An electromyographic study of a laser pointer–style device vs. mouse and keyboard in an object arrangement task on a large screen

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Abstract

A large body of HCI research focuses on devices and techniques to interact with applications in more natural ways, such as gestures or direct pointing with fingers or hands. In particular, recent years have seen a growing interest in laser pointer-style (LPS) interaction, which allows users to point directly at the screen from a distance through a device handled like a common laser pointer. Several LPS techniques have been evaluated in the literature, usually focusing on users' performance and subjective ratings, but not on the effects of these techniques on the musculoskeletal system. One cannot rule out that "natural" interaction techniques, although found attractive by users, require movements that might increase likelihood of musculoskeletal disorders (MSDs) with respect to traditional keyboard and mouse. Our study investigates the physiological effects of a LPS interaction technique (based on the Wii Remote) compared to a mouse and keyboard setup, used in a sitting and a standing posture. The task (object arrangement) is representative of user actions repeatedly carried out with 3D applications. The obtained results show that the LPS interaction caused more muscle exertion than mouse and keyboard. Posture played also a significant role. The results highlight the importance of extending current studies of novel interaction techniques with thorough electromyographic (EMG) analyses.

Keywords:
Wii Remote, laser pointer, muscle activity, EMG, 3D environments, large screen, object arrangement, ray casting

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1. Introduction

A large body of HCI research is devoted to create interaction techniques and devices that could allow users to interact with applications in more natural ways, such as gestures or direct pointing with fingers and hands. In particular, recent years have seen a growing interest in *laser pointer-style* (LPS) interaction, which allows users to point directly at the screen from a distance through a device which is handled like a common laser pointer. Applications projected on a large screen might especially benefit from LPS interaction, becoming more intuitive and natural to use with respect to mouse and keyboard. The use of laser pointers (Figure 1) is common in public presentations (e.g., during a meeting or a lecture), but the functions provided by these devices are generally limited to projecting a red or green spot on the screen and, if the device communicates with the computer through Bluetooth or infrared interfaces, scrolling through presentation slides.

Figure 1: A commercial laser pointer.

In the literature, many approaches have been proposed to integrate these basic functions with more complex features, allowing users to control the on-screen cursor and *GUI widgets* (windows, icons, buttons, scrollbars, etc.) with a single laser pointer (Kirstein and Müeller, 1998; Shizuki et al., 2006) or multiple laser pointers (Chen and Davis, 2002), using video cameras to track the laser spots on the screen and translate them into inputs to the application. Researchers have also replaced laser pointers with other devices for more flexibility, proposing various techniques based on LPS interaction (Bowman and Hodges, 1997; Cheng and Pulo, 2003; König et al., 2007; Ouramdane et al., 2006b).

Evaluations of these interaction techniques and devices usually focus on users' performance and subjective ratings. The latter are used to evaluate perceived comfort and task difficulty (e.g., Elmqvist and Fekete, 2008; MacKenzie and Jusoh, 2001) and, more rarely, perceived fatigue (e.g., Douglas et al., 1999), showing that users generally like LPS interaction. However, these studies do not consider some essential variables: while the effects of traditional interaction techniques and devices such as keyboard and mouse on the musculoskeletal system have been investigated in depth (Sommerich et al., 2006), very little is known about natural interaction techniques that have been proposed in recent years. More specifically, one cannot rule out the possibility that these novel techniques, although found attractive by users, require movements that might increase users' likelihood of *musculoskeletal disorders* (MSDs) with respect to traditional keyboard and mouse. It should also be noted that MSDs develop insidiously over time: the user is typically asymptomatic and unaware of the negative effects of the movements she repetitively performs until it is too late.

For the above reasons, physiological studies of natural interaction techniques are urgently needed and designers should be concerned about the future effects on users' health of the continuous use of the proposed techniques. The first goal of our study is thus to investigate physiological effects of a LPS interaction technique compared to a traditional mouse and keyboard setup. In particular, we use *electromyography* (EMG) to measure muscle activity.

A thorough analysis of muscle activity should also consider the typical postures in which users operate the considered devices. The sitting posture is the most common when using mouse and keyboard; on the other hand, the standing posture seems to be convenient for LPS interaction with large displays because of the mobility afforded to the user. Therefore, the second goal is to study the effects of the two considered techniques in each of the two postures.

To focus on a task which is representative of actual user activities repeatedly carried out with commercial 3D software, we choose an *object arrangement task* (Chittaro et al., 2009), which is relevant in different popular 3D tools, ranging from 3D modeling software (e.g., *Autodesk 3ds Max*) to game development tools (e.g., *Unity*), for building *3D virtual environments.* A 3D virtual environment (VE) is a computer-generated three-dimensional representation of a setting, such as 3D virtual exhibitions, virtual home/interior design and game levels. Object arrangement in a VE necessarily involves (i) 3D navigation (finding and reaching the place where a given object has to be positioned), (ii) object selection, and (iii) object manipulation, i.e., properly positioning, orienting and scaling the object.

The paper is organized as follows. In Section 2, we review the literature on LPS interaction, then Section 3 describes the interaction techniques considered in our study, while Section 4 presents the details of the experiment. Section 5 and 6 respectively illustrate and discuss the obtained results. Section 7 concludes the paper and presents future work.

2. Related work

Several approaches to support pointing, selection and object manipulation based on LPS interaction have been proposed in the literature. In Section 2.1, we describe the solutions based on the *ray casting* technique, which uses a virtual light ray to grab objects, with the ray direction specified by the user's hand or an handheld device (Bolt, 1980; Mine, 1995; Bowman and Hodges, 1997), while Section 2.2 illustrates the results of user studies which have dealt with LPS interaction.

2.1. Techniques based on ray casting

Systems based on the ray casting technique can be classified in two categories based on the kind of light they exploit, i.e., systems that use visible lasers and systems that use infrared instead of visible light. We briefly analyze both categories.

Systems based on visible laser. In these systems, video cameras are used to track a laser spot for matching the position of the on-screen cursor with the pointed location (Kirstein and Müeller, 1998), also adding visual feedback to both the laser spot (echoing it with a different cursor image for each action performed) and the GUI widgets, in order to make evident where the interaction will happen (Olsen and Nielsen, 2001). The laser spot color, shape and position are also used to trigger actions such as moving forward and backwards in a presentation or drawing on a virtual canvas (Shizuki et al., 2006).

Systems based on IR light. IR cannot be seen by the human eye. Thus, pointing an IR light towards the screen does not mask on-screen information. This also facilitates the use of on-screen cursors (the visual feedback), which can be changed in a very flexible manner (König et al., 2007). However, the feedback loop between the user's motor and perceptual systems is less effective with invisible light than with visible lasers, because users can only see the on-screen cursor, which usually suffers from latency problems (Cavens et al., 2002). Some researchers hide even the on-screen cursor, so the problems of *hand jitter* (the normal hand tremor which, albeit small, might result in a more noticeable cursor tremor) and high latency cannot be visually perceived. Cheng and Pulo (2003) proposed, for example, to exploit *hotspots* (i.e., logical highlighting of the currently pointed object) to let users know where they are pointing.

The Wii Remote is an affordable and widespread IR-based pointing device, which exploits two arrays of IR lights (the *Sensor Bar*, Figure 2b) placed over or below the screen to detect the pointed location (see Section 3.1). A specular approach is taken by Matveyev and Göbel (2003), who positioned the IR camera above the screen projector, and placed a single IR light on the handheld device, subdividing it into three smaller rays. By calculating angles and distances among the resulting multiple spots (detected by an IR video camera placed behind the screen), they allow users to rotate and translate objects along the z axis. Moreover, users can mechanically change the distance of one IR spot from the other two, and the change is recognized as a select operation.

2.2. User studies

Evaluations of LPS interaction techniques have focused on the assessment of user performance in pointing, selection and object manipulation tasks performed on 2D interfaces and VEs. Studies of LPS interaction which focus on 2D interfaces are quite common, and typically require users to point at and select geometric shapes or GUI widgets which lie on a plane. These studies typically use standard (ISO 9241-9) tests for the evaluation of pointing devices (e.g., Oh and Stuerzlinger, 2002) and similar evaluation instruments (e.g., Olsen and Nielsen, 2001; Myers et al., 2002; Campbell et al., 2008). *Tapping tests* are a typical example (e.g., Myers et al., 2002): participants are asked to move the cursor from a starting position and select a target figure, whose form, size and distance from other similar geometrical shapes are previously defined. The use of standard tests allows one to compare the results obtained with similar analyses performed on trackball, joystick, mouse and touchpad (Douglas et al., 1999; MacKenzie et al., 2001).

User studies of LPS interaction in VEs are less frequent. Bowman and Hodges (1997) evaluated two ray casting techniques, three virtual arm techniques based on *Go–Go* (Poupyrev et al., 1996), which allows a 3D virtual arm projected on screen to stretch longer than the user's real arm for reaching distant objects, and an indirect virtual arm stretching technique in which the buttons on a 3D mouse are used to stretch and retract the arm. Users could freely point, select and manipulate objects inside a VE using each technique and their comments were recorded to assess the strengths and weaknesses of each approach. Ray casting turned out to be the best technique for object selection, while virtual arm techniques were better suited for object manipulation.

Ouramdane et al. (2006a) evaluated ray casting and Go–Go with and without the assistance of their *FOLLOW-ME* technique. With FOLLOW-ME, when the cursor is far from the object that has to be selected, speed of approach is equal to hand speed, while it is reduced when the cursor is near the object. In the close proximity of the object, there is only one degree of freedom, so users' movements are interpreted only as *move closer to* or *move away from* the center of the object and the cursor moves on a 1D curve. In the evaluation, users had to select a series of static or moving 3D target objects, randomly appearing inside a VE. Elapsed time between the selection of two target objects, as well as the distance between the virtual tool (virtual pointer or virtual hand) and the target object were both considered as performance indicators. Results showed that FOLLOW-ME assistance could decrease the selection time necessary to reach the target object when using Go–Go, while it made little difference when using ray casting, perhaps because this is already a good method for selection, as shown by Bowman and Hodges (1997).

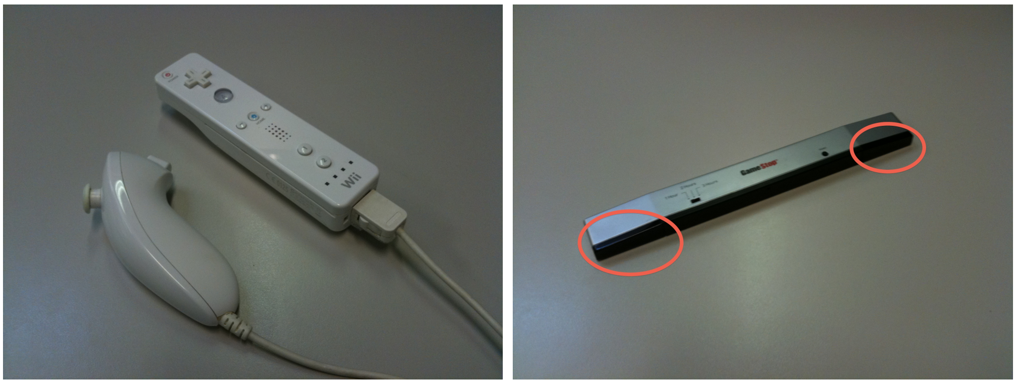
Mulder (1998) found that ray casting could also be a good approach for an object translation task when used inside a VE projected on a CAVE system. Users were asked to move a 3D sphere from a starting position to a target position inside a virtual box. Seven translation techniques were tested using a 6 DOF wand: three position control techniques, in which the wand movements control the position of the sphere; two velocity control techniques, in which the wand position and orientation controls the movement speed of the sphere; and two mixed techniques. *Stick*, a position control technique in which the 3D object is virtually attached to the wand with a segment, produced the fastest translations. Moreover, users perceived Stick as easy to use, intuitive and not fatiguing.

