Acta Psychologica 133 (2010) 180–190

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Effect of viewing angle on arm reaching while standing in a virtual environment: Potential for virtual rehabilitation

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ARTICLE INFO

Article history:
Received 8 July 2009
Received in revised form 8 November 2009
Accepted 14 November 2009

PsycINFO classification:
2330
2323
3380

Keywords:
Virtual reality
Motor processes
Arm-postural coordination
Visual perception
Rehabilitation

ABSTRACT

Functional arm movements, such as reaching while standing, are planned and executed according to our perception of body position in space and are relative to environmental objects. The angle under which the environment is observed is one component used in creating this perception. This suggests that manipulation of viewing angle may modulate whole body movement to affect performance. We tested this by comparing its effect on reaching in a virtually generated environment. Eleven young healthy individuals performed forward and lateral reaches in the virtual environment, presented on a flat screen in third-person perspective. Participants saw a computer-generated model (avatar) of themselves standing in a courtyard facing a semi-circular hedge with flowers. The image was presented in five different viewing angles ranging from seeing the avatar from behind (0°), to viewing from overhead (90°). Participants attempted to touch the furthest flower possible without losing balance or stepping. Kinematic data were collected to analyze endpoint displacement, arm-postural coordination and center of mass (COM) displacement. Results showed that reach distance was greatest with angular perspectives of approximately 45–77.5°, which are larger than those used in analogous real world situations. Larger reaches were characterized by increased involvement of leg and trunk body segments, altered inter-segmental coordination, and decreased inter-segmental movement time lag. Thus a viewing angle can be a critical visuomotor variable modulating motor coordination of the whole body and related functional performance. These results can be used in designing virtual reality games, in ergonomic design, teleoperation training, and in designing virtual rehabilitation programs that re-train functional movement in vulnerable individuals.

1. Introduction

Reaching for an object while standing is an essential component of numerous daily life activities. These activities are planned and executed according to an individual's visual perception of body position in space and relative to the object (Bernstein, 1967; Gibson, 1954; Lashley, 1930). In turn, this perception is the result of integration and interpretation of multiple visual control variables, with the angle under which the object is observed playing an essential role. Research has determined that angle of view can modulate processing in multiple brain areas involved in planning and preparing object-related voluntary movements (Baker, Donoghue, & Sanes, 1999; Bédard, Thangavel, & Sanes, 2008; DeSouza, Dukelow, & Vilis, 2002). Altering the angle can affect a participant's estimation of distance to an object (Gardner & Mon-Williams, 2001; Levin & Haber, 1993; Mon-Williams, McIntosh, & Milner, 2001) and alter the isometric muscle force a participant applies to an object (Vaillancourt, Haibach, & Newell, 2006). These findings suggest that by artificially altering viewing angle it may be possible to influence the performance of functional body movements such as reaching while standing.

Testing this possibility is important in light of growing interest in incorporating virtual reality simulations and computer games into rehabilitation programs for individuals with the risk of falling and incurring injuries during functional activities. Virtual reality (VR) technologies provide an opportunity for visual manipulation and repeated practice in a controlled safe environment (Rand, Kizony, & Weiss, 2004; Sveistrup, 2004). Almost any environment can be generated virtually and presented using different perspectives and angles to address participants' needs and rehabilitation goals. There is, however, little research on precisely how altering viewing perspectives can improve dynamic characteristics of movements.

In recreation and training applications of virtual reality, visual perspective, frequently referred as point of is an important characteristic. Participants can view the virtual world as if seen through

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doi:10.1016/j.actpsy.2009.11.006

their own eyes (first-person view), or they can view the world as if watching themselves through a camera, usually positioned somewhat above and behind (third-person view). The fully immersed or first-person view is thought to increase a participant's sense of virtual presence and immersion, but at the risk of increasing side effects such as nausea (Crosbie, Lennon, McNeill, & McDonough, 2006). In contrast, the third-person view is less immersive, but may be preferred for some recreation gaming (Salamin, Thalman, & Vexo, 2006) and rehabilitation applications (Rand et al., 2004; Yavuzer, Senel, Atay, & Stam, 2008) as a less expensive and more practically applicable approach.

The second important variable in a virtual rehabilitation is the angle of view. In a virtual environment, the visual scene can be represented from different angles. Some VR applications allow angular adjustment of the image relative to the head position. In others this cannot be done, and an individual is then limited to one particular presentation of the image. A real world remains constant and observing it in different viewing angles changes both the eye position and image projection on the eye retina, and normally reflects a change of position of the viewer. In contrast, a simulated environment is usually adjusted to the individual. In this environment eye movements in the orbits are minimal and accommodation is constant. Consequently, a participant is deprived of an important part of real world efferent information and proprioceptive feedback from extraocular muscles, and must rely mainly on retinal input. When performing motor skills in VR, it is important to determine the best viewing perspective and angle to facilitate motor performance. This question has not been investigated in a systematic way.

One possibility is that the effect of viewing angle in a virtual environment will be similar to that observed in the real physical world. There it has been shown that presentation of an object under an oblique angle rather than directly in line with the eyes can facilitate reading a book (Schmidt, Ullrich, & Rossner, 1993; Shieh & Lee, 2007), improve productivity of flight operators (Turville, Psihogios, Ulmer, & Mirka, 1998), and even reduce postural oscillations while standing (Kapoula & Lê, 2006). These results may be relevant to arm-postural coordination performed in the virtual environment and to fine-tuning virtual reality presentations for optimal performance. The purpose of this study was to determine how changes in viewing angle alter a functional arm movement performed in standing. In this study when we discuss viewing angle we refer to the angle defined by two vectors, the first vector being a horizontal line originating at the target of the reach and projected parallel to the ground, and the second being the line connecting the target with the spot where the virtual camera used to present the scene is positioned, making this a third-person version of the real world gaze angle (Fig. 1). As an experimental task, participants performed reaching forward and laterally while standing in a virtually generated garden presented on a flat screen using a third-person view. These movements are part of many daily tasks such as gardening, grocery shopping, doing laundry, etcetera. They also resemble the Functional Reach tests commonly used to predict fall risk and to track rehabilitation progress for individuals at risk of falling, due to age or illness, when performing functional activities (Duncan, Weiner, Chandler, & Studenski, 1990; Takahashi et al., 2006; Weiner, Duncan, Chandler, & Studenski, 1992).

2. Methods

2.1. Participants

A volunteer sample of eleven healthy young adults (10 female, 1 male) with a mean age of 24.2 years (range = 22–25) participated in the study. All signed informed consent documents approved by the facility Institutional Review Board and in compliance with the Declaration of Helsinki. Participants had no known visual or perceptual problems, movement impairments or other conditions that would place them at increased risk of falling. Nine individuals reported and were observed to be right-hand dominant and two were left-hand dominant.

