

## RESEARCH NOTE

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## The interaction of visual and proprioceptive inputs in pointing to actual and remembered targets

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**Abstract** Errors in pointing to actual and remembered targets presented in three-dimensional (3D) space in a dark room were studied under various conditions of visual feedback. During their movements, subjects either had no vision of their arms or of the target, vision of the target but not of their arms, vision of a light-emitting diode (LED) on their moving index fingertip but not of the target, or vision of an LED on their moving index fingertip and of the target. Errors depended critically upon feedback condition. 3D errors were largest for movements to remembered targets without visual feedback, diminished with vision of the moving fingertip, and diminished further with vision of the target and vision of the finger and the target. Moreover, the different conditions differentially influenced the radial distance, azimuth, and elevation errors, indicating that subjects control motion along all three axes relatively independently. The pattern of errors suggest that the neural systems that mediate processing of actual versus remembered targets may have different capacities for integrating visual and proprioceptive information in order to program spatially directed arm movements.

**Key words** Three dimensional pointing · Humans

### Introduction

Touching objects in three-dimensional (3D) space with the index finger under visual control is a simple motor task that can be performed very accurately. However, one's accuracy in pointing to a memorized target in darkness or with the eyes closed diminishes greatly. Under

these conditions, constant errors can reach 4–8 cm (Darling and Miller 1993), 7–9 cm (Adamovich et al. 1994), or even 10–15 cm (Soechting and Flanders 1989). One can try to explain this effect by positing inaccurate memory of target location. However, pointing experiments using a long pointer demonstrated that errors due to poor memory of target location are substantially less than the pointing errors (Soechting and Flanders 1989).

Another possible source of constant errors in pointing without visual feedback could be a nonaccurate transformation of target location, which is visually defined, to final fingertip position, which is based on proprioceptive information (see Soechting and Flanders 1989 for discussion). In experiments with planar pointing to actual targets without vision of the moving arm, Prablanc et al. (1986) showed that proprioceptive information is sufficient for accurate pointing. These investigators obtained azimuth errors of less than 2°. However, there is no experimental evidence that this effect is also valid in the case of 3D pointing movements to actual targets, where subjects must take into account the effect of gravity.

We investigated this problem by conducting experiments with 3D pointing to actual targets in a completely dark room, so that the subjects were not able to see their arms. Moreover, in order to clarify the extent to which visual information can improve the accuracy of sensorimotor transformations, we also investigated pointing in three dimensions to memorized targets when the subject was only able to see light-emitting diode (LED) on his moving index fingertip. Preliminary results have been published in abstract form (Fookson et al. 1993).

### Materials and methods

Five right-handed subjects, 25–45 years old, participated in the experiments. All subjects gave their informed consent prior to their inclusion in the study. This research received approval by the appropriate ethics committee and therefore was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Five target locations were presented in random order in 3D space by a programmable robot arm (Kothari et al. 1992). Four targets (lowermost P1, leftmost P2, uppermost P4, and right-

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most P5) formed a diamond in a frontal plane, centered in front of the right shoulder, with the two diagonals about 55 cm long. Target P3 was located in front of the right shoulder 15 cm further from the shoulder than this plane, at a distance approximately equal to the length of the subject's arm with clenched fingers (55–75 cm). Infrared-emitting diodes (IREDs) were affixed to the subject's limb segments at consistent positions which were referenced to the following bony landmarks: acromial process of the scapula (shoulder), lateral epicondyle of humerus (elbow), and ulnar styloid process (wrist), as well as on the nail of the index fingertip and on the robot arm tip. The subjects were asked to fully extend their right index finger and not to move it with respect to the wrist. The IREDs positions were recorded in three dimensions with optoelectronic cameras (Northern Digital Optotrak; see Kothari et al. 1992 for details). The subjects were seated with their right arm flexed at the elbow joint, forearm being semipronated and vertical, such that the hand was about 10 cm to the right of the subject's ear.

The targets were presented in a dark room using a small illuminated LED on the tip of the robot arm. Another visible LED was placed on the subject's index fingertip. Four visual feedback conditions were used in the experiment:

1. *No vision.* The robot arm held the target position for 1.5 s, a short auditory signal (tone) instructed the subjects to close their eyes, and then the robot arm retracted. A second auditory tone 1 s later signaled subjects to "touch" the memorized target with their index fingertip and then to bring their arm back to the initial position in a smooth continuous movement without "corrections" near the target. The subject's eyes were closed throughout the movement ("no-vision" condition).

In the other three conditions, the subject's eyes were open throughout the movement which was performed in a totally dark room. The robot arm held the target position for 1.5 s, a short auditory signal (tone) then instructed the subjects to begin the movement.

