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RESEARCH ARTICLE

It is all me: the effect of viewpoint on visual–vestibular recalibration

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Abstract Participants performed a visual–vestibular motor recalibration task in virtual reality. The task consisted of keeping the extended arm and hand stable in space during a whole-body rotation induced by a robotic wheelchair. Performance was first quantified in a pre-test in which no visual feedback was available during the rotation. During the subsequent adaptation phase, optical flow resulting from body rotation was provided. This visual feedback was manipulated to create the illusion of a smaller rotational movement than actually occurred, hereby altering the visual–vestibular mapping. The effects of the adaptation phase on hand stabilization performance were measured during a post-test that was identical to the pre-test. Three different groups of subjects were exposed to different perspectives on the visual scene, i.e., first-person, top view, or mirror view. Sensorimotor adaptation occurred for all three viewpoint conditions, performance in the post-test session showing a marked under-compensation relative to the pre-test performance. In other words, all viewpoints gave rise to a remapping between vestibular input and the motor output required to stabilize the arm. Furthermore, the first-person and mirror view adaptation induced a significant decrease in variability of the stabilization performance. Such variability reduction was not observed for the top view adaptation. These results suggest that even if all three viewpoints can evoke substantial adaptation aftereffects, the more naturalistic first-person view and the richer mirror view should be preferred when reducing motor variability constitutes an important issue.

Keywords Sensorimotor learning · Visual · Vestibular · Adaptation · Motor control

Introduction

In everyday life, we always ‘see’ the world from a first-person view. However, with the development of new technologies, we are exposed to an increasing number of situations in which we see ourselves interacting with our surroundings from different perspectives. For instance, video games often give the possibility to alternate between first- and third-person views. For certain types of interactions with the environment, specific viewpoints could actually be preferred over others. For example, the third-person view might be advantageous for navigation tasks (Salamin et al. 2006; Salamin and Thalmann 2010). Concerning sensorimotor control and learning, most of the studies that investigated the effect of viewpoint are based on the naturalistic first-person view, which is usually preferred for fine manipulation like teleoperation (Macedo et al. 1998). However, a recent study by Ustinova et al.

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(2010) suggested that higher viewpoints might actually allow for better motor performance.

In the present study, we used a visual–vestibular recalibration task to quantify the efficiency of different viewpoints on sensorimotor adaptation. In particular, we compared the naturalistic first-person view and the more artificial top view. In addition, we also measured the performance when sensorimotor adaptation takes place with a first-person view 'enriched' by a mirror view. The principle of this 'mirror view' was to provide the additional visual information one would get when performing the task in front of a mirror, as it is for instance the case in ballet classes, where mirrors are used to provide visual feedback about one's dancing performance in order to promote motor learning.

One of the paradigms that has been most extensively used to study sensorimotor adaptation is prism adaptation (Hay and Pick 1966; Welch et al. 1979). In prism adaptation, participants are instructed to perform a motor task, typically with the arm, while they are presented with biased visual feedback about the position of the effector, i.e., visual information that is incongruent with the actual effector position. This situation induces a mismatch between visual and proprioceptive cues, which usually gives rise to a visual recalibration of the proprioceptive-controlled motor output (see Redding et al. 2005 for a review). We used a paradigm based on a similar principle, but implying visual–vestibular rather than visual–proprioceptive recalibration. Specifically, participants had to keep their hand and stretched arm pointing at the top of an earth-fixed bottle during passive whole-body rotations, while they were presented with biased visual feedback about the amplitude of body motion relative to the environment. This created a mismatch between the body rotation sensed by the vestibular system and the visually perceived rotation, inducing a visual recalibration of the vestibular-controlled motor output. The visual scene was a virtual room containing various objects and landmarks—such as the bottle—and an avatar that provided the participants with visual information about their body. The main reason why we used such a visual–vestibular recalibration task is that it implied a displacement of the whole body with respect to the surroundings. Specifically, under these circumstances, we conjectured that seeing the whole body moving, as for instance in a top view, could be advantageous as compared to a first-person view, in which participants can only see their arm.

Varying the viewpoint on a scene and oneself is impossible in the real world, but the virtual reality technique (VR) allows such manipulations. VR combines excellent experimental control and high realism (Loomis et al. 1999), thereby constituting a unique tool for investigating human perception and action (see Tarr and Warren 2002 for a review). Interestingly, the flexibility provided by VR techniques can also be exploited for neurorehabilitation (Adamovich et al. 2009). Especially, a striking 55–75% of stroke survivors have continued limitations in upper extremity use (Kwakkel et al. 2003; Olsen 1990) despite the numerous training paradigms aiming at improving recovery (Kwakkel et al. 1999; Masiero et al. 2007; Platz et al. 2005; Ring and Rosenthal 2005; Summers et al. 2007). In this context, VR can be used to develop individualized, patient-centered neurorehabilitation paradigms for patients who suffered from stroke. In particular, VR training can be modified online to meet an individual's needs by creating adaptive training paradigms that can continually provide the most effective program for each patient in order to relearn motor skills, hereby optimizing the learning rate (Mahncke et al. 2006). Several studies have investigated VR's potential use in facilitating neurorehabilitation in paretic stroke patients, and the results have been quite promising (see for instance Siekierka et al. 2007). However, the specific conditions under which VR can accelerate recovery most efficiently are not well understood yet. Notably, a critical aspect in determining the usability of VR in neurorehabilitation applications is its efficacy in facilitating sensorimotor learning (Adamovich et al. 2009; Henderson et al. 2007). In line with this, it is important to determine whether and how motor learning is affected by the viewpoint. Specifically, if non-natural (e.g., top view) or enriched viewpoints (e.g., mirror view) turn out to promote sensorimotor learning, then integrating these viewpoints in neurorehabilitation programs might be beneficial.

Chan (2001) described VR as a system that allows the extension of our embodying capacities. Because in the present study the task was performed in a virtual world with which participants interacted with a 'virtual body', we assessed whether sensorimotor adaptation performance could be correlated with perceived presence and immersion in the virtual environment. Presence was defined by Witmer and Singer (Witmer and Singer 1998, p 225) as "the subjective experience of being in one place or environment, even when one is physically situated in another". Immersion is a construct that is related to presence, reflecting the realism and the possibilities of interaction with the VR environment. To measure the level of experienced spatial presence, immersion, and involvement in our virtual environment, participants filled out an English version of the Igroup Presence Questionnaire (IPQ; Schubert et al. 2001) after completing the experiment. In addition, we included a questionnaire on avatar embodiment for which we constructed questions concerning the perceived similarity between the self and the avatar, and the extent to which participants felt that the avatar responded to movements like their own body would do.