2.2. Experimental procedure

The experimental task consisted of reaching forwards and laterally in a virtual environment presented to participants on a

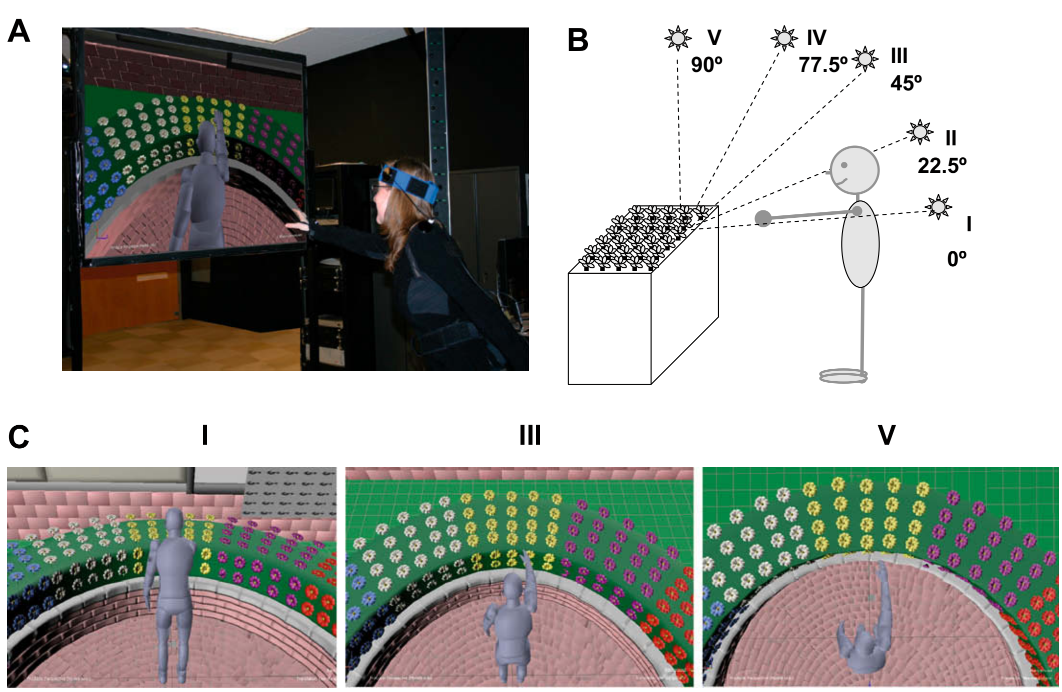

Fig. 1. (A) A participant faces the screen and views the computer-generated representation of herself (avatar) in the center of a patio surrounded by a hedge covered with colored flowers. (B) Schematic figure illustrating viewing angles from I to V. (C) Visual images presented to participant under viewing angles I, III, and V.

91×122 cm flat screen using a third-person view (Fig. 1A). While standing in front of the screen, the participant viewed a virtual representation of self (avatar) moving in real time (with minimal delay) in the middle of a patio surrounded by a semi-circular hedge covered with flowers. Bands of flowers of different colors helped distinguish reaching directions. The virtual environment was generated using Alias' Maya (Maya®, Version 7.0.1; Autodesk, Inc., San Rafael, USA) software and then projected on the screen (as a stream) with an InFocus LP530 projector. Movements of participants were recorded by an optical system for motion analysis ReActor2 Model 342 (Ascension Technology, FusionCore Version 1.4.0, NVIDIA Corporation, London, UK) at 30 Hz with 28 infrared markers placed on the major body landmarks. Based on the marker positions, a participant's avatar was created and then incorporated into the virtual environment.

The projection was designed so that the virtual garden hedge reached approximately waist level with the nearest flower appearing to be at a distance of approximately half of the estimated distance the avatar could reach while standing upright. The visual scene was presented in five equidistant viewing angles ranging from viewing the avatar from behind (I) to viewing from directly overhead (V, Fig. 1B). The angle of approximately 22.5° was considered to be the closest to a naturalistic view, similar to that which would be used in a real world garden matching the VR projection. Other angles were sequenced between the two extremes with between-camera step angles of approximately 22.5°. The virtual hedge had flowers projected on both its vertical (as if facing the avatar) and horizontal aspects. While observing the environment using angle I, the participant saw both hedge components and the entire avatar body (Fig. 1C). To prevent the avatar body blocking the view of the flowers, the image was rotated a few degrees in the transverse plane. This rotation was kept for each visual condition. Under visual angle V, participants saw the horizontal or upper component of the hedge and the avatar presented by the head, shoulders, and arms only, as sight of the legs was obscured by the avatar upper body. The other conditions were presented at intermediate angles, with the corresponding visual presentations of flowers and avatar.

Reaches began with participants standing comfortably with both arms at their sides and feet a comfortable distance apart. Reaching was performed with their dominant arm and an open hand, as if they were trying to touch a flower rather than pick it. They were instructed to reach and point at the furthest flower in the direction indicated by instructor (e.g. forward toward a yellow flower or laterally toward a red flower) without losing balance or taking a step. Forward reaches involved shoulder flexion (typically beyond 90°) and trunk bending in the sagittal plane, lateral reaches required shoulder abduction of approximately 90° and trunk movement in the frontal plane. After reaching the flower, if the participant continued to lower the arm, the hand would appear to "vanish" into the hedge. Participants were instructed to reach for the flower and then return to quiet standing, but not to pass the hand through the hedge. Five reaches were performed in random order in each visual angle in both forward and lateral directions, for a total of 50 virtual reaches.

2.3. Data analysis

During the task performance, kinematic data were collected by an optical system for motion analysis (ReActor 2) at 30 Hz. with 28 infrared markers placed on the major bony landmarks of the body. Movement trajectories of the hand endpoint, trunk, and leg were plotted from filtered (low-pass 8 Hz) position data collected from the markers placed on the dominant hand (second metacarpals), C7, and leg (greater trochanter). The leg was considered as a single segment including thigh and shank, since motion in the knee joint was minimal during reaches. The trunk segment included upper trunk and pelvis and was considered as a single segment as well, represented by C7 marker. The amplitude of linear displacements was measured as peak to peak displacement in the sagittal plane for forward reaches and in the frontal plane for the lateral reaches, since deviation was minimal or nearly constant in frontal plane for the forward reaching and in the sagittal plane for the lateral reaching across all visual conditions. The amount of endpoint displacement was expressed in absolute values and also as a percentage of body height only since previous studies of reaching have shown that the addition of other anthropomorphic factors such as arm length does not significantly improve estimates of reach distance after controlling for height (Duncan et al., 1990).

Reach movement time was calculated from the tangential velocity trace as the time between onset and offset of the endpoint marker displacement. Movement onset and offset were the points at which the velocity rose above or fell and remained below 5% of maximum velocity peak. Accuracy of the endpoint trajectory during reaching was determined by the index of curvature which was computed as a ratio of the actual length of the endpoint path to the shortest distance between initial and final position. Reaching to a target along an ideal straight line would result in an index of 1, while any deviation from the straight line would increase this index. Displacement was minimal or nearly constant in frontal plane for the forward reaching and in the sagittal plane for the lateral reaching across all visual conditions. Thus the index depended on displacement in the vertical and either forward or lateral directions. Displacement of the center of mass of the whole body was computed as an averaged mean of all segment centers of masses displacements in sagittal and frontal planes, respectively. The segmental centers of mass were calculated using regular anthropometric tables.