Existing studies of natural interaction techniques do not generally include the evaluation of users' physiological responses. A notable exception is the stress assessment carried out by Bérard et al. (2009). The study measured the performance of four devices used as indirect pointing devices in a 3D placement task: a traditional mouse; a mouse used together with the *DepthSlider*, i.e., an optically tracked physical slider to control translations along the z axis; the *SpaceNavigator*, a commercial 6 DOF device used to perform translations inside the VE; an optically tracked Wii Remote). Three physiological signals (galvanic skin response, blood volume pulse amplitude, heart rate) were recorded to measure the level of stress induced by using each device. Results showed that the mouse, despite lacking a third degree of freedom, was both more precise and less stressful than the other evaluated devices. Unfortunately, LPS interaction techniques were not included in this study, and the considered physiological recordings did not include users' muscle activity.

3. The considered interaction techniques

Millions of Wii consoles have been sold, making this entertainment device very popular. The Wii primary interface device is the Wii Remote, which is an intuitive, widespread and very well known device not only among gamers, but also in the general public. Moreover, the Wii Remote is being used as an alternative to mouse and keyboard also in some PC applications[1]. Our study employs the Wii Remote for the LPS interaction condition, while the second condition is based on a traditional mouse and keyboard setup.

In this section, we first illustrate the Wii Remote and how it was used in our study, then we describe in detail how users navigate inside the VE, point at and manipulate objects in each of the two experimental conditions.



(a) (b)

Figure 2: (a) The Nunchuck (on the left) connected to the Wii Remote (on the right); (b) the Sensor Bar used in the study (the two circles superimposed at the ends of the Sensor Bar highlight the position of the two IR arrays).

3.1. The Wii Remote

The Nintendo Wii Remote (Figure 2a) includes a small IR video camera with a resolution of 1024×768 pixels and a *field of view* (FoV) of about 40°, capable of tracking up to four IR sources with a 100 Hz sampling. This allows to use a Sensor Bar (Figure 2b), which contains two arrays of IR LEDs and is typically placed above or under the screen, to support detection of the location pointed by the device as well as the roll angle and the distance between the device and the bar itself. An additional device called Nunchuck, which includes a joystick and two buttons, can be connected to the Wii Remote as shown in Figure 2a.

To read the output data sent by the Wii Remote through a Bluetooth connection, we employed the *WiiYourself!*[2] library, that can return the position of each IR source relative to the IR camera viewport, the state of the buttons (neutral or pressed) and the tilt of the joystick on the Nunchuck.

To have the Wii Remote act as a direct pointing device that controls an on-screen cursor, the cursor coordinates are indirectly derived from (i) the position of the sensor bar relatively to the screen, (ii) the distance between the two IR LED arrays detected by the Wii Remote, and (iii) the size of the screen itself. If the difference between the actual pointed location and the

[1] see, for example, the applications listed at http://www.brianpeek.com/page/net-based-wiimote-applications.aspx

[2] http://wiiyourself.gl.tter.org/

cursor position on the screen is large, users might find it difficult to use the device, and the pointing performance might decrease (Cavens et al., 2002). To prevent this issue, we identified the Sensor Bar position and orientation for the experiment through a pilot test that preceded the user evaluation. Sensor Bar position and orientation were then checked before every user test to prevent possible deviations from the identified setup.

The smallest user's movement that can be detected by the Wii Remote, i.e., moving the cursor position one pixel of the IR camera resolution, would translate in our case to a cursor movement of about 2 pixels on the projection screen (corresponding to about 2-3 mm on the screen; see Section 4.2). Therefore, even if the user tries to keep the Wii Remote still, her hand tremor would make the cursor jitter noticeable on a projection screen. To solve this issue, a smoothing algorithm was implemented: after dismissing small movements (resulting in cursor motions of less than 1 cm on the projection screen), it calculates the smoothed cursor position as the weighted mean of the last 10 filtered locations (the more recent the detected position, the greater the weight). Since this inevitably introduces lag, during the pilot test we fine-tuned the filter to minimize lag, while keeping jitter under a level considered acceptable by users.

To calculate the total latency for the two devices (i.e., not only the latency caused by filtering, as with the Wii Remote, but also caused by other factors, such as the wired and wireless connection with the PC and the buffering of the screen projector), we employed a technique inspired by the one described by Pavlovych and Stuerzlinger (2009). Using a video camera, we recorded at 50 frames per s (i) the projection screen, (ii) the mouse moving the cursor on the screen from side to side, and (iii) the Wii Remote moving the cursor on the screen from side to side. Both devices were lying on a desk and, for each one, the cursor was repeatedly moved on the screen for a couple of minutes, with an interval of about 2 s between each pair of subsequent motions. To make it easier to calculate the latency of the cursor with the Wii Remote, we attached a real laser pointer to the device which projected a laser spot over the actual pointed location. Total latency is the difference between the instant when the device stops and the instant when the cursor stops. The video was analyzed manually, and we averaged a total of 15 measurements to remove any potential sampling artifacts. The average latency between mouse and cursor movement was 76 ms (SD = 8.3), while it was unsurprisingly higher for the Wii Remote and equal to 233.3 ms (SD = 20.9).

3.2. Navigating the VE

In a VE, objects can be far from users, thus perceptively small and difficult to select and manipulate with sufficient precision. Moreover, objects and locations might be outside the actual user's field of view. For these reasons, in an object arrangement task users should be able to move the viewpoint.

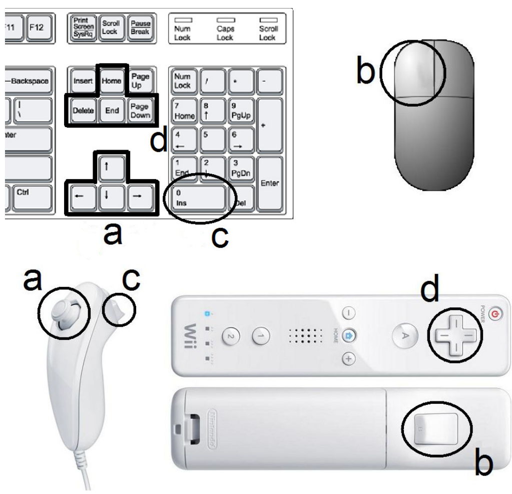


Figure 3: The controls for the two interaction techniques. *a*: navigation; *b*: viewpoint orientation, object selection and coarse manipulation; *c*: manipulation type; *d*: fine manipulation.

To navigate the VE in our study, participants used the arrow buttons on the keyboard or the joystick on the Nunchuck (see Figure 3a). Behavior of controls has been kept consistent with typical conventions adopted in video games. By pressing the up and down buttons on the keyboard (respectively, moving the joystick forward and backwards on the Nunchuck), users move the viewpoint forward and backward in the VE along their current viewing direction. By pressing left or right buttons on the keyboard (respectively, moving the joystick left or right on the Nunchuck), users change viewpoint orientation, rotating it counter-clockwise or clockwise respectively. In video games (especially *first person shooters*), left and right arrows or joystick movements are often used to *strafe*, i.e., move laterally the viewpoint without changing its orientation. However, this approach could be too complex for users who have little or no experience with video games. Our technique thus follows the approach of simpler video games, which allows for the viewpoint to move and change orientation by using only the four keyboard arrows or the Nunchuck joystick. Both motion speed and rotation speed are constant.

As an additional possibility, viewpoint orientation can also be changed using the mouse or the Wii Remote: the viewing direction can be moved up, down, left or right by pressing the left button on the mouse (respectively, the trigger *B* button on the Wii Remote, see Figure 3b) when the cursor is not over an object, and then dragging the cursor over the screen.

3.3. Pointing at and selecting an object

To point and select with LPS interaction, we employed IR-based ray casting. In particular, we have been inspired by other systems proposed in the literature (e.g., Olsen and Nielsen, 2001; König et al., 2007) and also from some video games for the Wii console, e.g., Konami's *Eledees*[3] in which players have to make small creatures come out from objects inside a house by grasping, tossing and shaking those objects.

The on-screen cursor moves along the x and y axis, and when it hovers over an object, a *bounding box* for the object is highlighted (see the white box around the large "K" object in Figure 6). This approach is used, for example, by Cheng and Pulo (2003). Then, by pressing the left button on the mouse (respectively, the *B* button on the Wii Remote, see Figure 3b), the object is *selected* (i.e., it is possible for the user to manipulate it). We employed the *B* button on the Wii Remote and the left mouse button, already used to change viewpoint orientation, because these buttons are easily accessible to users. The pilot test showed that using the same button for object selection and for viewpoint orientation did not generate confusion in users.

Since the experimental task concerned the arrangement of objects which stand on the floor, to facilitate users in carrying out manipulations we constrained objects to be bound to the VE floor (in other words, they could not float above the floor or on the walls). When an object is selected, the on-screen cursor is moved to the center of the object bottom surface (i.e., the contact surface between the floor and the object). The cursor remains attached to the center of the bottom surface until the user releases the button, then it returns to the location currently pointed by the mouse or the Wii Remote. During the pilot test, we also tried the approach of

[3] http://uk.games.konami-europe.com/game.do?idGame=141

always keeping the cursor in the position pointed by the device, but users preferred the solution described above, because the cursor better highlights the actual position of the object on the floor, so they felt more confident in performing object translations.

3.4. Manipulating the selected object

Once an object is selected, three *manipulation types* can be applied to it, i.e., the user can change its position (by moving it around), orientation (by rotating it around its vertical axis) and size (by making it bigger or smaller). Only one manipulation type can be performed at a time to keep controls as simple as possible. Using the *0* key on the numeric keyboard (respectively, the *Z* button on the Nunchuck, see Figure 3c), the user can switch among the three manipulation types.

Each manipulation type is associated to a different cursor icon on the screen, giving visual feedback about which manipulation can be currently applied (Figure 4). The cursor icon is normally white, but it turns green while manipulation is performed.

Figure 4: From left to right, the three cursor icons associated respectively to translation, rotation and size manipulation.

After selecting an object, the user drags the cursor on the screen to manipulate it. Dragging changes one of the object properties (position, orientation or size) based on the chosen manipulation type.

With translation, the user changes the object position inside the VE. The vertical component of the cursor drag moves the object closer or away from the user, while the horizontal component moves the object to the left or to the right.

During an object arrangement task, users often need to move the selected object to a position that is outside the current field of view. Generally, these situations can be handled by exploiting the navigation controls (respectively, keyboard arrows and Nunchuck joystick) during an object translation. However, to make it easier to change the orientation of the field of view, we allow users to simply move the object near the screen borders and the viewpoint orientation inside the VE continuously changes, while maintaining the object inside the user's field of view.

