Control Performance With Three Translational Degrees of Freedom

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Abstract

For multiple DOF systems, it is important to determine how accurately operators can control each DOF, and what the influence of the perceptual, information processing and psychomotor components on performance is. Sixteen right-handed male students participated in 2 experiments: one involving positioning and one involving tracking with 3 translational DOFs. We used two control-display mappings that differed in the coupling of the vertical and depth dimensions to the up-down and fore-aft control axes, to separate perceptual and psychomotor effects. We observed information processing effects in the positioning task: Initial error correction on the vertical dimension lagged in time behind the horizontal dimension. The depth dimension error correction lagged behind both, which was ascribed to the poorer perceptual information. We observed this perceptual effect also in the tracking experiment: Tracking error along the depth dimension was 3.8 times larger than along the other dimensions. Motor effects were also present, with tracking errors along the up-down axis of the handcontroller being 1.1 times larger than along the fore-aft axis. These results indicate that all three components contribute to control performance. Actual applications of this research include interface design for remote control and virtual reality applications.

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Control Performance With Three Translational Degrees of Freedom

Simultaneous control of multiple degrees of freedom (DOFs) is required in many control interfaces. Examples include: tele-operation; cursor control in CAD/CAM software; and virtual environments (e.g., Bejczy, 1980; McKinnon & Kruk, 1991). In such situations, integrating DOFs in one handcontroller is advantageous for two reasons. First, the number of input devices, and thus the number of limbs needed, is reduced. Second, control performance can be improved with integrated controls, especially when an integrated multiple DOF display is used (Regan, 1960; Chernikoff & LeMay, 1963; Fracker & Wickens, 1989).

Understanding the limitations of the human operator in manual control tasks with multiple DOFs is necessary for an adequate design of systems that require the simultaneous control of multiple DOFs. The question arises how accurately the human operator is able to control each translational DOF, when an integrated control device in combination with an integrated display is used. A common observation is that the tracking accuracy in the depth dimension of the display is worse than in the vertical and horizontal dimensions (e.g., Massimino, Sheridan & Roseborough, 1989; Kim, Tendick & Stark, 1991; Zhai & Milgram, 1993, 1994). In addition, performance differences between these last two DOFs have also been observed (Zhai, Milgram & Rastogi, 1997). Three factors can contribute to asymmetrical control performance between the DOFs: differences in perceptual information, in information processing, or in psychomotor capabilities. These factors will be briefly discussed in the next section.

In most applications the information on actual and preferred position will be displayed visually, although auditory, haptic, and tactile displays are possible as well. Differences in the quality of the displayed visual information for each dimension may occur, such as degraded depth information in 2D displays (Massimino et al., 1989; Kim et al., 1991; Sollenberger & Milgram,

1993; Zhai & Milgram, 1993, 1994). These differences in display quality may account for a large part of the differences in tracking performance between the visual dimensions, especially for the depth dimension.

There are indications that limitations in information processing capacity may also play a role in asymmetrical control performance. For instance, Zhai et al. (1997) found different learning curves for the three visual dimensions in simultaneous 3D tracking tasks, with the tracking error along the vertical and depth dimensions being higher than along the horizontal dimension in the first phase of the experiment. Zhai and colleagues ascribed the difference between the horizontal and vertical dimensions to a shortage of attentional resources in the early stages of learning, when participants had difficulty in controlling all DOF simultaneously, combined with higher attentional priority for the horizontal dimension. This difference disappeared in the second and subsequent phases, when more attentional resources may have been freed up due to the increase in experience with the control system. These results are in compliance with the notion that priority differences diminish when task execution shifts from controlled to more automatic during the course of learning (Schneider & Shiffrin, 1977). According to Zhai et al. (1997), such attentional priority differences may be the result of our daily experiences, in which movement visual stimuli are distributed more often in the horizontal direction than in the vertical direction.

