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EVALUATING ON-LINE CONTROL OF GOAL-DIRECTED ARM MOVEMENT WHILE STANDING IN VIRTUAL VISUAL ENVIRONMENT

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Abstract. *The control of visually guided movement has been showed to be optimised when motor programming quickly integrated the visual information to update on-going motor commands. The purpose of this study was to verify this proposition for movement executed in virtual visual environment (VE), by exploring the effect of immersion on the on-line visuomotor control of goal-directed arm movement. Six subjects participated in the experiment, in which hand reaching toward a stationary or a moving virtual visual target (double step paradigm) was executed in standing posture. The analysis of the hand kinematics and postural adjustment showed an accurate control of movement and balance in both reaching conditions. This indicates that the immersion do not affects the on-line control processes used by the CNS to adjust movement in interactive VE.*

Key words. *Goal-directed movement, visual double step, on-line visuomotor co-ordination, virtual environment*

1. INTRODUCTION

The interactive virtual reality is more and more applied to studies on human motor behaviour such as goal-directed hand movement or postural equilibrium, in motor behaviour research, clinic evaluation, training and performance (Carrozzo and Lacquaniti, 1998; Riva, 1998,

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2001; Wann et al., 1998). In such situations, subject must use the visual information available in the virtual environment (VE) to plan and control movement and balance, as naturally as possible. However, VE exposure often causes errors in the visual guidance of motor activities. Moreover, the difficulty to obtain a functional human-VE interaction strongly reduced the experimental, therapeutic and ergonomic interests of the VE. The spatial compatibility between the virtual scene and the feasibility of the movement is one of the most important points to consider in order to reach an acceptable level of realism compatible with an effective interactivity (e.g. Kennedy and Stanney, 1996). Consequently, the development of the virtual visual environment for neurobehavioural experiments must take into account the principles of the visuomotor transformation, which correspond to the transfer processes of afferent visual information in motor commands. The characteristics of this natural co-ordination between visual perception and action are assessed by studying movement and balance variables. These variables give information on the visuomotor processes involved to adjust movement and posture to the environmental perturbations. Visual information plays a major role for the planning and the control of corrective movement. Its role has been extensively explored in the adjustment of goal-directed movement (Jeannerod 1988; Desmurget et al., 1998) and standing posture (Massion, 1992). Previous studies on hand reaching have shown that subjects are able to modify the hand trajectory when the location of the visual target changes during movement (e.g. Prablanc and Martin, 1992). When executed in standing posture, these hand trajectory corrections are integrated at postural level by changing the hip strategy during movement correction (Martin et al., 2000). This indicates that the central nervous system (CNS) uses on-line control processes to adjust movement and posture. The reprogramming of motor commands is established on the basis of visual cues of the hand compared to the target location (associated to proprioceptive information) in a visuo-spatial frame of reference. The preservation of the on-line control of movement is an important factor for the functional interactivity between subject and VE. However, little is known on the corrective adjustment of goal-directed movement in standing posture in VE. This study was carried out in order to analyse how the motor commands are updated to compensate for the unexpected modification of the virtual visual scene. The aim is to determine the influence of the VE immersion on the on-line processing of motor commands. In this experiment, both hand reaching movement and postural stability have been analysed when subject had to adjust the hand trajectory in response to a sudden change of the virtual target location. The analysis of the hand kinematics and the postural equilibrium could provide information on the degree of disturbance of the visuomotor processes induced by the VE immersion. In this context, the following questions can be asked: Does the “virtuallity” of the visual stimuli have an effect on the visual guidance of hand movement? What visuomotor strategy does the CNS use when rapid adjustment of reaching movement is required in VE? Is the on-line processing of motor commands modified in VE?

2. MATERIALS AND METHODS

2.1. Subjects

Six right-handed men (aged 22-40 years) participated in the experiment. All subjects had normal or normal-corrected vision and had never experienced VE. Five subjects were naive to the purpose of the experiment; one was familiar with its objectives. The experiment lasted one hour per subject.