With rotation, the user changes the orientation of the object along its vertical axis. The user rotates the selected object clockwise by dragging the cursor to the left, and counter-clockwise by dragging the cursor to the right. The angle of object rotation is proportional to the length of the cursor drag.

With size manipulation, the user changes the object size. By dragging the cursor up and down, the object becomes respectively bigger or smaller. The change in size is proportional to the length of the cursor drag.

In the following, we refer to all the above described manipulation capabilities as *coarse manipulation*. Besides coarse manipulation, we provide also *fine manipulation* capabilities respectively through the four buttons on the keyboard and the *directional pad* on the Wii Remote (the "plus"-shaped button) as highlighted in Figure 3d. Fine manipulations occur at a low, fixed speed to give users the ability to manipulate objects more accurately. More precisely, a fine translation moves an object for about 0.6 m in a second inside the VE (which measures 7.5 m $\times$ 13.3 m), a fine rotation rotates an object for about 70° in a second, and a fine size manipulation makes an object about 60% bigger or smaller in a second. In coarse manipulation, each user can instead perform manipulations at a different variable speed, which can reach values as high as about 10 m in a second inside the VE for translations and 500° in a second for rotations. Due to this variability in performing coarse manipulations, the ration between the speed of coarse and fine manipulations varies with the user.

Fine and coarse manipulations are mutually exclusive and, to prevent errors, the controls for coarse manipulation are disabled when using the controls for fine manipulation, and vice versa. Participants were thus invited to use one hand for coarse and fine manipulations, and the other hand to perform navigation and choosing the manipulation type.

In fine manipulations, the controls that move the selected object close or away from the users are respectively the two central keyboard keys among the four highlighted in Figure 3d and the *up* and *down* buttons of the directional pad on the Wii Remote, while the controls that move the selected object left or right are the other two keyboard keys in Figure 3d and the *left* and *right* buttons of the directional pad on the Wii Remote. During a fine rotation, the selected object can be rotated clockwise or counter-clockwise by pressing respectively the leftmost and rightmost keyboard keys among the four highlighted in Figure 3d and the *left* and *right* buttons of the directional pad on the Wii Remote. During a fine size manipulation, the object can be made bigger or smaller by pressing respectively the two central keyboard keys in Figure 3d and the *up* and *down* buttons of the directional pad on the Wii Remote.

4. Experimental evaluation

The study follows a within-subject design with *interaction technique* (based on Wii Remote and Nunchuck or based on mouse and keyboard) and *posture* (sitting or standing) as independent variables (hereinafter, *IVs*). For conciseness, in the following we refer to "Wii Remote and Nunchuck" as *W&N* and to "mouse and keyboard" as *M&K*.

4.1. Participants

The evaluation involved a sample of 18 users (13 M, 5 F) with various educational backgrounds (seven computer science, two literature and philosophy, two engineering, two physiotherapy, one education, one mathematics, one agricultural science, one mechanical design, one natural science), recruited among graduate and undergraduate university students and people from other occupations. Their age ranged from 20 to 58, averaging at 27.4 (SD = 8.8).

All of them had at least basic experience with M&K and 11 of them used M&K with VEs (mostly games) at least once a week. Five participants used W&N at least once a week to play games.

4.2. Materials

The VE was run on a PC in fullscreen mode and projected on a 240×160 cm projection screen at UXGA resolution (1600×1200 pixels). The distance between the screen and the user was about 3.5 m. A common USB mouse and PS/2 keyboard were employed for M&K.

To record users' physiological data, we employed seven sensors, positioned as shown in Figure 5: four EMG sensors for *surface electromyography* (SEMG, i.e. muscular electrical activity measured over the skin surface), coupled with disposable triode electrode pads; a thermometer for peripheral temperature (recorded on the little finger of the left hand); an IR *photoplethysmograph* (PPG) for *blood volume pulse* (BVP, i.e. change in blood volume caused by the cardiac cycle, recorded on the ear lobe); a girth sensor for respiration measurements. These signals were recorded and stored on a second PC. Two webcams were used to record videos of respectively the projection screen and the body of the subject during the task for reviewing purposes.

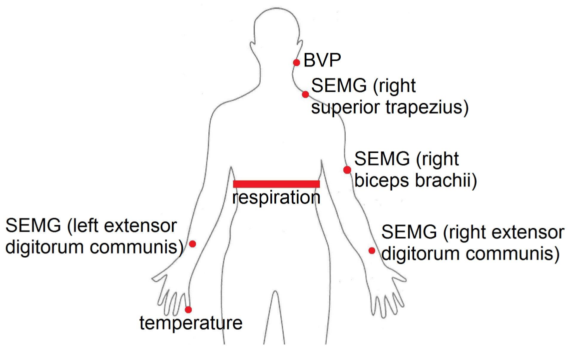


Figure 5: Position of the seven sensors. The silhouette represents the back of a human body.

During the experiment, two VEs were used. A training VE represented a group of three houses and was used by participants to practice with controls. The experimental VE reproduced a rectangular room of a museum and was used to perform the experimental task. The frame rate of the projected image was kept above 30 frames per second for both VEs.

4.3. Task

For each of the four combinations of interaction technique and posture, participants performed a task which requires to arrange a blue "K" object and a green "Z" object. Each of the two objects was initially positioned in front of the user and not selected. Users had to arrange each object in such a way that it matched position, orientation and scale of a red, semitransparent copy of the object itself (see, for example, Figure 6).

For each experimental condition, object position and orientation as well as initial user orientation were changed. However, to keep task complexity constant, objects and targets were always placed at the four corners of the museum room and initial distances as well as differences in size and orientation between object and target remained the same. Users started always at the center of the VE, facing the two objects they had to arrange during the task (Figure 7a).

The task started with a short sound, which was repeated as soon as an the object and the corresponding target were properly matched (Figure 7b). Error tolerance thresholds were used in determining object and target

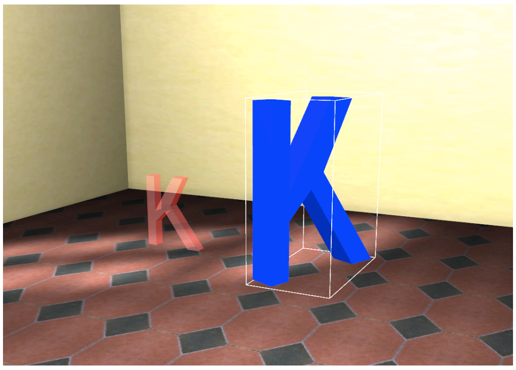
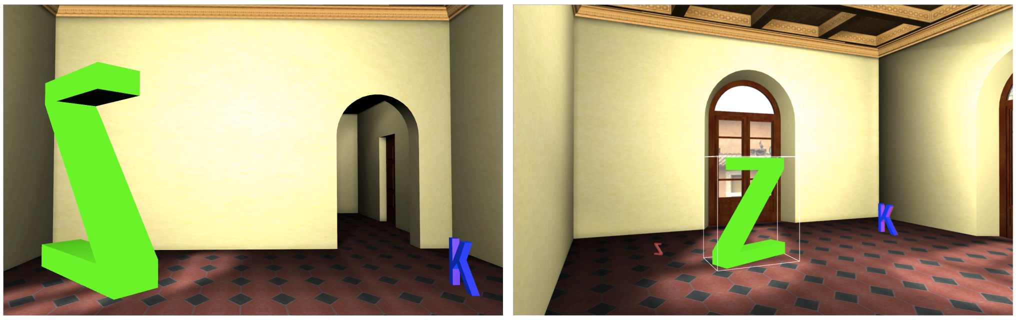


Figure 6: An object to be arranged (on the right) and the corresponding target object (on the left). In this example, the object to be arranged is currently selected (bounding box highlighted).

match: a match was detected when (i) the distance between object and target is no more than 0.2 times the height of the target; (ii) the size of the object is between 80% and 120% the size of the target; (iii) the difference in orientation between the object and its target is no more than 30°. These thresholds were determined during the pilot test to obtain a level of complexity that is reasonable for users. The system did not check the accuracy of the match while users were carrying out a manipulation, but only after its conclusion, to prevent participants from getting the correct match by chance by simply performing quick object manipulations over targets.



(a) (b)

Figure 7: (a) User's viewpoint at the beginning of the task; (b) the user has matched the "K" target, and is arranging the "Z" object.

4.4. Procedure

Participants were verbally briefed about the nature of the task, the use of the physiological sensors and the use of the two webcams during the test. They were asked to fill a demographic questionnaire concerning gender, age, educational background and occupation, experience with M&K and W&N, experience with 3D video games and 3D software.

All participants, including the only left-handed subject, chose to use keyboard and Nunchuck with the left hand and Wii Remote and mouse with the right hand. We thus measured the biceps and trapezius activity from the right arm and shoulder as illustrated in Figure 5.

The skin of forearms, right arm and right shoulder of participants was cleaned using a cotton pad and denatured alcohol, then the seven sensors were applied (see Section 4.5). A sheet with a human silhouette (Figure 5), pinpointing the exact position of each sensor, was shown to participants to let them know in advance how many sensors had to be applied and where. To facilitate the placement of the four SEMG electrodes, participants were asked to wear only a T-shirt during the experiment. Room temperature was maintained at about 21°C for reliable measurement of participants' peripheral temperature.

Once the sensors were placed, participants sat in a comfortable position and were asked to relax for about three minutes, while the baseline for the physiological signals was recorded. During this time, a video with relaxing images and music was shown in a dim light. Participants could close their eyes and only listen to the music if they preferred.

Each participant then performed the task in the four conditions following a different order, to prevent learning effects. The order of the four different object placements (see Section 4.3) was varied independently. There were 24 possible orders of conditions and 24 orders of object placement. Each participant was randomly assigned to one order of condition and one order of object placement in such a way that each order was assigned to at most one participant.

To comfortably use M&K, a common desk (78 cm tall) and a taller one (106 cm) were employed, respectively for the sitting and standing posture. In the sitting condition, the chair was adjustable in height and equipped with armrests, which could be used by participants as they felt more natural (Figure 8).

Before each task, participants were allowed to spend unlimited time trying an object arrangement task inside the training VE to practice with

Figure 8: A participant performing a task with W&N in sitting position.

controls and familiarize with the task itself and the tolerance levels of object and target match. During this time, they were provided with an instruction sheet illustrating the controls of each interaction technique; they could also ask questions to the experimenter. After training, participants were asked to wait for about three minutes to return to a relaxed state.

During the experimental task, the control instruction sheet, as well as a simple map of the experimental VE, pinpointing the participants' starting position as well as the position of objects and targets (Figure 9), were available to participants. The map was used to make participants initially aware of the position of the two targets, which were not visible from the starting position.

After all tasks were completed, physiological sensors were removed and participants were asked to fill a questionnaire that asked to rank from 1 (best) to 4 (worst) the four conditions (ties were allowed) with respect to ease and comfort of navigation, ease and comfort of coarse and fine manipulation, perceived level of exertion and overall pleasantness of the condition.

