*, *period* and *total*. For example, trial right distance corresponds to the mean of the covered distance by right hand by trial during a corresponding period of time. While period right distance represents the overall covered distance by the right hand during the period of time 15s, *total* right distance measures the covered distance by right hand from the starting of the first period of time to the end of the current period of time. In table 1 we provide a description for each feature. We then based our analysis of these correlations on the scale recommended in JASP [54].

Overall, we found a moderate correlation between *total* time and both right ($r = .352, p < .001$) and left arm perceived fatigue ($r = .356, p < .001$). We also found moderate correlation between total right distance and right arm fatigue ($r = .48, p < .001$) and a moderate correlation between total left distance left arm fatigue ($r = .46, p < .001$) (see Table 2). For trial and period features, we found small or trivial correlations ($-.2 < r < .3$).

Regarding correlations for each hands synchronicity conditions, we found that for one-handed conditions (1HR and 1HL), there is a large correlation between the total distance of the used hand and the perceived fatigue for the respective arm. We also found a large correlation between time and the perceived fatigue by the used arm. For example, for 1HR, total right distance and total time were correlated with the right arm perceived fatigue. This suggests that the more the right covered distance/ total time increases, the more the perceived fatigue by the right arm increases. For two handed conditions (2HO and 2HT), we found small correlations between all features and perceived fatigue by both arms.

4.4. Qualitative data and user feedback

In this section, we accompany our quantitative data with qualitative data that we believe provides insights on the different used strategies to reduce perceived fatigue and users feedback and preferences.

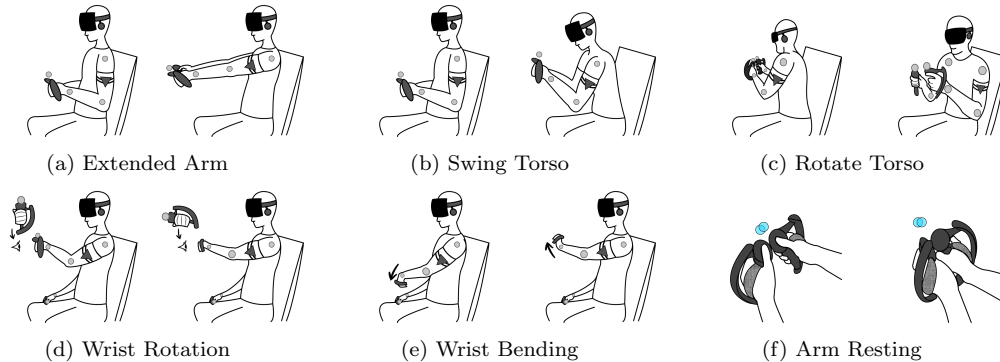


Figure 4: Schematic illustration of the different strategies.

4.4.1. User strategies to reduce perceived fatigue

We report here-after, the five main strategies elaborated by participants in order to reduce arm fatigue, extracted from observations and users comments.

1. **Straightening the bust:** some participants were observed straightening the bust when performing up and down movements for all hands synchronicity. Our participants felt that having a good bust posture was crucial to reduce their fatigue. One participant said: “reaching top targets is complicated and fatiguing. Thus, changing posture and particularly straightening the bust helps me access these targets more easily and with less fatigue”. Additionally, one participant commented that straightening the bust when performing the task with “the *1HR* was more comfortable”. This strategy is correlated to the findings of Côté, Fuller et Yang [41, 14, 42].
2. **Swinging the upper body and the back:** some participants swung their body following the sagittal axis to complete the far and near tasks 4b. Our participants felt that by doing so, they did not have to extend too much their arms to complete the task 4a. One participant said: “swinging the torso back and forth simplifies the movement which makes the exercise less tiring for the arm”. This strategy was also observed in the previous work [41, 14, 42].
3. **Rotating the torso:** for the left right (\vec{X}) direction, some participants tended to rotate around their longitudinal axis 4c to “reduce the fatigue”. They accompanied the movement with the bust to avoid too much arm extension like for the previous strategies. Again this strategy is correlated to the findings of Cote et al. [41, 14, 42].

4. **Using the wrist:** some participants rotated their wrist up to 90° to reduce their perceived arm fatigue 4d. One participant argued that by doing so he “used different muscles which permitted to rest the others and therefore reduced the arm fatigue”. We also observed that some participants used their wrist to augment the amplitude of their movement without involving the others arm joints 4e. Additionally, one participant used continuous circular movement “like a reel” when going from one target to another for the *2HO* configuration.
5. **Supporting one arm with the other:** this strategy is used with *2HT* condition. Some participants took advantage of the proximity of their two hands to rest one hand on the other so that the movement was supported only by one arm (see Figure 4f). Additionally, in order to reduce their fatigue, they regularly switched hands.

4.4.2. User Feedback on Perceived fatigue

We report here user preferences and feedback on perceived fatigue:

- **Preference for the dominant hand:** all participants found that the exercise was easier when using their right hand as it is their dominant hand. However, but interestingly, our participants felt that with the other hands synchronicity conditions, as the exercise is more difficult, their arm speed decreased which in turn decreased the perceived fatigue. For example, one participant who was using the alternating hands condition said: “I had to decrease my movement speed because it is difficult to get the rhythm back when one misses a target”. Conversely, another participant who was using the non-dominant hand *1HL* said “I feel that I am less precise when using my non-dominant hand. Thus, I slow down my movements in comparison with my dominant hand, which in turn decreases fatigue”.
- **Preference for the directions on the horizontal plan:** all participants found that the two directions on the horizontal plan (\vec{X} and \vec{Z}) are the easiest to handle and consequently less fatiguing than the reminder directions. Importantly, the diagonal directions (\vec{BH} , \vec{DF} , \vec{CE} and \vec{AG}) were found hard to handle in particular when the target was on the opposite side of the used arm (\vec{CE} and \vec{DF}). Our participants preferred however \vec{BH} and \vec{AG} directions over \vec{CE} and \vec{DF} ones in terms of perceived fatigue. For instance, our participants were

observed keeping the elbow close to their body when moving through \overrightarrow{BH} and \overrightarrow{AG} directions while with \overrightarrow{CE} and \overrightarrow{DF} , an extension of the arm is needed to complete the task which may demands more physical effort to complete the task. For \overrightarrow{Y} direction, some participants felt that, although this direction was easier than the diagonal ones, it was still more fatiguing than the directions on the horizontal plane as it implied more muscle fatigue. These results support the findings of [35] for horizontal and vertical tactile surfaces.

- **Finding a rhythm might simplify the exercise:** some participants suggested adding music in order to simplify the exercise. Some quotes: “the movement ends up being fully acquired and we can then speed it up, especially when alternating hands which is apparently very rhythmic and which would be funnier if it had been done with music”, “music is missing to give a rhythm to the movement. It would be more fun and more engaging to perform the task”.

5. Free-form observations 1: Free Hands Synchronicity in a One Line Sequential Pointing Task

Our first experiment evaluated each hands synchronicity separately. By doing so, we were able to understand the pros and the cons of each hands synchronicity. However, to better understand the evolution of the arm fatigue during a pointing task accordingly to user preferences, we designed a free hands synchronicity task to observe user’s behavior.

At the end of experiment 1, the ten participants came back one more day to do a free hand simple pointing task. The apparatus and methodology are the same as in the previous experiment. The task was also identical *i.e.*, a pointing task, but it lasted 20 minutes. We only tested the \overrightarrow{Y} direction for a greater range of bio-mechanical effects [35]. Participants were, then, instructed to perform the task as quickly and accurately as possible while being free to use their preferred hand, number of hands and hands synchronicity. Participants could also switch from one hands synchronicity to another whenever they felt fatigued. Participants were also not forced to use all possible hands synchronicity if they didn’t feel the need to.

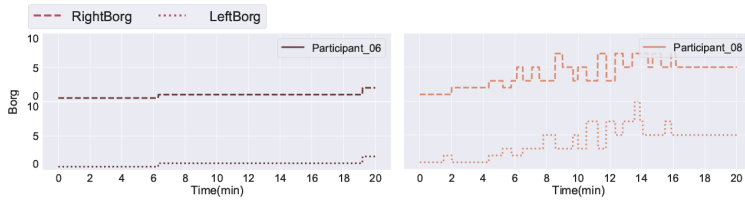


Figure 5: Right and left arm fatigue perceived by users P6 and P8.

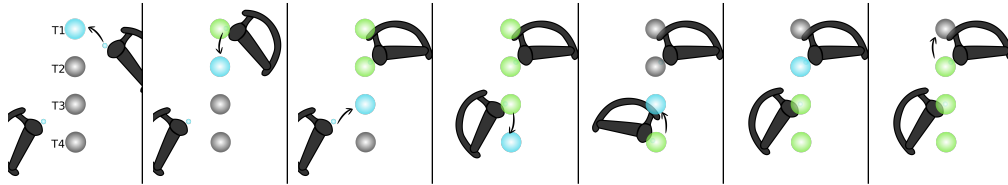


Figure 6: Here is the sequence of target that P9 follows during a short time (less than one minute). Both hands being usable to validate the targets, they are tinted in blue.

