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Exploring the Role of Sensor Noise in Movement Variability

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***Abstract*—Numerical simulations were used to explore the consequences of a spatially non-uniform sense of hand position on arm movements in the horizontal plane. Isotropic or anisotropic position errors were introduced into several starting hand positions and the resulting errors in movement direction were quantified. Two separate simulations were performed. In one simulation planned movement directions were defined relative to the starting position of the hand. Movement errors generated in this simulation resulted from a failure to compensate for differing initial conditions. In a second simulation planned movement directions were defined by the vector joining the sensed starting position with a fixed target position. Movement errors in this simulation resulted from both uncompensated changes in initial conditions as well as errors in movement planning. In both simulations, directional error variability generally increased for starting positions closer to the body. These effects were most pronounced for the anisotropic distribution of starting positions, particularly under conditions where movements were directed toward a fixed spatial location.**

I. Introduction

Limb movements are inherently variable and become even more variable in the presence of disorders affecting the nervous system. This variability is the result of noise that arises at one or more stages of movement production. For example, noise in the systems responsible for estimating limb or target position (i.e. proprioception and vision) can contribute to movement variability [1, 2]. Noise can also arise during the movement planning process, e.g. in planning the required movement vector or in transforming this vector from visual to motor coordinates [3]. Lastly, noise can arise at the execution stage of movement production, i.e. in the specification of motor output [4]. The contributions of planning and execution noise to movement variability for 2D arm movements are well known. Here we describe, using simulations, the contribution of sensor noise to variability in 2D arm movements, particularly noise in the sensors conveying information about initial conditions (starting limb position/configuration).

Limb position can be estimated using information provided by vision, proprioception (via tactile and muscle spindle afferents), and efference copy (i.e. information about previous motor commands). The relative weighting of these signals to the final estimate has been examined under various experimental conditions and has been found to depend upon movement time, sensorimotor context, stage of motor planning, and also on whether the hand is static or moving [5-9]. This weighting is not arbitrary however but appears to reflect an integration strategy that is statistically optimal, i.e. integration appears to be related to the relative precision of somatic (proprioception/efference copy) and visual input [10, 11].

The precision of both somatic and visual information varies with the position of the limb in the workspace. For example, localization on the basis of somatic signals is more precise when the hand is closer to the body and is more precise in depth (radial direction with respect to the shoulder) than in azimuth [10, 12]. Vision is also more precise for positions closer to the eyes/body but is more precise in azimuth than in depth. These differences in relative position lead to a weighting of somatic and visual signals during the estimation of static limb position that is both position and direction dependent. That is, the joint probability distribution describing the static position of the hand in the horizontal plane can appear to be isotropic or anisotropic depending on the hand's position in the workspace and is generally smaller for positions closer to the body [10, 13].

Although the precision of limb position sense in the workspace has been characterized, the consequences of this variability in position sense on movement production across the workspace are not well known. Buneo et al [1] examined the effects of random perturbations of the elbow joint on movements in different directions and found that the effects of these perturbations were movement direction dependent. Here we assessed the consequences of random perturbations of hand (arm endpoint) position on movement direction, using two models of endpoint precision (isotropic and anisotropic).

II. Methods

A. General Simulation Methods

Movements were simulated using custom Matlab® code (The Mathworks Inc., Natick, MA). To simulate movements in different directions we first computed joint torques derived from idealized arm movements, under the assumptions that hand paths are rectilinear and tangential velocity profiles are bell-shaped. Simulated movements were 0.15 m in amplitude and 350 ms in duration. Arm endpoint ('hand') trajectories were converted to time-varying angular motions at the shoulder and elbow using standard trigonometric equations. After numerical differentiation of the angular motions, shoulder and elbow torques were calculated using the

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equations of motion for a rigid two-link manipulator [14], with anthropometric and mechanical parameters taken from [9]. After obtaining the joint torques, movements in a given direction were simulated by simultaneously solving for the shoulder and elbow angular positions and velocities using a fourth order Runge-Kutta method, then transforming the angular motions into hand paths.

To examine the effects of initial arm configuration on patterns of directional errors, movements were simulated using several different initial arm postures. For simplicity discussion is focused here on the two most extreme postures (results from other postures were intermediate between these two). The corresponding 'near' and 'far' hand locations were approximately 30 cm apart. The initial posture for the near hand location corresponded to 150° of elbow flexion (full elbow extension = 0°) and -7.3° of shoulder flexion (horizontal adduction) relative to a straight line passing through the shoulders. The initial posture for the far location was 80° of elbow flexion and 30.1° of shoulder flexion.