The extent to which the arm, trunk, and legs contributed to the endpoint (hand) transport toward the final position or target, was determined for each of experimental modes. The contribution of each segment was computed by subtracting of the displacements of the two other segments from the total displacement of the endpoint (hand marker) and expressed as a percentage of the total displacement.

The reaching while standing involves multiple body segments, as trunk, arms, and legs. Inter-segmental coordination was analyzed in term of absolute means of angular displacement and timing of the arm, trunk, and leg segments to answer the question of how arm-postural strategies were modified as reaching distance changes, if so. Overall expectation was that inter-segmental coordination would improve to provide body stability when participants reached further. Angular displacement was measured as a deviation of the segment from the ideal vertical reference line perpendicular to the ground and passing through the ankle marker for leg, through the hip marker for the trunk, and through the shoulder marker for the arm. For both forward and lateral reaches, positive means of angles indicated that the segment was deviating in the direction of the reach, while negative means indicated a segment angular shift in the opposite direction. Temporal coordination between segments was analyzed using cross-correlation methods according to the following equation:

$$R_{(\tau)} = \frac{\int_0^T x(t+\tau)\cdot y(t)\cdot dt}{\|x\|\cdot\|y\|};\ \|x\| = \left(\int_0^T x^{2(t)\cdot dt}\right)$$

where x and y are the displacement of the segments; τ is time lag; t is the time; variables x and y are the data sets.

Cross-correlation coefficients determined a direction of displacement and coupling strength between pairs of segments arm-trunk, trunk-leg, and arm-leg at a zero time lag. A negative mean coefficient was interpreted as movement of measured parameters in opposite directions, while a positive coefficient indicated displacement in the same direction. Mean coefficients falling between −0.25 and 0.25 were considered as indicating no coordination between two segments. Time lag was calculated from the sequence of each segment's involvement in the movement as the delay of one segment with respect to the other in each pair. Time lags and leads were analyzed for a time window corresponding to 100% of each trial movement time.

One-way Analysis of Variance (ANOVA) with post-hoc tests was used to analyze the influence of the viewing angles (I–V) on the endpoint and the COM displacements, index of curvature. Mixed two-way ANOVA with factors of segment (arm, trunk, legs), and viewing angles (I–V) was used to compare different movement parameters. Those parameters included the angular and linear displacements of different body segments, their contribution to the endpoint displacements during reaches, and coefficients of cross-correlation. Temporal coordination was compared using the factors of time lag (arm-trunk, arm-legs) and viewing angles (I–V).

3. Results

3.1. Endpoint displacement

Fig. 2A shows sample trajectories of endpoint displacement from one representative participant performing forward (left panel) and lateral (right panel) reaching using angles I–V. Trajectories on both plots have approximately similar shape and curve for each angle, but differ in movement amplitude depending on the view. Participants reached further when using visual angles III–V, which correspond approximately to 45–90°. Endpoint displacement was accompanied by the trunk and leg displacement, as shown in Fig. 2B (left and right panels). As with the endpoint trajectories, displacements of trunk and legs varied with the visual angle. Specifically an increase in trunk displacement led to greater endpoint amplitude at higher visual gaze angles. The leg segment deviated from the initial position (vertical lines) either in the direction of the reach or in the opposite direction.

On average, participants demonstrated greater endpoint displacements in the forward than in the lateral direction both in terms of absolute means of distance (Table 1), and means normalized to the participants' height (Fig. 3). ANOVAs revealed a significant difference in normalized endpoint displacements between viewing angles ($F_{4,40} = 4.67$, $p < 0.01$ for forward reaching, and $F_{4,40} = 9.32$, $p < 0.001$ for lateral reaching). Post-hoc comparisons showed that participants reached further when the scene was presented under the angles from approximately 45–90° compared to the reaches performed under those corresponding to viewing the avatar from directly or from the more real world angle of 22.5° (Fig. 3, angles I vs. III–V for forward reaching, $p < 0.05$; angles I, II vs. III–IV for lateral reaching, $p < 0.01$). Deviation between maximum and minimal reaches performed in different visual conditions

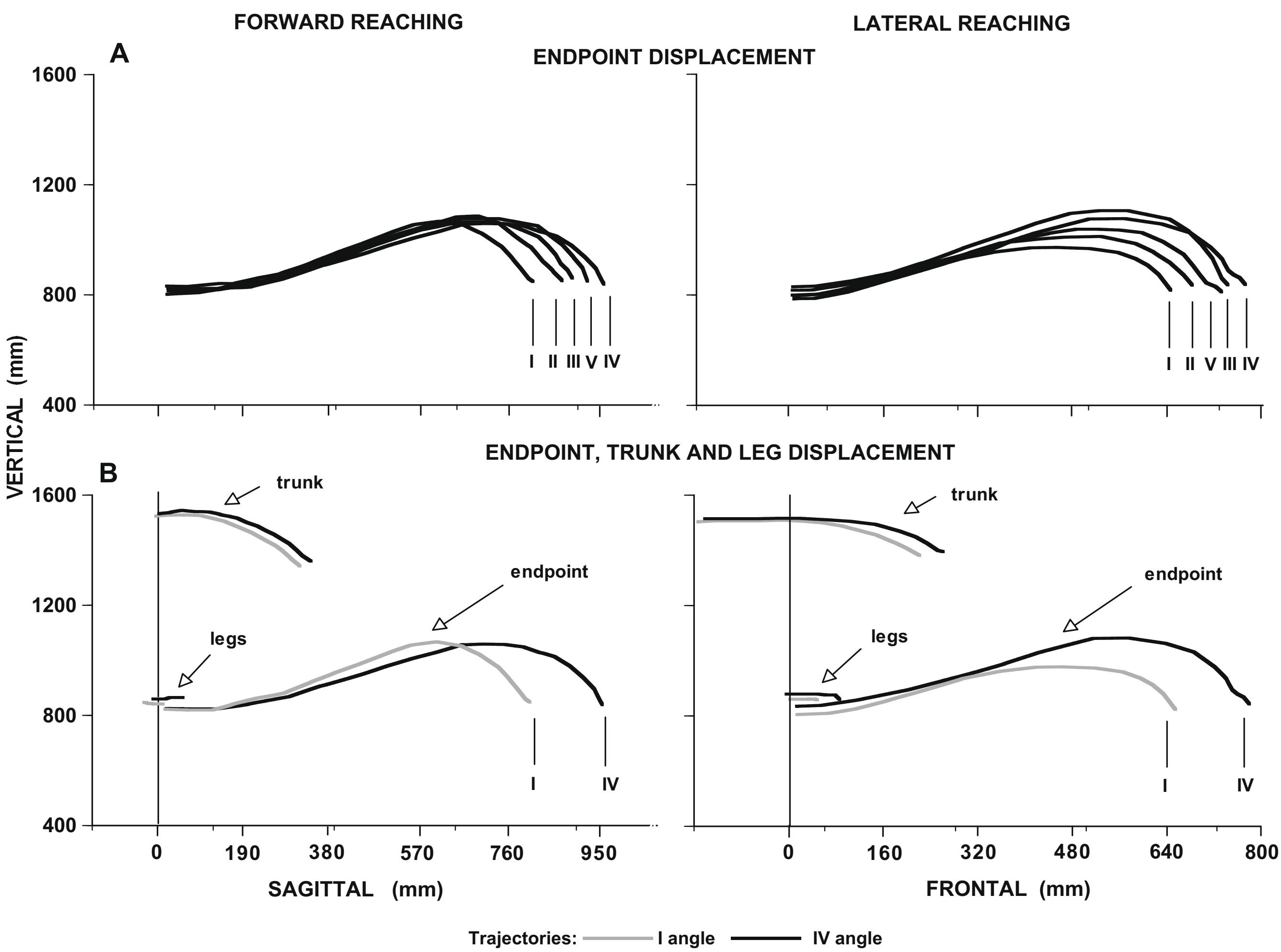

Fig. 2. (A) Trajectories of endpoint displacement during forward (left panel) and lateral (right panel) reaches performed by one representative participant. I–V indicate trajectories of reaches performed under different viewing angles from 0° to 90°. (B) Illustration of the trajectories of the arm endpoint, trunk, and leg displacements at angles I and IV from the same participant.