The scores of the questionnaires were correlated with the strength of motor adaptation.

Materials and methods

Participants

A total of 24 subjects participated in the experiment (first-person view: age 21–45, mean = 26, 3 men; top view: age 24–28, mean = 26, 4 men; mirror view: 21–39, mean = 26, 3 men). All participants were right-handed, had normal stereovision, and were naïve to the aim of the study. They all gave written informed consent for participating in the experiment, which was performed in accordance to the ethical standards laid down in the 1964 Declaration of Helsinki. Eight subjects participated in the first-person view, eight in the top view, and eight in the mirror view condition.

Apparatus

The experiment took place in the 12 by 12 meter Cyberneum Tracking Lab (see Fig. 1a) in which the position of infrared-reflective rigid-body marker objects can be identified in 3D (x, y, z) space across all six degrees of freedom using an optical tracking system of 16 infrared Vicon MX13 cameras (Vicon Motion Systems, Oxford, UK). Tracking of objects was accomplished using ViconTracker software and a wireless connection.

Subjects seated comfortably in a robotic wheelchair capable of 360° rotations (BlueBotics, Lausanne, Switzerland). They wore a neck brace that restricted tilt as well as rotational head movements, so that the head remained aligned with the trunk during the experiment. A fully immersive head-mounted display (HMD, NVIS nVisor SX-60) was steadily but comfortably fixed to their head to present the virtual scene in stereo. The field of view provided by the HMD was 44° horizontally and 60° diagonally. Five infrared-reflective Vicon markers were fixed on the HMD, so that the position and orientation of the participants' head were continuously tracked, and the visual scene updated accordingly. In addition, participants wore an 'adapted' glove on their right hand, with four Vicon markers fixed on top of it. This glove was used to update the position and orientation of the avatar arm in the virtual scene. Finally, the position and orientation of the wheelchair were tracked using four Vicon markers. A picture of the setup is shown in Fig. 1b.

Movements in tracking space were rendered in real-time with a delay of about 30 ms. Perspective on the scene was determined by determining the position of the head markers at the beginning of the experiment. The tracking system was sampled at 120 Hz, and the visual scene updated at a stable refresh rate of 60 Hz taking into account head motion in space. Stereo images were presented at a resolution of 1,280 × 1,024 pixels per eye. Presentation was synchronized to the HMD display to avoid image-tearing artifacts. The 3D visual environment was developed in Virtools 4.1 (3DVIA http://www.3ds.com).

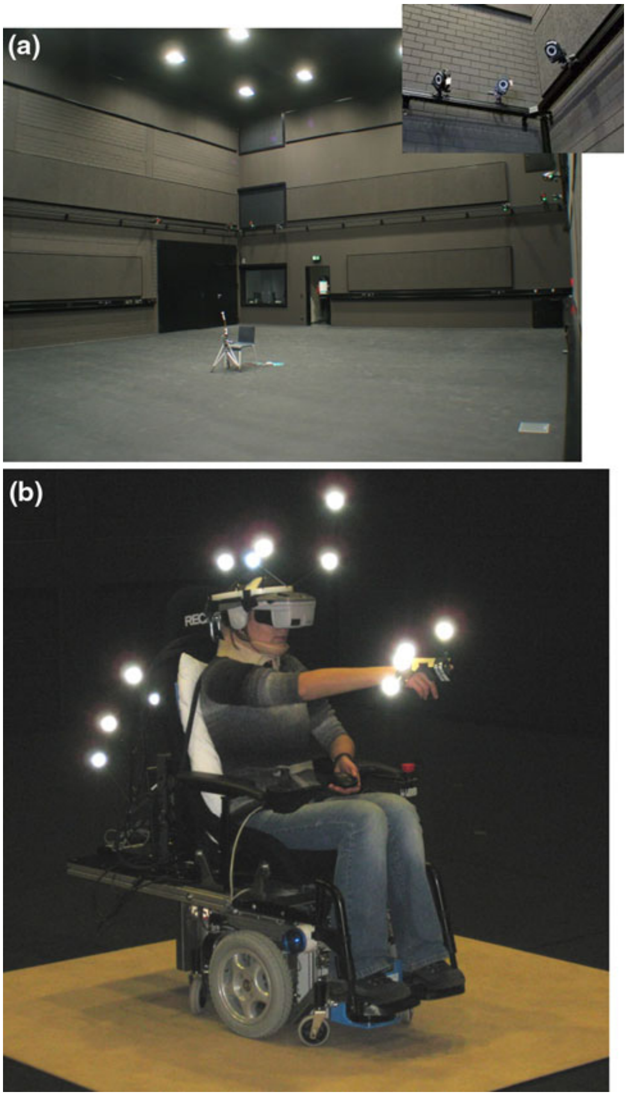

Fig. 1 MPI tracking hall. A 12 × 12 meter room equipped with 16 VICON cameras (**a**). A participant seating on the motorized wheelchair, equipped with the infrared-reflective VICON markers, the neck brace and the HMD (**b**)

Virtual scene and avatar

The virtual scene consisted of a room with landmarks (e.g., windows, doors, pictures on the walls), a brown circular table of 200 cm in diameter with a 60-cm opening in the center, and a green bottle with 30 cm of height located on the table. The participants were seated in the central opening of the table, surrounded by the table plate. At the beginning of all trials, the orientation of the participants in the room and the position of the bottle on the table in front of them were always identical. An avatar arm provided the participants with visual feedback about the position and movements of their arm in space. At the beginning of the experiment, the length of the participant's arm was measured and the avatar arm was scaled accordingly. This measurement was also used to adjust the distance of the bottle so that it was exactly at reaching distance. A first-person view on the virtual scene and the avatar arm is shown in Fig. 2.

Task

At the beginning of each trial, the virtual scene was displayed, and the participants had to stretch their right arm and position the index finger on the top of the bottle. The visual feedback provided by the avatar arm allowed the participants to precisely position their finger on the top of the bottle. After 3 s, the participants were passively rotated counterclockwise, resulting in a change of their orientation in the virtual scene. During the wheelchair rotation, participants were required to keep their arm and hand still in space (i.e., in the virtual room) so that their index finger remained on the top of the bottle. Because the bottle was earth-fixed, a rightward compensatory movement of the arm was necessary to counteract the counterclockwise whole-body rotation and keep the finger on the top of the bottle (see Fig. 3).

Design

The experiment consisted of three sessions: (1) a pre-test phase; (2) an adaptation phase; and (3) a post-test phase.