2. *Vision of target.* The LED on the fingertip was off. Thus, the subject saw the target but did not see either his arm or the environment. The intensity of the target LED on the robot arm was adjusted to prevent the possibility of the subject seeing his finger at a distance larger than 1–2 cm from the target. A strong overhead light was turned on between trials to prevent dark adaptation. Moreover, the subject was asked to move fast in order to reduce the time when his finger was near the target. Thus, the only available visual information throughout the movement was the point-light target ("target-vision").

3. *Vision of finger.* The target LED went off just before the signal to move, but the LED on the fingertip was on throughout the movement. This condition with visual feedback only from the fingertip will be referred to as "finger-vision."

4. *Vision of finger and target.* Both the target and fingertip LEDs were illuminated throughout the movement ("target-finger-vision").

Each condition involved a total of 40 trials (five targets  $\times$  eight trials). In all four conditions, the subjects were instructed to touch the actual or memorized target "as accurately and as fast as possible." After the stop near the target, the arm was to be returned immediately to the initial position, without any additional corrective submovements. This instruction was necessary in order to prevent subjects from using any visual information about their arm position during movements to an actual target in the target-vision condition to correct (intentionally or unintentionally) the final arm position. Such information could potentially be obtained if subjects moved their hand back and forth, continually crossing the line of sight between the eyes and the target (an LED).

The positions of the IREDs were sampled at a rate of 100 Hz and digitally low-pass filtered at 8 Hz using a modified Butterworth filter. The errors were calculated at the moment of movement reversal, when the endpoint tangential velocity was minimal. Constant and variable radial (distance), azimuth, and elevation errors were calculated in a spherical frame of reference with the origin in the shoulder (see Soechting and Flanders 1989). Radial dis-

tance, azimuth, and elevation errors were defined as positive if the final arm position was further, to the right of, or higher than the target, respectively. In addition, 3D absolute constant errors (hereafter called 3D errors) were calculated as a mean distance between the fingertip and the target across all trials in the Visual feedback  $\times$  Target location subcondition. Variable 3D errors (hereafter called variable errors) were calculated in a Cartesian frame of reference as the mean square root of standard deviations of coordinates of endpoint locations around the coordinates of the mean endpoint location across all trials in the Visual feedback  $\times$  Target location subcondition. The error values were subjected to a repeated-measures ANOVA (four visual feedback conditions  $\times$  five target locations). Post hoc analyses used the Neuman-Keuls test.

## Results

The ANOVA revealed a significant influence of the visual feedback condition on the 3D error values ( $F_{3,12}=22.94$ ,  $P=0.0001$ ; see Fig. 1A). The errors were maximal in the no-vision condition (see Table 1) and were significantly larger than in finger-vision condition by an average of 3.93 cm ( $P<0.01$ ). The errors in the finger-vision condition were significantly larger than in target-vision condition by an average of 2.45 cm ( $P<0.05$ ). The error values in target-vision and finger-target-vision conditions were not significantly different ( $P>0.05$ ).

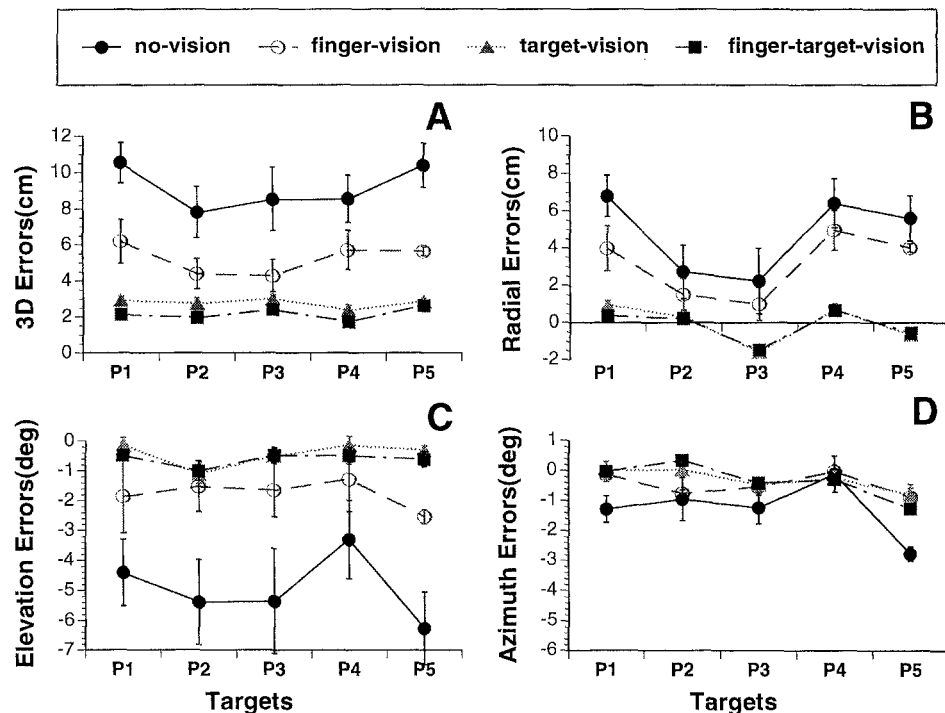
The visual feedback conditions significantly influenced the radial distance ( $F_{3,12}=7.73$ ,  $P=0.004$ ) and elevation ( $F_{3,12}=17.9$ ,  $P=0.0001$ ) constant errors; azimuth constant errors did not change significantly ( $F_{3,12}=2.0$ ,  $P=0.17$ ). The post hoc analysis revealed that the visual feedback conditions influenced the elevation and radial constant errors in different ways (see Fig. 1B, C). Radial errors did not significantly decrease with vision of finger compared with the no-vision condition ( $P>0.05$ ). However, the constant elevation errors were reduced significantly by an average of  $3.23^\circ$  ( $P<0.01$ ).