Table 1
Kinematic data of reaching movements (means ± SE) in presented in different angles (I–V).

Condition		I	II	III	IV	V
Forward reaching						
Endpoint displacement (mm)		879 ± 15.9	912 ± 9.9	936 ± 21.2	950 ± 21.4	917 ± 18.2
Movement time (s)		1.10 ± 0.3	1.15 ± 0.3	1.14 ± 0.4	1.13 ± 0.5	1.09 ± 0.3
Endpoint peak velocity (mm/s)		1002 ± 38.7	1060 ± 47.7	1084 ± 57.6	1103 ± 55.2	1078 ± 54.6
Linear displacement (mm)	Arm	459 ± 9.6	456 ± 8.9	458 ± 11.8	461 ± 9.6	458 ± 8.7
	Trunk	448 ± 11.8	438 ± 8.9	440 ± 8.8	451 ± 9.7	431 ± 8.8
	Leg	−26.3 ± 8.6	18.2 ± 9.6	37.4 ± 11.2	42.7 ± 8.6	27.5 ± 8.7
Angular displacement (°)	Arm	69.1 ± 6.8	71.4 ± 4.9	71.3 ± 4.0	72.4 ± 5.0	71.6 ± 4.2
	Trunk	54.3 ± 1.7	53.6 ± 1.6	53.8 ± 1.5	54.5 ± 1.6	53.2 ± 1.6
	Leg	−1.7 ± 1.4	1.2 ± 1.4	2.4 ± 1.2	2.8 ± 1.2	1.8 ± 1.3
Lateral reaching						
Endpoint displacement (mm)		749 ± 24.2	756 ± 4.0	813 ± 28.8	812 ± 26.7	784 ± 28.0
Movement time (s)		1.18 ± 0.4	1.12 ± 0.4	1.11 ± 0.6	1.19 ± 0.5	1.21 ± 0.6
Endpoint peak velocity (mm/s)		898 ± 47.7	907 ± 41.7	937 ± 36.6	920 ± 48.9	952 ± 30.6
Linear displacement (mm)	Arm	344 ± 13.8	340 ± 9.9	349 ± 9.8	341 ± 10.5	345 ± 9.8
	Trunk	359 ± 10.1	366 ± 9.6	398 ± 11.2	385 ± 10.4	376 ± 12.4
	Leg	44.9 ± 7.8	49.1 ± 6.6	65.0 ± 8.9	73.1 ± 7.6	66.6 ± 7.9
Angular displacement (°)	Arm	53.3 ± 3.9	53.9 ± 4.8	56.7 ± 3.9	56.0 ± 4.8	59.5 ± 4.1
	Trunk	39.0 ± 2.7	39.9 ± 2.4	42.3 ± 2.0	40.7 ± 2.2	39.2 ± 2.5
	Leg	2.9 ± 0.9	3.2 ± 1.2	4.2 ± 1.1	4.8 ± 0.9	4.3 ± 1.1

was approximately 70 mm in forward direction and 60 mm in the lateral direction (Table 1). The increased segmental displacement was accompanied by slightly increased deviation of the COM excursion during both types of reaching (Fig. 3B), but with no significant differences between viewing conditions. Overall, lateral reaching was characterized by greater COM displacement. While reaching laterally participants approached closer to the borders of the base of support at approximately 170 mm. The borders of the base of support were estimated as a distance between initial position of the COM (before participant started reaching) and sagittal position of the toe marker for the forward direction, and frontal position of the ankle marker in the lateral reaching.

Reaching trajectories under more oblique visual angles (III–V) demonstrated greater deviation from the shortest path to a target. This is illustrated in Fig. 3C which shows means of index of curvature for all conditions. As visual angle increased, the index also increased ($F_{4,40} = 6.41$, $p < 0.01$ for forward reaching, and $F_{4,40} = 5.67$, $p < 0.01$ for lateral reaching). Significant differences were found between angles I and III–V, and II vs. V ($p < 0.05$ for forward reaching) and between angles I and IV–V and II vs. V ($p < 0.05$). Reaches in all conditions were performed at a similar speed and did not differ in terms of movement time and velocity peak (Table 1).

3.2. Arm, trunk, and legs contribution to the endpoint displacement

Both forward and lateral reaches were performed primarily by displacement of the arm and trunk, with much less leg segment involvement. This is evident from Table 1, which contains the absolute values of displacements, and from Fig. 4A and B which presents the relative means, calculated as the ratio of segment movements to the total endpoint displacement.

The pattern of segment recruitment varied with the viewing angle ($F_{4,120} = 2.03$, $p < 0.05$ for the forward reaching, $F_{4,120} = 2.87$, $p < 0.01$ for the lateral reaching). During forward reaching performed under viewing angle I the arm and trunk displaced similar distances (about 450 mm), each covering more than 50% of the total distance. In forward reaching, the leg segment shifted in the direction opposite to the endpoint movement, as reflected by the negative absolute and relative means for this segment (Table 1, Fig. 4A). As viewing angle increased, arm and trunk displacement did not change significantly ($p > 0.05$), but did decrease their relative contribution to the total distance reached. In the higher angle reaches, the leg changed movement direction, demonstrating progressively increasing amounts of forward displacement, related to the visual angles ($p < 0.01$). In reaches performed under angles III–IV, leg forward shift constituted 4.5% of the total endpoint displacement, thereby reducing the contribution of the trunk and arm segments to the total reach.

Lateral reaching was characterized by slightly different intersegmental recruitment. Under all viewing angles, all three segments shifted in the same direction to produce the endpoint displacement. The leg segment increased its absolute and relative involvement (from 44 to 66 mm) in endpoint transport in angles III–V as compared to angle I (Table 1; Fig. 4B, $p < 0.01$). Absolute displacement of the trunk increased from 359 to 376 mm, while a relative contribution remained unchanged.