Fig. 2 First-person view on the virtual scene, with the participant having his right arm stretched and pointing at the top of the bottle

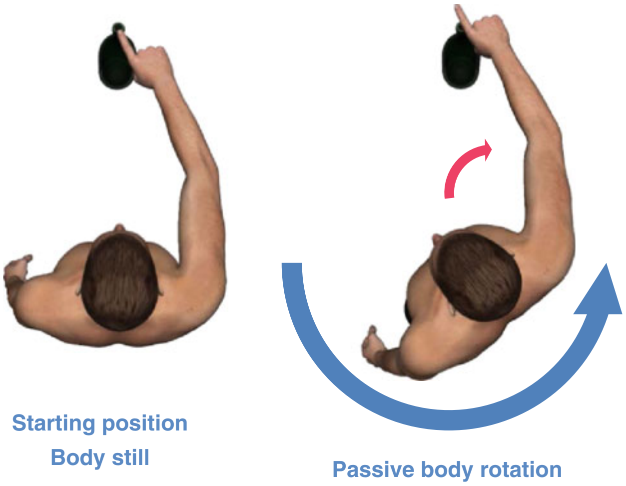

Fig. 3 Participants' task was to keep pointing toward the top of the bottle during passive counterclockwise whole-body rotation. A rightward compensatory arm movement was required to counteract the leftward rotation of the wheelchair

The time course of a trial is presented in Fig. 4. In the pre-test and post-test phase, the visual scene disappeared before body rotation, so that the rotation occurred without any visual information about the motion and arm movement. During the adaptation phase, the visual scene was visible for the whole duration of the trial, thereby providing visual feedback about the amplitude and speed of body motion in the room and with respect to the bottle. However, the displayed rotational speed was manipulated to rotate with a gain of 0.7 relative to the real rotational speed of the wheelchair. As a consequence, the virtual world rotation was 30% smaller than the actual rotational movement of the wheelchair (see Fig. 5). Comparing participants' performance between the pre- and post-test phase allowed us to quantify adaptation.

Three different viewpoints were used during the adaptation phase, with three different groups of subjects. In the first-person view, participants could see the avatar as they would normally see their own body, the camera being approximately at eye's height. In the top view, the scene was viewed from above, and the participants could see the upper half of the body of the avatar, the lower part being hidden under the table. Finally, in the mirror view, the scene was observed from a first-person view, but in addition, a virtual mirror was placed in front of the avatar, providing supplementary information about the body and the bottle in space. This view corresponded to how one would view oneself in a large mirror in the real world, with left and right reversed. A general overview of the experiment is presented in Fig. 6, in which the three viewpoints are displayed. In the first-person and mirror view conditions, the gain of the visual rotation was altered by reducing the speed of the optic flow. In top view, this

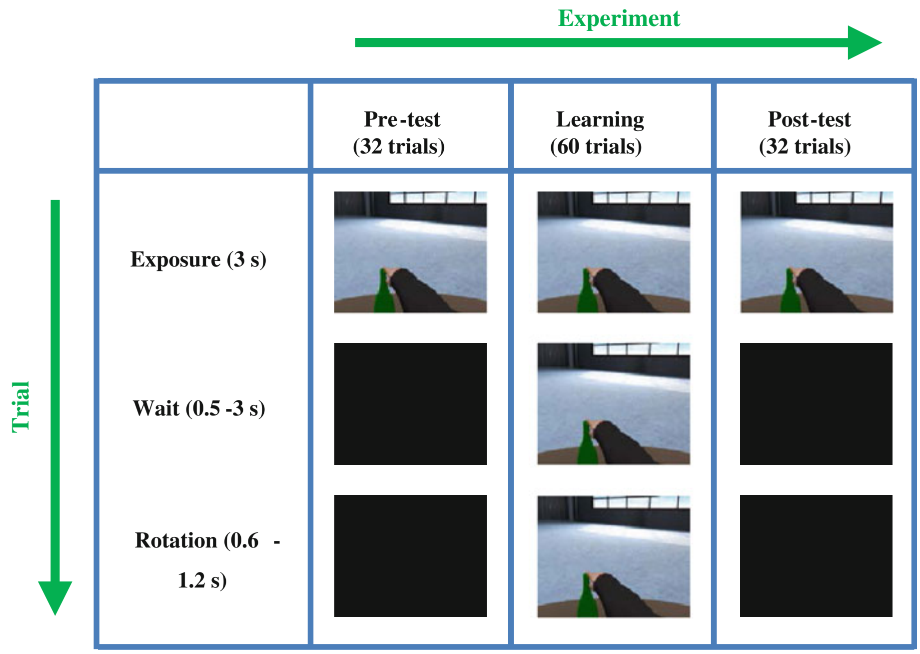

Fig. 4 Time course of a trial. In the pre-test and post-test sessions, body rotation occurred without any visual feedback. During the adaptation phase, visual feedback about rotation amplitude was provided and the participants could see their 'avatar' arm

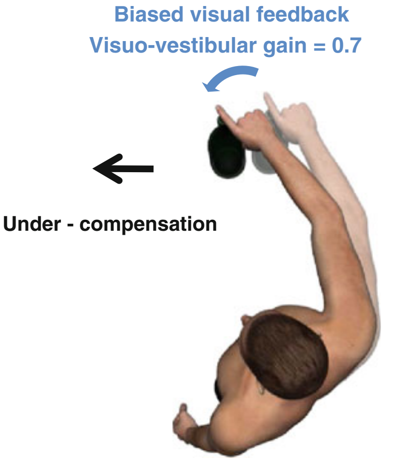

Fig. 5 In the adaptation phase, the virtual world rotated with a gain of 0.7 relative to the real-world rotation. The arm movement required to keep pointing toward the top of the bottle was of smaller amplitude than the one that would be required if visual feedback about the rotation were correct. Therefore, participants learned to under-compensate for the vestibular-sensed body rotation

was achieved by rotating the scene about the avatar with reduced velocity as compared to the actual body rotation.

Four different rotation amplitudes were used: 15, 25, 35, and 45°. The rotations were presented using a raised cosine profile and lasted from 600 to 1,200 ms, depending on their amplitude. The participants performed 8 trials per rotation amplitude in both the pre- and post-test session (i.e., for a total of 32 trials in each session), and 15 trials per rotation amplitude in the adaptation session (i.e., for a total of 60 trials). In addition, eight practice trials identical to the pre-test trials were performed at the beginning of the experiment to acquaint the participants with the virtual environment and make sure they understood the task. In total, the experiment consisted of 132 trials and lasted about 45 min. In each session, the presentation order of the trials was completely randomized. Just before the experiment, the participants were given a 60-s first exposure to the virtual environment. During this period, they were encouraged to look around and move their arm in space to familiarize themselves with the environment.