4.5. Data collection

During the experiment, the following data were recorded:

- *Task completion time*: the time taken to complete the task, defined as the time elapsed between the starting sound and the detection of a correct match for both objects;

- *Navigation time*, *coarse manipulation time* and *fine manipulation time*: the time spent by users on each of the three activities;

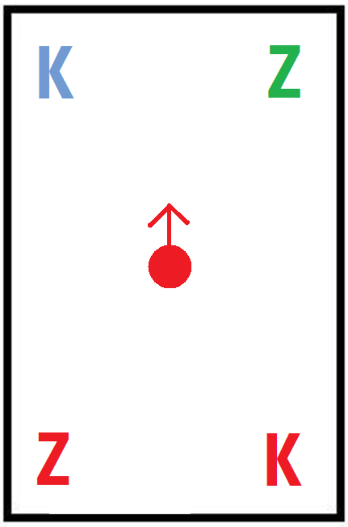


Figure 9: An example of room map given to participants. The participants starting position as well as viewing direction are represented by the central dot and arrow. Colored letters show the position of the objects to be manipulated (here, the "K" and "Z" letters at the top of the map, which are respectively blue and green) and the targets (here, the "Z" and "K" letters at the bottom, which are both red). Note that the targets are initially outside of the users field of view.

- *BVP signal*, *respiration signal* and *temperature signal*: the signals recorded by the PPG, girth, and thermometer sensors;

- *Surface EMG (SEMG) signals* (*left extensor digitorum communis*, *right extensor digitorum communis*, *right superior trapezius* and *right biceps brachii*): the electric activity of these muscles, recorded on the participants' skin;

- *Subjective preferences*: the results of the ranked choice questionnaire.

From the raw physiological data just described, these additional data were derived:

- *Heart rate*, *BVP amplitude*, *respiration frequency*, *respiration amplitude* and *peripheral temperature*: these values were averaged over 5–s epochs to reduce artifacts, especially BVP artifacts caused by head movements;

- *Mean activity* of *left extensor digitorum communis*, *right extensor digitorum communis*, *right superior trapezius* and *right biceps brachii*: the mean value of the *root mean square* (RMS) transformation of the four SEMG signals, averaged over one-second epochs (epochs for SEMG signals need to be shorter than BVP epochs because of the faster variations of these signals). A *notch filter* (band-stop filter), centered on the 50 Hz frequency, was applied to remove typical AC interference caused by electronic devices;

- *Total muscle activity*: the value of the *integrated SEMG* (IEMG) signals for each muscle. These values are derived from the area below the RMS EMG curves;

- *Mean values of the EMG power spectrum mean frequency*: each muscle fiber "discharges" at a particular frequency, so the EMG power spectrum (in which squared amplitudes of the frequency spectrum are considered) is the combination of the discharge frequencies of all the muscle fibers under the electrode. In the literature, the median frequency of the EMG power spectrum is sometimes measured, but it shows greater variability (De Luca, 1984; Andreassi, 2007). Values are smoothed over two seconds epochs;

- *EMG gradients*: linear regression slopes of each considered muscle activity, derived from the RMS transformation of the four SEMG signals averaged over 1–s epochs;

- *Linear regression slopes of the mean values of the EMG power spectrum mean frequency*: the mean frequency trend over time for the considered muscle activities, derived from the mean frequency values of the power spectrum averaged over 2–s epochs.

The four studied muscles were chosen after consulting with an occupational therapy clinician and two physiotherapists. In particular, we measured the activity of (i) left and right extensor digitorum communis muscles because they extend the medial four digits of the hands (the two SEMG sensors applied over the forearms are affected also by the activity of the thumbs), (ii) superior trapezius muscle of the arm used to hold the mouse and the Wii Remote, because this muscle is typically under heavy load in computer work (Wahlström, 2005), and (iii) biceps brachii muscle of the arm used to hold the mouse and the Wii Remote, because this muscle is particularly involved in the lifting of objects (the Wii Remote in our case). We decided not to focus on trapezius and biceps muscles of the other arm because they are much less activated by the considered task. As we reported in Section 4.4, all participants used the right arm to handle the mouse and the Wii Remote. Mean EMG and IEMG values were used to assess how much muscle effort was required to participants in each condition. EMG gradients were instead considered because there is evidence that they are related to level of motivation: the higher the motivation, the steeper the slope (Andreassi, 2007).

Mean frequency values and their linear regressions are good indicators of a sustained muscle contraction and a signal of localized muscle fatigue (Andreassi, 2007; Merletti et al., 1990; Tassinary et al., 2000): the "faster" fibers contract at the beginning of muscular contraction and are subsequently replaced by the "slower" ones. Therefore, during a prolonged muscle activity the mean frequency decreases (the power spectrum graph tends to "shift" to the left).

Circulatory and respiration system measurements were used to assess the users' stress level. Sympathetic arousal tends to increase heart rate and respiration frequency, while decreasing peripheral temperature, BVP amplitude and respiration amplitude (Andreassi, 2007). However, we also have to take into account that postural differences cause significant variations in the circulatory system (Jones et al., 2003): in particular, the standing position causes the heart rate to increase and the BVP amplitude to decrease.

Task completion time as well as all key, button and joystick actions were automatically logged by the system. Action timings were used to calculate the duration of navigation and each manipulation type for each task.

5. Results

One participant was excluded from the analysis, because a 3D modeling error in the VE caused him to get stuck in a wall, preventing him to complete the first task. The sensor on the right forearm of a second user produced abnormal measurements of right extensor digitorum communis due to thick hair; therefore, values recorded on this muscle for this user were excluded from analysis.

Baseline values recorded before task execution (as described in Section 4.4) were removed from physiological data before analysis to account for individual differences.

To analyze data, we performed a repeated measures two-factor analysis of variance (ANOVA). Since this parametric test assumes that data follow a Gaussian distribution, we checked data normality using the Shapiro and Wilk normality test (1965). When data were not normally distributed, we first tried to apply mathematical transformations to make the distribution more symmetric (Cohen, 2000). When data could not be normalized, we employed the non-parametric *ANOVA-Type Statistics* (ATS) proposed by Akritas and Brunner (1997) and further refined by Brunner et al. (1999).

When the analysis revealed interactions among IVs, we investigated them, as suggested by Cohen (2000), by performing cell-to-cell comparisons and adjusting the p-value with Bonferroni correction. The comparisons were carried out using t-tests or, when the data could not be normalized, the non-parametric Wilcoxon test.

Overall, muscle activity results and completion times produced the most interesting outcomes, with M&K producing better results than W&N in most of the cases. This was reflected also in subjective preferences.

In the following sections, we describe all the findings in detail.

5.1. Task completion time

Task completion time data was not normally distributed and a square root transformation was applied to normalize it. Figure 10 shows the untransformed mean values of task completion time in the four experimental

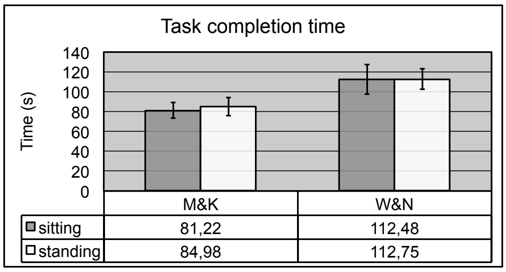
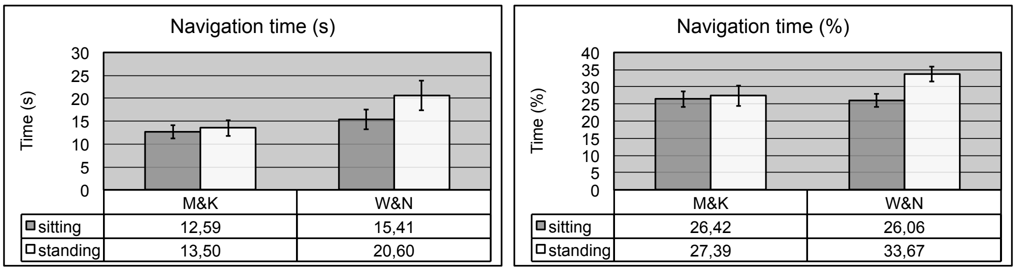


Figure 10: Mean completion time. Error bars indicate standard error of the mean.

conditions. There was neither a significant interaction between the two IVs, nor a significant main effect of posture. A significant main effect of interaction technique was instead detected ($F(1, 64) = 12.266$, $p < 0.01$): carrying out the task with W&N required about 36% more time than with M&K.

5.2. Navigation time, coarse manipulation time, fine manipulation time

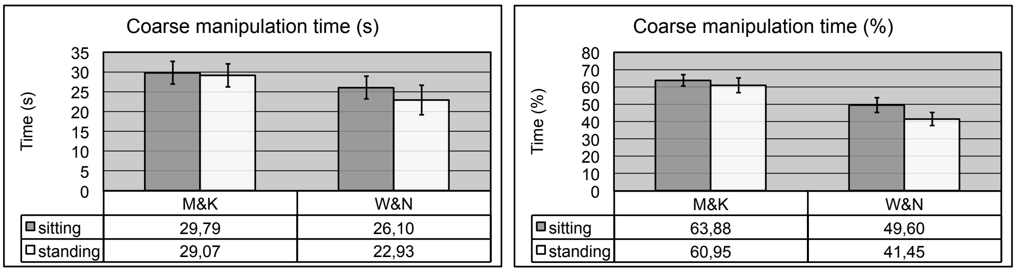


(a) (b)

Figure 11: (a) Mean navigation time in seconds and (b) mean navigation time expressed as a percentage of the sum of navigation, coarse and fine manipulation times. Error bars indicate standard error of the mean.

Navigation time data in seconds was not normally distributed and a square root transformation was applied, while navigation time expressed as a percentage of the sum of navigation time, coarse manipulation time and fine manipulation time followed a Gaussian distribution. Figure 11 shows the untransformed mean values of navigation time expressed in seconds as well as a percentage. The analysis of navigation time in seconds showed that interaction between the two IVs as well as main effect of posture were not significant. Main effect of interaction technique was instead significant ($F(1, 64) = 4.665$, $p < 0.05$): users navigated for a longer time with

W&N than M&K. When analyzing the navigation time data as a percentage, neither interaction between the two IVs nor main effect of interaction technique were significant. Main effect of posture was instead significant ($F(1, 64) = 5.326$, $p < 0.05$): users navigated for a longer time when standing than when sitting.

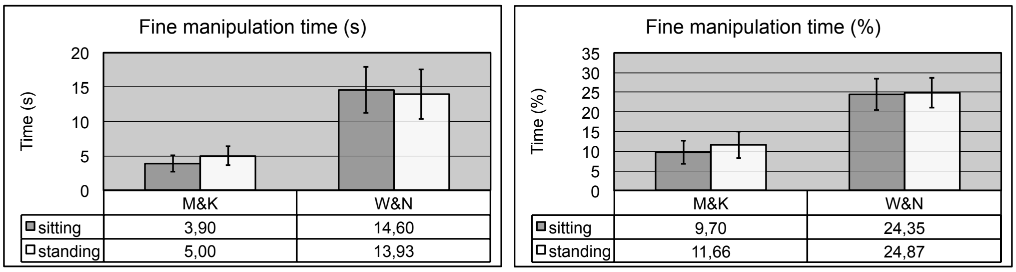


(a) (b)

Figure 12: (a) Mean coarse manipulation time in seconds and (b) mean coarse manipulation time expressed as a percentage of the sum of navigation, coarse and fine manipulation times. Error bars indicate standard error of the mean.