2.2. Virtual environment

The effect of the VE on goal-directed movement has been examined using 3-dimensional (3D) stereoscopic scene to generate virtual visual target. In the VR-room, virtual visual targets were generated by a SGI Onyx 3400 computer connected to three synchronised CRT Barcos video-projectors with geometric corrections. The image of the target was projected on a 180 degrees curved-screen. Subjects wore stereo-shutter glasses for 3D-vision (Crystal Eyes, StereoGraphics Inc.; see fig. 1). In order to use hand kinematics as a direct measure of the on-line movement control in VE, 3D kinematics were recorded with an optoelectronic motion capture system (Optotrack 3020 real-time system, NorthernDigital™). Markers (light emitted diodes, LED) were placed at the middle-eyes,

Fig. 1. Installation of the subject in the VE-room. Subject stood on the forceplate and executed pointing movements from the starting position toward the virtual target. The Optotrack system is placed at the bottom of the curved-screen.

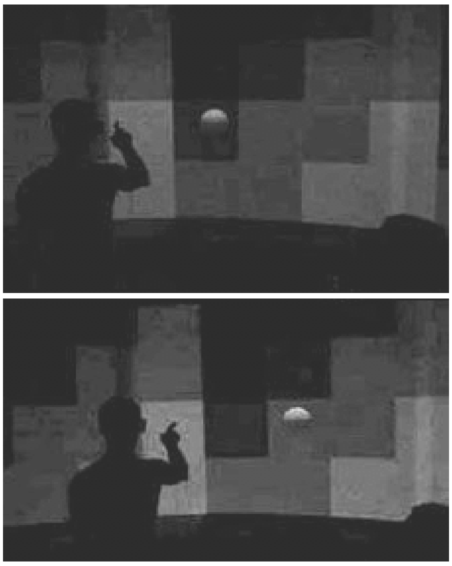

Fig. 2. Reaching movement directed toward a stationary virtual target (control condition in the upper frame) and a displaced target during movement (Double step condition in lower frame). Target is perceived in the prehension space.

on the right index finger tip, under the right elbow, and on both sides of the shoulders and hips. In this study, only hand kinematics is presented. The sampling rate was 60Hz to be synchronise with the target generating system. This frequency allowed (1) the calculation of the height of the virtual target initial position based on the middle-eyes LED position, and (2) the real-time processing of the distance between the hand and the target referenced to the 3D-coordinates of the index LED's. Data were processed with a Butterworth 4th order filter (dual pass with a 10 Hz cut off frequency) prior to calculation of displacement kinematics. To evaluate the postural adjustment associated to reaching, an AMTI™ forceplate allowed to analyse the momentum of the ground reaction forces generated around the x medio-lateral and z vertical axis (respectively Mx and Mz) at the level of centre of foot pressure (COP). The sampling frequency was 500Hz. These data gave information on the automatic postural processes organised to counteract the equilibrium perturbation due to the arm movement.

2.3 Procedure

In the initial position, subject stood on a forceplate at the centre of the VE-room (Fig.1). His right hand was in contact with the lower extremity of the sternum, the index finger in extension. Subject was instructed to keep his eyes on the target to make the 3D perception easier. At the beginning of each trial, after a ready signal, a virtual target was displayed in order to be perceived on the structured surface of the screen, i.e. about 3 meters in front of the subject at the eyes height (calculated from of the middle-eyes LED). Two seconds later, the target was moved (1 m/s) toward the subject following a rectilinear path along the sagittal axis. The target stopped in the prehension space, at a distance corresponding to 80% of the right arm length extended in a pointing position. This distance was chosen to reduce the conflict between vergence and accommodation. As soon as the target stopped, subject had to point toward it quickly and as accurately as possible. The target size was 5-cm radius. When the index finger had reached the target (i.e. when the 3D-coordinates of the index finger tip matched with those of the virtual target), a sound signal indicated the end of the trial, the subject getting back to the initial position. Two pointing conditions were presented. In the *Control* condition (30 trials), the target stayed at the same position during the pointing movement. In the *double step* condition, a step target occurred randomly in 25% of the trials (10 trials) at hand movement onset (detected from real-time acquisition of the index LED), turning off the initial target and simultaneously lighting up an other one located 20 degrees on the right (Fig.2). This paradigm is called the "visual double-step" (Pélisson et al, 1986). Pair-wise comparisons between control and double step conditions were processed for hand kinematics dependant variables, in order to determine if the visual double step affects the control processes of the visually guided movements in VE. The analysis also focused on the effects of the virtual target displacement while reaching on the dynamic postural adjustments.