Data analysis

For each trial, performance was quantified by comparing fingertip position in space before and after body rotation. The angular difference in degrees represented the rotation-evoked stabilization error. Over- and under-compensatory arm movements were assigned positive and negative values, respectively. For each type of viewpoint, the main effect of adaptation was assessed by comparing stabilization errors in the pre- and post-test session. Specifically, average stabilization errors were entered in a 2 × 4 [session (pre-test, post-test) * rotation amplitude (15, 25, 35, 45°)] repeated measures analysis of variance (ANOVA). For each viewpoint, we also assessed whether the adaptation contributed to reduce the variability of stabilization responses. The standard deviations of stabilization error were entered in the same repeated measures ANOVA design as the average errors. Stabilization error and variability were always measured in degrees.

To test the effect of viewpoint on sensorimotor adaptation, we compared the amplitude of the adaptation between the three viewpoint conditions. For each viewpoint, two

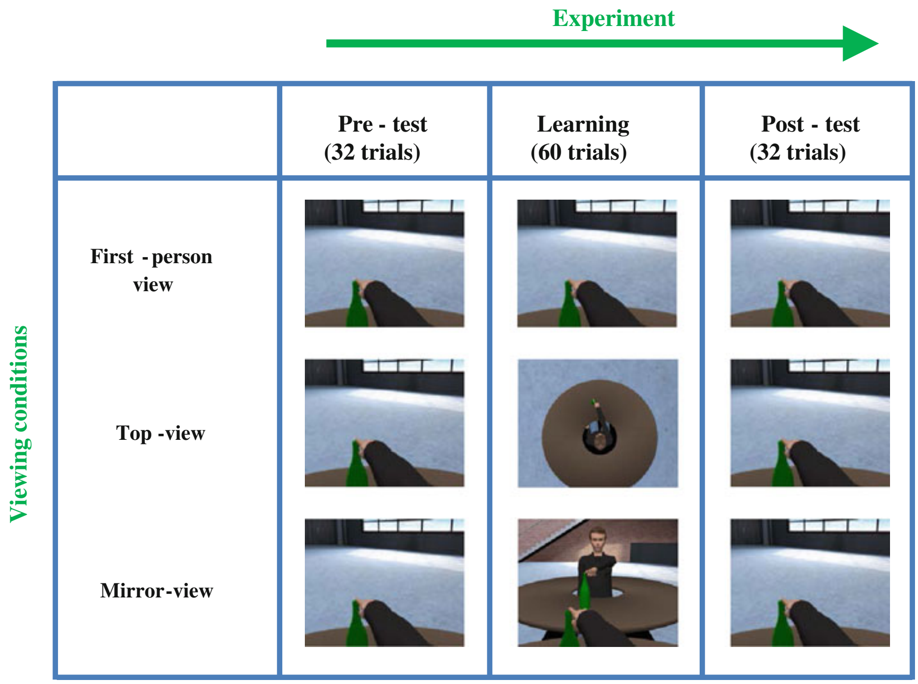

Fig. 6 Experimental design. For all three conditions (groups of participants), the perspective on the visual scene presented at the beginning of the pre- and post-test trials was always the first-person view. Viewpoints on the virtual scene in the adaptation phase varied between conditions

measures of adaptation were used, namely relative aftereffect and absolute aftereffect. Relative aftereffect was defined as the difference in the mean stabilization error between the pre- and post-test session. Absolute aftereffect was defined as the mean post-test performance. For both relative and absolute aftereffects, average values were entered in a 3 × 4 [viewpoint (first-person view, top view, mirror view) * rotation amplitude (15, 25, 35, 45°)] mixed model ANOVA, with the viewpoint as between-groups factor and rotation amplitude as within-subjects factor. The same mixed model ANOVA design was used to compare arm stabilization variability between viewpoint conditions (using individual standard deviations) as well as arm stabilization performance during the adaptation phase. This last analysis was performed to assess whether participants complied with task instructions and to make sure that the adaptation phase exhibited similar effects for the three viewpoint conditions. Here again, stabilization error and variability were always measured in degrees.

The internal consistency of the Igroup Presence Questionnaire (IPQ) was assessed by calculating the reliability coefficient Cronbach's alpha for the total test score. In addition, Cronbach's alpha was calculated for the Avatar Embodiment Questionnaire. Average scores on the subscales were put in a 3 × 4 [viewpoint (first-person view, top view, mirror view) * subscale (General Question, Spatial Presence, Involvement, Experimental Realism)] mixed model ANOVA design, to investigate whether different viewpoints influenced feelings of presence, involvement, and realism of the virtual environment differently. The same procedure was used to investigate the Avatar Embodiment Scale. In addition, bivariate correlational analyses on the subscales, questions, total test score, and adaptation aftereffects were performed, correlating the behavioral effects with the scores on the subscales.

For all ANOVAs, the reported values are Huynh–Feldt-corrected and post hoc tests were performed using Bonferroni correction for multiple comparisons ($\alpha = 0.05$).

Results

Main effect of adaptation on stabilization errors (within-group analysis)

For all three viewpoint conditions, stabilization errors in the post-test session were significantly biased in the counterclockwise direction as compared to performance in the pre-test session (see Fig. 7). In other words, in the post-test trials, subjects compensated less for body rotation than they did in the pre-test trials, confirming that sensorimotor adaptation occurred. In addition, for all three viewpoints, there was a significant interaction between the session and the rotation amplitude, the difference between post- and pre-test sessions increasing with rotation amplitude ($P < 0.05$).