Finally, anatomical and muscular characteristics of the hand and arm may govern performance differences between DOFs. The forces and motions that can be exerted in particular directions with the hand differ considerably (e.g., Hazelton, Smidt, Flatt & Stephens, 1975; Hallbeck, Kamal & Harmon, 1992), due to the geometry of the wrist joint and forearm and the characteristics of the muscles that control movement in each direction. Such effects of the motor system may partially be compensated for by using different gain settings for each control axis separately, in order to obtain an optimal transfer function between control input and resulting task performance on each individual DOF (e.g., Zhai et al., 1997). There are drawbacks to this approach, however, because any differences in performance between the DOFs may still be attributed to differences in the transfer functions used for each DOF. For instance, this approach assumes that the optimal transfer function for each separate DOF is still optimal in a multiple DOF setting. But it can be hypothesised that differences in applied transfer functions in such a setting force an operator to learn each transfer function independently in order to become proficient with that DOF. This can potentially result in different learning curves and performance between DOFs.

The Present Experiments

In studies on human control performance with multiple DOFs, a confounding of the above-mentioned factors is generally present. For instance, the forward control axis (i.e., the control axis parallel to the sagittal plane) is often coupled to the visual depth dimension (e.g., Massimino et al., 1989). The present paper describes two control-display mappings that are used to investigate the relation between the visual and motor system in the control of translational DOFs. The mappings are depicted in Figure 1. The first is spatial-motion mapping, in which the directions of control input to the handcontroller (i.e., the control axes) parallel the directions of motion of the controlled object in the display (i.e., the visual dimensions), regardless of the orientation of both (e.g., Spragg, Finck & Smith, 1959; Worringham & Beringer, 1998). The second is reference-plane mapping, in which the reference-plane of the display (i.e. the frontal plane of the screen) is mapped on the reference-plane of the handcontroller (i.e. the tabletop), see also Spragg et al. (1959); Buïel and Breedveld (1995); Van Erp, Oving and Korteling (1996). In our study, the two reference-planes were at a 90° angle. Using these two control-display mappings allows one to separate the effects of the visual and the motor systems for two of the three translational DOFs. That is, by coupling two different control axes to a particular visual dimension by means of two different control-display mappings, one can estimate the effect of the motor system for that particular DOF. And by using the same control axis for two different visual dimensions, one can gain insight in the effect of the visual system. This is not possible with only one mapping, which always results in a confounding of the two components.

This paper reports two experiments: positioning a cursor and tracking a target. The goal of the positioning experiment is twofold. The first goal is to investigate possible limitations of the information processing system in multiple DOF control, expressed in accompanying attentional priority differences among visual dimensions. In positioning tasks, such possible priority differences can be found by analysing error correction over time within a trial, which is different from analysing performance effects over trials (e.g., Zhai et al., 1997). Because competition for attentional resources between DOFs can only occur within a trial, but not between succeeding trials, it is essential to study within trial differences between DOFs. Comparison over trials can be used to identify learning effects. More specifically, attentional priority differences should be found in the early stages of error correction in a trial, with lagging of one or more DOFs in error correction compared to the other DOFs. Differences may also be found in later stages of control, but it may be difficult to attribute them to attentional priority differences when no differences are observed in the early stages. Therefore, early error correction for the different DOFs is of primary interest in this experiment. The second goal is to investigate whether there are performance differences between the different mapping principles. It is possible that one of the mapping principles is more compatible with existing population stereotypes for the control of multiple translational DOFs than the other mapping principle, as found by Buïel and Breedveld (1995).

The main goal of the second experiment is to investigate the effect of the visual and the psychomotor component on tracking accuracy in three dimensions. This is done by looking at the tracking performance for each control axis. Differences between the two control-display mappings regarding tracking accuracy with a particular control axis indicate the effect of the visual system on control performance, while performance differences among the control axes that are coupled to the same display dimension give an indication about the contribution of the motor system. In addition, multiple sessions are included to study the effect of practice on tracking performance for each axis.