To simulate the precision of hand position estimation, we introduced random perturbations into the initial hand position. Two random error patterns (isotropic and anisotropic; 60 perturbations each) were used in these simulations. The isotropic (circular) error distribution had a standard deviation of 0.02828 m along any given axis. The anisotropic (elliptical) distribution had a standard deviation of 0.02 m along its minor axis and 0.04 m along its major axis and was thus equal in area to the isotropic distribution. For the anisotropic distribution, the minor axis was collinear with a vector pointing from the shoulder to the hand, an approximation to the anisotropy in somatically based hand localization reported by van Beers and colleagues [10, 12].

The perturbations gave rise to directional errors by breaking the association among the initial conditions, the joint torques at the shoulder and elbow, and movement direction. The initial conditions following perturbation were considered to be the 'sensed' conditions. These conditions differed from the 'actual' conditions, which corresponded to the near or far postures described above. When movement direction was defined relative to the initial hand position (Fig. 1a), perturbations caused no change in planned movement vectors (blue), i.e. this vector was simply a translated version of the vector required for the actual initial conditions (black). However, since joint torques depend on the initial conditions (even for the same movement with respect to the hand), perturbations caused the wrong torques to be selected for the required movement. This resulted in deviations of the actual trajectory from the required trajectory through the conducting chain of forward transformations. These deviations were quantified by subtracting the initial movement direction (defined by a vector connecting the hand positions at 0 and 120 ms into the movement) of the actual trajectory from that of the required trajectory. The variability of these directional errors (α) were quantified by calculating the circular standard deviation.

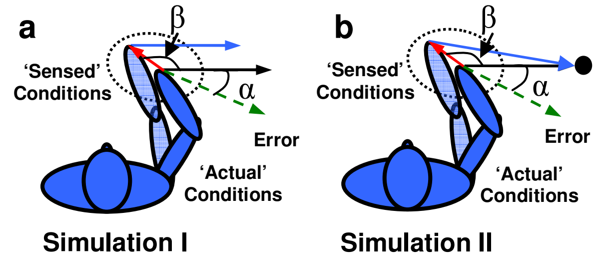

Fig. 1. Movement conditions in the two simulations. (**a**) Simulation I. Planned movement directions (blue vectors) were defined relative to the initial hand position. Planned vectors translated with perturbations of the initial hand position (red vector) causing movement errors (green vector). Black vectors represent required movements for the actual conditions. (**b**) Simulation II. Movements were planned toward a fixed spatial target (black sphere). Perturbations resulted in a translation and rotation of the planned movement vector. The dotted ellipse is an exaggerated representation of the anisotropic distribution used to simulate hand position estimation.

B. Simulation I: Errors in Sensing Initial Conditions

In Simulation I the planned movement direction was defined relative to the initial hand position only (Fig. 1a). In this case, directional errors resulted from a failure to compensate for differing initial conditions.

C. Sensitivity Analysis of Perturbation Amplitude and Direction

Since perturbations could vary in both amplitude and direction, sensitivity analyses were conducted for Simulation I to independently examine the effects of perturbation amplitude (ρ) and perturbation direction (β) on movement direction. For the analysis of perturbation amplitude, three different amplitudes were used (0.005, 0.01, 0.02m) and for each selected amplitude simulations were conducted for 24 perturbation directions spaced 15° apart. For the sensitivity analysis of direction, perturbation amplitude was fixed at 0.01m and directional errors were evaluated for each of 8 perturbation directions spaced 45°apart.

D. Simulation II: Errors in Sensing Initial Conditions + Errors in Trajectory Planning

In Simulation II the planned movement direction was defined by a vector connecting the initial hand position to a fixed spatial target (Fig. 1b). As a result, errors in the initial position caused a rotation of the planned trajectory. Directional errors in this case can be attributed to two sources: 1) a failure to compensate for changing initial conditions and 2) errors in trajectory planning.