The change of visual feedback condition from finger-vision to target-vision condition again differentially influenced the radial and elevation constant errors. Here the radial errors were reduced significantly by mean of 3.12 cm ( $P<0.01$ ), but the elevation errors were not significantly changed ( $P>0.05$ ). No significant changes in either type of errors were found when comparing the finger-target-vision and target-vision condition ( $P>0.05$ ).

Subjects never touched the targets in conditions 1 and 3, touched them not more than once in condition 2 and not more than 4–5 times in condition 4. Therefore we assumed no influence of touching the actual targets on pointing accuracy. No significant effect of visual feedback condition on movement speed was found ( $F_{3,12}=0.1$ ,  $P=0.95$ ).

Visual feedback conditions significantly influenced the variable errors ( $F_{3,12}=6.38$ ,  $P=0.006$ ). The post hoc analyses revealed no significant difference for all conditions, except for no-vision, the condition with the largest error values (see Table 1). The same result was obtained for elevation variable errors ( $F_{3,12}=9.1$ ,  $P=0.0001$ ). In the case of variable radial distance error ( $F_{3,12}=3.85$ ,  $P=0.04$ ), no significant difference was found for all con-

**Fig. 1A–D** Mean pointing errors for each target location across visual feedback conditions. Bars represent SEMs. Targets P1, P2, P3, and P4 formed a rhombus in a frontal plane, centered in front of the right shoulder. P3 was located in a plane 15 cm more distally (see text). **A** 3D errors; **B** radial distance errors; **C** elevation errors; **D** azimuth errors



**Table 1** Pointing errors (mean±SEM) for different visual feedback conditions pooled across target locations. Shifts to the right, further, and higher than the target were considered to be positive

Errors	Conditions			
	No-vision	Finger-vision	Target-vision	Finger-target-vision
3D (cm)	9.16±0.60	5.23±0.45	2.78±0.12	2.16±0.13
Variable (cm)	3.50±0.24	2.49±0.22	2.64±0.12	2.28±0.22
Constant errors				
Radial distance (cm)	4.76±0.59	3.10±0.64	-0.02±0.28	-0.14±0.21
Azimuth (deg)	-1.27±0.37	-0.47±0.23	-0.29±0.10	-0.33±0.15
Elevation (deg)	-5.00±0.56	-1.77±0.28	-0.44±0.12	-0.61±0.13
Variable errors				
Radial distance (cm)	1.41±0.14	1.38±0.13	1.47±0.10	0.96±0.09
Azimuth (deg)	1.53±0.13	0.87±0.09	1.16±0.07	0.72±0.06
Elevation (deg)	2.11±0.19	1.31±0.14	1.43±0.11	1.06±0.09

ditions, except for target-finger-vision, the condition with the smallest error values. For azimuth variable errors ( $F_{3,12}=15.68$ ,  $P=0.0001$ ), the error differences were significant for all pairs of conditions except for the finger-vision versus finger-target-vision conditions.

## Discussion

The accuracy of pointing evaluated by absolute constant (3D) error values was significantly different in three experimental conditions: no-vision (approximately 9 cm), finger-vision (approximately 5 cm), and target-vision (approximately 2 cm; see Table 1 and Fig. 1A). In the target-vision condition, when the subject could see the target but not his arm throughout the movement, the results are close to those of Prablanc et al. (1986) for planar pointing movements. In these experimental condi-

tions, subjects were able to successfully integrate visual information about the target with the proprioception from the arm and to use such information to generate accurate motor commands.