Main effect of adaptation on stabilization variability (within-group analysis)

For the three viewpoints, hand stabilization variability was reduced in the post-test as compared to the pre-test (see Fig. 8a). In other words, the adaptation session contributed to

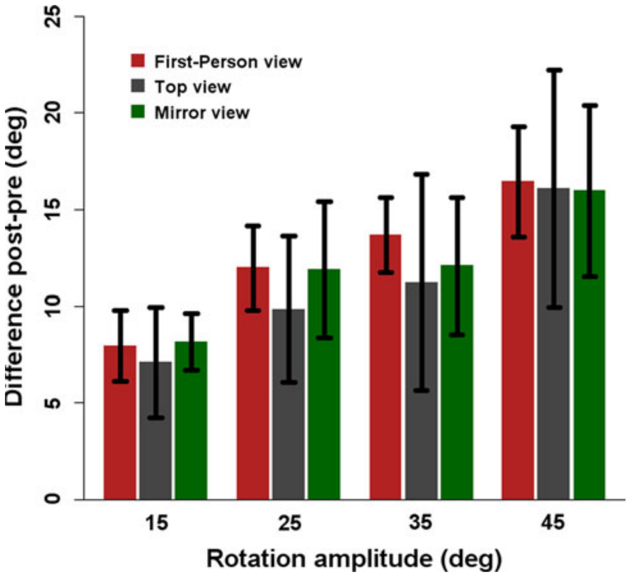

Fig. 7 Effect of adaptation on stabilization performance for the three viewpoints and for each rotation amplitude. The bar represents the difference of performance in degrees between the post- and pre-test sessions. Error bars represent standard error. The overall difference between post- and pre-test performances is significant for all three viewpoint conditions ($F(1, 7) = 33.50$, $P < 0.001$, $F(1, 7) = 5.99$, $P < 0.05$, $F(1, 7) = 14.60$, $P < 0.01$, for the first-person, top and mirror view, respectively)

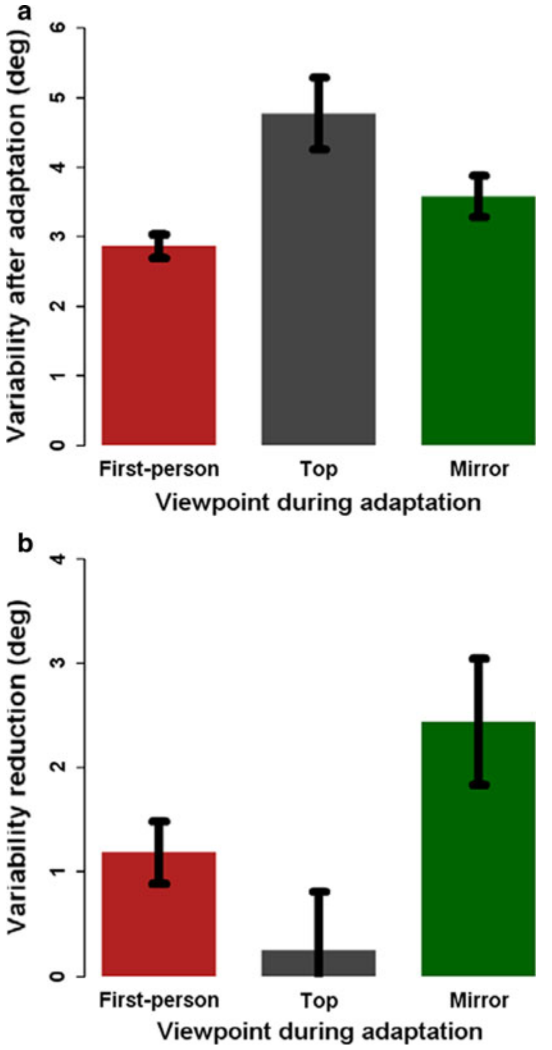

Fig. 8 Mean variability of the hand stabilization performance in the post-test session. This variability was significantly higher for the top view condition than for the other two viewpoint conditions (**a**). Reduction in variability resulting from learning during the adaptation session. For each viewpoint, this reduction was measured by comparing the mean standard deviation of hand stabilization performance in the pre- and post-test sessions. *Error bars* represent standard error. The reduction in variability is significant for the first-person and mirror view, but not for the top view (**b**)

reduce the variability of the arm motor output. This reduction was significant when the adaptation session took place with a first-person ($F(1, 7) = 14.12$, $P < 0.01$) and a mirror view ($F(1, 7) = 5.40$, $P < 0.05$), but not with a top view.

Effect of the viewpoint on stabilization errors (mixed model analysis)

Relative (i.e., difference in stabilization error between the post- and the pre-test session) and absolute aftereffects (i.e., stabilization error in the post-test session) did not significantly differ between the three viewpoint conditions. In other words, the adaptation-evoked under-compensation was comparable for the three types of viewpoint. However, the mixed model ANOVA revealed a main effect of rotation amplitude on the relative aftereffect ($F(3, 63) = 18.17$, $P < 0.05$), larger rotations inducing a larger difference between post- and pre-test stabilization errors. This latter effect confirms the interactions between session and rotation observed for each of the three viewpoint conditions.

Effects of the viewpoint on stabilization variability (mixed model analysis)

The mixed model ANOVA revealed a main effect of the viewpoint on the absolute stabilization variability ($F(2, 21) = 4.29$, $P < 0.05$). Specifically, stabilization variability in the post-test session was larger for the top view (SD = 4.77) than for the first-person view (SD = 2.86; $P < 0.001$) and the mirror view (SD = 3.58; $P = 0.06$), though the difference barely failed to reach significance in this latter case (see Fig. 8a). This effect was not caused by differences intrinsic to the subjects' groups, because the groups did not differ from one another when comparing stabilization variability in the pre-test session. Concerning relative stabilization variability (difference post–pre), the main effect of the viewpoint failed to reach significance, but planned pairwise comparisons using Bonferroni correction indicated that the mirror view gave rise to a significantly larger decrease in variability than the top view (net reduction in variability of 2.44 vs. 0.24 degrees, $P < 0.01$, see Fig. 8b). Finally, no significant effects were found for the different rotation angles or the interaction rotation*viewpoint.

Effect of the viewpoint on errors and variability during adaptation—control (mixed model ANOVA)

The same mixed model ANOVA was run on stabilization errors and stabilization variability values measured during the adaptation session (i.e., when visual feedback was provided during the rotation). This was done to make sure that performance during the adaptation phase was identical with the three viewpoints. Neither the errors (-10.68, -10.78, and -10.20 on average for the first-person, top view, and mirror view, respectively) nor the variability values (0.85, 1.98, and 2.19 on average for the first-person, top view, and mirror view, respectively) differed significantly between the three viewpoint conditions.

IPQ questionnaire

For the total number of test items ($n = 14$), the reliability coefficient Cronbach's alpha was 0.81. The Cronbach's alpha coefficient for the Avatar Embodiment Questionnaire ($n = 3$) was 0.88, indicating a relatively high internal consistency of the items for both questionnaires. The 3 × 4 mixed model ANOVA revealed no significant effect of the viewpoint on the scores of the different subscales, suggesting that the viewpoints resulted in similar experiences in terms of presence and immersion.