Similar to navigation time, coarse manipulation time data was not normally distributed and a square root transformation was applied. Figure 12 shows the untransformed mean values of coarse manipulation time expressed in seconds and as a percentage of the sum of navigation time, coarse manipulation time and fine manipulation time. Analysis of coarse manipulation time data in seconds showed lack of main effects and interaction. The analysis of coarse manipulation time data as a percentage showed neither a significant interaction between the two IVs, nor a significant main effect of posture. Main effect of interaction technique was instead significant ($F(1.64) = 16.766$, $p < 0.001$): users spent less time using coarse manipulation with W&N than M&K.

Fine manipulation time data in seconds as well as a percentage could not be normalized. Figure 13 shows the mean values of fine manipulation time expressed in seconds as well as a percentage of the sum of navigation time, coarse manipulation time and fine manipulation time. The analysis of fine manipulation time in seconds revealed neither a significant interaction between the two IVs, nor a significant main effect of posture. Main effect of interaction technique was significant ($ATS = 27.403$, $p < 0.001$). The analysis of fine manipulation time as a percentage produced similar results, with a significant main effect of interaction technique ($ATS = 19.086$, $p <$



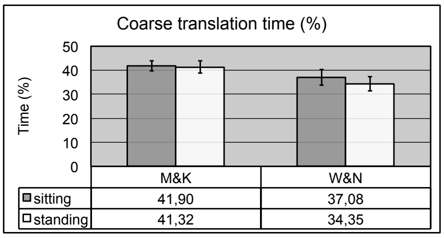
(a) (b)

Figure 13: (a) Mean fine manipulation time in seconds and (b) mean fine manipulation time expressed as a percentage of the sum of navigation, coarse and fine manipulation times. Error bars indicate standard error of the mean.

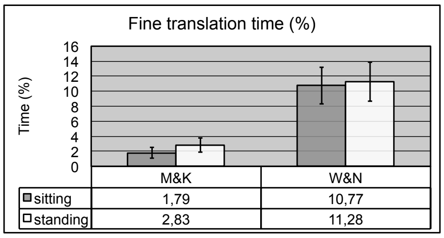
0.001). These two results show that participants used fine manipulation for a longer time with W&N than M&K.

We analyzed in detail coarse and fine translation, rotation and size manipulation data expressed as a percentage of the sum of navigation time, coarse manipulation time and fine manipulation time. The mean values are shown in Figure 14. Coarse translation data was normally distributed, while other data were not following a Gaussian distribution and could not be normalized. The analysis showed no interaction between IVs, and five main effects: a main effect of interaction technique for fine translation time ($ATS = 32.582$, $p < 0.001$), coarse rotation time ($ATS = 10.38$, $p < 0.01$), fine rotation time ($ATS = 5.26$, $p < 0.05$), coarse size manipulation time ($ATS = 9.026$, $p < 0.01$) and fine size manipulation time ($ATS = 6.493$, $p < 0.05$). These results show that participants, with W&N, used less coarse rotation and size manipulation rather than M&K, while they used more fine translation, rotation and size manipulation with W&N rather than M&K.

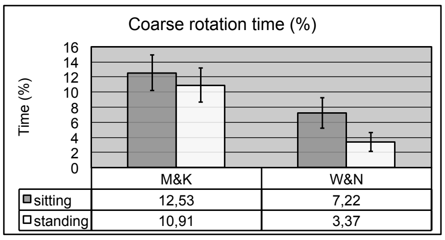
Since, as seen in section 3.2, participants could change viewpoint orientation in two different ways (i.e., by dragging the cursor with the mouse and the Wii Remote, and by pressing left and right arrow buttons on the keyboard and moving left and right the Nunchuck joystick), we analyzed in detail the time spent by participants using the two possibilities. The mean values are reported in Figure 15. An ATS analysis of the difference in usage proportions of the two possibilities (see third column of Figure 15) revealed no significant differences among conditions.



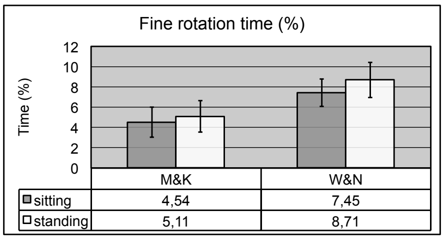
(a)



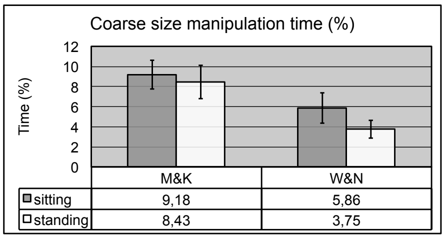
(b)



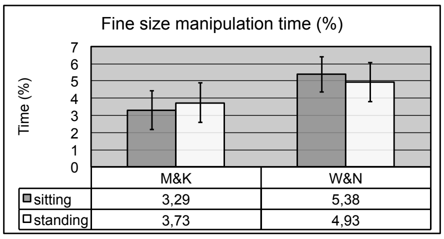
(c)



(d)



(e)



(f)

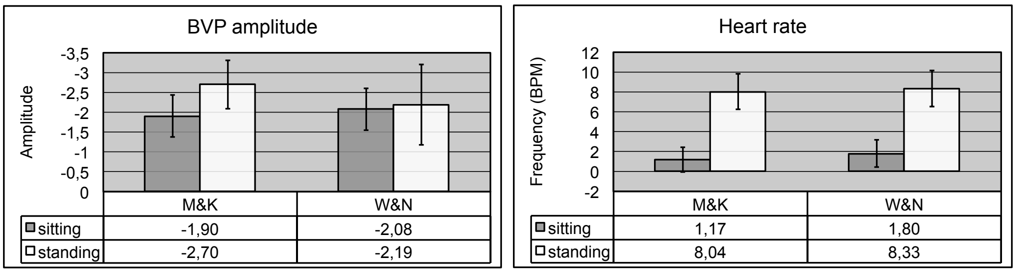
Figure 14: Mean time, in percentage of the sum of navigation time, coarse manipulation time and fine manipulation time, spent on coarse and fine translation, rotation and size manipulation. Error bars indicate standard error of the mean.

Task	Orient. with pointing (%)		Orient. with keys/joystick (%)		Difference (%)	
	Mean	SD	Mean	SD	Mean	SD
M&K sitting	26,09	29,34	73,91	29,34	47,83	58,68
M&K standing	34,33	32,09	65,67	32,09	31,33	64,19
W&N sitting	29,99	29,22	70,01	29,22	40,03	58,44
W&N standing	33,78	27,38	66,22	27,38	32,44	54,75

Figure 15: Time spent by users in viewpoint orientation, split in percentage between usage of mouse and Wii Remote pointing, and usage of keyboard buttons and Nunchuck joystick. The third column provides the average difference of the two percentages.

5.3. BVP, respiration and temperature measurements

If baseline values are greater than the recorded values during the task, the data obtained by subtracting the baseline are negative. In the following sections, when all mean values in a chart are negative, we reverse the scale for ease of reading.



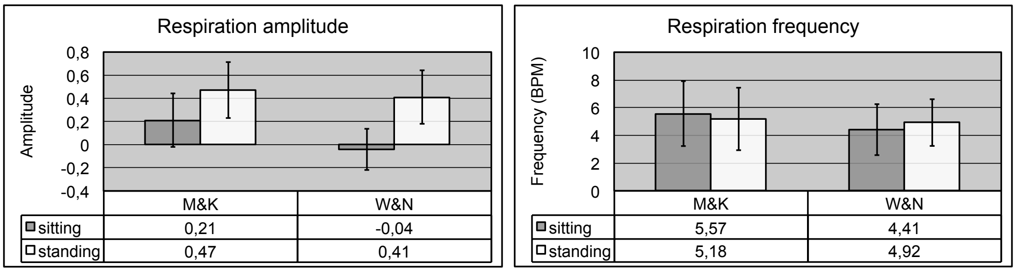
(a) (b)

Figure 16: Change of BVP amplitude (chart with reversed scale) and heart rate with respect to baseline values. Error bars indicate standard error of the mean.

BVP amplitude data was not normally distributed and could not be normalized, while heart rate data followed a Gaussian distribution. Figure 16 shows the untransformed mean values for the two measures. The figure does not specify a measure unit for BVP amplitude, because amplitude concerns a relative quantity. ATS analysis of BVP amplitude revealed neither a significant interaction between the two IVs, nor a significant main effect of interaction technique. A significant main effect of posture was instead detected ($ATS = 7.833$, $p < 0.01$). Similarly, ATS analysis of heart rate revealed a significant main effect of posture ($F(1, 64) = 32.903$, $p < 0.001$): participants had lower BVP amplitude values and higher heart rate with respect to baseline values when standing than sitting.

Respiration amplitude and respiration frequency data could not be normalized. Figure 17 shows the mean values for the two measures (in this figure, *BPM* stands for breaths per minute). The analysis of these two measures revealed neither a significant interaction between the two IVs, nor significant main effects of interaction technique and posture.

Peripheral temperature data was not normally distributed. All values were initially increased by a constant to become equal or greater than 1, in such a way that a square transformation could be applied. Figure 18 shows the untransformed mean values for this measure. The analysis revealed



(a) (b)

Figure 17: Change of respiration amplitude and respiration frequency with respect to baseline values. Error bars indicate standard error of the mean.

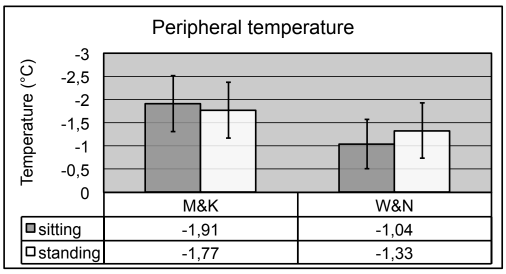
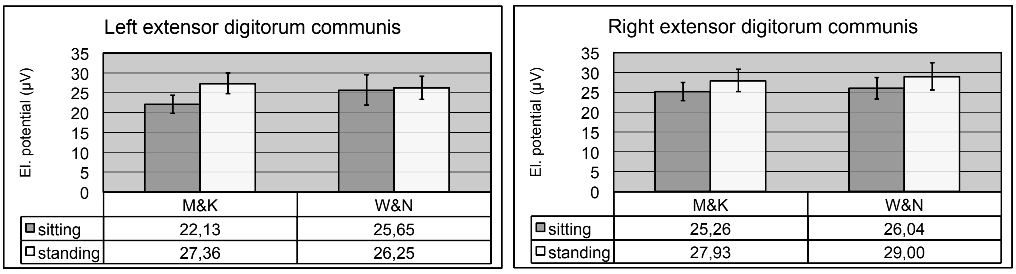


Figure 18: Change of peripheral temperature (chart with reversed scale) with respect to baseline values. Error bars indicate standard error of the mean.

no significant interaction between the two IVs and no significant main effect of posture. Main effect of interaction technique was instead significant ($F(1, 64) = 8.765$, $p < 0.01$): participants showed a higher peripheral temperature with W&N than M&K with respect to baseline values.