In the no-vision condition, subjects made large errors (about 9 cm), a finding that is close to those of Soechting and Flanders (1989) and Darling and Miller (1993). However, in our experiments subjects overshoot the targets, even for the most distant target location P3 (see Fig. 1B). This is in contrast to the findings of Soechting and Flanders (1989) and Darling and Miller (1993), where subjects undershot distant targets. One may assume that these discrepancies can be explained by the differences in experimental conditions in this study from the previous ones: a different initial arm posture (vertical forearm), and a different means of target presentation (light points in a dark room). According to preliminary data we have collected (unpublished observations), each

of these differences may make a contribution to this effect.

Subjects made large errors (9 cm) in the no-vision condition, where the movements were made toward a remembered target not an actual one; whereas much smaller errors were obtained in the target-vision condition in which subjects saw the target throughout the movement. The simplest explanation of the difference in accuracy between these two conditions might be poor memory of target location. However, Soechting and Flanders (1989), based on their experiments with a long pointer, showed that target location is stored in memory with much higher accuracy than the accuracy of pointing. Thus, it is not the process of forgetting the target location, but rather, difficulties in the integration of visual and proprioceptive information that can explain pointing errors to remembered targets.

We would like to suggest the following explanation for this problem of integrating visual and proprioceptive information: actual and memorized targets may activate different neural subsystems that have different capabilities for integrating information from different modalities and in generating accurate motor commands. In the case of pointing to actual targets, visual signals from the target may project to brain areas that had elaborated, during the evolutionary process, fine mechanisms for control of visually guided movements and are capable of accurate integration of visual and proprioceptive afferent information. However, the spatial representation of the remembered target might be mediated through other brain areas. It is possible that these areas, which deal with memory for spatial location, are not as capable of accurate integration of remembered target coordinates with the proprioceptive information from the arm, or can not transfer this data as accurately to motor areas of the brain. In favor of this hypothesis are the results of Becker and Fuchs (1969) and Gnadt et al. (1991), who showed that even such stereotyped movements as visual saccades are made with much larger errors in the case of remembered targets, compared with actual ones.

Under the vision-finger condition, the brain areas that deal with spatial memory not only contain coordinates of the remembered target but also get information from the visual system about the working point location. Therefore, the motor control system can directly compare finger and target coordinates, and there may be no need to use the proprioceptive signals from the arm.

An interesting result of the present study is the differential influence of visual feedback conditions on the radial and elevation errors (no effects on constant azimuth errors were found, presumably because they were very low – overall mean  $1.27^\circ$  – even in the worst, no-vision condition; see Table 1). In the case of movement to an actual target without vision of the arm (target-vision condition), the subjects were able to correctly assess the distance and directional coordinates of the target and to move the arm accurately to the target. In the case of movements to remembered targets in finger-vision condition, this accurate evaluation of distance can not be

used for movement control without introducing additional errors. However, directional information can be used successfully for movement planning in this condition.

An explanation for these differences might be that the azimuth and elevation coordinates of the target can be assessed easily by the location of the target image on the retina, while more complex binocular mechanisms are necessary for evaluation of the distance to a point-light in a dark room. Therefore, the directional and radial target coordinates are probably processed in different information channels.

The differential influence of visual feedback conditions was also found for variable directional and radial errors. The variable azimuth and elevation errors decreased significantly when any kind of additional visual information (target LED or finger LED) was available during the movement. However, the variable radial distance error decreased significantly only when both the visual sources were available during the movement.

It has been shown that direction and distance can be mediated by different anatomic structures within the nervous system. Georgopoulos et al. (1986) found neurons in different areas of the cortex that encode movement direction, but not amplitude. It also has been argued that distance and direction of movement to an actual target are planned relatively independently (see Rosenbaum 1980; Ghez et al. 1993). We showed in our experiments that the possibility of seeing the working point throughout the movement toward a remembered target changes in different ways the elevation and distance errors when compared with movement without visual feedback. Thus, one may suggest that, for movement planning that uses not the actual target coordinates but the information from spatial memory structures, distance and direction are processed relatively independently.

Finally, we found a marked difference in the magnitude of the azimuth and elevation constant errors and in the dependency of these errors on the visual feedback conditions. For movements to remembered targets, elevation errors were 2–3 times larger than azimuth errors (see Table 1). In the target-vision condition compared with the finger-vision condition, the elevation errors decreased significantly, but azimuth errors remained unchanged. Thus, we suggest that information about the target's distance, elevation, and azimuth is processed through relatively independent channels, and that subjects control the motion along all three axes relatively independently.

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