3.3. Inter-segmental coordination

Similarly to the linear displacements, reaching under different visual conditions altered absolute angular displacements of all three segments (arm, trunk, and leg). In the forward direction, angular motion of the arm and trunk remained practically unchanged across all the trials, varying non-significantly from 69° to 72° for the arm and from 53° to 55° for the trunk (Table 1). As noted above, leg segment action changed with viewing angle. In angle I participants shifted the leg away from the reaching direction (negative means). In angles II–V the leg tended to move with the trunk and arms in the reaching direction. This was most consistently demonstrated in reaches performed under middle to superior angles (III–V). ANOVAs did not show an effect of experimental mode on the absolute arm, trunk, and leg angular displacement, but revealed a significantly greater angular motion in legs (positive vs. negative means in Table 1) during reaches performed under angles III–V (post-hoc test $p < 0.01$) than I–II.

During lateral reaching, all angular displacements occurred in the same direction, but differed by amplitude depending on the viewing angle ($F_{4,120} = 6.67$, $p < 0.01$). Trunk and leg segments progressively increased displacement from viewing angle I to V, with this most seen under angles III–V ($p < 0.001$). Overall, the angular motions repeated a pattern observed during analysis of the linear displacements of the similar segments.

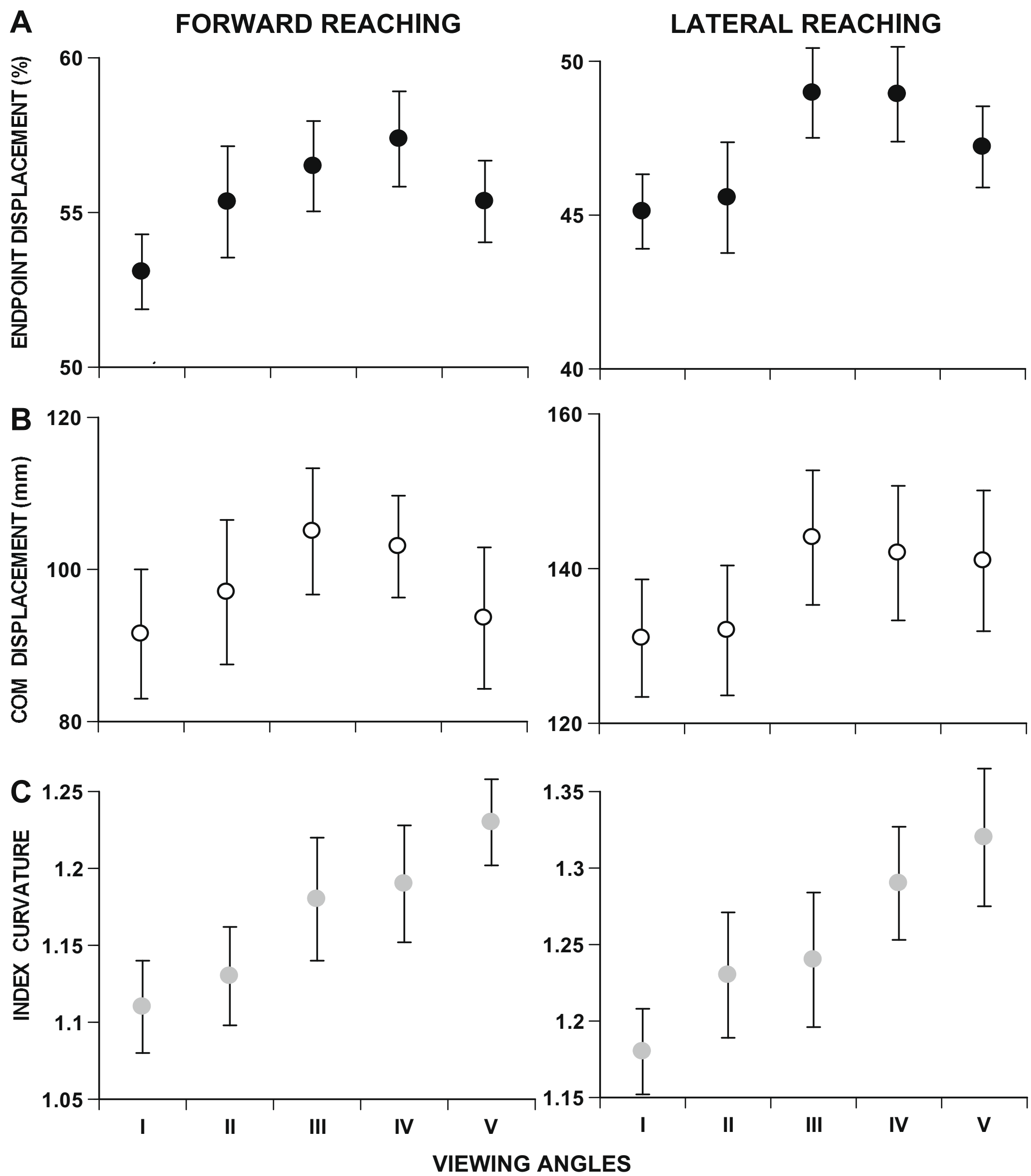

Fig. 3. Endpoint displacements (means ± SE) normalized to the participants' heights and expressed as percentage of reach distance (A), the displacement of the center of mass (B), and index of curvature (C). Data are presented for forward (left panel) and lateral (right panel) reaching, under viewing angles I–V.

Visual angle influenced the timing of the arm, trunk, and leg movement. This is seen from Fig. 5, which shows the averaged angular velocity profiles ± SD of the arm and postural segments. During reaching under angle I performed in the forward and lateral directions the arm and leg movements were initiated earlier than movement of the trunk, as shown in Fig. 5A. The trunk initiated movement somewhat later. The trajectory shapes of forward and lateral reaches, made using viewing angle IV (Fig 5B) matched each other more closely than those made using the other gaze angles, and both initiation and termination of all the segmental movements at this angle showed greater synchrony.

Inter-segmental coordination was quantified using cross-correlation coefficients at a zero time lag. Fig. 6A presents averaged individual means of inter-segmental coupling between pairs: arm-trunk, trunk-leg, and arm-leg. The strongest coupling characterized arm-trunk coordination with means (r) ranging between 0.87 and 0.37 ($F_{2,30} = 11.12$, $p < 0.001$ for forward reaching, $F_{2,30} = 10.23$, $p < 0.001$ for lateral reaching). Arm-trunk coordination remained practically unchanged throughout all visual conditions in both forward and lateral reaches. Leg segment coordinated with the trunk and arm to a smaller extent and there was considerable variability in this coupling, particularly during reaching under visual angles I and II. The coefficients deviated from positive to negative, suggesting that the leg could shift in the same or opposite direction as the arm and trunk segments, depending on the viewing angle. As participants performed forward reaches using angle IV, and as they reached laterally using angles III–V, coupling of leg-trunk and arm-leg segments was significantly increased ($p < 0.05$).

