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INVESTIGATING COORDINATION IN MULTIDEGREE OF FREEDOM CONTROL II: CORRELATION ANALYSIS IN 6 DOF TRACKING

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In these two companion papers, methods developed in a series of studies in the 1940's and 1950's are applied to the analysis of 6 DOF control devices used in modern human machine systems such as teleoperation and virtual environments. Contrary to the early studies, the current work showed that the simultaneous time on target in multidegree of freedom tracking was higher than the product of component time on target scores. The distribution of linear correlation coefficients between the tracking errors of different degrees of freedom tended to be skewed towards the positive values. These results suggested that subjects' discoordination in early multidegree of freedom tracking studies was likely due to the limitation of human machine interfaces at that time. With well designed interfaces, subjects exhibited more coordinated trials than discoordinated trials in multidegree of freedom tracking.

INTRODUCTION

The companion paper "Investigating Coordination in Multidegree of Freedom Control I: Time-on-Target Analysis of 6 DOF Tracking" introduced the historical background of coordination in multidegree of freedom control, described a 6 DOF tracking experiment and presented a Time-on-Target (TOT) based analysis of coordination performance in the experiment. The TOT based analysis showed a trend opposite from that found in the early studies: simultaneous TOT (STOT) tends to be greater than the product of TOTs in the component dimensions, suggesting the existence of coordinated multiple degree of freedom control.

Complementary to TOT based coordination analysis, we have also conducted a linear correlation analysis based on the same 6 DOF tracking experiment described in Part I. We computed the correlation coefficient, r, directly from the tracking errors of the various degrees of freedom. A positive linear correlation indicates the degree that two variables co-vary. Its magnitude indicates the degree that the two errors are simultaneously reduced. In this sense, a correlation coefficient can serve as a measure of coordination, as suggested in (Senders, Wallis, & Senders, 1956) in their use of the Phi coefficient (derived from the Product Moment Correlation).

In addition to correlations between different pairs of the 6 degrees of freedom, we also calculated correlations between the Euclidean total magnitude of translation mismatch and total rotation mismatch (magnitude of the rotation vector) in each trial of tracking in the experiment. Our goal was to gain insights as to whether translation and rotation were integrated or separated aspects of 3D object manipulation. As reviewed in Part I of this paper, a persistent controversy in 6 DOF manipulation has been whether rotation and translation should be assigned to two separate hands (Rice, Yorchak, & Hartley, 1986, O'Hara, 1987, McKinnon & King, 1988). In lights of Jacob and colleagues (Jacob, Sibert, McFarlane, & Mullen, 1994), only those variables that are perceptually integrated should be controlled with one multidegree of freedom controller. Similar conclusions arise from the proximity compatibility principle (Wickens, 1992).

RESULTS

The Distribution of Correlation Coefficients

The correlation coefficient (r) between every two degrees of freedom, such as X-Y, X-Z, Y-Z, in each trial of 6 DOF tracking was calculated. Figure 1 shows the distribution of r from 26 subjects, 5 experimental phases, 4 tracking paths and two types of controllers all lumped into one plot. Approximately 3/4 of the r's were on the positive side (r>0)