III. Results

The results of Simulation I are shown in Figure 2. For the isotropic perturbation distribution (left) directional error variability increased and became more isotropic when the hand was positioned closer to the body ('Near'). For the anisotropic perturbations, directional error variability was generally isotropic but was also larger for the near position. The increase in directional error when the hand is closer to the body can be attributed to the larger changes in joint angle that

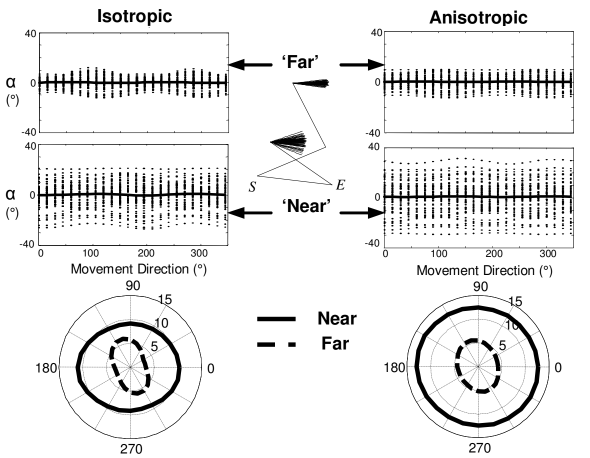

Fig. 2. Results of Simulation I for the isotropic (left) and anisotropic (right) perturbation distributions. Top two rows of plots depict directional error as a function of movement direction for the far and near hand positions. Bottom row of plots shows polar plots of the circular standard deviation of the directional errors. Inset illustrates the far and near postures as well as the simulated handpaths for a movement direction of 0°.

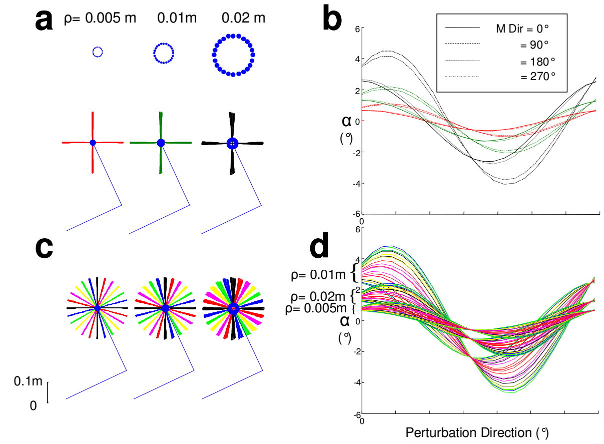

Fig. 3. Sensitivity analyses of perturbation amplitude (ρ) and direction (β). (**a**) Blue circles illustrate perturbations in 24 directions and three amplitudes (0.005, 0.01, and 0.02m). Also shown is the two link system representing the upper and lower arm and simulated handpaths for 4 movement directions. (**b**) Directional error (α) for each of the four movement directions as a function of perturbation direction and amplitude (colors). (**c**) Simulated handpaths for 24 movement directions (colored vectors), 24 perturbation directions and 3 amplitudes. (**d**) Directional error for the data shown in **c.**

accompany a given displacement of the endpoint at this position. This larger change in joint angles results in a larger difference in the torques required to move in a given direction (compared to more extended arm postures), thus the effect of a given perturbation is larger at this position.

Since these simulations produced random perturbations that varied in both magnitude and direction it was difficult to independently assess the effects of these perturbation components on the observed patterns of movement errors in Simulation I. As a result we also conducted separate sensitivity analyses of perturbation amplitude (ρ) and direction (β). Figure 3 shows the results of these analyses for one arm posture (similar results were obtained for the other arm postures). Even when considered separately, the effects of perturbation amplitude and direction were complex. For most movement directions, progressively larger perturbation amplitudes in a given direction (e.g. 45°) produced progressively larger errors, with a possible relation $\alpha \approx k \cdot \rho$. However, k appeared to vary substantially across perturbation directions, being largest for perturbations directed at 45° and 225°. This particular pattern of variation across directions may explain why anisotropic perturbations in Simulation I resulted in relatively isotropic directional errors. That is, in that simulation perturbations were small along directions where k is expected to be large and vice-versa, possibly mitigating natural variations that would arise from more isotropic perturbations.

The effects of perturbation direction on directional error can be ascertained by looking across perturbation directions in the plots on the right of Fig. 3. However, these effects are perhaps best appreciated in the format shown in Fig. 4. Here, directional errors are plotted in polar form, where the orientation of each vector corresponds to a particular movement direction and the magnitude of this vector corresponds to the magnitude of the directional error (solid lines = clockwise (positive) errors; dotted lines = counterclockwise (negative) errors). This figure reinforces the observation that, in general, directional errors were larger for initial hand locations closer to the body (for reasons indicated above). This figure also reinforces that, for any given perturbation direction, errors across movement directions were generally anisotropic, though the extent of this anisotropy differed for different perturbation directions. For oppositely directed perturbation directions (e.g. 45° and 225°), directional errors were approximately equal in magnitude but opposite in sign.