3. RESULTS

The personal sensation of subjects during and after the experiment indicates that neither motion sickness, nor after-effects or maladaptive transfer were observed despite the long VE-exposure.

3.1. Kinematics of arm reaching

3.1.1. Hand trajectory and accuracy of pointing

Figure 3A shows the 2D-pointing trajectory of a representative subject for the control and the double step conditions. The first point to note is that in control condition subjects was able to point toward the target with a direct hand path, without any perturbation of the reach. A weak variability of the trajectory in both conditions was also observed. The stability of the initial and final positions of the hand indicates the reproducibility of the pointing and balance during the VE

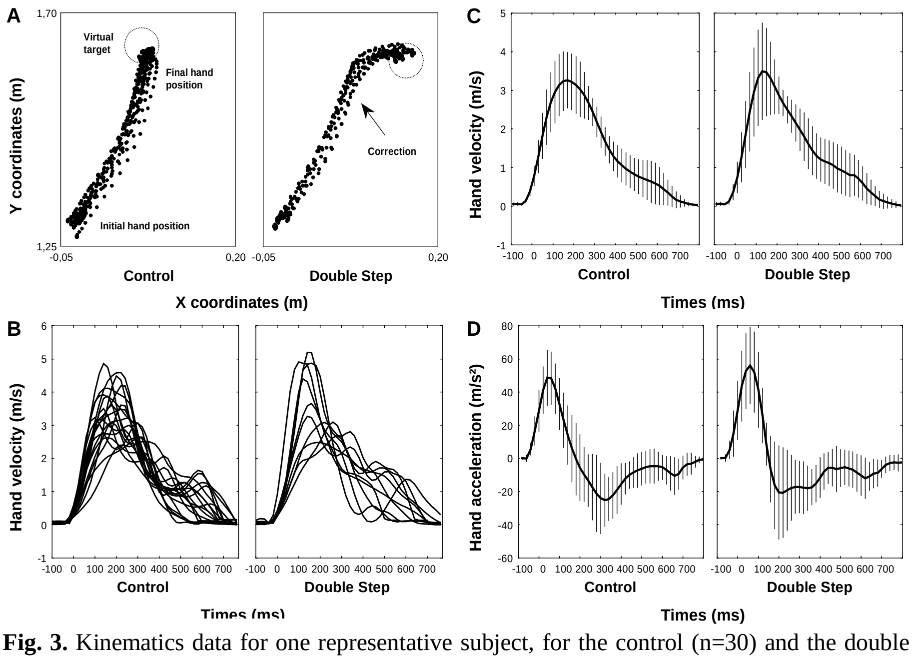

Fig. 3. Kinematics data for one representative subject, for the control (n=30) and the double step (n=10) conditions. **A.** Upper view of the 2D trajectories of the index finger, from the hand starting position toward the virtual visual target. **B.** Profiles of the 3D-resultante velocity of the index. **C.** Mean and standard deviation of the 3D-velocity of the index. **D.** Mean and standard deviation of the 3D-acceleration of the index.

session. This reproducibility is estimated to be identical to that observed in natural situation. In both conditions, the final accuracy of pointing is maintained. It was the required condition to validate the trial. In the double step condition, hand trajectories are smoothly corrected in the last third of the pointing to reach the new target location accurately.