Experiment 1

Method

Participants and task

Sixteen male students (age range 19 - 26 years) participated in the experiment. They had normal or corrected-to-normal vision, were right-handed, and were paid for their participation. None reported colour-deficient vision. This homogeneous participant group was chosen to minimise effects of sex and age, to which spatial tasks may be rather sensitive (Anastasi, 1958). The task for the participants was to position a cursor cube as quickly as possible in a target cube using 3 translational DOFs with linear rate control. Correct positioning was defined as keeping the cursor cube within an area around the target cube (margin of 0.3 cubesize) for 0.5 s.

Stimuli and displays

The target and cursor cubes and the visual database were computer generated. The two cubes were of equal size and always had the same orientation in the database. Each side of the red cursor cube and green target cube had a different colour saturation in order to distinguish the sides from each other. To provide a strong cue for relative depth position, the target cube was made semi-transparent (i.e., a relative transparency of 0.5). In this way, the control cube was always visible without the loss of the occlusion cue for depth. Application of semi-transparency can reduce the potential negative effects of occlusion (i.e., no depth information available for the

occluded object) on control performance (Zhai, Buxton & Milgram, 1994). No binocular depth cues were employed in the experiment.

Ninety different target-cursor pairs that described the starting positions of the cursor and target were used. These 90 pairs were derived from an initial set of 15 pairs, which involved randomly chosen points on a virtual sphere as the target and the mirrored co-ordinates as the cursor positions. By scaling the initial Euclidean distance between the centres of the cursor and target cubes of this initial set with 4, 5, or 6 times the cubesize, 45 pairs were created. And by switching the target and cursor positions in these 45 pairs, a complementary set of 45 pairs was created. This resulted in 30 different stimulus pairs per initial distance. Summed across these 30 pairs, no difference existed between the three dimensions in the total error that had to be corrected. In addition, a minimum distance error of 1 2/3 cubesizes had to be corrected on all three dimensions in each trial.

To vary the quality of the visual information, the cubes were positioned in different visual environments: one completely empty, and two enriched environments (see Figure 2). One of the visually enriched environments presented a forward looking view, while the other resembled a downward looking view. These environments differed in the orientation of the side wall bricks (i.e., 90° rotation in downward view) and in the visibility of the background scene (i.e., external world with trees and visible horizon). This background scene was visible in the forward view only; a dark haze obscured the background in the downward view. The different environments were used to avoid the possibility of favouring a particular control-display mapping due to the orientation of the visual environment, since one of the mappings could be more compatible with this display orientation than the other mapping. For instance, Buïel and Breedveld (1995) observed that their visual display was perceived by their participants as representing a downward looking view, and that the participants performed better with a particular control-display mapping (i.e., reference-plane mapping) than with another mapping (i.e., spatial-motion mapping). In both enriched environments, sticks that intersected with the walls were attached to the cubes. These sticks presented the participants an additional depth cue.

Instrumentation

An Evans & Sutherland ESIG 2000 graphics processor generated the displays. The geometric field-of-view was 43° × 33° (H × V) with the computer graphics eyepoint located in the centre and 45 cm in front of the monitor screen (Mitsubishi HL7955SBK). The display resolution was in proportion to these fields-of-view. The visual database measured 8.3 × 7.3 cubesizes (H × V) and was oriented parallel to the normal viewing vector. At a reference distance of 14.6 cubesizes from the computer graphics eyepoint, the cubes subtended a visual angle of approximately 3.9° (i.e., a physical size of approximately 3.1 cm on the display screen). The participants were positioned at the computer graphics eyepoint, but were not restricted to this position, and viewed the display with both eyes.