Time lag of the trunk and leg movement with regard to the arm is presented in Fig. 6B, with positive means reflecting arm leading and negative means reflecting arm lagging. Overall, movement lag was affected by visual presentation ($F_{4,120} = 11.4$, $p < 0.001$ for forward reaching, $F_{4,120} = 12.5$, $p < 0.001$ for lateral reaching). During forward reaching under angle I, the leg movement in most cases led arm movement, with time differences ranging from −48 to 13 ms (Fig. 6B). Trunk segment movement lagged behind arm seg-

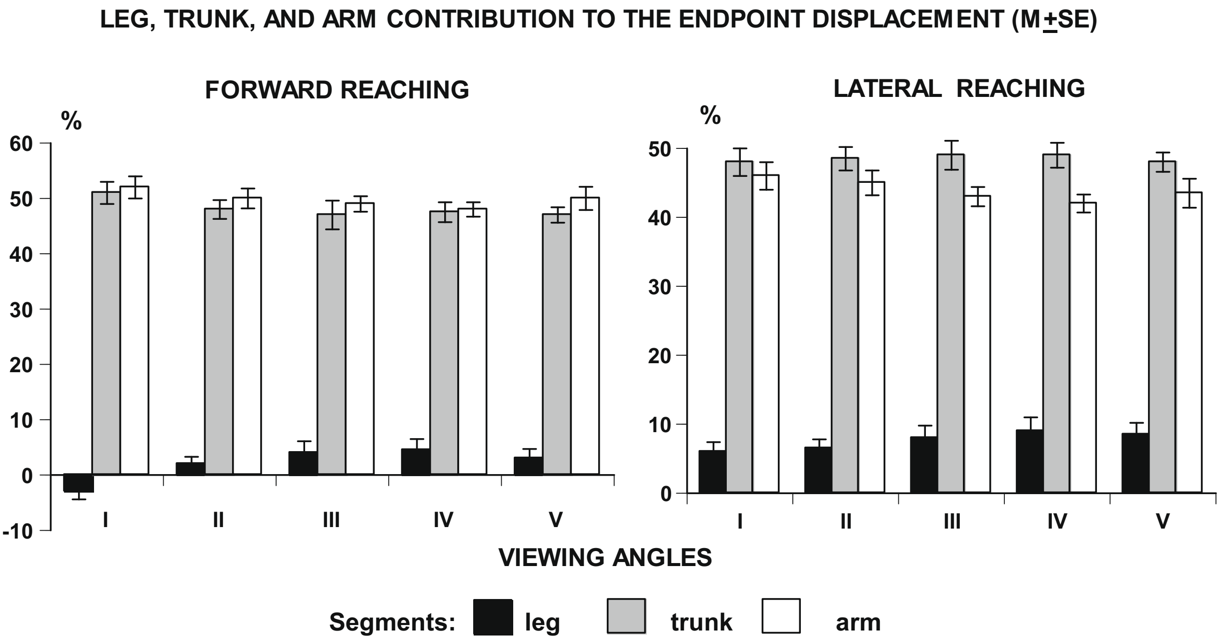

Fig. 4. Means ± SE of the arm (open bars), trunk (grey bars), and leg (black bars) contribution to endpoint displacement during forward (left panel) and lateral (right panel) reaching performed using visual angles I–V. Means were expressed as a percentage of total reach distance.

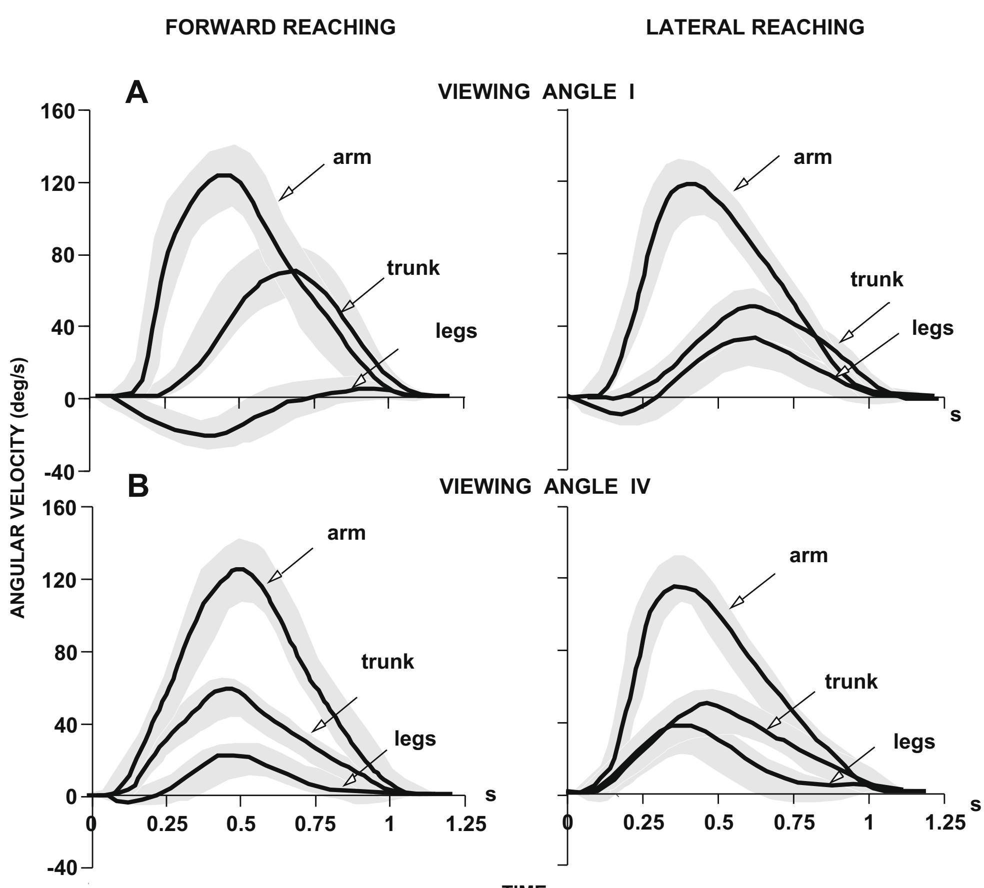

Fig. 5. Averaged angular velocity profiles of the arm, trunk, and leg segment displacements during forward and lateral reaches performed in viewing angle I (A) and angle IV (B). The grey shadow area represents deviation (±1SD) from averaged means.

ment movement by about 100 ms. These patterns reflect characteristic reach performance. Participants would first make postural adjustments by displacing the leg, then lift the arm and then add trunk movement to assist in arm transport as they continued to reach. Movement timing was altered as angles changed from I to V, with differences being significant when comparing angles I–V