6. Results for free-form observations 1

One participant (P1) stopped the task after 10 minutes of exercise as he felt very tired. Consequently, we excluded this participant from the analyses. Below, we report results for our nine remaining participants.

We found that the perceived fatigue for the right and left arm increased either simultaneously (P2, P4, P6, P7, P9 and P10) or alternately (P3, P5 and P8) depending on the participant. Figure 5 shows an example of the evolution of the fatigue in these two cases. Interestingly, for all participants except P3 and P8, the perceived fatigue did not exceed a moderate level (*i.e.*, 3 on the Borg C10 scale), suggesting that participants used efficient strategies to control their fatigue. Regarding the use of hands, all participants used one hand at a time and alternated between 1HR and 1HL hands synchronicity conditions. All of them used one hand during a short period of time (smaller than one minute) and then switched to the other hand and so on. In addition, P10 alternated between right and left hands every one or two trials.

Our participants commented that they “changed their hands whenever they felt that their fatigue was increasing, to permit the current hand to rest”. Some quotes: “by switching frequently my hands, I permit my hands to rest and avoid getting very fatigued”, “using one hand at time protects both my arms from getting very fatigued and the exercise from becoming very hard to do”. Interestingly, none of our participants used the *2HT* synchronicity

during the whole task as they felt that the task did not require the use of two hands. However, we notice that participants P8 and P10 sometimes had both their hands in the bottom targets (*i.e.*, T4 and T3) and that P9 started the exercise by using a variation of *2HO* technique with the left hand on T3 and T4 and the right hand on T1 and T2 as shown on Figure 6. In addition, participants claimed that they “preferred avoiding fatiguing their two hands at the same time and rather distributed the perceived fatigue between the two hands over the exercise”.

7. Discussion for experiment 1 & free-form observations 1

In this section, we discuss our findings on the effect of hands synchronicity on perceived fatigue when performing a simple pointing task.

7.1. Fatigue and gestural interfaces in VR

In the controlled experiment, as suggested by our analysis of Kendall’s *W* concordance coefficients and the finding of increasing consensus between participants’ fatigue ratings over time, we can argue that people tend to converge on the same preferences with practice for these exercises.

Overall, one-handed conditions (*1HR* and *1HL*) were more fatiguing for their respective used arm than the two-handed conditions (*2HO* and *2HT*) in particular for the last periods of time. For the left arm, this result is supported for the diagonals and for the vertical directions (\overrightarrow{BH} , \overrightarrow{DF} , \overrightarrow{CE} and \overrightarrow{Y} for *2HO* and \overrightarrow{CE} for *2HT*). In terms of reduced fatigue, our participants expressed preferences for the directions on the horizontal plane (\overrightarrow{Z} and \overrightarrow{X}) over the vertical and diagonal directions. Consequently, these directions should be used with precautions and only for short periods of time to limit muscle fatigue [55, 56]. This finding is correlated with those of Al-Megren et al. [35] who found that vertical displays were more fatiguing than horizontal ones due to the required arm elevation.

Our participants used only one handed conditions in our free task while alternating the hands very frequently, using each hand for a short period of time and switching to the other hand whenever they felt that their fatigue was growing. This strategy was motivated by the fact that the simple pointing task does not require the use of both hands, and thus our participants preferred using one hand to avoid fatiguing their two hands at the same time. This suggests that one-handed interactions should be preferred over two-handed ones whenever possible, and that gestures should enable users

to freely switch between hands at any time. Additionally, the non-dominant hand should be equally exploited as the dominant hand, but the dominant hand should be picked whenever the used hand is predefined.

Looking at our analysis of correlations, we found that the cumulative covered distances and cumulative time were the most correlated with the perceived arm fatigue. Moreover, we observed a set of body postures changes and strategies used by our participants to reduce their fatigue. Consequently, the covered distance, the time and the change in body posture could be used to detect an increase in the perceived fatigue and consequently to inform gesture design by favoring hands synchronicity and movement directions that are less fatiguing to articulate. Designers should also allow users to rest whenever they feel the need to and slow down their movement speed. Finally, our participants suggested that adding a rhythmic music while performing the task could be a solution to simplify the task and help reducing the perceived fatigue, as proposed by Reynaert et al. [17].

7.2. Performance/Fatigue trade-off

One-handed conditions are generally more efficient than two-handed conditions. In particular, the performance differences are widened for \overrightarrow{CE} and \overrightarrow{DF} directions which correspond to the directions requiring the most extension for respectively the right and the left arm. Our results indicate that the one-handed conditions were faster than the two-handed conditions for some diagonal directions, especially for the \overrightarrow{CE} direction. One-handed conditions were also faster than for the synchronization of ordered hands when moving in the vertical direction (\overrightarrow{Y}). Additionally, the right hand permitted to produce more trials than ordered two-handed movements. This result was consistent across different directions. However, with the right hand more trials are produced compared to the movements produced by both hands together in the targets only for the directions along the three main axes and the \overrightarrow{DF} diagonal. Both one-handed conditions produced more trials when moving in the frontal plane (\overrightarrow{X} and \overrightarrow{Y}) than when moving in diagonal directions (\overrightarrow{CE} for 1HR and \overrightarrow{DF} for 1HL) where one end of the sequence of targets was on the side opposite to the resting position of the used hand which involves the greatest extension through the arm.

Thus, where possible, horizontal directions should be preferred to limit both the muscle fatigue [55, 56, 35] and performance deterioration. However, if diagonal directions should be used, then prefer diagonals that do not need the extension of the left and right arms. Our participants preferred \overrightarrow{BH} and

\overrightarrow{AG} directions over \overrightarrow{CE} and \overrightarrow{DF} ones as with these directions, they kept the elbow close to their body which demands less effort and therefore less fatigue.

Our participants felt that two-handed conditions were more difficult to perform, which is correlated to the findings of [45]. Consequently, they slowed down their movements' speed to remain accurate, which in turn reduced their perceived fatigue. However, our results seem to be contradicting findings in the literature [23, 44, 22], which suggested a greater efficiency of two-handed interactions. In fact, two-handed conditions here seem to be less efficient than one-handed conditions, *i.e.*, longer trial times, lower number of trials. We believe that this is due to our task which favors one-handed interactions through the selection of a sequence of aligned targets while selecting one target at a time. In contrast, we observe that in one handed conditions, participants performed more trials and were more efficient. This increase in speed could explain the higher level of fatigue for one hand conditions.

8. Experiment 2: Controlled Hands Synchronicity in a Composite Pointing Task

We conducted a second experiment to evaluate the effect of hands synchronicity on user perceived arm fatigue and performance during a composite pointing task in VR environment. The composite task is made of two lines of targets to point at, similar to those of the simple task (cf. 3), but can be performed either sequentially using one hand over all the task or done by cooperating the two hands either synchronously or asynchronously (one after the other) such that each hand is concerned by one line of targets. This task, in addition to increasing the cognitive load (in particular when using two handed conditions), would require more effort to accomplish a trial (in particular for the one-handed conditions). As for experiment one, we were more curious about arm fatigue than absolute speed performance and consequently this task was performed repeatedly during two minutes for the different conditions.

The experiment uses the same apparatus than in experiment 1 (see 3.2).

8.1. Participants

Ten new participants (all males) volunteered to take part in our experiment, aged between 22 and 35 years (mean=25.9, s.d=4.5). They were right handed. Three participants used mid-air gestures frequently, three had already used mid-air gestures and four never or rarely did.

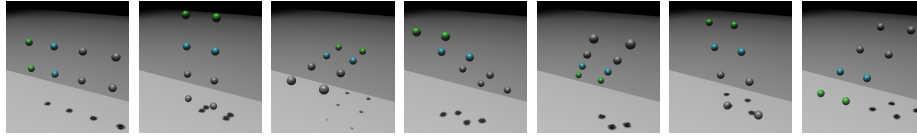


Figure 7: The 7 directions as participants can see in the virtual environment for a small spacing. From left to right: \vec{X} , \vec{Y} , \vec{Z} , \vec{AC} , \vec{BH} , \vec{CE} , \vec{DF} .

8.2. Design

Independent measures are analyzed using a $4 \times 2 \times 7 \times 8$ repeated measures within-subjects analysis of variance for the factors: *spacing*, *hands synchronicity*, *direction* and *periods of time*.

Spacing is the distance between the two sequences of targets (see Figure 7) and covers two values: *large*: 50 cm, *small*: 10 cm. These two values were defined based on the mean dimensions of the male human body [47, 48], the large one corresponding to the mean spacing between shoulders.

Direction and *periods of time* are the same than in experiment one.