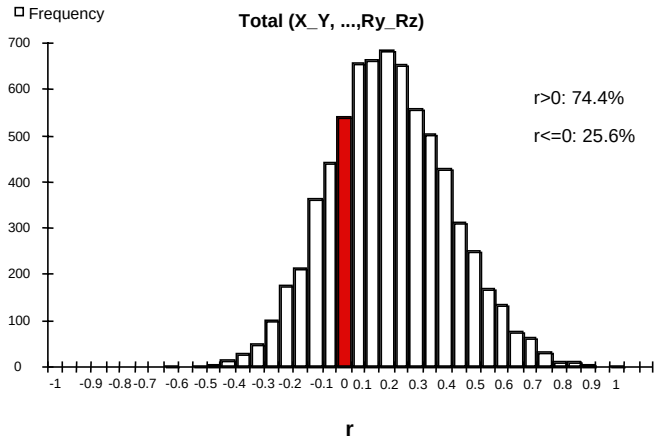
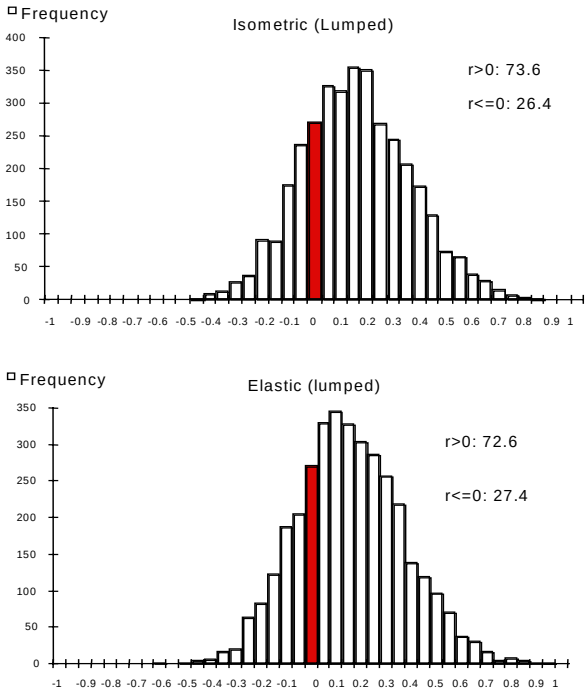


***Figure 1**. Total distribution of correlation coefficient r*



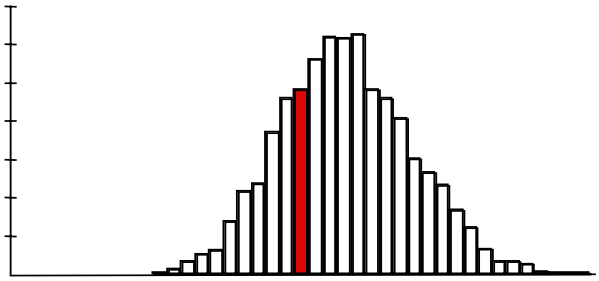


Figure 2 Similar distribution of correlation coefficient was found for two different controllers

and 1/4 were zero or negative (r<=0). In other words, there were more coordinated pairs of degrees of freedom than discoordinated ones.

The Consistency of the r Distribution

The r distribution varied little from controller to controller (Figure 2), from the first experimental phase to the last experimental phase (Figure 3) or from one tracking trajectory to another. It was also very consistent for all pairs of degrees of freedom, such as between X and Y, or between X and Ry, or between Rx and Ry (Figure 4). There was not one pair of degrees of freedom that was particularly more discoordinated than any other pair.

Coordination Between Translation and Rotation

The positive valued correlation between total translational error magnitude (Euclidean distance) and the total rotation error were more frequent than those between all pairs of DOF, with 88.6% trials positively correlated and 11.4% negatively correlated (Figure 5). This suggests that the rotational and translational aspects of the 3D tracking task were treated in an integrated manner by the subjects.

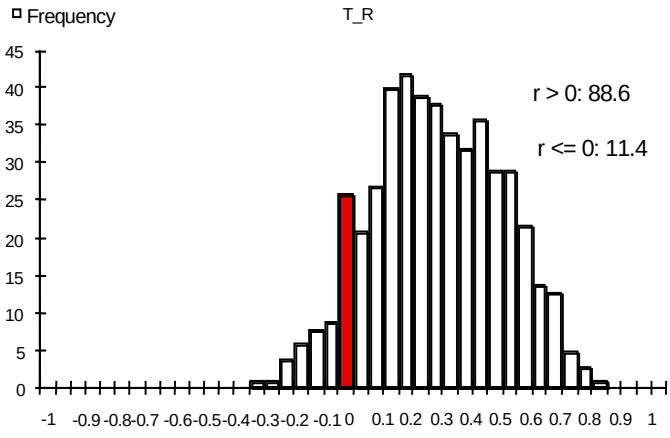


Figure 5 High degree of correlation coefficients were found between translation and rotation

Individual Differences

There were individual differences in the distribution of correlation coefficient r. Figure 6 shows a sample of individual data. For Subject C, only 59.7 % tracking was positively correlated, but the mean r value was 0.18. For Subject I, 85.7% tracking was positively correlated, but the mean r value was only 0.12. Subject K had 66.7% positively correlated tracking, with mean r value at 0.20.