5.4. Mean muscle activity

Left extensor digitorum communis and right trapezius data were initially not normally distributed. To obtain normality, these data were initially increased by a constant to become equal or greater than 1, so that a square root transformation could be applied to both data sets. Right extensor digitorum communis and right biceps brachii data followed a Gaussian distribution. Figure 19 shows the untransformed means for left extensor digitorum communis and the means for right extensor digitorum communis, while Figure 20 shows the untransformed means for right superior trapezius and the means for right biceps brachii.

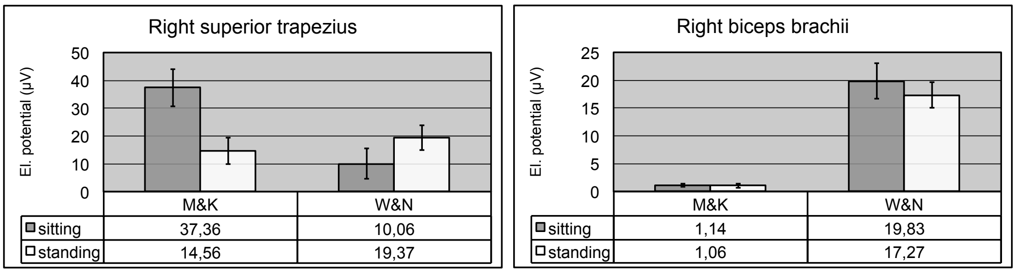


(a) (b)

Figure 19: Change of mean activity for left and right extensor digitorum communis with respect to baseline values. Error bars indicate standard error of the mean.

The analysis of mean activity of left and right extensor digitorum communis revealed neither a significant interaction between the two IVs, nor a significant main effect of interaction technique. Main effect of posture was instead significant for both muscles (left muscle: $F(1, 64) = 6.983$, $p < 0.05$; right muscle: $F(1, 60) = 5.477$, $p < 0.05$): participants showed a greater mean activity of left and right extensor digitorum communis when standing than sitting.

The analysis of right superior trapezius data revealed a significant interaction between the two IVs ($F(1, 64) = 32.386$, $p < 0.001$). A significant main effect of interaction technique ($F(1, 64) = 5.595$, $p < 0.05$) was also detected, while main effect of posture was not significant. Investigation of



(a) (b)

Figure 20: Change of mean activity for right superior trapezius and right biceps brachii with respect to baseline values. Error bars indicate standard error of the mean.

the interaction showed that with M&K the mean activity of right superior trapezius was significantly higher when sitting than standing ($t(16) = 3.915$, $p < 0.01$). Results show also that mean muscle activity was significantly higher with M&K than W&N ($t(16) = 3.959$, $p < 0.01$) when sitting. No significant difference between W&N and M&K was found when standing.

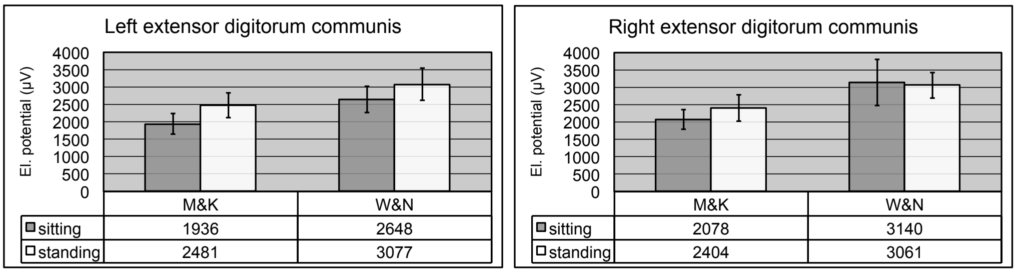
The analysis of right biceps brachii data revealed neither a significant interaction between the two IVs, nor a significant main effect of posture. Main effect of interaction technique was significant ($F(1, 64) = 41.079$, $p < 0.001$): mean biceps muscle activity was higher with W&N than M&K.

5.5. Total muscle activity

IEMG data recorded from left extensor digitorum communis was normally distributed. To normalize right extensor digitorum communis and right superior trapezius data, a square root transformation was applied to the former, while the latter was initially increased by a constant to become equal or greater than 1, in such a way that a square root transformation could be applied. Right biceps brachii could not be normalized. Figure 21 shows the untransformed IEMG values for left and right extensor digitorum communis, while Figure 22 focuses on right superior trapezius and right biceps brachii.

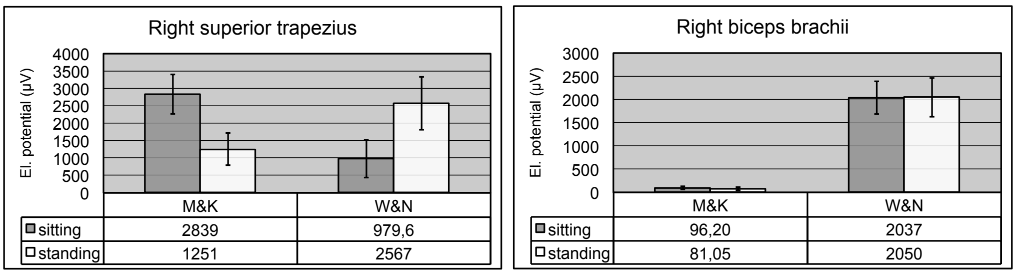
The analysis of IEMG data of left and right extensor digitorum communis revealed no interaction and one main effect. The main effect of interaction technique for the right extensor digitorum communis was significant ($F(1, 60) = 9.533$, $p < 0.01$): total muscle activity was higher with W&N than M&K.

The analysis of IEMG data of right superior trapezius showed that interaction between the two IVs was significant ($F(1, 64) = 26.393$, $p < 0.001$),



(a) (b)

Figure 21: Change of IEMG data for left and right extensor digitorum communis with respect to baseline values. Error bars indicate standard error of the mean.



(a) (b)

Figure 22: Change of IEMG data for right superior trapezius and right biceps brachii with respect to baseline values. Error bars indicate standard error of the mean.

while both main effects were not significant. Investigation of the interaction showed that with M&K the total activity of right superior trapezius was significantly higher when sitting than standing ($t(16) = 3.727$, $p < 0.01$). With W&N, total muscle activity was significantly higher when standing than sitting ($t(16) = 3.274$, $p < 0.01$). Moreover, IEMG was significantly higher with M&K than W&N ($t(16) = 3.33$, $p < 0.01$) when sitting.

ATS analysis of IEMG data of right biceps brachii revealed no significant interaction between the two IVs and no significant main effect of posture. Main effect of interaction technique was significant ($ATS = 83.143$, $p < 0.001$): the total activity of the right biceps brachii was higher with W&N than M&K.

5.6. EMG power spectrum mean frequency

Mean frequency data from the activity of left extensor digitorum communis, right superior trapezius and right biceps brachii was normally distributed. It did not follow a Gaussian distribution and could not be normalized for right extensor digitorum communis.

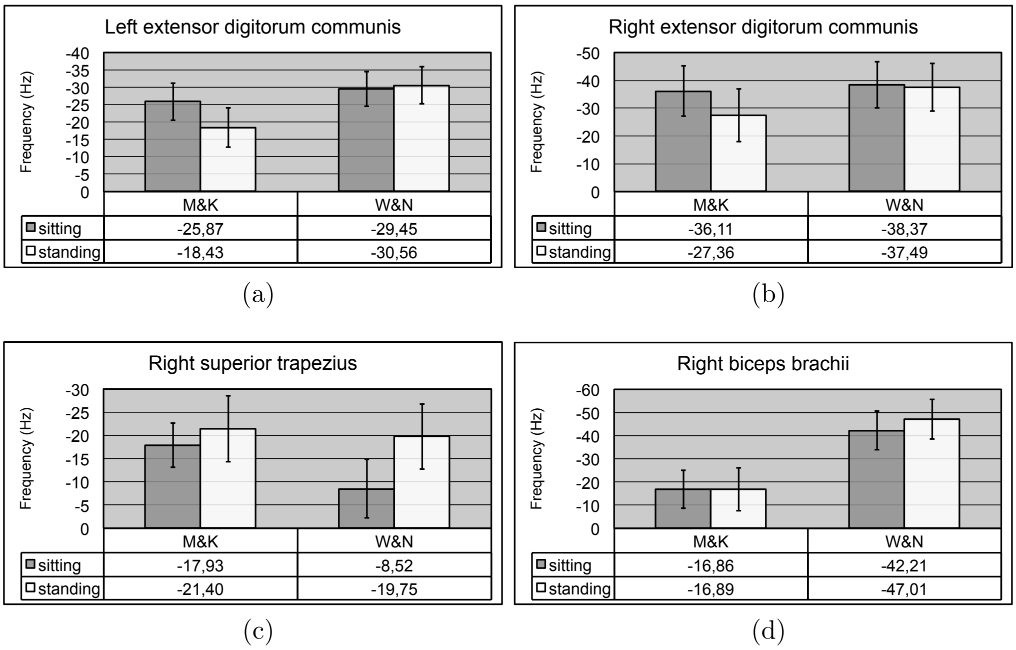


Figure 23: Change of mean power spectrum frequency for the four muscles (charts with reversed scale) with respect to baseline values. Error bars indicate standard error of the mean.

The analysis of mean frequency data for left extensor digitorum communis (Figure 23a) revealed a significant interaction between the two IVs ($F(1, 64) = 7.444$, $p < 0.05$) and a main effects of interaction technique ($F(1, 64) = 14.319$, $p < 0.01$) as well as posture ($F(1, 64) = 5.214$, $p < 0.05$). Investigation of the interaction showed that with M&K the mean frequency was higher when standing than sitting ($t(16) = 3.195$, $p < 0.01$), and that the mean frequency was higher with M&K than W&N ($t(16) = 5.006$, $p < 0.001$) when standing.

The analysis of mean frequency data for right extensor digitorum communis (Figure 23b) revealed a significant interaction between the two IVs ($ATS = 5.854$, $p < 0.05$) and a main effect of interaction technique ($ATS = 10.452$, $p < 0.01$) as well as posture ($ATS = 11.983$, $p < 0.001$). Investigation of the interaction showed that with M&K the mean frequency was higher when standing than sitting ($W = -132$, $p < 0.001$), and that the mean frequency was higher with M&K than W&N ($W = 122$, $p < 0.01$) when standing.

The analysis for right superior trapezius (Figure 23c) revealed no significant interaction between the two IVs and no significant main effect of posture. A significant main effect of interaction technique was observed ($F(1, 64) = 4.815$, $p < 0.05$): mean frequency values were lower with M&K than W&N.

The analysis for right biceps brachii (Figure 23d) revealed no significant interaction between the two IVs and no significant main effect of posture. A significant main effect of interaction technique was observed ($F(1, 64) = 43.11$, $p < 0.001$): mean frequency values were lower with W&N than M&K.

5.7. EMG gradients

EMG gradients values were not normally distributed. EMG gradients data for right extensor digitorum communis was increased by a constant to become equal or greater than 1, in such a way that a square root transformation could be applied. Data recorded from other muscles could not be normalized.

ATS analysis of EMG gradient for left extensor digitorum communis (Figure 24a) revealed that neither interaction between the two IVs nor main effects IVs were significant. The analysis for right extensor digitorum communis (Figure 24b) showed no significant interaction between the two IVs and no significant main effect of posture. A significant main effect of interaction technique was found ($F(1, 60) = 14.146$, $p < 0.05$): the muscle activity showed a steeper increase over time with W&N than with M&K.