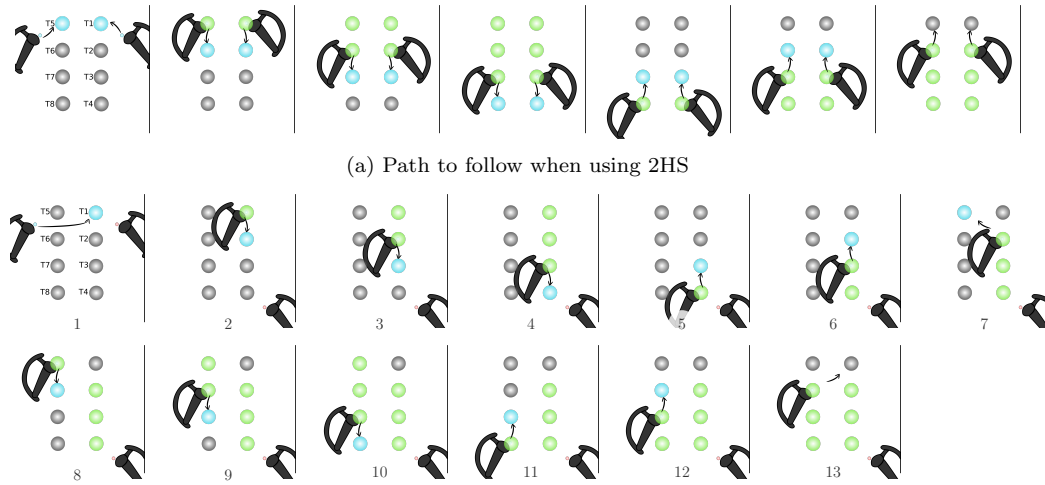
Hands synchronicity covered the used hands and their synchronicity to accomplish the composite pointing task: (1) *1HR*: right-handed sequential movements, (2) *1HL*: left-handed sequential movements, (3) *2HS*: two-handed synchronous movements, and (4) *2HA*: two-handed asynchronous movements. For the two-handed conditions, each hand point on the targets localized on the side closed to this hand. In addition, as we are concerned with the overall duration of the experiment, we decided not to evaluate the two handed synchronicity (*2HT* and *2HO*) used in the first experiment in order to reduce the experiment duration.

8.3. Procedure & Task

One day before starting the main experiment, participants were instructed to complete the same effort task than for the first experiment.

Participants were instructed to point at two sequences of spherical targets of 5 cm of diameter (sequence 1: t1-t2-t3-t4-t3-t2 and sequence 2: t5-t6-t7-t8-t7-t6) as quickly and accurately as possible (see Figure 8).

In the one-handed conditions, participants have to point on the targets sequentially starting by the sequence 1 and then the sequence 2 (*i.e.*, t1-t2-t3-t4-t3-t2-t5-t6-t7-t8-t7-t6). In the two-handed conditions, as here we have two sequence of targets, we consider to use each hand to point the sequence of targets closed to that hand, *i.e.*, with the right hand participants selected



(a) Path to follow when using 2HS

(b) Path to follow when using 1HR, 1HL, 2HA. For 1HR, participant had to use only the right hand. For the 2HA, participant had to use the right hand for the right line (T1-4) and then the left hand for the left line (T5-8).

Figure 8: Targets selection sequences.

the sequence 1, and with the left hand the sequence 2. Consequently, for *2HS*, participants were instructed to use their both hands simultaneously, each hand selecting the corresponding sequence of targets. For the *2HA* condition, participants were instructed to complete at first the sequence 1 with their right hand and then the sequence 2 with the left hand.

For *1HR*, *1HL* and *2HA*, each trial began after the target t_1 was successfully selected and ended with the selection of the target t_6 . While in the *2HS*, each trial began after the targets t_1 or t_5 were successfully selected and ended by the selection of the targets t_2 and t_6 . The coloring of targets follow the same rules as in the first experiment (see 3.4). Unlike our first experience, at no time do we need to have both hands in the target. Finally, for the *2HS*, we do not count an error if the two targets to validate are not pointed at the exact same time, the only constraint is that the next trial can start only when the two last targets (*i.e.* t_2 , t_5) are selected.

In the experiment phase, we used similar procedure than in the first experiment (see 3.4). The only difference comes from the addition of the spacing conditions. These were presented in a balanced order across participants for each hands synchronicity condition. So that, participants completed two times a 14 minutes pointing task with a 10 minutes break in between. On average, the experiment took 240 minutes done over four days.

9. Results for Experiment 2 - Controlled

9.1. Consensus between users on the perceived fatigue

We report here the level of agreement between participants in terms of their right arm fatigue and left arm fatigue during a pointing task (of two sequences of targets) in a virtual environment. We analyzed 8960 (2 (right and left arm fatigue) $\times 4480 = 4$ (hands synchronicity) $\times 7$ (directions) $\times 8$ (time periods) $\times 10$ (participants) $\times 2$ (spacings)) individual ratings of absolute fatigue collected from 10 participants.

In the following, we report significant results.

9.1.1. Right Arm fatigue

We found a lower degree of consensus between participants' assessments of right arm fatigue, as opposed to experiment 1. However, Kendall's coefficients stayed above .4, which is confirmed by moderate Cohen effect sizes ($W=.446$, $\chi^2(442)=1972$, $p<.0001$). When calculating agreement for each hands synchronicity condition, Kendall's W coefficients stayed above .4 ($.403 < W < .561$ for *1HR*, *2HA* and *2HS* conditions). The level of agreement between participants also stayed moderate when we ran the analysis for each movement direction condition ($.383 < W < .544$) and each spacing condition (large: $W=.469$ and small: $W=.466$). Like in experiment 1, we also found that the bigger the period of time, the higher the degree of consensus between participants, with Kendall's W coefficients varying from .198 to .518.

Repeated-measures ANOVA tests revealed significant main effects of *hands* ($F_{3,2.5e+09} = 757.14$, $p < .0001$), *direction* ($F_{6,6.3e+08} = 69.24$, $p < .0001$), *spacing* ($F_{1,9.9e+07} = 60.73$, $p < .0001$) and *time* ($F_{7,2.3e+09} = 289.94$, $p < .0001$) on right arm fatigue with *hands* \times *direction* ($F_{27,6.9e+08} = 16.68$, $p < .0001$), *hands* \times *spacing* ($F_{7,1.8e+08} = 15.86$, $p < .0001$), *hands* \times *time* ($F_{31,2.2e+09} = 58.05$, $p < .0001$), *direction* \times *spacing* ($F_{13,7.5e+07} = 3.49$, $p < .0001$), *direction* \times *time* ($F_{55,6.6e+08} = 7.78$, $p < .0001$), *spacing* \times *time* ($F_{15,1.8e+08} = 7.65$, $p < .0001$), *hands* \times *direction* \times *time* ($F_{223,7.8e+08} = 2.22$, $p < .0001$), *hands* \times *direction* \times *spacing* ($F_{55,2.9e+08} = 3.25$, $p < .0001$), *hands* \times *spacing* \times *time* ($F_{63,3.8e+08} = 3.80$, $p < .0001$) interactions.

Post-hoc tests revealed that *1HR* was rated more fatiguing than *1HL* in \overrightarrow{CE} , \overrightarrow{DF} and \overrightarrow{Y} directions for the four last period of time (75 s-120 s), in \overrightarrow{AG} and \overrightarrow{Z} for 90 s-120 s and in \overrightarrow{BH} and \overrightarrow{X} for 105 s-120 s and *1HR* was more fatiguing than *2HA* in \overrightarrow{AG} for 105 s-120 s, in \overrightarrow{CE} for 60 s, 90 s and

105 s, in \overrightarrow{DF} for 90 s and in \overrightarrow{Z} for 105 s ($p < .05$). In addition, when using *1HR*, the last period of time (120 s) was rated more fatiguing than 15 s-30 s in the direction \overrightarrow{Y} , than 15 s-45 s in all directions except \overrightarrow{AG} and \overrightarrow{Y} and than 15 s-60 s in \overrightarrow{AG} , the period of time 105 s was rated more fatiguing than 15 s-30 s in the directions \overrightarrow{BH} , \overrightarrow{DF} and \overrightarrow{Y} , than 15 s-45 s in \overrightarrow{AG} , \overrightarrow{CE} , \overrightarrow{X} and \overrightarrow{Z} , the period of time 90 s was rated more fatiguing than 15 s-30 s in the directions \overrightarrow{DF} , \overrightarrow{Y} and \overrightarrow{Z} , than 30 s in \overrightarrow{AG} and finally the period of time 90 s was rated more fatiguing than 15 s-30 s in the direction \overrightarrow{Y} ($p < .05$). Besides, *1HL* was rated less fatiguing than *2HS* in \overrightarrow{Y} direction for the four last period of time (75 s-120 s), in \overrightarrow{CE} , \overrightarrow{DF} , \overrightarrow{X} and \overrightarrow{Z} for 105 s-120 s and in \overrightarrow{AG} and \overrightarrow{BH} for 120 s ($p < .05$). In addition, we found when using *2HS* that the last period of time (120 s) was rated more fatiguing than 15 s-30 s in the direction \overrightarrow{AG} , than 15 s-45 s in the directions \overrightarrow{DF} , \overrightarrow{Y} and \overrightarrow{Z} and than 15 s-60 s in \overrightarrow{X} , the period of time 105 s was rated more fatiguing than 15 s-30 s in the directions \overrightarrow{DF} and \overrightarrow{Z} , than 15 s-45 s in \overrightarrow{X} and \overrightarrow{Y} , the periods of time 90 s and 70 s were rated more fatiguing than respectively 15 s-45 s and 15 s-30 s in the direction \overrightarrow{Y} ($p < .05$). We also found that, when using *2HA*, the period of time 120 s was rated more fatiguing than 15 s-45 s in the direction \overrightarrow{Y} ($p < .05$).