3.1.2. Hand velocity and acceleration

Figure 3B shows the modulus of hand velocity profiles for all the trials of the representative subject. For control and double step conditions, the hand velocity is regulated in the same way, showing a main peak velocity followed by successive regulations. These profiles indicate on-line adjustments of the pointing velocity in the second half of the trajectory. This is clearly illustrates by mean profiles of hand velocity (Fig. 3C). For control and double step conditions, pointing are composed of an acceleration phase (from the movement onset to the peak velocity) followed by a longer deceleration phase (from peak velocity to the end of pointing) with discernible control point. This bell-shape profile is identical to those observed in natural goal-directed movement. The mean acceleration of index finger showed in figure 3D reinforced this kinematics similarity. For both conditions, the hand trajectory adjustments occurred during the deceleration phase, and there was only one peak of acceleration and deceleration despite the trajectory correction in double step condition. These results are similar to those obtained with pointing executed in the real word. Table 1 presents the mean values and standard deviation of the amplitude and time of

	Control	**Double step**
Movement time (ms)	**652** ±139	**665** ±107
Peak Hand Velocity (m/s)	**3,32** ±1,30	**3,55** ±1,23
Acceleration Time (ms)	**156** ±65	**146** ±58
Peak Hand Acceleration (m/s²)	**52,91** ±22,06	**55,21** ±31,55
Time to PHA (ms)	**58** ±36	**56** ±17
Peak Hand Deceleration (m/s²)	**-25,33** ±27,51	**-20,83** ±30,91
Time to PHD (ms)	**319** ±109	**217** ±96 *
Deceleration time (ms)	**496** ± 124	**519** ± 103

* : $p<0.05$

Table 1. Summary table of means and standard deviations of hand kinematics variables for the control and double step conditions.

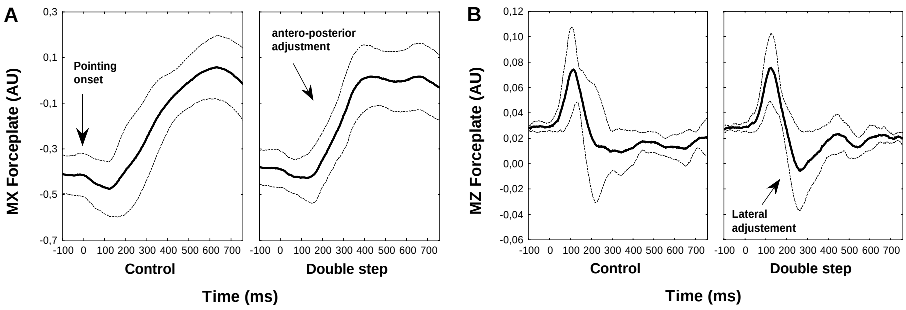

Fig. 4. Means and standard deviation of the forceplate momentum data for one representative subject, for the control (n=30) and the double step (n=10) conditions (data in arbitrary unit). **A.** Momentum around the medio-lateral X-axis of the forceplate (Mx). **B.** Momentum around the vertical Z-axis of the forceplate (Mz).

the hand kinematics parameters. For most of them, neither the amplitude nor the timing of reaching parameters was significantly affected by the double step. The movement time, calculated from velocity thresholds at the onset and the end of pointing, was not significantly different for the control vs. the double step conditions. The only effect of the double step on kinematics parameter was the significant decrease of the time to peak deceleration, which indicate the modification of the initial motor commands. These kinematics data are identical to those presented in the large literature concerning visually guided movement (see Jeannerod, 1988 for a review). Consequently, these results indicate that the VE-exposure has no specific effect on the kinematics of the reaching.