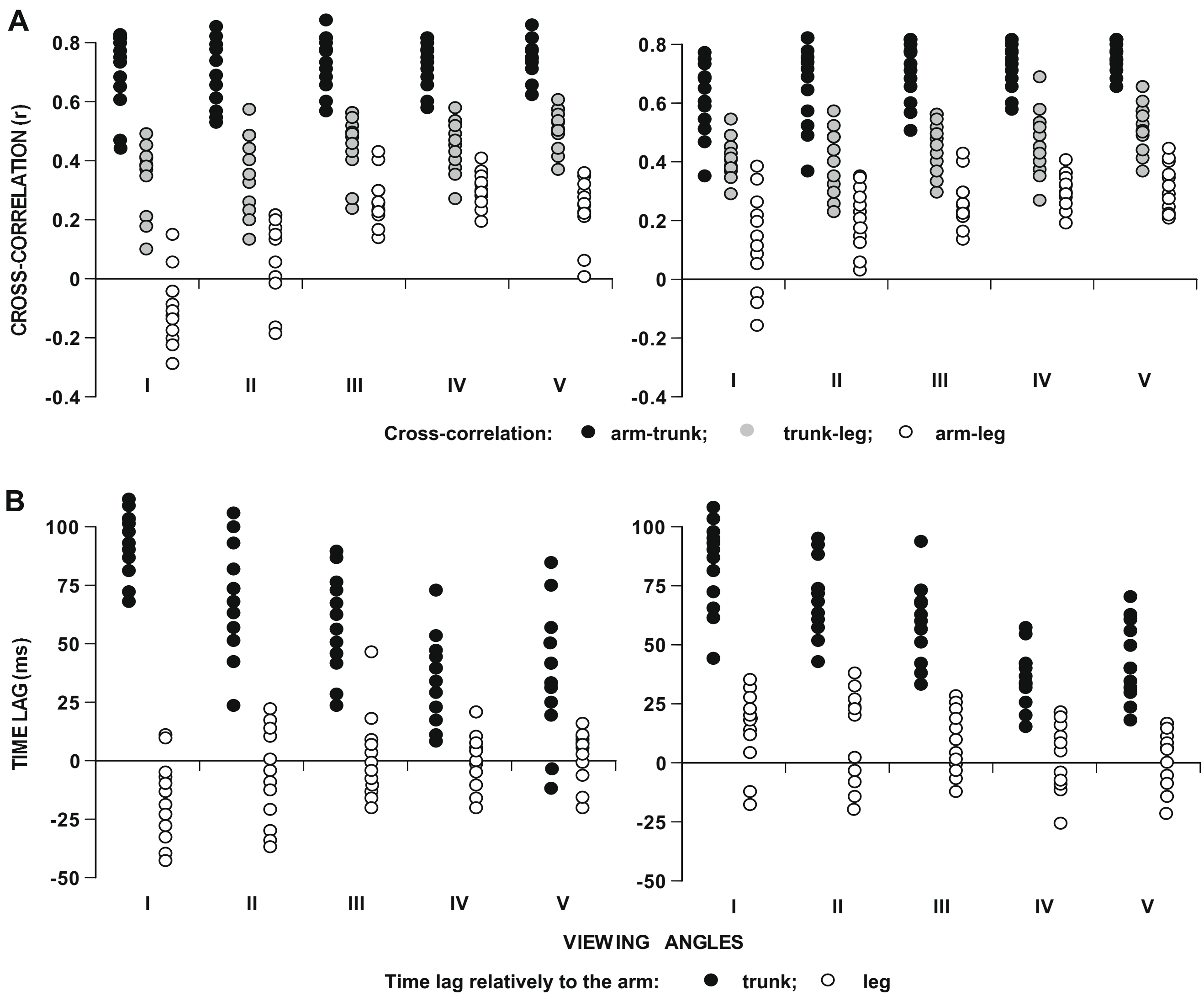

Fig. 6. Averaged individual means of the cross-correlation coefficients (A) between pairs: arm-trunk (black circles), trunk-leg (grey circles), and arm-leg (open circles). Time lag of the trunk (black circles) and leg (open circles) segments relatively to the arm (B) with positive means reflecting arm leading and negative means reflecting arm lagging.

($p < 0.01$). When using visual angles III–V, participants moved all three segments with minimal time lag. In these conditions leg might equally lead or lag the arm movement.

During lateral reaches the leg would either lag or lead arm movement, while trunk movement was always delayed with regard to the arm. This sequence was similar in all viewing angles. However, the means of lag and lead times were decreased under higher angles particularly when angles I and II were compared to angles III, IV, and V ($p < 0.01$). In other words, movements of the arm, trunk and leg became more synchronous under higher angles in a manner similar to that seen during forward reaches.

4. Discussion

4.1. Basic findings

Manipulation of visual angles in a virtual environment influenced reaching distance and other kinematic characteristics in forward and lateral reaches. All participants reached further, but with less accuracy (as represented by increased index of curvature) in the virtual environment presented under higher, particularly mid-range, viewing angles. This increase was achieved by altering inter-segmental coordination, greater use of the leg and trunk segments in arm transport to the target, and reduced inter-segmental temporal delay. This was seen in both forward and lateral reaches. Larger reaches were accompanied by increased curvature of the arm path, which was not essential for movement completion.

4.2. Effect of visual angle

After the sessions approximately 73% of all participants expressed a preference for the 45° angle, while 27% preferred 77.5° or 90° angles. None preferred the two lowest angles. The largest reaches were made using these preferred presentations. This finding was surprising as teleoperation literature has generally considered that a more naturalistic presentation would be most advantageous for manipulation. Some studies have reported participant fatigue and skill deterioration when scenes are presented under angles distorting the natural point of view (Lewis, Wang, Manojlovich, Hughes, & Liu, 2003; Macedo, Kaber, Endsley, Powanusorn, & Myung, 1998). There are several possible explanations for this effect.

One possibility is that that the higher points of view allowed participants to see not only the target, but a path to the target, and the manner in which the hand executed the movement. Observing your hand activates additionally movement-related brain areas e.g. the supramarginal gyrus, the posterior part of the cingulate cortex, the dorsal premotor area, posterior parietal cortex, and the cerebellum (Inoue et al., 1998, Medendorp, Beurze, Van Pelt, & Van Der Werf, 2008). These areas are all important for mapping visual information to motor commands. Confirming this statement, Brouwer, Vuong, and Kanai (2006) showed a significant effect of visual perspective on performance of finger tapping when the hand moving toward the target was visible for participants. No effect was seen when they only saw the static target. Furthermore, while observing themselves performing actions in third-person views, our participants could perceive their actions as if performed by other individuals. This perception could stimulate activity of mirror neurons that are thought to be located in premotor area in both monkeys and humans, and to facilitate motor performance (Buccino, Binkofski, & Riggio, 2004; Oztop & Arbib, 2002).

Altered perception of distance may be another mechanism influencing reaching performance. Levin and Haber (1993) showed that viewing a target in an open field under a more oblique angle increased object distance estimates. Interpreting this in the framework of our experiment, the virtual flowers observed more obliquely were perceived as located relatively farther than those observed at other angles. In addition, the visual scene presented under lower angles could offer more three-dimensional cues allowing an absolute distance coding of the target location. In the more overhead projections, participants were able to code the estimated distance to the flower relative to the viewed arm length. The use of these independently coded processes could modify processing of visual signals and account for the observed effect.

A third explanation is that angular perspectives affect perception of object size. Recent studies utilizing the Ebbinghaus visual illusion paradigm showed an influence of object size perception on multiple movement parameters such as position, orientation, displacement, speed, direction of motion, and force production during grasping (Westwood, Dubrowski, Carnahan, & Roy, 2000; for review Franz, Fahle, Bülthoff, & Gegenfurtner, 2001; Smeets, Brenne, de Grave, & Cuijpers, 2002). In our experiment the targets (flowers) observed at lower visual angles could be estimated as smaller and more "crowded" (located too close to each other) when compared to the targets observed from more middle and overhead views. "Crowded" objects are less well recognized than objects perceived as having more space between them (e.g. Pelli & Tillman, 2008). The middle-angle flowers were possibly estimated as larger, thereby facilitating performance. Increasing image size can assist initiation of aiming movement at a target or catching an approaching object (Ishihara & Imanaka, 2007; Lee & Lishman, 1975; Lee, Young, Reddish, Lough, & Clayton, 1983).