Tests also revealed that with both spacings and over each directions, *1HR* was rated more fatiguing than *1HL* and *2HA* and *1HL* was rated less fatiguing than *2HS* ($p < .05$). In addition, we found that *1HR* was rated more fatiguing than *2HS* for \overrightarrow{AG} and \overrightarrow{DF} with both spacings and for \overrightarrow{CE} with large spacing ($p < .05$). Further, we found that *2HA* was rated more fatiguing than *1HL* for \overrightarrow{Y} with both spacings and for \overrightarrow{CE} and \overrightarrow{Z} with large spacing ($p < .05$). We also found that *2HS* was rated more fatiguing than *2HA* for \overrightarrow{CE} , \overrightarrow{DF} and \overrightarrow{X} with both spacings, for \overrightarrow{BH} with large spacing and for \overrightarrow{AG} and \overrightarrow{Z} with small spacing ($p < .05$). In addition, when using *1HR*, \overrightarrow{DF} and \overrightarrow{Y} were rated more fatiguing than \overrightarrow{BH} with both spacings and than \overrightarrow{X} with small spacing and \overrightarrow{AG} , \overrightarrow{CE} and \overrightarrow{Z} were rated more fatiguing than \overrightarrow{BH} with small spacing ($p < .05$). Finally, when using *2HA* or *2HS* with small spacing \overrightarrow{Y} was rated more fatiguing than all other directions and when using *2HS* with large spacing \overrightarrow{X} and \overrightarrow{Y} were rated more fatiguing than respectively \overrightarrow{AG} and all diagonal directions ($p < .05$).

9.1.2. Left Arm fatigue

Similarly to right arm fatigue, we found a moderate degree of consensus between participants' assessments of left arm fatigue ($W=.535$, $\chi^2(442)=2365$, $p<.0001$). When calculating agreement for each hands synchronicity, Kendall's W coefficients stayed above .4 ($.404 < W < .548$ for *1HL*, *2HA* and *2HS* conditions). The level of agreement between participants also stayed moderate when we ran the analysis for each movement direction condition ($.487 < W < .657$) and each spacing condition (large: $W=.547$ and small: $W=.550$). Like in experiment 1, we also found that the bigger the period of time, the higher the degree of consensus between participants, with Kendall's W coefficients varying from .363 to .657.

Repeated-measures ANOVA revealed a significant effect of *hands* ($F_{3,2.7e+09} = 869.32$, $p < .0001$), *direction* ($F_{6,6.e+08} = 67.76$, $p < .0001$), *spacing* ($F_{1,3.7e+07} = 22.39$, $p < .0001$) and *time* ($F_{7,2.3e+09} = 290.07$, $p < .0001$) on right arm fatigue with *hands* \times *direction* ($F_{27,6.1e+08} = 14.58$, $p < .0001$), *hands* \times *spacing* ($F_{7,1.7e+08} = 15.23$, $p < .0001$), *hands* \times *time* ($F_{31,2.0e+09} = 53.62$, $p < .0001$), *direction* \times *spacing* ($F_{13,9.7e+07} = 4.53$, $p < .0001$), *direction* \times *time* ($F_{55,7.2e+08} = 8.62$, $p < .0001$), *spacing* \times *time* ($F_{15,1.3e+08} = 5.12$, $p < .0001$), *hands* \times *direction* \times *time* ($F_{223,7.5e+08} = 2.13$, $p < .0001$), *hands* \times *direction* \times *spacing* ($F_{55,2.3e+08} = 2.58$, $p < .0001$), *hands* \times *spacing* \times *time* ($F_{63,2.4e+08} = 2.32$, $p < .0001$) interactions.

Post-hoc tests revealed that *1HL* was rated more fatiguing than *1HR* in \overrightarrow{AG} , \overrightarrow{CE} , \overrightarrow{DF} and \overrightarrow{Y} directions for the five last period of time (60 s-120 s) and in \overrightarrow{BH} , \overrightarrow{X} and \overrightarrow{Z} for 75 s-120 s and *1HR* was more fatiguing than *2HA* in \overrightarrow{AG} for 60 s, in \overrightarrow{BH} for 90 s-120 s, in \overrightarrow{X} for 75 s-90 s and in \overrightarrow{Z} for 75 s ($p<.05$). In addition, when using *1HL*, the last period of time (120 s) was rated more fatiguing than 15 s in the direction \overrightarrow{Z} , than 15 s-30 s in the direction \overrightarrow{CE} and than 15 s-45 s in \overrightarrow{BH} and \overrightarrow{Y} , the period of time 105 s was rated more fatiguing than 15 s-30 s in the direction \overrightarrow{CE} , than 15 s-45 s in \overrightarrow{Y} and the period of time 90 s was rated more fatiguing than 15 s-30 s in the direction \overrightarrow{Y} ($p<.05$). Besides, *1HR* was rated less fatiguing than *2HS* in \overrightarrow{Y} direction for the four last period of time (75 s-120 s), in \overrightarrow{CE} and \overrightarrow{DF} for 75 s-120 s and in \overrightarrow{AG} , \overrightarrow{BH} and \overrightarrow{Z} for 105 s-120 s ($p<.05$). In addition, we found when using *2HS* that the last period of time (120 s) was rated more fatiguing than 15 s-45 s in the directions \overrightarrow{AG} , \overrightarrow{CE} , \overrightarrow{Y} and \overrightarrow{Z} and than 15 s-60 s in the direction \overrightarrow{DF} , the period of time 105 s was rated more fatiguing than 15 s-30 s in the direction \overrightarrow{Z} and than 15 s-45 s in \overrightarrow{AG} , \overrightarrow{CE} , \overrightarrow{DF} and \overrightarrow{Y} , the

period of time 90 s was rated more fatiguing than 15 s-30 s in the direction \overrightarrow{DF} and than 15 s-45 s in \overrightarrow{Y} and the period of time 70 s was rated more fatiguing than 15 s-30 s in the direction \overrightarrow{Y} ($p < .05$). We also found that, $1HR$ was rated less fatiguing than $2HA$ for 120 s in \overrightarrow{DF} and for 105 s-120 s in \overrightarrow{Y} and when using $2HA$, the period of time 120 s was rated more fatiguing than 15 s-30 s in the direction \overrightarrow{DF} and than 15 s-45 s in the direction \overrightarrow{Y} and the period of time 105 s was rated more fatiguing than 15 s-30 s in the directions \overrightarrow{DF} and \overrightarrow{Y} ($p < .05$).

Tests also revealed that over each directions, $1HL$ was rated more fatiguing than $1HR$ and $2HA$ with both spacing and $1HR$ was rated less fatiguing than $2HS$ with large spacing and with small spacing except for the direction \overrightarrow{X} ($p < .05$). In addition, we found that $1HL$ was rated more fatiguing than $2HS$ for \overrightarrow{AG} , \overrightarrow{CE} , \overrightarrow{X} and \overrightarrow{Z} with both spacings and for \overrightarrow{BH} and \overrightarrow{DF} with large spacing ($p < .05$). Further, we found that $2HA$ was rated more fatiguing than $1HR$ for \overrightarrow{DF} and \overrightarrow{Y} with both spacings and for \overrightarrow{AG} , \overrightarrow{CE} and \overrightarrow{Z} with large spacing ($p < .05$). We also found that $2HS$ was rated more fatiguing than $2HA$ for \overrightarrow{CE} , \overrightarrow{DF} and \overrightarrow{X} with both spacings, for \overrightarrow{BH} and \overrightarrow{Y} with both spacings and for \overrightarrow{AG} , \overrightarrow{CE} and \overrightarrow{Z} with small spacing ($p < .05$). In addition, when using $1HL$, \overrightarrow{CE} and \overrightarrow{Y} were rated more fatiguing than \overrightarrow{X} with large spacing ($p < .05$). Further, when using $2HA$ with large spacing, \overrightarrow{CE} was rated more fatiguing than \overrightarrow{X} with small spacing, \overrightarrow{DF} and \overrightarrow{Y} were rated more fatiguing than \overrightarrow{AG} and \overrightarrow{BH} and \overrightarrow{Y} was rated more fatiguing than \overrightarrow{CE} , \overrightarrow{X} and \overrightarrow{Z} ($p < .05$). Finally, when using $2HS$ with both spacings \overrightarrow{CE} and \overrightarrow{Y} were rated more fatiguing than respectively \overrightarrow{X} and all directions except \overrightarrow{CE} and with small spacing \overrightarrow{DF} was rated more fatiguing than \overrightarrow{x} ($p < .05$).

9.2. User Performances

This section reports statistical tests for the same dependent variables than in experiment 1.

9.2.1. Trial time

There were significant main effect of hands ($F_{3,1.9e+09} = 495.94$, $p < .0001$), direction ($F_{6,5.2e+08} = 55.58$, $p < .0001$), spacing ($F_{1,8.9e+08} = 606.50$, $p < .0001$) and time ($F_{7,7.1e+07} = 6.11$, $p < .0001$) on trial time with $hands \times direction$ ($F_{27,3.5e+08} = 8.06$, $p < .0001$) and $hands \times spacing$ ($F_{7,3.5e+08} = 31.86$, $p < .0001$) interactions.