Comparing the shape of the polar plots for the near and far hand positions shows that for some perturbation directions (e.g. 45°, 225°) the plots are similar in shape and, in addition to scaling, appear to simply rotate clockwise as the hand approaches the body. This is most likely an effect of the shoulder rotation that accompanies the change in hand position; since movement direction was defined in a reference frame that was fixed in space, the spatial tuning of shoulder and elbow torque would be expected to rotate by an amount equal to the change in shoulder position between the near and far positions. Since movement errors depend on differences in torque, the patterns of error would be expected to rotate by roughly the same amount. More complex changes in the shape of the polar plots with changes in hand position most likely arose from the changes in elbow angle, which affect the joint torques in a more complex fashion [1].

The results of Simulation II are shown in Figure 5. Recall that in this simulation, planned movement directions are defined by a vector connecting the initial hand position with a fixed spatial target. Thus, this simulation is more like what human subjects might encounter in real life. As in Simulation I we found that, for most movement directions, directional error variability increased when the hand was positioned

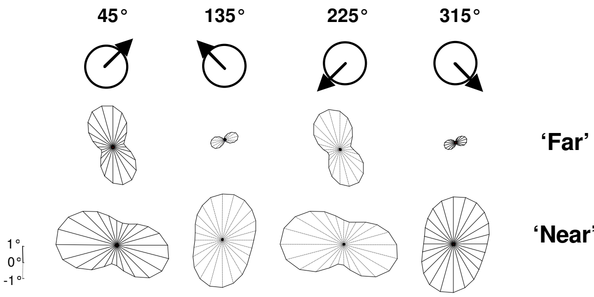

Fig. 4. Sensitivity analysis of perturbation direction. Results for four perturbation directions (columns) are shown. Movement direction errors are plotted in polar form for both the far (middle row) and near (bottom row) hand positions. In the polar plots, the orientation of each vector corresponds to a particular movement direction and the magnitude of each vector corresponds to the magnitude of the directional error (solid lines = clockwise (positive) errors; dotted lines = counterclockwise (negative) errors).

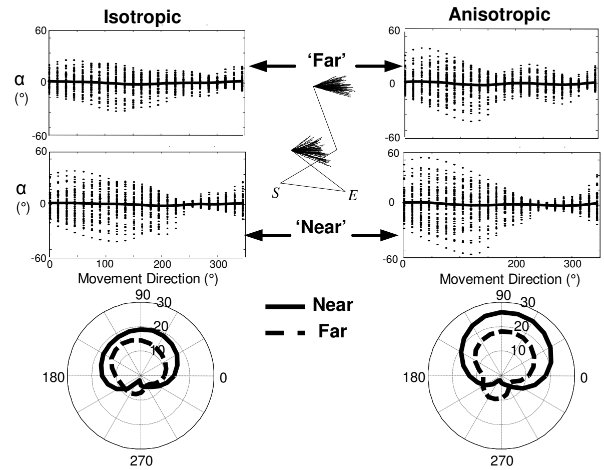

Fig. 5. Results of Simulation II. Figure conventions as in Fig. 2.

closer to the body. However, the variability in directional error was generally larger and more anisotropic than that observed in Simulation I. The larger directional error variability and larger anisotropy in Simulation II can be explained by the additional directional errors introduced in the early stages of movement planning. That is, in this simulation not only was the initial starting position altered but the planned movement trajectory as well. The extremely small directional error variability associated with some movement directions appears to result from the canceling out of these two separate sources of directional error. Likewise, the large directional error variability for some movement directions may be caused by the summation of the two different sources of error when they are equal in sign.

IV. CONCLUSIONS

There were three main findings: 1) For both simulations and both perturbation patterns, directional error variability increased for hand positions closer to the body. 2) In Simulation I, directional error variance became more isotropic for initial hand positions closer to the body, particularly for anisotropic endpoint perturbations. 3) Directional errors were larger and more anisotropic in Simulation II than errors in Simulation I.

These results suggest that the precision of hand position sense has important implications for the neural systems involved in movement execution. Even small errors in estimating hand position (~2 cm) result in large directional errors, particularly along certain movement directions, and need to be minimized during movement production. The improvement in the precision of endpoint estimation observed in human subjects for hand positions close to the body appears to compensate for the relatively larger directional errors that are generated in these positions for a given perturbation. Similarly, the observed anisotropy in precision appears to compensate in part for a similar, but rotated pattern of directional error anisotropy that arises due to perturbations in a given direction. In other words, variations in precision in human subjects may reflect the outcome of an optimization process that seeks to maximize error prediction across the workspace.

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