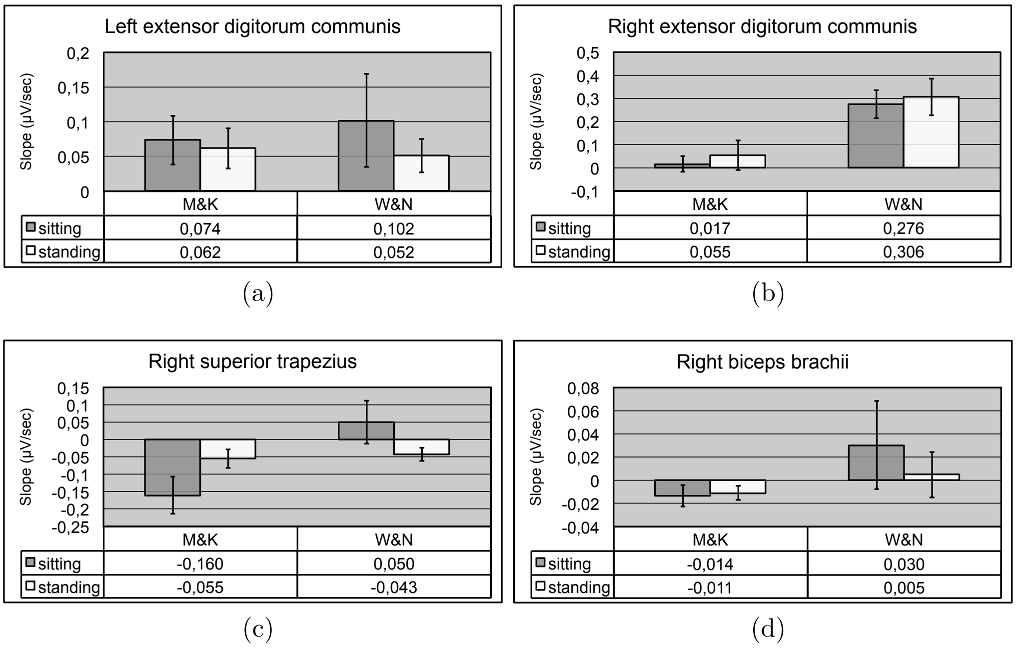
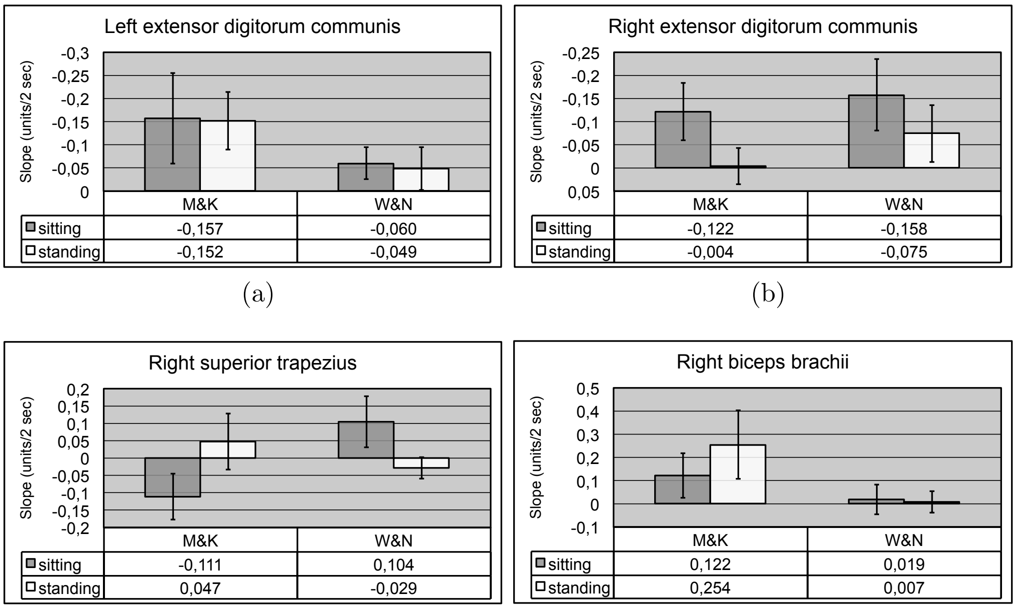


Figure 24: Change of EMG gradient data for the four muscles. Error bars indicate standard error of the mean.

ATS analysis of EMG gradient for right superior trapezius (Figure 24c) revealed a significant interaction between the two IVs ($ATS = 4.083$, $p < 0.05$) and a main effect of interaction technique ($ATS = 18.133$, $p < 0.001$). Investigation of the interaction showed that EMG gradient was higher with W&N than M&K ($W = -125$, $p < 0.01$) when sitting.

ATS analysis of EMG gradient for right biceps brachii (Figure 24d) revealed that neither interaction between the two IVs, nor main effects were significant.

5.8. Linear regression slope of the mean frequency of EMG mean power spectrum



(a) (b) (c) (d)

Figure 25: Linear regression slope of left and right extensor digitorum communis (charts with reversed scale), right superior trapezius and right biceps brachii. Error bars indicate standard error of the mean.

Linear regression slope values were not normally distributed. Only left extensor digitorum communis slopes could be normalized by increasing values by a constant to become equal or greater than 1, in such a way that a square transformation could be applied. The analysis of linear regression slopes did not find significant differences for any analyzed muscles.

5.9. *Ranked choice questionnaire*

Ranked choice questionnaire data was analyzed with ATS. Mean values are shown in Figure 26.

ATS analysis of first and second item data (Figures 26a and 26b) revealed no significant interaction between the two IVs and no significant main effect of posture. Main effect of interaction technique was significant (ease: $ATS = 3.993$, $p < 0.05$; comfort: $ATS = 9.919$, $p < 0.05$): navigation was perceived as easier and more comfortable with M&K than W&N.

ATS analysis of third item data (Figure 26c) revealed that neither interaction between the two IVs nor main effect of interaction technique were significant. Main effect of posture was significant ($ATS = 3.932$, $p < 0.05$): participants found coarse manipulation easier when sitting than standing.

ATS analysis of fourth item data (Figure 26d) revealed no significant interaction between the two IVs while both main effects were significant (posture: $ATS = 3.998$, $p < 0.05$; interaction technique: $ATS = 19.042$, $p < 0.001$): participants found coarse manipulation more comfortable when sitting than standing, and more comfortable with M&K than W&N.

ATS analysis of fifth and sixth item data (Figures 26e and 26f) revealed that neither interaction between the two IVs, nor main effect of interaction technique were significant. Main effect of posture was significant (ease: $ATS = 3.902$, $p < 0.05$; comfort: $ATS = 4.825$, $p < 0.05$): fine manipulation was perceived as easier and more comfortable when sitting than standing.

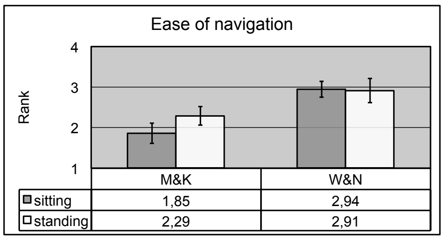
ATS of seventh and eighth item data (Figures 26g and 26h) revealed neither significant interactions nor main effects.

6. Discussion

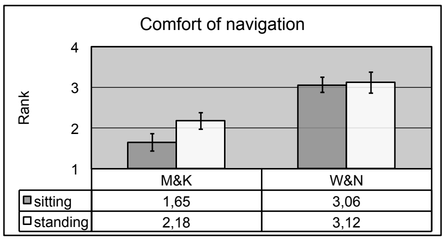
In this section, we discuss in detail the experimental results reported in Section 5.

6.1. *User performance*

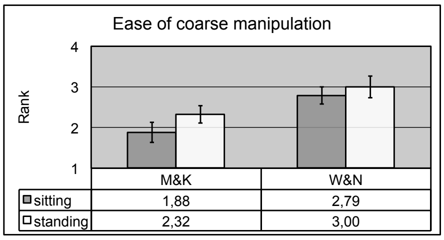
As the analysis has shown (Section 5.1), it took participants more time to complete the task with W&N than M&K. This result confirms the findings presented in the literature (e.g., MacKenzie et al., 2001; Olsen and Nielsen, 2001; Myers et al., 2002) but on a task (object arrangement) that to the best of our knowledge has not been considered before in the evaluation of LPS interaction techniques. Considering the detailed analysis of how participants spent time with W&N, it turns out that they navigated more,



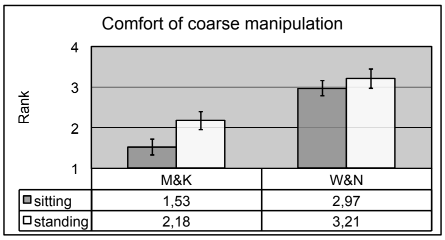
(a)



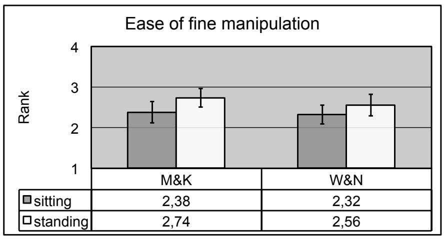
(b)



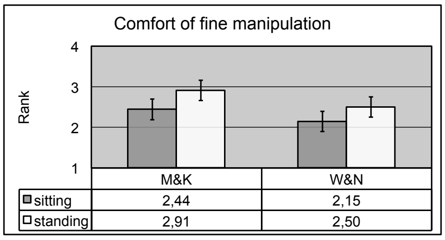
(c)



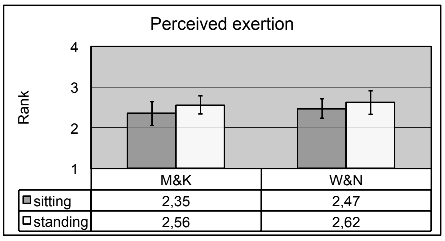
(d)



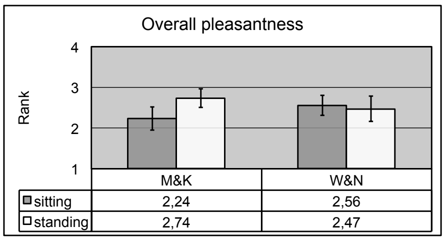
(e)



(f)



(g)



(h)

Figure 26: Mean values for the eight items of the questionnaire. Ranks range from 1 (best) to 4 (worst). Error bars indicate standard error of the mean.

performed less coarse manipulation and more fine manipulation (which generally requires more time than coarse manipulation) with respect to M&K.

Differences in object manipulation time between the two interaction techniques can be better understood by looking at the way participants used the two devices for manipulation. To keep the on-screen cursor in the current position, the user does not need to apply any force to the mouse, while she needs to continuously hold the LPS device in hand and point steadily at the screen, which results in more fatigue and muscle strain (see Section 6.2). Similarly, to move the cursor over a small distance, the mouse requires much less force than the LPS device, and to perform fine manipulations with M&K, participants have to move their hands from the mouse to the keyboard arrows, and once they are done back again to the mouse.