Post-hoc tests revealed that $1HR$ is faster than $1HL$ for the directions \overrightarrow{AG} and \overrightarrow{DF} and in the opposite, $1HL$ is faster than $1HR$ for \overrightarrow{CE} ($p <$

.05). In addition, for all directions, $2HS$ is faster than remaining hands synchronicities ($p < .05$). $2HA$ is faster than $1HR$ (respectively $1HL$) when moving the hands in \overrightarrow{CE} (respectively, \overrightarrow{DF} , \overrightarrow{AG} and \overrightarrow{Y}) directions ($p < .05$). Additionally, with $2HS$, \overrightarrow{Y} direction is faster than all remaining directions and \overrightarrow{Z} is faster than \overrightarrow{X} ($p < .05$). For $2HA$, \overrightarrow{BH} direction is faster than \overrightarrow{CE} , \overrightarrow{Y} is slower than all remaining directions except \overrightarrow{BH} and \overrightarrow{Z} is slower than the directions \overrightarrow{AG} and \overrightarrow{BH} ($p < .05$). For $1HR$, \overrightarrow{CE} direction is slower than all remaining directions and \overrightarrow{Y} is faster than the other directions except \overrightarrow{DF} ($p < .05$). For $1HL$, \overrightarrow{Y} is slower than \overrightarrow{AG} , \overrightarrow{DF} and \overrightarrow{Z} , \overrightarrow{AG} and \overrightarrow{DF} are slower than \overrightarrow{BH} , \overrightarrow{CE} and \overrightarrow{X} and, finally, \overrightarrow{DF} is slower than \overrightarrow{Z} ($p < .05$).

When using one hand conditions and $2HS$, the large spacing demands more time than the small spacing to complete the task ($p < .05$). For both spacings, $1HL$ is slower than $1HR$ ($p < .05$). Additionally, for the large spacing, $1HL$ and $1HR$ are slower than $2HA$ ($p < .05$). For both spacings, $2HS$ is faster than the three remaining hands synchronicities ($p < .05$).

9.2.2. Number of trials

There were significant main effects of hands ($F_{3,2.4e+09} = 734.48$, $p < .0001$), direction ($F_{6,5.0e+08} = 54.25$, $p < .0001$), spacing ($F_{1,1.4e+09} = 1074.16$, $p < .0001$) and time ($F_{7,6.7e+08} = 63.37$, $p < .0001$) on number of trials with $hands \times direction$ ($F_{27,4.6e+08} = 10.97$, $p < .0001$), $hands \times spacing$ ($F_{7,5.9e+08} = 55.57$, $p < .0001$) interactions.

Post-hoc tests revealed that $1HR$ implies more trials than $1HL$ for the directions \overrightarrow{AG} and \overrightarrow{DF} ($p < .05$). In addition, for all directions, $2HS$ produced more trials than all hands synchronicities ($p < .05$). $2HA$ is faster than $1HL$ when moving the hands in \overrightarrow{AG} , \overrightarrow{BH} and \overrightarrow{DF} directions ($p < .05$). With $2HS$, \overrightarrow{Y} (respectively, \overrightarrow{Z}) direction produced more trials than all remainder directions (respectively, \overrightarrow{X} direction) ($p < .05$). For $2HA$, \overrightarrow{CE} and \overrightarrow{Z} directions imply less trials than \overrightarrow{AG} , \overrightarrow{BH} and \overrightarrow{Y} and \overrightarrow{Y} implies more trials than \overrightarrow{DF} and \overrightarrow{X} ($p < .05$). With $1HR$, \overrightarrow{CE} produced less trials than both \overrightarrow{X} and \overrightarrow{Z} directions which imply less trials than \overrightarrow{Y} and both \overrightarrow{DF} and \overrightarrow{Y} produced more trials than \overrightarrow{AG} , \overrightarrow{BH} and \overrightarrow{CE} ($p < .05$). While with $1HL$, \overrightarrow{DF} implies less trials than all remaining directions except \overrightarrow{AG} which implies less trials than \overrightarrow{BH} , \overrightarrow{CE} , \overrightarrow{Y} and \overrightarrow{Z} directions ($p < .05$).

When using any hands synchronicity, small spacing produced more trials than large spacing ($p < .05$). Additionally, for both large and small spacing, $2HS$ produced more trials than $1HR$, $1HL$ and $2HA$ conditions ($p < .05$).

<i>Cumul</i>	Overall		1HR		1HL		2HS		2HA	
	B. R	B. L	B. R	B. L	B. R	B. L	B. R	B. L	B. R	B. L
Borg (B.)										
Distance	.299	.266	.601	-.129	-.066	.564	.431	.458	.288	.348
Dist R	.458	-.178	.603	-.112	-.226	.348	.433	.462	.285	.339
Dist L	-.096	.521	.387	-.290	-.046	.580	.428	.454	.288	.356
Time	.379	.36	.665	-.002	.002	.624	.553	.573	.385	.426

Table 3: Correlation results

We also found that, for both spacings, *1HR* implies more trials than *1HL* ($p < .05$). For small spacing, *2HA* produced more trials than both one handed conditions ($p < .05$). Finally, for large spacing, *2HA* produced less trials than *1HR* ($p < .05$).

9.3. Correlations between performances & perceived fatigue

As in experiment 1, we computed the Spearman Correlation between the different users performances measures and participants self perceived fatigue for right arm and left arm (see Table 1). Overall, we found that cumul right distance is moderately correlated with right arm fatigue ($r = .458$, $p < .001$). Similarly, cumul left distance correlated largely with left arm fatigue ($r = .521$, $p < .001$) (see Table 3). Regarding correlations for each hands synchronicity conditions, we found that for one-handed conditions (*1HR* and *1HL*), there is a large correlation between the perceived fatigue by the respective arm and both time and the cumul distance of the used hand. For two handed conditions (*2HA* and *2HS*), we found moderate correlations between all features and perceived fatigue by both arms.

9.4. User Feedback on Perceived fatigue

Our participants were observed using three of the five strategies used in experiment 1 to reduce their arms fatigue, namely (1) straightening the bust, (2) swinging the upper body and the back, and (3) using the wrist. In addition two new strategies were observed:

- **Changing the movement articulation:** most of our participants found that depending on movement direction, the task could be physically demanding for the shoulders which increased the perceived arm fatigue and consequently they changed the articulation of their movement by using the elbow more. This strategy was used for all hands

synchronicity but seemed to depend on the movement direction. For example, one participant using the *1HR* while moving through \overrightarrow{BH} direction said “depending on the direction, the task involves different muscles. For example, for the current direction, only the elbow moves so it is not really fatiguing. However, when moving vertically, my back cannot help the movement so shoulders are very fatigued, that’s why I changed my movement and used the elbow more.”

- **Resting the arm during the task:** our participants commented that when pointing on the bottom targets, they took advantage of this situation to rest the used arm. One participant using the *1HR* with \overrightarrow{X} direction said “here, my arm is able to rest because my elbow is closed to my belly when I am selecting the bottom targets.” In addition when using *2HA*, our participants commented that as this condition divided the task between hands in asynchronous style, it allowed them to rest one arm while the second was performing the task which reduce the perceived fatigue. One quote “I put my hand on my knee to rest when the other is working.”

Participants found that the task was easier and less fatiguing when using the two handed asynchronous movements condition than when using the remainder hands conditions as they were able to rest their non used arm whatever the second hand was performing the task. Some quotes: “alternating hands does not fatigue much because there is always one resting arm when the other is completing the exercise” and “using one hand than the second is much easier than when using one hand over the task or the two hands on the same time”. This feedback is correlated with our findings in free-form observations 1 where our participants used one hand interaction while alternating the hands each time they felt their perceived arm fatigue would increase. In contrast, our participants felt that the *2HS* condition, while it was faster as in the same time each hand made a part of the task, it was the most fatiguing for both the arms and the back. In addition, our participants felt that the *1HL* condition was also a difficult and fatiguing input condition as in this condition “only the non-dominant hand is used”.

As in experiment 1, our findings indicate that the horizontal direction \overrightarrow{Z} should be preferred while the diagonals directions should be used with precaution, in particular for the diagonals that demand the extension of the arm (\overrightarrow{CE} and \overrightarrow{DF}). However, contrarily to experiment 1, for \overrightarrow{Y} direction, our findings indicate that while it is a fatiguing direction, it is the most

efficient direction in particular for the two handed conditions. This finding could be explained by the fact that the task is parallel to the user body and symmetric. Consequently, frontal plan could be exploited for short time exercise, as long as the task is symmetric and could be performed by the two hands. However, when moving the hands through \vec{X} direction, our findings indicate that the task is very complicated in particular when using 2HS. This could be explained by the fact that with this direction, the user must place one hand above the other.