The control device was a Basys SpaceMaster, which is a force-sensing handcontroller with 6 DOF. It consists of a small, spring-loaded ball mounted on top of a vertical stick. By exerting force on the ball (pushing or pulling), the participants moved the cursor with linear rate control. This also resulted in a small, detectable movement of the ball of maximally 5 mm for each of the translational DOFs. The maximum digital output of the SpaceMaster was obtained at a deflection of approximately 2 mm. The elastic stiffness for each of the three translational DOFs ranged from 1.0 to 1.2 N/mm. Update and sampling frequency of the total system was set at 30 Hz. It should be noted that the handcontroller had the same orientation to the operator with both mappings, and thus that a particular control axis was always coupled to a particular psychomotor DOF. But since the mechanics of the translational axes of the handcontroller were similar (i.e., motion range and elastic stiffness), no performance differences were expected from this.

Experimental design

Two performance measures were calculated: trial completion time (in seconds), and percentage of trial time needed to correct the first 10% of the initial distance error, calculated for each visual dimension. This 10%-point was chosen because we wanted to focus on the initial control actions of the participants. Where necessary, the percentage of trial time was obtained by linear interpolation between the sampled time point when the corrected error was more than 10% for the first time and the previously sampled point in time. The results were analysed with an analysis of variance (ANOVA) with mapping (2) as a between-subjects variable and display (3), initial distance (3) and session (2) as within-subjects variables. To compare the percentage of trial time between visual dimensions, the statistical design included dimension (3). Significant effects were further analysed by post-hoc Tukey tests. An α of .05 was used in all tests.

Procedure

Participants performed Experiment 1 during the morning. Upon arrival, they were randomly assigned to one of the control-display mapping conditions, and subsequently received written instructions about the positioning task and the specific control-display mapping. Next, they were familiarised with the task and experimental setting. They were allowed to move the cursor cube freely for one minute to get a feel for the control-display mapping. This was followed by six practice trials. Shortly after these practice trials, the experimental trials started. Each participant completed a total of six blocks: two sessions with the three different display types. The order of the display types was partially balanced over subjects. Each block consisted of the same 90 target-cursor pairs, with the order of these stimulus pairs randomised for each block. There was a break after each completed block of approximately 10 minutes. No feedback on task performance was given.

Results and discussion

The measure of completion time showed a main effect of initial distance [$F(2, 28) = 52.58$, $p < .01$], with faster completion times when the initial distance was smaller (means of 5.6, 5.2 and 4.9 s for initial distances of 6, 5, and 4 cubesizes, respectively). A main effect of session was also observed [$F(1, 14) = 61.80$, $p < .01$], showing faster completion times in the second session (5.7 and 4.8 s for the first and second session, respectively). No other significant main or interaction effects were found. Because only mapping was varied between subjects, the absence of any performance differences between the two mappings suggests that these mappings are equally compatible with existing population stereotypes for the control of multiple translational DOFs.

The results of the analysis of the percentage of trial time needed for initial 10% error correction are reported in Table 1. No main effects of mapping or display were found. The *significant* effect of initial distance showed that for the longest distance of 6 cubesizes, relatively less trial time was needed to correct the first 10% error than for the other two distances (means of 17.9%, 18.6% and 18.6% for initial distances of 6, 5 and 4 cubesizes, respectively). This difference may be caused by higher initial control speeds that can be obtained at longer trajectories, thereby reducing the relative amount of time needed to correct the initial part of the error, compared to smaller trajectories.

The significant main effect of dimension indicated that the horizontal dimension is generally corrected first, followed closely by the vertical dimension, and that the correction on the depth dimension is lagging behind considerably. This effect of dimension is apparent in Figure 3. The later error correction on the depth dimension is not surprising and can be ascribed to the degraded visual information for this dimension. However, given that the quality of the visual information in the display was the same for the horizontal and vertical dimensions (e.g., equal resolution and

background structure), the lag of the vertical dimension relative to the horizontal dimension points to an attentional priority for the horizontal dimension, as suggested by Zhai et al. (1997) to explain control differences between these two DOFs.