The mean scores per subscale were correlated with the mean relative aftereffect per participant. Three measurements showed a significant positive correlation with the strength of relative aftereffect, namely the Involvement scale (*Pearson's* $r = 0.69$, $P < 0.01$; see Fig. 9a), the Total IPQ test score (*Pearson's* $r = 0.45$, $P < 0.05$; see Fig. 9b), and the Avatar Embodiment Questionnaire (*Pearson's* $r = 0.45$, $P < 0.05$, see Fig. 9c). Concerning the Involvement scale, higher reported involvement corresponded to larger aftereffects. For the total IPQ test, higher levels of presence and immersion correlated with stronger adaptation effects, as did higher levels of embodiment and/or perceived similarity between the avatar and the self as measured with the Avatar Embodiment Questionnaire.

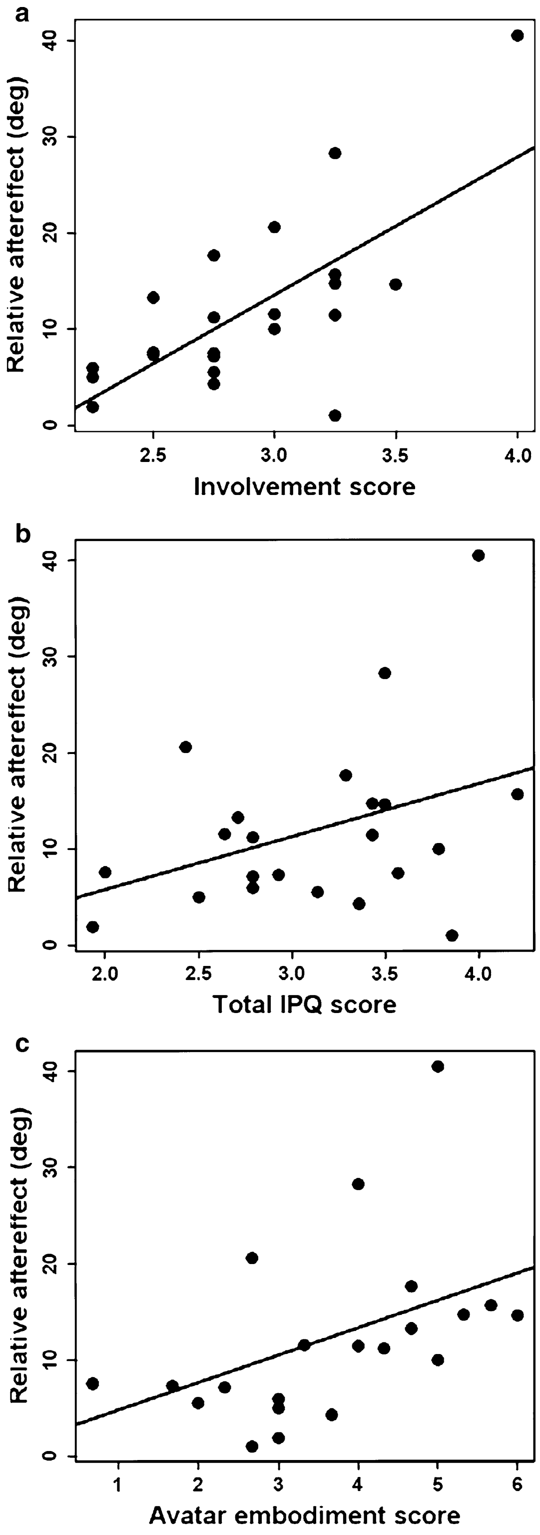

Fig. 9 Correlation between the adaptation-evoked relative aftereffects (*Y axis*) and the score on the Involvement scale (**a** Pearson's $r = 0.69$, $P < 0.01$), the total IPQ (**b** Pearson's $r = 0.45$, $P < 0.05$), and the Avatar Embodiment Questionnaire (**c** Pearson's $r = 0.45$, $P < 0.05$)

Discussion

Using a state-of-the-art VR setup and a visual–vestibular recalibration paradigm, we tested how different viewpoints on the visual scene affect sensorimotor adaptation. The three viewpoints that we used, namely first-person, top view, and mirror view, gave rise to sensorimotor adaptation, the motor performance of the subjects being significantly different before and after adaptation. Specifically, for all three viewpoints, the adaptation phase successfully induced a remapping between vestibular cues and the motor output required to maintain the hand stable in space during whole-body rotation. The amplitude of this remapping was comparable for the three viewpoint conditions, and it correlated positively with the subjective feeling of presence and immersion experienced by the subjects (as assessed by the Igroup Presence Questionnaire and the Avatar Embodiment Questionnaire). In addition, with first-person and mirror view, adaptation contributed to reduce the variability of the motor output, hand stabilization variability being significantly smaller in the post-test session than in the pre-test session.

Our results show that visual information can be used to recalibrate vestibular-evoked motor output. Specifically, after exposure to an altered gain between vestibular and visual cues about the amplitude of body rotation, subjects showed a significant bias of the vestibular-evoked arm movements as compared to the arm movements produced before exposure. The direction of this bias corresponded to the biased visual feedback provided during the exposure, and its amplitude was larger for larger body rotations, which confirms that sensorimotor adaptation occurred as the gain of the visual bias was constant. In the past, several studies showed that visual information can be used to recalibrate motor responses controlled by kinesthetic afferents. The most famous studies in that direction are prism adaptation paradigms (Hay and Pick 1966; Redding et al. 2005; Welch et al. 1979) and the rubber hand illusion (Botvinick and Cohen 1998; Kammers et al. 2009). Concerning specifically arm motor responses controlled by vestibular afferents, we are only aware of one study showing such a visual recalibration. In this study, Bresciani et al. (2005) have shown that visual signals can be used to adapt/recalibrate reaching movements performed during whole-body motion. The results of the present experiment extend these previous findings and show for the first time that sensorimotor adaptation can occur with different viewpoints on the visual scene.

In the three pre-test sessions, i.e., when rotation occurred without visual feedback, participants tended to produce a motor response that over-compensated for the body rotation, 'overshooting' the actual position of the bottle/target. This indicates that the amplitude of body rotations was somehow overestimated. Such vestibular-evoked overestimation of body rotations (Israël et al. 1995; Ivanenko et al. 1997; Jürgens et al. 2003) and translations (Harris et al. 2000; Israël et al. 1993) have consistently been reported with pure perceptual tasks. These overestimations are usually explained by the higher gain of the vestibular system as compared to the visual system (Ivanenko et al. 1997). However, other studies have highlighted that as opposed to perceptual tasks, vestibular-evoked arm motor responses tend to be accurate (Bresciani et al. 2002; Guillaud et al. 2006; Blouin et al. 2010). Therefore, the overestimations observed in the present study could relate to the virtual environment and, more particularly, to the use of a head-mounted display (Loomis and Knapp 2003; Creem-Regehr et al. 2005).