Finally, for the spacing distance between the two lines of targets, nine of our participants expressed preference to the smallest one over the largest one as they found the largest one demanding “more physical effort and time”. For example, one participant said: “the large spacing forces me to turn the head to follow the movement on the lines and it lead to more mistakes and so it is more complicating than the small one”. The remainder participant found the large spacing “more engaging because it requires more thinking and so it is less boring.”

10. Free-form observations 2: Free Hands Synchronicity in a Two Lines Sequential Pointing Task

Our previous experiment (cf. section 8) evaluated each hands synchronicity separately. By doing so, we are able to understand the pros and the cons of each hands synchronicity. However, to better understand the evolution of the arm fatigue during a composite pointing task accordingly to user preferences, we designed a free hands synchronicity experiment.

At the end of experiment 2, the ten participants came back one more day to perform a free hands composite pointing task. The task was identical to the previous experiment *i.e.*, pointing task but during 10 minutes per spacing. We tested only one direction axis, and selected the \vec{Y} direction. As in free-form observations 1, participants could switch from one hand synchronicity to another whenever they felt fatigued. Participants were also not forced to use all possible hands synchronicity if they didn’t feel the need to. Finally, we asked participants to rate their right and left arms fatigue every 15s.

11. Results for free-form observations 2

One participant (P1) used two hands synchronous movements over all the task and for both spacing conditions. For this participant, the perceived

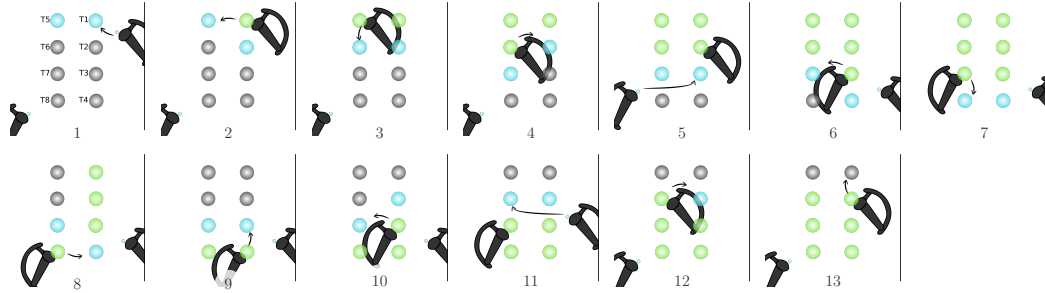


Figure 9: Example of a path followed by the participant P4. (P3 and P5 followed the same path of targets but with only one hand at a time.)

fatigue for both arms did not exceed the level of moderate for the large space condition. However, for the small condition, the perceived fatigue increased from extremely low to moderate and then strong (5) at 9min. In contrast, the remainder participants did not use the two handed synchronous movements as they preferred alternating the perceived fatigue between hands during the task in order not to fatigue both hands simultaneously.

Eight participants (P3, P5-P7, P9-P10 over all the task, P4 for large spacing condition and P8 for small spacing condition) used mainly one handed synchronicity while alternating between 1HR and 1HL conditions. Like in free-form observations 1, four (P4, P7, P10 and P9) of them used the same hand during a short period of time smaller than one minute (P4 around 15s, P7 around 30s, P9 around 1min30s and P10 mostly changed at every 1 or 2 trials) and then switched to the other hand and so on. For three of these four participants (P4, P7, P10), the perceived fatigue did not exceed a moderate level (3). However, P9, who alternated less frequently than the three other participants, reached highest level of perceived fatigue and explained that “*I have tried to use my two hands simultaneously but it was too fatiguing so I decided to alternate my hand when I felt very or extremely fatigued*”. The next two participants (P6 and P8) used mainly one-handed synchronicity with an optimization *i.e.* when they finished a trial on the left sequence of targets, they started the next one on the left sequence of targets and vice versa. Participant P6 alternated between right and left hands less frequently than P8 and his perceived fatigue increased and decreased alternatively between very light (1) and hard (5) while for P8 the perceived fatigue was stable from light (2) to moderate(3). P3 and P5 did not follow the classical way to complete trials. Instead of following a sequence of targets as we had defined

for experiment 2, they go back and forth between the two sequences of targets (*e.g.*, T1-T5-T6-T2-T3-T7-T8-T4-T3-T7-T6-T2). For both of them on the small spacing, the fatigue increased and decreased simultaneously on the two arms and did not exceed a moderate level (3). However, for large spacing condition, P5 had a similar result but his perceived fatigue reached a hard level of fatigue (5). Meanwhile, P3 had a peak of fatigue on the left arm probably caused by an exclusive use of the left arm during approximately one minute.

Two participants (P2 over all the task and P8 for large spacing condition) used mainly two hands asynchronous movement 2HA with an optimization in their arm fatigue by starting the next trial with the last used hand in the previous trial. Consequently, their “*arms were not moving at the same time which permit to rest one hand while the other is doing the task*” implying a stable perceived arm fatigue between 2 and 3.

For small spacing, one participant (P4) used a technique which mixed the one of P3 and P5 (same path of targets) and the one used by the participant P9 of the previous free-form observation (upper targets handled by right hand and the bottom ones by left hand) as shown on Figure 9. His perceived fatigue increased similarly for the two arms from 0.5 to 5.

12. Discussion for experiment 2 and free-form observations 2

In this section, we discuss our findings on the effect of hands synchronicity on perceived fatigue when performing a composite pointing task.

12.1. Fatigue and gestural interfaces in VR

Overall, we found comparable results than in experiment 1 for the consensus, *i.e.*, the higher the period of time is the higher the consensus between participants’ ratings becomes. However, the values of Kendall’s W coefficients of concordance being lower here, suggests that composite pointing task is a factor with a stronger influence on the self-perceived arm fatigue than the simple pointing task.

One-handed conditions were more fatiguing for their respective used arm than the two-handed conditions (2HS and 2HA) in particular for the last periods of time and for the vertical direction and/or the diagonal directions that demands a maximal extension of the used arm (*e.g.*, \overrightarrow{CE} for 1HR). Our findings indicate also, that for all hands synchronicity, these directions are the most fatiguing ones. These findings are consistent across different

spacing conditions and are also correlated with both the findings of [35] and our findings in experiment 1. Consequently, horizontal directions should be preferred whenever possible.

Despite that our findings indicate that the two-handed conditions were less fatiguing than the one-handed ones, in our free-form observation, most of our participants used one-handed conditions while alternating between right and left hand each time they felt their perceived fatigue increasing which, by doing so, did not exceed a moderate level. This finding is correlated with our findings in free-form observations 1 which confirmed that designers should design for flexible input by allowing users to alternate between hands as frequently as they need, whenever no specific synchronicity is required. However, when the hands synchronicity is a predefined parameter like in experiment 2, users prefer the 2HA condition as (1) the task is divided in two parts performed sequentially and such that each part is made with one different hand, which permits one arm to rest while the other is working and consequently reduce the perceived fatigue and (2) each hand performs the part of the task that is closer to it, which makes the task easier. This finding is in disagreement with our findings in experiment 1 where our participants preferred using the dominant hand when the hands synchronicity was a defined parameter. This could be explained by the fact that in experiment 1, the 2HA condition is not evaluated, the participants alternating hands for each new pointed target. It could also be explained by the fact that the task is a simple pointing task which does not require two hands as commented by our participants. Consequently, whenever a task requires bimanual interaction, designers should prefer a 2HA synchronicity and assign a role to each hand according to the target laterality.

As in experiment 1, we found that the cumulative covered distance and cumulative time are the most correlated descriptors with respectively the perceived arm fatigue. We also observed a set of body postures changes and strategies used by our participants to reduce their perceived arm fatigue. These findings are correlated with our findings in experiment 1 and confirmed that these points could be indicators of increased fatigue.

12.2. Performance/Fatigue trade-off

Two handed conditions were not only less fatiguing but also more efficient. For instance, *2HS* is the fastest hand synchronicity, produces more trials than the remainder hands conditions. These findings are not consistent across different directions, in particular for the directions \overrightarrow{BH} and \overrightarrow{X} . This

is not surprising since, with 2HS, participants completed simultaneously the two lines of targets while in the remainder hands conditions, participants completed sequentially the two lines of targets. These findings are also correlated to those of [45, 46] for touch surfaces. Consequently, two-handed synchronous movements could be equally exploited, as they were not perceived more fatiguing to perform and were more efficient than one-handed articulations, as long as the task is symmetric, *i.e.*, performed with two hands simultaneously with each hand used for a different part. However, designers should avoid using two-handed synchronous input for a long period of time, as in our free-form observations, participants preferred not fatiguing both hands at the same time.

Our findings also indicate that two-handed asynchronous movements is faster than the one handed conditions in particular for the diagonals directions that demands the greatest extension of the used arm (*i.e.*, \overrightarrow{CE} for 1HR and \overrightarrow{DF} for 1HL) and for large spacing for 1HL. In addition, 2HA produced shorter distances than one-handed conditions for their respective hand. This is consistent across different spacing and direction conditions. It could be explained by the fact that in the 2HA condition, the laterality of the used hand is respected and the task is divided between the two hands that collaborate together to perform the task, while in one-handed conditions, the whole task is performed by the same hand. These findings confirm again that 2HA input should be chosen whenever the task can be done with two hands each performing the part of the task closest to it. It is also interesting to observe that this hand input was used by two participants in our free task but with an optimization by starting a trial from the side where the previous trial ended. Overall, designers should observe how users naturally perform repetitive trials and allow for flexibility in hand choice.