The significant interaction of dimension and initial distance is in accordance with the main effect of dimension: the post-hoc test of the interaction showed that all differences between the three visual dimensions were significant at each initial distance. The interaction only shows that the relative lag of the depth dimension is larger when the initial distance is larger (see Figure 3). This effect probably reflects that important cues for error on the depth dimension (e.g., relative size) are of higher quality when the cursor and target cubes are in closer proximity along the horizontal and vertical dimensions of the display. And with a decrease in initial distance, the two cubes achieve close proximity more quickly, thereby enhancing the error correction for the depth dimension, and subsequently reduce the lag in error correction for the depth dimension.

Attentional effects are hypothesised to diminish with increased proficiency in task execution. Exactly such a reduction was observed in the interaction between dimension and session, which is shown in Figure 4. This figure shows that the significant differences among all dimensions in the first session, as indicated by the post-hoc test, were reduced in the second session. In addition, the difference between the horizontal and vertical dimensions in the second session was no longer significant, suggesting comparable control performance for these two visual dimensions. These findings support the hypothesis that the observed control differences between the horizontal and vertical dimensions were the result of differences in attentional priority when attentional demands were relatively high.

Experiment 2

Method

Participants and tasks

The same 16 participants who took part in Experiment 1 in the morning completed Experiment 2 in the afternoon. They performed two 3-DOF tracking tasks: a standard pursuit tracking task followed by a modified pursuit tracking task. The cursor cube was operated with linear rate control. In both tasks, the instruction was to minimise the error between the cursor cube and the target cube. The main difference between the two tasks was that the external error displacement acted on the position of the target cube in the standard task and on the position of the cursor cube (i.e., the controlled element) in the modified task. Thus motion of the cursor cube in the modified task was the resultant of control input and external error displacement, whereas cursor cube motion in the standard task was the result of control input only. These two tracking tasks can be viewed as instances of common manipulation tasks: capturing a moving element in an environment with a remote manipulator, and keeping a manipulator in a fixed position despite external disturbances.

Stimuli, displays and instrumentation

For both tracking tasks a 150s disturbance trace was constructed, with more than 90% of the power below 0.5 Hz. The end and beginning of the trace connected smoothly, making it possible to use different starting points in the trace. The same trace was used for all three DOFs, but for each trial and for each DOF a different starting point on the disturbance trace was chosen. Participants were allowed to intercept the signal in the first 10 s of each trial, followed by 150 s of effective tracking. Since the duration of the total disturbance trace was only 150 s, the first 10 s of the trace was repeated at the end of the effective trial. In the standard tracking task, the disturbance trace was added to the position of the target cube, resulting in a moving target cube.

In the modified tracking task, the target cube remained stationary in the centre of the display and the disturbance trace was added to the position of the cursor cube. The displays and instrumentation in this experiment were the same as in Experiment 1.

Experimental design

For each trial, the Root Mean Square (RMS) of the tracking error was calculated for each control axis. The RMS error was calculated over the 150 s of effective tracking in a trial. The RMS error was analysed with an ANOVA with mapping (2) as a between-subjects variable and display (3), initial distance (3) and session (2) as within-subjects variables. The statistical design also included control axis (3) to compare the RMS error between the three control axes (note that the effect of visual dimension can be found in the interaction of mapping and axis). Significant effects were subjected to post-hoc Tukey tests with α set at .05.

Procedure

After completing Experiment 1 in the morning and taking a lunchbreak, the participants were introduced to the tracking experiment. Each participant was assigned to the same control-display mapping, and the same order of display conditions as in Experiment 1. Since the participants were already familiarised with the experimental setting, they were only additionally familiarised with each tracking task for one minute per display type. Each participant first completed six sessions of the standard pursuit tracking task, followed by six sessions of the modified pursuit tracking task. Each session consisted of three trials, with one trial in each display condition, resulting in 18 trials per tracking task. The order of the display types was partially balanced over subjects. There was a break of approximately 10 minutes after each completed session. Again, no feedback was given during the experiment.