In addition, the mid-range angles may provide improved estimates of participants' body representation in space and postural stability limits. These constrain functional arm movements (Gabbard, Cordova, & Lee, 2007). During quiet stance eye fixation on a target located angularly down (at a vertical gaze angle of 15°) from the straight forward view increases postural stability more than fixating on a target straight ahead (Kapoula & Lê, 2006). The authors suggested that proprioceptive signals from external oblique ocular muscles could act to modify postural responses through vestibulospinal or cervicospinal reflexes. If this effect carries into the higher angles our participants preferred, greater postural stability under those gaze angles could encourage participants to use postural capacities to a greater extent, resulting in longer reaches. Our virtual presentations did not require participants to substantially change eye position in the orbits, suggesting other factors (e.g. changes in image processing on the eye retina) were incorporated into their improved reaching performance.

Physiologically, viewing a target under different angles alters neural firing properties in the visual cortex and changes activity in related cortical and sub-cortical structures (Rosenbluth & Allman, 2002; Trotter & Celebrini, 1999). Experimentally, this has been shown to be a powerful mediator of estimated object properties and distances (Gardner & Mon-Williams, 2001; Levin & Haber, 1993; Mon-Williams et al., 2001), isometric muscle force (Vaillancourt et al., 2006), and cognitive tasks including reading and display watching (Schmidt et al., 1993; Shieh & Lee, 2007; Turville et al., 1998). In a real world situation, this may be partially due to proprioceptive feedback from extraocular muscles or changes in image processing on the eye retina. In our study, visual presentation was changed without participants having move their eyes, suggesting that changes in reaching performance was modified by the information derived from the different angular perspectives. However, changes in head position during bending forward, while keeping image at the same level can generate some eye movements as well. Eye and head coordination was not analyzed, so an effect of eye muscle proprioceptive feedback on movement performance cannot be completely eliminated.

This study does not address specific neural mechanisms used to facilitate the reach-to-point movement, but reports the finding that viewing angles of approximately 45.0–77.5° were advantageous for increasing reaching distance and arm-postural coordination in a third-person presentation virtual environment. The viewing angle effect might be different, however, in a fully immersive (first-person view) environment, where the angle changes simultaneously with head movement, and lower angle might become more oblique as a forward reach is performed. A different view may then be preferred. This speculative statement may be partially supported by the study of Brouwer et al. (2006). They investigated tapping a target, presented horizontally under different camera perspectives ranging from naturalistic to oblique (medio-lateral direction) first-person views. Results showed the tapping time was quickest when the target was projected in most naturalistic perspective.

4.3. Inter-segmental coordination

Increased reaching in virtual space was primarily produced by increased involvement of the trunk and leg segments. This is consistent with findings in sitting reaches to a target in healthy individuals and those with neurological disabilities (Levin, Michaelsen, Cirstea, & Roby-Brami, 2002; Rossi, Mitnitski, & Feldman, 2002). In sitting reaches, balance maintenance was not a major issue. Our experiment examined how participants utilize postural segments without loss of stability when reaching in standing.

A tendency to underuse the transport capacity of the trunk and legs segment was observed during the forward reaches under low visual angles. These began with a slight shift of the legs in the direction opposite to reaching, followed by arm and significantly delayed trunk movements. This leg segment action probably reflects the mechanism known as anticipatory postural adjustment, used to counterbalance body segments and prevent falling during performance of functional movements (Belen'ki et al., 1967; Massion, 1994). According to the theory of anticipatory control, postural (axial) synergies are controlled centrally to stabilize the COM, either at the moment or prior to movement of a focal body mass. If so, in our experiment the CNS should have continued moving the leg segment in the opposite direction to maintain stability as the reaching distance increased. Instead our participants began shifting the leg toward the reaching direction as viewing angle increased, thereby increasing reach distance. This is consistent with results of Stapley, Pozzo, Cheron, and Grishin (1999), who reported reduced backward displacement of the hip during the reaching for an object located at 30% of body height distance compared with a target at 5% distance. Later, the same group suggested that postural components do not entirely compensate for the perturbing effect caused by arm movements, but assist movement execution by shifting the COM toward the target (Pozzo, Stapley, & Papaxanthis, 2002). Under some circumstances the effect of reducing COM displacement may be present despite the extended reaching distance. This helps diminish a destabilizing momentum created by the whole body movement. COM displacement in our participants did not change significantly between visual conditions.

Another question was to what extent postural segments assist in arm transport without balance loss. Although the COM in our participants never crossed the border of the projected base of support (see Section 3), body mass shift during the larger reaches rendered participants inherently less stable. One possible strategy to extend the reach without balance loss would be to increase speed and reduce a perturbation effect on postural stability, respectively (Kaminski, 2007). We did not find significant speed changes across the viewing conditions. Kaminski (2007) also showed that coupling between the arm and postural segments increased dramatically as reaching distance extended beyond arm's reach. This helped compensate for the instability in the greater reach distances regardless the movement speed. Inter-segmental kinematics in our participants were modified similarly. During larger reaches all body segments (arm, trunk, and legs) were more coordinated with smaller time lag. The data support the idea that when the task does not require extensive arm movement, the CNS prioritizes balance maintenance over reaching. When increased reach distance becomes the priority, postural synergies are activated simultaneously with the focal (arm) components to assist in hand transport to the target.

4.4. Application for virtual rehabilitation

Many neural mechanisms are involved in facilitating reaching under different viewing angles. Each would benefit from systematic investigation, looking both at performance and preference. Investigating viewing angles in virtual presentations, Zhou, Jiang, Qu, and Zhu (2003) reported the best judgment of size for objects was in a virtual environment presented 60°, and suggested this as optimum for teleoperation and design research. Consistent with these results, our finding suggests that visual angles between our 45 and 77.5° positions may be the preferred virtual presentation for training individuals to improve reaching ability, when high reaching precision is not required, such as when training individuals with balance deficits. These results may be used in gaming and rehabilitation industries for designing virtual environments for recreation and functional balance rehabilitation.

Recently there has been interest in incorporating customized and "off-the-shelf" computer games into rehabilitation of individuals with post-stroke hemiparesis, children with cerebral palsy, and older individuals. Some systems that have been used are the PlayStation 2 EyeToy, Interactive and Rehabilitation Exercise System (IREX), the Nintendo Wii, and X-box (Bryanton et al., 2006; Chen et al., 2007; Deutsch, Borbely, Filler, Huhn, & Guarrera-Bowlby, 2008; Morrow, Docan, Burdea, & Merians, 2006; Rand et al., 2004; Thornton et al., 2005; Yavuzer et al., 2008). All these gaming platforms utilize the third-person visual perspective. These approaches are frequently preferable in rehabilitation settings, as less expensive, more applicable, and allowing movements similar to those made in equivalent first-person virtual environment and physical world (Levin, Knaut, Magdalon, & Subramanian, 2009). Thus, the perspective under which a third-person visual scene is presented to a participant becomes a therapeutic variable to be manipulated in virtual rehabilitation simulations to optimize outcomes.

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