The amplitude of the motor bias induced by the adaptation session was similar for the three viewpoints. The absolute and relative biases after exposure were slightly larger with first-person and mirror view adaptation than with top view adaptation, but the observed differences were quite small and not significant. In addition, for all three viewpoints, the amplitude of the adaptation-evoked bias was relatively large, with a difference of over 12° on average between the pre- and post-test sessions. Therefore, the absence of differences between the three types of viewpoint might simply reflect a ceiling effect of the sensorimotor adaptation process.

Constant errors are not the only hallmark of motor learning. Indeed, learning is usually characterized by reduction variability of motor performance (Körding and Wolpert 2004). In that respect, response variability can be used as a measure of adaptation efficiency. When comparing hand stabilization errors in the pre- and post-test sessions, we found a systematic reduction in response variability after the adaptation session, for all viewpoints. This reduction was significant with the first-person and the mirror view adaptation, but not with the top view adaptation. In addition, the variability reduction resulting from mirror view adaptation was significantly larger than the small reduction induced by top view adaptation. This 'advantage' of the more naturalistic first-person and mirror views over the top view might actually result from some specificity of practice. Specifically, it has been suggested that sensorimotor representations based on sensory feedback from previous experiences with a motor task are central to motor learning. In other words, learning would be specific to the conditions under which it occurred (Proteau et al. 1992; Tremblay 2010; Tremblay and Proteau 1998). In our experiment, the visual sensory feedback during the adaptation phase of the first-person and mirror view was similar or identical to the visual sensory feedback in the pre- and post-test phases (the scene being presented from a first-person view). This was not the case for the top view condition. As such, the post-test session in the first-person and mirror view might has created more effective conditions for adaptation effects to show than the top view's post-test. In any case, our results suggest that if increasing motor efficiency constitutes a critical aim of the adaptation (e.g., for neurorehabilitation purposes), the naturalistic first-person view and the rich mirror view are more suitable than and should be preferred to the 'artificial' top view.

The finding that the first-person view creates efficient motor adaptation conditions is in line with typical findings from teleoperation studies (Macedo et al. 1998). Several other studies have also suggested that first-person perspectives are best for actions that consist of manipulations, whereas third-person perspectives are preferred for moving actions, such as navigation (Salamin et al. 2006; Salamin and Thalmann 2010). This account is hard to interpret in light of the present study, as the stabilizing of the arm can be seen as a moving action, but does not consist of moving about, neither of manipulating an object. In the current study, the top view proved the worst adaptation conditions compared to the other two viewpoints. It gave rise to a significant aftereffect but did not allow the significant decrease in performance variability observed with the other two viewpoints. In that respect, our results contrast recent findings that a top view allows the best performance and is preferred by participants for a reaching task (Ustinova et al. 2010). A reason for this discrepancy could lie in the nature of the task used by Ustinova and colleagues. Specifically, in this latter study, subjects were required to extend the arm and hand as far as possible to pick daisies from a virtual hedge while keeping balance. For this task, a higher viewpoint provided an overview over the hand and targets, so that the movement trajectory of the hand toward the target could be planned well. In the present study, participants had to stabilize the arm in space after pointing to a target, for which having an overview probably is less important.

Overall, the mirror view showed the largest decrease in performance variability, suggesting that it provided the most efficient conditions to evoke motor adaptation. These findings can be explained in terms of visual richness. Indeed, the mirror view included a normal first-person view plus an additional mirror view, providing additional information about the precise hand and target location. In line with this, previous works have shown that augmented feedback can improve performance on certain motor tasks, more so than real-world training (e.g., Armstrong 1970). For example, training in virtual environments on isometric tasks was shown to be more effective than training in a real-world task (Todorov et al. 1997).

Interestingly, some other perceptual measures correlated with motor adaptation performance. More precisely, we found that the size of the relative aftereffect was positively correlated with the Involvement scale and the Total IPQ test score. Typically, the more participants allocated attention to the virtual world rather than to the real world, the more they felt involved in the virtual environment and the larger was the aftereffect they exhibited. We also found a significant positive correlation between the relative aftereffect and the Avatar Embodiment Questionnaire, suggesting that when participants felt more embodied with the avatar, they typically showed a larger relative aftereffect. It is difficult to determine whether higher levels of embodiment perception caused the stronger aftereffect or whether participants who could adapt better to the gain consequently experienced higher levels of embodiment with the avatar. However, it still is remarkable that a subjective construct as embodiment perception was found to correlate with performance on the experimental task. Therefore, our findings contribute to the notion that perceptual constructs such as avatar embodiment, spatial presence, and involvement are important factors when exploiting the VR technique, going hand in hand with behavior and motor adaptation.

Conclusion

By exploiting the flexibility of VR, we have shown that the viewpoint on the visual scene is a factor that modulates sensorimotor adaptation. The three viewpoints that we used proved efficient in inducing strong adaptation. Accordingly, using different viewpoints in fun and versatile VR applications could be a strategy to break training monotony and preserve a higher level of motivation. However, providing a mirror view during practice seems to constitute the best option when reducing the variability of motor performance is the pursued goal. We believe that our results provide some useful information for the future development of VR applications oriented toward neurorehabilitation (Henderson et al. 2007; Siekierka et al. 2007). Future research should elucidate whether this is the case for all types of motor adaptation or only certain types of tasks.

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Appendix

Avatar Embodiment Questionnaire

14. I had the feeling that the avatar was me

☐ ☐ ☐ ☐ ☐ ☐ ☐

Fully disagree Fully agree

15. The avatar responded to my movements as my own body would do

☐ ☐ ☐ ☐ ☐ ☐ ☐

Fully disagree Fully agree

16. I felt that I was the avatar

☐ ☐ ☐ ☐ ☐ ☐ ☐

Fully disagree Fully agree

References

Adamovich SV, Fluet GG, Tunik E, Merians AS (2009) Sensorimotor training in virtual reality: a review. NeuroRehabilitation 25:29–44

Armstrong TR (1970) Feedback and perceptual-motor skill learning: a review of information feedback and manual guidance training techniques. Technical Report No. 25, Human Performance Center, University of Michigan

Blouin J, Guillaud E, Bresciani JP, Guerraz M, Simoneau M (2010) Insights into the control of arm movement during body motion as revealed by EMG analyses. Brain Res 1309:40–52

Botvinick M, Cohen J (1998) Rubber hands 'feel' touch that eyes see. Nature 391:756