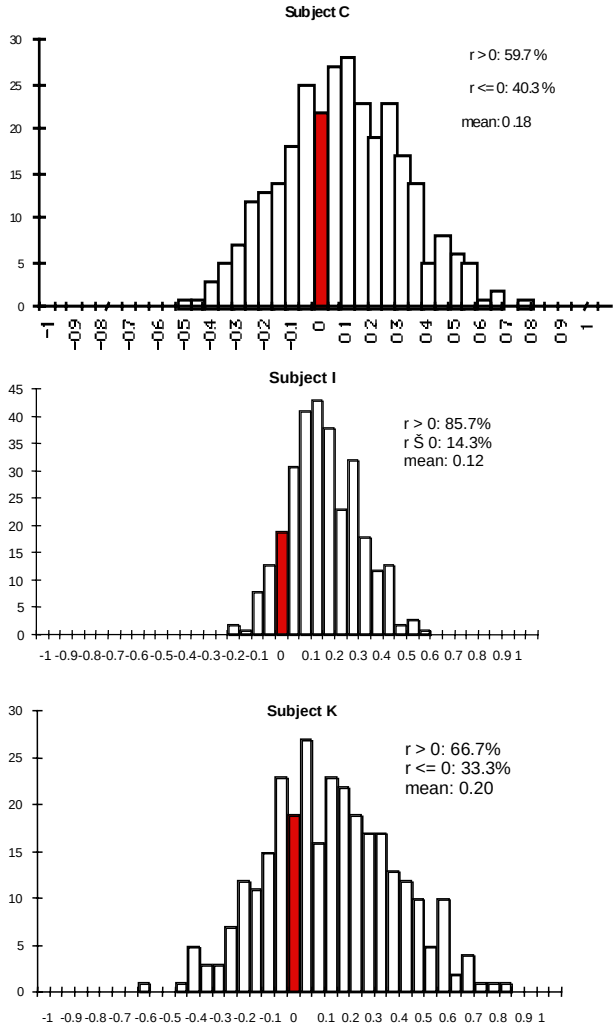


Figure 6 *A sample of individual r distribution*

CONCLUSIONS AND DISCUSSIONS

Contrary to early findings with regards to multiple DOF tracking, the present study revealed that subjects *could* co-ordinate multiple degrees of freedom, if the human machine interfaces are designed properly. Early studies (Ellson, 1947); (Gardner, 1950; Senders, Christensen, & Sabeh, 1955; Senders et al., 1956) showed that in 2 or 3 DOF tracking tasks, subjects' simultaneous TOT tended to be lower than the product of component TOT's in each dimension, suggesting while tracking error in one dimension was reduced, errors in other dimensions tended to increase. The current study showed that in a tracking task with more degrees of freedom (6), simultaneous TOT tended to be higher than the product of the component TOT's.

The distribution of linear correlation coefficient in the present study was, interestingly, a mirror image of what was found earlier (Compare Figure 1 with Figure 7). Figure 1 shows that about 3/4 of the tracking trials were positively correlated while Figure 7 shows about 3/4 of the trials to be negatively correlated. Note again that the data in Figure 7 were collected from subjects dealing with two (or one pair of) degrees of freedom while data in Figure 1 were collected from subjects controlling six (or 15 pairs of) degrees of freedom.

If we examine the task at a higher level by taking total translational error and total rotational error as two variables, the correlation coefficients were even more positively distributed (Figure 5). This suggests that subjects treated rotation and translation as integrated aspects of a 3D object, providing evidence to support one handed design of 3D object DOF manipulation.