3.2. Postural control

The effects of the visual double step on standing posture were analysed using Mx and Mz forceplate momentum at COP level. Figure 4 shows the average of the Mx and Mz for the representative subject, in control and double step conditions. It is interesting to note that for both conditions, a quiet standing was processed before and after the hand reaching. In the double step condition, a significant increase of the Mx value occurred early in the pointing and lasted until the hand had reached the moving target. A significant increase of the Mz is also observed in the left direction opposite to the direction of the double step, i.e. the direction of hand trajectory correction. These COP momentum modifications observed during movement, in both the anterio-posterior and lateral direction, indicate that when the hand trajectory must be corrected, on-line postural adjustments occurred very quickly. This automatic postural control compensates for the visual double step perturbation by participating dynamically to the re-alignment of the hand trajectory on the new target location. However, the important variability found in the data could minimise this synergy between postural adjustments and hand trajectory correction.

4. DISCUSSION

The rapid adjustment of goal-directed arm movement while standing requires the capability to integrate multisensory information from the body and the environment. In real word, when perturbation appears during the execution of visually guided movements, on-line control processes allow to update motor commands and correct movements (Prablanc and Martin, 1992). The aim of this study was to determine whether the VE influences the control of goal-directed movement, and estimate the efficiency of the on-line visuomotor adjustments when reaching to visual target while standing in virtual visual environment. The results show that hand reaching toward a virtual target was programmed and controlled in a similar way to that of real visual environment. When reaching toward the stationary virtual target the visuomotor processes guided the hand as accurately as in the natural environment, and with identical kinematics adjustments. When a double step target occurred during the pointing, subjects was able to modify the trajectory of their hand to reach the new target location accurately. This indicates that on-line control processes of goal-directed movement are preserved in VE. Indeed, the regulation of the hand kinematics observed in the second half of the pointing can be considered as the consequence of the normal programming of corrective sub-movements. At balance level, the dynamic postural adjustment was processed in a parallel way to automatically counteract the effect of the hand trajectory correction. These movement and posture adjustments was synchronised, and their programming and control did not induced additional movement time when reaching correction. The accurate adjustment of the hand on the target, the correction of the trajectory, and the synergistic postural adjustment, indicate that the capacity to modify movement in VE is maintained thanks to the persistence of the on-line motor control despite the artificial characteristics of the visual information. A possible explanation of this result could be that in our experiment vision had provided a sufficient information at the same time for the accurate control of movement, the stability of the standing posture, and the co-ordination of both. This raises the question of the effect of the characteristics of the visual information on the movement control in VE. In this experiment, the static and dynamic characteristics of the virtual visual environment (respectively the structured background and the fixed or moving target) have allowed the re-programming of motor commands for a functional co-ordination between movement and balance. This result indicates that the visuomotor processes involved in the control of gesture in VE can be based on the processing of elementary visual cues (like in non-photorealistic rendering environment). These basic cues could allow an on-line control as long as they participate to the elaboration of a functional visual frame of reference. Consequently, get the fundamental information for visuomotor control seems to be a prerequisite for adaptive behaviour in interactive VE. Thus, our findings lend support for the hypothesis that if functional characteristics of the virtual stimuli correspond to those of natural stimuli, visuomotor co-ordination could be processed without conflict, and produce interactive behaviour as natural as in the real visual environment. The challenge is now to determine the functional characteristics and the essential components of the natural visuomotor behaviour to implement in the VE. The generalisation of the findings to more complex motor behaviour in VE must be, however, tempered, due to the simplicity of our pointing task which is not completely relevant of more global motor tasks. Therefore, it would be interesting to measure the movement-posture co-ordination with more target and/or more complex task or stimuli, like visuomanual pursuit or interception of 3D-moving object, bimanual reaching or accurate grasping. Moreover, because an important variability was found in the data, it would be pertinent to perform this kind study with more trials and on larger populations.

5. CONCLUSION

This study has showed that the motor processes used by CNS to control visuomotor co-ordination in real situation still have a functional efficiency in immersive VE. The variables describing the on-line adjustment of movement and balance, such as pointing accuracy, kinematics of arm movement, and dynamic equilibrium, could be used to identify reliable measures of goal-directed movement and balance in VE. These functional measures could serve as indicators for comfort of the subject and ergonomics of VE and tasks, and consequently, for the development and the certification of protocols for neurobehavioural research, clinic and ergonomics.

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