Our findings indicate also, that there was no significant difference between 1HR and 1HL in terms of performance and fatigue. However, as in experiment 1, participants preferred using their dominant hand.

Like in experiment 1, our findings indicate that the horizontal direction \overrightarrow{Z} should be preferred while the diagonal directions should be used with caution, in particular for the diagonals that demand the extension of the arm (\overrightarrow{CE} and \overrightarrow{DF}). However, contrarily to experiment 1, we found that the \overrightarrow{Y} direction, although it is a fatiguing direction, is the most efficient direction in particular for the two handed conditions. Consequently, \overrightarrow{Y} direction could be exploited for short time exercise, as long as the task is symmetrical and

can be performed with two hands. However, when moving the hands through \vec{X} direction, our findings indicate that the task is very difficult in particular when using 2HS. This result is consistent with our previous justification since in this direction, we lose the symmetry which made it possible to respect the laterality of the hands.

Finally, our findings indicate that a small spacing (10cm) is faster and produces more trials than a large one (40 cm) in particular when using 2HS or the two one-handed conditions. The small spacing was also the preferred spacing by our participants. Consequently, whenever possible, designers should prefer a small spacing over a large one when the task is composed of two symmetrical sub-tasks.

13. Conclusion

In this paper, we reported a first investigation of the effect of hands synchronicity on users' perceived arm fatigue during simple and composite pointing tasks in VR environment. For each task, we evaluated the perceived arm fatigue when using predefined and free hands synchronicity.

By employing correlation analysis, we reported significant correlations between the subjective perception of fatigue and descriptors that characterize the arm movement. We hope that our results on the perception of arm fatigue in VR environment together with new findings on user performances and preferences will prove useful to designers and practitioners, assisting them toward improved VR experience that considers users' perceived arm fatigue.

13.1. Overall guidelines

To optimize the relationship between fatigue and efficiency, it seems necessary to **select the synchronicity of hands in relation to the task performed** *i.e.* favor the use of one hand when the interaction is simple and for composite tasks, favor the use of two synchronous hands over a short period of time or of two asynchronous hands. Furthermore, it might be desirable to **offer the user the possibility of using their hands as they wish** *i.e.* to alternate when they want or take breaks, so that they can auto-regulate fatigue. Besides, **distance covered by the hand and changes in user posture could be used in real-time as indicators of fatigue to trigger changes in the interface, or notifications.** Finally, we note that the directions of movement along the vertical axis and some diagonals

are more tiring than those of the horizontal plane, which suggests that it would be better to **favor the use of horizontal directions**.

13.2. Limitations

Like any study, ours has limitations. For example, our participants were younger than the average population, were all right-handed and were all men. Elderly people, children, women or left-handed people may behave differently. In addition, we had participants of different sizes while all the dimensions of our experiments were fixed according to average sizes. Some participants could therefore have more ease than others in reaching certain targets placed far or high. In addition, we only had ten participants per pair of experiments *i.e.* ten for experiment and free-form 1 and ten more for experiment and free-form 2. Another limitation of our experiment tasks is their abstract nature where more realistic tasks could lead to new results which could be interesting to evaluate in future work.

13.3. Future work

For each controlled experiment (experiments 1 and 2), we only considered four conditions of hands synchronicity. We also, used only two spacing conditions in the composite pointing tasks. Future work will investigate other hand conditions and other spacing conditions, which could lead to more refined insights.

Because perceived fatigue assessment is consistently linked to hand synchronicity, an interesting question would be to design a predictive model to estimate the arm fatigue in VR environment, which may further be used by designers to suggest posture changes.

Finally, participants suggested adding music to simplify the exercise and to reduce the mental fatigue due to the repetitiveness of the task. Reynaert et al. [17] studied the effect of the rhythm on the perceived fatigue when using one single hand. Future work could investigate the effect of rhythm on different hands synchronicity conditions.

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References

- [1] C. Cadoz, Le geste canal de communication homme/machine: la communication “instrumentale”, *Technique et science informatiques* 13 (1) (1994) 31–61.
- [2] R. Aigner, D. Wigdor, H. Benko, M. Haller, D. Lindbauer, A. Ion, S. Zhao, J. Koh, Understanding mid-air hand gestures: A study of human preferences in usage of gesture types for hci, *Microsoft Research TechReport MSR-TR-2012-111* 2 (2012) 30.
- [3] A. Capobianco, M. Veit, D. Bechmann, A preliminary study of two-handed manipulation for spatial input tasks in a 3d modeling application, in: *Computer-Aided Design of User Interfaces VI*, Springer, 2009, pp. 77–88.
- [4] E. Cordeiro, F. Giannini, M. Monti, D. Mendes, A. Ferreira, A Study on Natural 3D Shape Manipulation in VR, *The Eurographics Association*, 2018. doi:10.2312/stag.20181296.
URL <https://diglib.eg.org:443/xmlui/handle/10.2312/stag20181296>
- [5] D. A. Bowman, S. Coquillart, B. Froehlich, M. Hirose, Y. Kitamura, K. Kiyokawa, W. Stuerzlinger, 3d user interfaces: New directions and perspectives, *IEEE computer graphics and applications* 28 (6) (2008) 20–36.
- [6] D. A. Bowman, E. Kruijff, J. J. LaViola, I. Poupyrev, An introduction to 3-d user interface design, *Presence* 10 (1) (2001) 96–108.
- [7] J. J. LaViola, 3d gestural interaction: The state of the field, *ISRN Artificial Intelligence* 2013 (2013).
- [8] J. J. LaViola Jr, E. Kruijff, R. P. McMahan, D. Bowman, I. P. Poupyrev, 3D user interfaces: theory and practice, *Addison-Wesley Professional*, 2017.
- [9] F. Argelaguet, C. Andujar, A survey of 3d object selection techniques for virtual environments, *Computers & Graphics* 37 (3) (2013) 121–136.
- [10] J. Jankowski, M. Hachet, A survey of interaction techniques for interactive 3d environments, in: *Eurographics 2013-STAR*, 2013, p. 30.

- [11] M. Carter, E. Velloso, J. Downs, A. Sellen, K. O’Hara, F. Vetere, Pathsync: Multi-user gestural interaction with touchless rhythmic path mimicry, in: Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, 2016, pp. 3415–3427.
- [12] S. Boring, M. Jurmu, A. Butz, Scroll, tilt or move it: using mobile phones to continuously control pointers on large public displays, in: Proceedings of the 21st Annual Conference of the Australian Computer-Human Interaction Special Interest Group on Design: Open 24/7 - OZCHI ’09, ACM Press, Melbourne, Australia, 2009, p. 161. doi:10.1145/1738826.1738853.
URL <http://portal.acm.org/citation.cfm?doid=1738826.1738853>
- [13] J. D. Hincapié-Ramos, X. Guo, P. Moghadasian, P. Irani, Consumed endurance: a metric to quantify arm fatigue of mid-air interactions, in: Proceedings of the 32nd annual ACM conference on Human factors in computing systems, ACM, 2014, pp. 1063–1072.
- [14] J. R. Fuller, K. V. Lomond, J. Fung, J. N. Côté, Posture-movement changes following repetitive motion-induced shoulder muscle fatigue, *Journal of Electromyography and Kinesiology* 19 (6) (2009) 1043–1052.
- [15] H. Wang, How will different control/display ratios influence muscle fatigue and game experience in virtual reality games? (2016).
- [16] V. Reynaert, F. Berthaut, Y. Rekik, L. Grisoni, The effect of control-display ratio on user experience in immersive virtual musical instruments, International Conference on New Interfaces for Musical Expression <https://nime.pubpub.org/pub/8n8br4cc> (4 2021).
URL <https://nime.pubpub.org/pub/8n8br4cc>
- [17] V. Reynaert, F. Berthaut, Y. Rekik, L. Grisoni, The Effect of Rhythm in Mid-air Gestures on the User Experience in Virtual Reality, in: C. Ardito, R. Lanzilotti, A. Malizia, H. Petrie, A. Piccinno, G. Desolda, K. Inkpen (Eds.), *Human-Computer Interaction – INTERACT 2021, Lecture Notes in Computer Science*, Springer International Publishing, Cham, 2021, pp. 182–191. doi:10.1007/978-3-030-85613-7_13.