This could explain why, with W&N, participants spent more time using fine manipulation controls, which do not require to keep the device pointed at the screen. Indeed, by observing the participants, we noticed that, with the Wii Remote, they tended to make large changes with coarse manipulation to put the object roughly near the target, and then relying only on fine manipulation.

The difference in cursor latency, discussed in Section 3.1, might also have played a role, making users prefer fine manipulations (in which latency is reduced). Cavens et al. (2002) and Teather et al. (2009) pointed out that cursor latency affects negatively users' performance in Fitts and Tunnel tasks (Accot and Zhai, 1997). Moreover, the non-linear relationship between mouse and cursor speeds (the slower the mouse moves, the smaller is the distance travelled by the cursor) could have played a role: moving the cursor over small distances might have been easier with M&K because, with small mouse movements, the cursor can be controlled with a greater precision than W&N. As reported by Casiez et al. (2008), however, the effect of cursor acceleration on user performance is quite small.

6.2. Muscle activity

Left and right extensor digitorum communis. The analysis showed that the mean activity of left and right extensor digitorum communis is affected by posture: it is higher when the task is performed in a standing rather than sitting position. A factor that contributes to explain this result is that using the chair with the armrests allows for a position that puts less strain on extensor digitorum communis muscles.

Results also showed that power spectrum mean frequency was lower with W&N than M&K, and was higher when standing than when sitting.

Since lower values are an indication of a sustained muscle contraction and a signal of localized muscle fatigue (Merletti et al., 1990), these results indicate that muscle activity was more fragmented with M&K than W&N, giving participants more opportunities to recover from strain. This is also confirmed by total activity data, which showed that the accumulated activity of each muscle was greater with the LPS device than M&K. We can hypothesize that participants applied a more constant force to fingers with W&N to keep the LPS device constantly pointing at the screen. Similarly, results show that the standing position (which can be considered the most advantageous posture for LPS interaction with large displays because of the mobility afforded) requires a more constant muscle exertion with W&N than M&K.

A significantly steeper EMG gradient for the right extensor digitorum communis was also observed with W&N. Andreassi (2007) reviews various findings in the literature which correlate this kind of result with user involvement in the task. Thus, the use of the LPS device might require a greater level of user involvement to successfully complete the task with respect to M&K, perhaps due to the greater muscle control required to keep the device pointing at the screen during the task.

Right biceps brachii. The analysis of mean and total biceps activity revealed that W&N elicits a greater muscle activity with respect to M&K. This is not surprising, since the LPS device requires to point at the screen keeping the forearm lifted and the biceps under load, thus causing strain. Even if the chair used during the experiment was provided with armrests, the analysis revealed no significant difference between EMG values recorded when sitting or standing. As we observed during user evaluation, users generally leaned their right elbow on the armrest, but not their forearm. Power spectrum mean frequency data confirms that the LPS device required a sustained muscle contraction, thus causing more muscle fatigue.

The greater biceps activity might have consequences on the motor system if used for prolonged time: Sommerich et al. (2006) reports various studies which correlate sustained muscle contraction in the upper extremities with growing risks of cumulative disorders.

Right superior trapezius. The analysis of trapezius data shows that its mean activity was greater with M&K than W&N, and that the mean frequency of the power spectrum was higher with W&N than M&K. We thus hypothesize that the shoulder muscle was generally less strained by the use of the

LPS device, because the force needed to handle it was localized more in the biceps brachii. While mean and total muscle activity with M&K was greater when sitting rather than standing, the opposite was observed for W&N, probably thanks to the use of the chair armrests. More interestingly, the total muscle activity with the LPS device was greater in the standing than sitting posture, although, as we pointed out before, the standing posture could be considered more advantageous for LPS interaction with large displays.

Finally, EMG gradient data in the sitting posture was significantly higher with W&N than M&K, suggesting again that the use of the LPS device requires a greater level of involvement.

The shoulder complex provides the greatest range of motion of all the body joints, at the cost of reduced joint stability and potential for entrapment of various soft tissues when the arm is elevated or loaded (Sommerich et al., 2006): various structures under the shoulder complex (the *brachial plexus* muscle, the *subclavian artery* and shoulder nerves) can be compressed by muscles or bones when the humerus is elevated or when the shoulder is loaded indirectly, i.e., when holding a load in the hand. In this context, the superior trapezius, together with other scapular muscles, elevates the shoulder to position and move the arm in space for the purpose of hand function (Clarkson, 2000). This suggests that superior trapezius and general shoulder activity are strongly related, as pointed out by Aarås (1994). The trapezius can become strained when the arm is held in an elevated position for long periods (Sheumann, 2007). Therefore, the EMG data we collected, especially considering the differences caused by posture, should call attention to the effects on the shoulder caused by the use of LPS devices for extended periods of time, even if their weight is relatively small (in our study, it was about 140 g). Rozmaryn (2005) reports that if a load is held in the hand, the load moments at the elbow and the shoulder can become large relative to the flexor tendon moments required at both joints. Thus, even small loads cannot be supported for sustained periods (Rozmaryn, 2005), especially if the arm or forearm is elevated and pushed forward.

6.3. Other physiological measurements

The analysis showed that posture greatly affected the circulatory system, as expected (Jones et al., 2003). Moreover, the significant difference in peripheral temperature recorded with the two interaction techniques can be explained by noting that Nunchuck and keyboard have to be handled differently, thus eliciting differences in peripheral blood circulation at the left hand measurement site. More generally, participants' left hand was cooler during the evaluation with respect to the baseline (see Figure 18) because their forearm were generally kept elevated and stationary, causing poor blood circulation in peripheral vessels.

Overall, circulatory, respiratory and temperature measurements did not provide important differences in mental stress between the two interaction techniques: the availability of fine manipulation probably mitigated the mental stress caused by the less precise interaction with objects offered by coarse manipulation, and users did take advantage of fine manipulation.

6.4. Subjective preferences

Participants perceived W&N as more difficult and less comfortable than M&K during coarse manipulation. This is consistent with the observations about muscle activity reported earlier. The difference in perceived ease of use could also be explained by the fact that all participants had at least basic experience and were familiar with M&K (as reported in Section 4.1), while less participants had used W&N before the evaluation.

Participants' perception of navigation is also characterized by more difficulty and less comfort with W&N than M&K. We observed that, while the Nunchuck did not require to point at the screen, participants tended to keep the left forearm elevated at the same height of the right arm during task execution, thus possibly reducing comfort. Surprisingly, even though navigation with W&N was perceived as more difficult than with M&K, some participants' informal comments reported that they appreciated the use of the Nunchuck joystick to move inside the VE. A few participants who play more frequently video games on PC or the Wii reported that they found initially unnatural to use left and right arrows on the keyboard and left and right joystick movements on the Nunchuck to change the viewpoint orientation instead of strafing (see Section 3.2), but they quickly got used to it.

No clear preference between the two interaction techniques emerged with fine manipulation, probably because fine manipulation is carried out in both cases by pressing buttons (without the need to point at the screen), and objects move, rotate and scale at the same speed.

Generally, participants preferred the sitting posture to carry out the tasks, and perceived sitting as more comfortable, probably thanks to the fact that they could use the armrests or the desk to lean their forearms. Furthermore, the standing posture is generally more fatiguing: see, for example, the postural effects on the circulatory system, reported in the previous section.

Differences in perceived fatigue and pleasantness with the two interaction techniques were consistent with SEMG analysis, but they were small and did not reach statistical significance.

7. Conclusions

The results of the presented study indicate that M&K granted a better performance than W&N in object arrangement, and that M&K was also the interaction technique preferred by participants. This is consistent with results reported in the literature by studies that compared the mouse to LPS devices (e.g., MacKenzie et al., 2001; Olsen and Nielsen, 2001; Myers et al., 2002).

The EMG physiological data produced interesting results, which provide new insights about LPS interaction. The EMG analysis we performed, seen in the light of findings from medical and ergonomics literature (e.g., Aarås, 1994; Rozmaryn, 2005; Sommerich et al., 2006; Sheumann, 2007), suggests that, for left and right extensor digitorum communis and for biceps brachii, the risk of *work-related upper extremity disorders* (WUEDs) and more generally of MSDs could be greater with W&N than M&K. Moreover, results from the analysis of superior trapezius reported a lower muscle activity with W&N than M&K, but the standing posture caused a greater amount of superior trapezius activity with W&N than M&K. This result is particularly interesting since the standing posture should be the most advantageous one for LPS interaction with large displays because of the mobility afforded.

Our results might potentially concern any handheld LPS device, since it is likely to require movements and postures similar to those observed in our study (for example, continuously pointing at the screen). However, more advanced LPS interaction techniques assist users in selection and manipulation tasks in various ways: e.g., *InterSelect* (de Haan et al., 2005) estimates which object the user wants by employing selection volumes; *Bubble Cursor* (Grossman and Balakrishnan, 2005) resizes and reshapes dynamically the circular cursor so that it contains only one object; *SQUAD* (Kopper et al., 2011) uses a spherical cursor for a first selection step, allowing users to further refine the selection by discrete steps which discard unwanted objects. Advanced LPS interaction techniques could thus elicit a lower muscle activity and afford a better performance. Therefore, it is important to assess in depth the effects on the musculoskeletal system for each of these more advanced techniques.

As stressed by Sommerich et al. (2006), it is presently impossible to define the dose–response relationships and exposure limits for WUEDs (i.e., a quantification of exposure involved in work and a determination of health outcomes), but there is sufficient evidence to link WUEDs to workplace exposures. In general, MSDs are frequently originated and perpetrated by mechanical microtrauma which is often ascribed to muscle overuse, i.e., the repeated use or an excessive load that causes stress to tissues (Sahrmann, 2002). Repeated use can occur in long duration, such as the computer user who performs the same activity everyday for months or years. From this perspective, our study highlights the importance of extending current studies of novel interaction techniques with thorough EMG studies. Indeed, the current HCI literature focuses more on designing interactions that are "more natural" than traditional mouse and keyboard setups, but fails to explore their effects on the musculoskeletal system that become important when the technique is adopted in the workplace or at home.

In future studies, the use of LPS interaction on multi-sided projected VEs (e.g., CAVE) and panoramic 360° displays deserves additional attention, given the greater shoulder activity in the standing posture that we found in our study. With these setups, users are typically required to stand up and walk around to interact with the VE. We could hypothesize that, in these conditions, object arrangement might be actually more comfortable and intuitive with LPS devices rather than M&K. In more detail, users could point directly at the screen while standing as well as moving inside the physical room while, using the traditional mouse interface, they would instead be bound to a chair or a desk and forced, for example, to turn their head (also stressing neck muscles) to look at the displays.

Future studies should also focus on further exploring the design space of LPS interaction techniques. For example, we could consider various advanced techniques (de Haan et al., 2005; Grossman and Balakrishnan, 2005; Ouramdane et al., 2006a; Kopper et al., 2011) or the use of *6DOF ray casting*: instead of using LPS interaction to simply control the cursor (which represents a virtual ray perfectly orthogonal to the screen), we could employ virtual rays starting from the device that follow the orientation of the device itself. In this way, since users would be able to control the orientation of the ray, it might be easier to perform objects selections and manipulations, which might help to reduce muscle activity.

Finally, in future studies we will consider the activity of a greater number of muscles, to obtain more detailed information about the effects of novel interaction techniques on the musculoskeletal system.

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