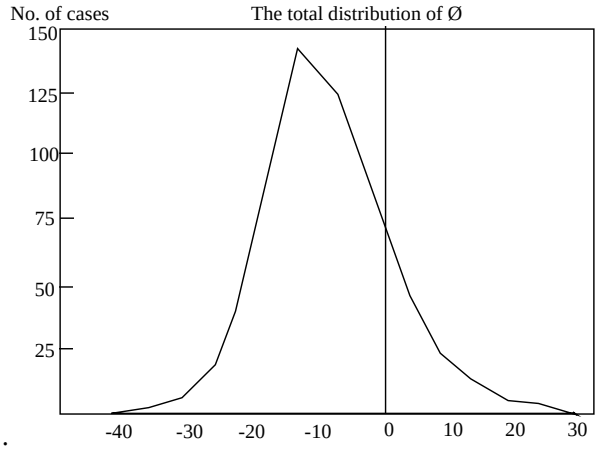


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Figure 7 *Senders' Ø distribution (Adapted from (Senders et al., 1956) Reprinted with permission)*

We have taken two complementary approaches to the study of coordination in multidegree of freedom manual control. Both of the two approaches were motivated by early historical thinking. For the current analysis of 6 DOF tracking, the two approaches differed both computationally and conceptually. The TOT analysis was based on the comparison of simultaneous time-on-target in all 6 degrees of freedom and the product of 6 one DOF time-on-target in each dimension. In other words, it examined subjects' coordination in 6 DOF tracking at a higher level: if all but one degree of freedom was off target, it was not considered coordinated behavior. In contrast, the correlation analysis was conducted at a component level: it examined relationships between each and every pair of degrees of freedom.

Although the two approaches were different, the conclusions drawn from them are very consistent: there was little fundamental conflict in controlling 6 degrees of freedom, effort paid to one degree of freedom does not necessarily cause destructive interference to other degrees of freedom. On the other hand, neither the C factors derived from TOT's nor the means of the r distribution were very high, suggesting that subjects 6 DOF control was far from perfectly coordinated.

To conclude, the current study further develops methods in early multidegree of freedom tracking studies and links them to the analysis of modern 6 DOF control devices. Our results suggested that subjects' discoordination in early studies was likely due to the design and construction limits of human machine interfaces at that time. With the current interfaces, subjects exhibited more coordinated trials than discoordinated trials in multidegree of freedom tracking tasks.

In addition to one handed control in the current study vs. two handed control in Ellson's and Senders' studies, there are a few other interface differences as well. The display space and the control space in the current study are much more isomorphic than in the earlier work. Also the control space is more perfectly harmonized. By this it is meant that the control output in display terms, the C/D gain, was uniform across all inputs for the isometric control and optimized for subjective harmonization for the EGG. Furthermore, the current 6 DOF interfaces use rate control instead of position control as in the early studies. It can be speculated that rate control may better facilitate coordination, since it removes the anatomical constraints of the human arm. Any or all of these differences may have contributed to the shift from discoordination to coordination. We must also point out that the subjects in the present study have grown up in a different environment from those of the 1940s and 1950s. Most important is the question of exposure to computer games.

Remaining Issues and Future Work

Although measures used in this study have been informative on the control coordination issues that we are interested in, they are far from ideal. First, complete linear cross-correlation functions (with various phase lags), instead of just correlation coefficients with zero lag, should be derived from the experimental data. If subjects still had to quickly switch attention and control between degrees of freedom, there would be a peak correlation between different degrees of freedom at non-zero phase lag. Senders did perform such an analysis for one trial of one subject and found that the correlation, negative at tau = 0, became positive at a time shift of about .45 seconds (Senders, 1996). The difficulty in such an analysis lies in its computational demands. A function, not a coefficient, has to be computed between every pair of degrees of freedom for every trial of tracking data. These functions then have to be aggregated in a mathematically valid approach. Future work also includes seeking alternative measures of coordination (Zhai, 1995).

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