- [18] A. Cockburn, P. Quinn, C. Gutwin, G. Ramos, J. Looser, Air pointing: Design and evaluation of spatial target acquisition with and without visual feedback, *International Journal of Human-Computer Studies* 69 (6) (2011) 401–414.
- [19] C. Harrison, S. Ramamurthy, S. E. Hudson, On-body interaction: armed and dangerous, in: *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, 2012, pp. 69–76.
- [20] G. Borg, Borg’s perceived exertion and pain scales, Borg’s perceived exertion and pain scales, *Human Kinetics*, Champaign, IL, US, 1998, pages: viii, 104.
- [21] S. G. Hart, L. E. Staveland, Development of nasa-tlx (task load index): Results of empirical and theoretical research, in: *Advances in psychology*, Vol. 52, Elsevier, 1988, pp. 139–183.
- [22] N. Chaconas, T. Höllerer, An Evaluation of Bimanual Gestures on the Microsoft HoloLens, in: *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2018, pp. 1–8. doi:10.1109/VR.2018.8446320.
- [23] Z. Huang, J. Limke, J. Kong, A Comparative Study on Inter-Device Interaction: One-Handed Interaction VS Two-Handed Interaction, in: *Proceedings of the 9th International Symposium on Visual Information Communication and Interaction, VINCI ’16*, ACM, New York, NY, USA, 2016, pp. 67–74, event-place: Dallas, TX, USA. doi:10.1145/2968220.2968236.
URL <http://doi.acm.org/10.1145/2968220.2968236>
- [24] J. Young, M. Trudeau, D. Odell, K. Marinelli, J. Dennerlein, Wrist and shoulder posture and muscle activity during touch-screen tablet use: Effects of usage configuration, tablet type, and interacting hand, *Work* (Reading, Mass.) 45 (Mar. 2013). doi:10.3233/WOR-131604.
- [25] V. Florimond, *Basics of surface electromyography applied to physical rehabilitation and biomechanics*, Montreal, Canada: Thought Technology Ltd (2009).

- [26] M. Cifrek, V. Medved, S. Tonković, S. Ostojić, Surface emg based muscle fatigue evaluation in biomechanics, *Clinical biomechanics* 24 (4) (2009) 327–340.
- [27] L. Genaro Motti Ader, N. Vigouroux, P. Gorce, Biomechanical analysis of the user’s movements during tactile interaction: Postures of older aged users’ wrists, in: *Proceedings of the XVI Brazilian Symposium on Human Factors in Computing Systems, IHC 2017*, ACM: Association for Computing Machinery, 2017, p. 9.
- [28] J. Freund, E.-P. Takala, A dynamic model of the forearm including fatigue, *Journal of Biomechanics* 34 (5) (2001) 597–605. doi:10.1016/S0021-9290(01)00009-4.
URL <https://linkinghub.elsevier.com/retrieve/pii/S0021929001000094>
- [29] A. Freivalds, *Biomechanics of the upper limbs: mechanics, modeling and musculoskeletal injuries*, CRC press, 2011.
- [30] W. Rohmert, Ermittlung von erholungspausen für statische arbeit des menschen, *Internationale Zeitschrift für angewandte Physiologie einschließlich Arbeitsphysiologie* 18 (2) (1960) 123–164.
- [31] S. Jang, W. Stuerzlinger, S. Ambike, K. Ramani, Modeling Cumulative Arm Fatigue in Mid-Air Interaction based on Perceived Exertion and Kinetics of Arm Motion, in: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI ’17*, ACM Press, Denver, Colorado, USA, 2017, pp. 3328–3339. doi:10.1145/3025453.3025523. URL <http://dl.acm.org/citation.cfm?doid=3025453.3025523>
- [32] Z. Liu, D. Vogel, J. R. Wallace, Applying the cumulative fatigue model to interaction on large, multi-touch displays, in: *Proceedings of the 7th ACM International Symposium on Pervasive Displays*, 2018, pp. 1–9.
- [33] M. Bachynskyi, A. Oulasvirta, G. Palmas, T. Weinkauff, Is motion capture-based biomechanical simulation valid for HCI studies?: study and implications, in: *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI ’14*, ACM Press, Toronto, Ontario, Canada, 2014, pp. 3215–3224. doi:10.1145/

2556288.2557027.

URL <http://dl.acm.org/citation.cfm?doid=2556288.2557027>

- [34] A. Hareendran, N. K. Leidy, B. U. Monz, R. Winnette, K. Becker, D. A. Mahler, Proposing a standardized method for evaluating patient report of the intensity of dyspnea during exercise testing in COPD, *International Journal of Chronic Obstructive Pulmonary Disease* 7 (2012) 345–355. doi:10.2147/COPD.S29571.
URL <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3379870/>
- [35] S. Al-Megren, A. Kharrufa, J. Hook, A. Holden, S. Sutton, P. Olivier, Comparing fatigue when using large horizontal and vertical multi-touch interaction displays, in: *IFIP Conference on Human-Computer Interaction*, Springer, 2015, pp. 156–164.
- [36] B. Ahlstrom, S. Lenman, T. Marmolin, Overcoming touchscreen user fatigue by workplace design, in: *Posters and Short Talks of the 1992 SIGCHI Conference on Human Factors in Computing Systems, CHI '92*, Association for Computing Machinery, Monterey, California, 1992, pp. 101–102. doi:10.1145/1125021.1125103.
URL <http://doi.org/10.1145/1125021.1125103>
- [37] H. Kang, G. Shin, Effects of touch target location on performance and physical demands of computer touchscreen use, *Applied Ergonomics* 61 (2017) 159–167.
- [38] C. List, M. Kipp, Is bigger better? a fitts' law study on the impact of display size on touch performance, in: *IFIP Conference on Human-Computer Interaction*, Springer, 2019, pp. 669–678.
- [39] M. Liu, M. Nancel, D. Vogel, Gunslinger: Subtle Arms-down Mid-air Interaction, in: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology, UIST '15*, Association for Computing Machinery, Charlotte, NC, USA, 2015, pp. 63–71. doi:10.1145/2807442.2807489.
URL <http://doi.org/10.1145/2807442.2807489>
- [40] J. Ruiz, D. Vogel, Soft-constraints to reduce legacy and performance bias to elicit whole-body gestures with low arm fatigue, in: *Proceedings*

of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM, 2015, pp. 3347–3350.

- [41] J. N. Côté, P. A. Mathieu, M. F. Levin, A. G. Feldman, Movement reorganization to compensate for fatigue during sawing, *Experimental brain research* 146 (3) (2002) 394–398.
- [42] C. Yang, J. Bouffard, D. Srinivasan, S. Ghayourmanesh, H. Cantú, M. Begon, J. N. Côté, Changes in movement variability and task performance during a fatiguing repetitive pointing task, *Journal of biomechanics* 76 (2018) 212–219.
- [43] C. Yang, S. Leikam, J. N. Côté, Effects of different fatigue locations on upper body kinematics and inter-joint coordination in a repetitive pointing task, *PloS one* 14 (12) (2019) e0227247.
- [44] K. Kin, B. Hartmann, M. Agrawala, Two-handed marking menus for multitouch devices, *ACM Transactions on Computer-Human Interaction* 18 (3) (2011) 1–23. doi:10.1145/1993060.1993066.
URL <http://dl.acm.org/citation.cfm?doid=1993060.1993066>
- [45] Y. Rekik, W. Merrad, C. Kolski, Understanding the Attention Demand of Touch and Tangible Interaction on a Composite Task, in: 2019 International Conference on Multimodal Interaction, ICMI '19, Association for Computing Machinery, Suzhou, China, 2019, pp. 319–328. doi:10.1145/3340555.3353723.
URL <http://doi.org/10.1145/3340555.3353723>
- [46] Y. Rekik, R.-D. Vatavu, L. Grisoni, Understanding users' perceived difficulty of multi-touch gesture articulation, ICMI '14, Association for Computing Machinery, New York, NY, USA, 2014. doi:10.1145/2663204.2663273.
URL <https://doi.org/10.1145/2663204.2663273>
- [47] J. T. McConville, C. E. Clauser, T. D. Churchill, J. Cuzzi, I. Kaleps, Anthropometric relationships of body and body segment moments of inertia, Tech. rep., ANTHROPOLOGY RESEARCH PROJECT INC YELLOW SPRINGS OH (1980).

- [48] Anthropometry & Biomechanics (2020).
URL <https://msis.jsc.nasa.gov/sections/section03.htm#3.3.1%20Body%20Size>
- [49] S. S. Shapiro, M. B. Wilk, An analysis of variance test for normality (complete samples), *Biometrika* 52 (3/4) (1965) 591–611.
- [50] M. Kay, J. O. Wobbrock, Package ‘artool’ (2020).
- [51] J. Wobbrock, L. Findlater, D. Gergle, J. Higgins, The aligned rank transform for nonparametric factorial analyses using only anova procedures, *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2011).
- [52] M. G. Kendall, B. B. Smith, The problem of m rankings, *The annals of mathematical statistics* 10 (3) (1939) 275–287.
- [53] J. Cohen, A power primer., *Psychological bulletin* 112 (1) (1992) 155.
- [54] M. Goss-Sampson, *Statistical analysis in jasp: A guide for students* (2019).
- [55] N. K. Vøllestad, Measurement of human muscle fatigue, *Journal of Neuroscience Methods* 74 (2) (1997) 219–227. doi:[https://doi.org/10.1016/S0165-0270\(97\)02251-6](https://doi.org/10.1016/S0165-0270(97)02251-6).
URL <https://www.sciencedirect.com/science/article/pii/S0165027097022516>
- [56] J. Wahlström, Ergonomics, musculoskeletal disorders and computer work, *Occupational medicine* 55 (3) (2005) 168–176.