Bresciani JP, Blouin J, Sarlegna F, Bourdin C, Vercher JL, Gauthier GM (2002) On-line versus off-line vestibular-evoked control of goal-directed arm movements. NeuroReport 13:1563–1566

Bresciani JP, Gauthier GM, Vercher J, Blouin J (2005) On the nature of the vestibular control of arm-reaching movements during whole-body rotations. Exp Brain Res 164:431–441

Chan M (2001) Embodiment, perception, and virtual reality. LNAI 2117:83–94

Creem-Regehr SH, Willemsen P, Gooch AA, Thompson WB (2005) The influence of restricted viewing conditions on egocentric distance perception: implications for real and virtual indoor environments. Perception 34:191–204

Guillaud E, Simoneau M, Gauthier GM, Blouin J (2006) Controlling reaching movements during self-motion: body-fixed versus Earth-fixed targets. Mot Control 10:330–347

Harris LR, Jenkin M, Zikovitz DC (2000) Visual and non-visual cues in the perception of linear self-motion. Exp Brain Res 135:12–21

Hay JC, Pick HLJ (1966) Gaze-contingent prism adaptation: optical and motor factors. J Exp Psychol 72:640–648

Henderson A, Korner-Bitensky N, Levin M (2007) Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery. Top Stroke Rehabil 14:52–61

Israël I, Chapuis N, Glasauer S, Charade O, Berthoz A (1993) Estimation of passive horizontal linear whole-body displacement in humans. J Neurophysiol 70:1270–1273

Israël I, Sievering D, Koenig E (1995) Self-rotation estimate about the vertical axis. Acta Otolaryngol 115:3–8

Ivanenko Y, Grasso R, Israël I, Berthoz A (1997) Spatial orientation in humans: perception of angular whole-body displacements in two-dimensional trajectories. Exp Brain Res 117:419–427

Jürgens R, Nasios G, Becker W (2003) Vestibular, optokinetic, and cognitive contribution to the guidance of passive self-rotation toward instructed targets. Exp Brain Res 151:90–107

Kammers MPM, de Vignemont F, Verhagen L, Dijkerman HC (2009) The rubber hand illusion in action. Neuropsychologia 47:204–211

Körding KP, Wolpert DM (2004) The loss function of sensorimotor learning. Proc Natl Acad Sci USA 101:9839–9842

Kwakkel G, Wagenaar RC, Twisk JW, Lankhorst GJ, Koetsier JC (1999) Intensity of leg and arm training after primary middle-cerebral-artery stroke: a randomised trial. Lancet 354:191–196

Kwakkel G, Kollen BJ, van der Grond J, Prevo AJH (2003) Probability of regaining dexterity in the flaccid upper limb: impact of severity of paresis and time since onset in acute stroke. Stroke 34:2181–2186

Loomis JM, Knapp JM (2003) Visual perception of egocentric distance in real and virtual environments. In: Hettinger LJ, Haas MW (eds) Virtual and adaptive environments. Erlbaum, Mahwah, pp 21–46

Loomis JM, Blascovich JJ, Beall AC (1999) Immersive virtual environment technology as a basic research tool in psychology. Behav Res Methods Instrum Comput 31:557–564

Macedo JA, Kaber DB, Endsley MR, Powanusorn P, Myung S (1998) The effect of automated compensation for incongruent axes on teleoperator performance. Hum Factors 40:541–553

Mahncke HW, Bronstone A, Merzenich MM (2006) Brain plasticity and functional losses in the aged: scientific bases for a novel intervention. Prog Brain Res 157:81–109

Masiero S, Celia A, Rosati G, Armani M (2007) Robotic-assisted rehabilitation of the upper limb after acute stroke. Arch Phys Med Rehabil 88:142–149

Olsen TS (1990) Arm and leg paresis as outcome predictors in stroke rehabilitation. Stroke 21:247–251

Platz T, Eickhof C, van Kaick S, Engel U, Pinkowski C et al (2005) Impairment-oriented training or Bobath therapy for severe arm paresis after stroke: a single-blind, multicentre randomized controlled trial. Clin Rehabil 19:714–724

Proteau L, Marteniuk RG, Levesque L (1992) A sensorimotor basis for motor learning: evidence indicating specificity of practice. Q J Exp Psychol A 44:557–575

Redding GM, Rossetti Y, Wallace B (2005) Applications of prism adaptation: a tutorial in theory and method. Neurosci Biobehav Rev 29:431–444

Ring H, Rosenthal N (2005) Controlled study of neuroprosthetic functional electrical stimulation in sub-acute post-stroke rehabilitation. J Rehabil Med 37:32–36

Salamin P, Thalmann D (2010) Providing the best third-person perspective to a video-through HMD. VRLAB-CONF-2010-003

Salamin P, Thalmann D, Vexo F (2006) Benefits of a third-person perspective in virtual and augmented reality. Proceedings of the ACM symposium on Virtual reality software and technology. ACM, New-York, pp 27–30

Schubert T, Friedmann F, Regenbrecht H (2001) The experience of presence: factor analytic insights. Presence 10:266–281

Siekierka EM, Eng K, Bassetti C, Blickenstorfer A, Cameirao MS et al (2007) New technologies and concepts for rehabilitation in the acute phase of stroke: a collaborative matrix. Neurodegener Dis 4:57–69

Summers JJ, Kagerer FA, Garry MI, Hiraga CY, Loftus A et al (2007) Bilateral and unilateral movement training on upper limb function in chronic stroke patients: a TMS study. J Neurol Sci 252:76–82

Tarr MJ, Warren WH (2002) Virtual reality in behavioral neuroscience and beyond. Nat Neurosci 5(Suppl):1089–1092

Todorov E, Shadmehr R, Bizzi E (1997) Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task. J Mot Behav 29:147–158

Tremblay L (2010) Vision and goal-directed movement: neurobehavioral perspectives. In: Elliott D, Khan M (eds) Vision and movement: control of directed action. Human Kinetics, Champaign, pp 281–291

Tremblay L, Proteau L (1998) Specificity of practice: the case of powerlifting. Res Q Exerc Sport 69:284–289

Ustinova KI, Perkins J, Szostakowski L, Tamkei LS, Leonard WA (2010) Effect of viewing angle on arm reaching while standing in a virtual environment: potential for virtual rehabilitation. Acta Psychol (Amst) 133:180–190

Welch RB, Widawski MH, Harrington J, Warren DH (1979) An examination of the relationship between visual capture and prism adaptation. Percept Psychophys 25:126–132

Witmer BG, Singer MJ (1998) Measuring presence in virtual environments: a presence questionnaire. Presence 7:225–240