Results and discussion

The ANOVA on RMS tracking error is summarised in Table 2. The ANOVA did not show a main effect of mapping. This is in agreement with the results of Experiment 1. Also, no significant main or interaction effects of tracking task were found.

The main effect of display showed an advantage of the visually enriched displays over the empty display (mean RMS error of 0.50, 0.51 and 0.54 cubesizes for the forward looking, downward looking and empty display, respectively). This is not surprising, since several studies have indicated that perception of object motion improves in the presence of static textured backgrounds (Bonnet, 1984; Blakemore & Snowden, 2000). The difference is small however, which may be explained by the fact that RMS error in the empty display is approximately 0.5 cubesize. This indicates that the cubes were in relative close proximity, and probably partially occluded each other for a considerable portion of a trial. This prolonged partial occlusion may have negated the absence of any static background texture to some degree.

The significant main effect of session showed a positive learning effect. This can be seen in Figure 5, which depicts the interaction between mapping, session and axis. However, this significant interaction indicated that learning effects were only present on the visual depth dimension. This finding is not completely in accordance with the results of Zhai et al., (1997), who found learning effects on all visual dimensions. In addition, they found differences in performance, especially in the first experimental phase, and in the learning curve for the vertical and depth dimensions compared to the horizontal dimension. However, the results of our experiment showed neither absolute performance differences nor different learning effects on the horizontal and vertical dimensions. Only the learning effect for the depth dimension was replicated. It should be noted that the participants in our study had more experience with the experimental equipment before the start of the tracking experiment than those in the Zhai et al.

(1997) study since, in our study, they also participated in the preceding positioning experiment. And the results of our first experiment showed that the initial differences between the horizontal and vertical dimensions were reduced, or even nullified, with experience (see Figure 4). Thus it is possible that this difference was no longer present at the start of the tracking experiments. Another point is that the participants in the Zhai study had to track all 6 DOFs simultaneously (i.e., three translational and three rotational DOFs), whereas the participants in the present study only had to track the three translational DOFs. It has been observed that with 6 DOF control, operators tend to allocate control within rotation and translation groups separately (Masliah & Milgram, 2000; see also Fracker & Wickens, 1989). This makes it plausible that the participants in the study of Zhai et al. (1997) may have had more difficulty dividing their attention among the different (groups of) DOFs, resulting in more asymmetrical control behaviour in the first stages of the experiment.

The main effect of axis showed the smallest tracking errors with the X-axis and larger tracking errors for the Y-axis and Z-axis (mean RMS error of 0.26, 0.61 and 0.68, respectively). More interesting, however, is the significant interaction between mapping and axis (see Figure 6, which depicts the tracking error as a function of control axis and visual dimension). On the basis of this interaction, effects of the visual and motor components of tracking performance can be estimated.

Concerning the visual component, Figure 6 shows that tracking errors along the depth dimension of the display are approximately 3.8 times larger than along the horizontal and vertical dimensions. This is in accordance with the results of Massimino et al. (1989), who found enlarged tracking errors up to a factor 5 on the depth dimension. Zhai et al. (1997), on the other hand, reported an increase of about 1.3, the same figure found by Korteling, Oving, Van Emmerik and Van Erp (1997) in a one-DOF tracking task. However, this increase in RMS error for the depth dimension in this latter study may be an underestimation of the increase compared to simultaneous tracking tasks, since participants did not have to divide their attention between DOFs. Zhai et al. (1997) ascribed the relatively low tracking error in their study to the use of binocular disparity and other visual enhancements for the depth dimension, such as perspective projection and semi-transparency. This implies that enhancement of the visual display can reduce differences in control performance between DOFs.

Concerning the psychomotor component, the tracking error obtained using the Z-axis was 1.1 times greater than that obtained using the Y-axis, regardless of the visual dimension it was coupled with. This indicates a small differential in the motor component of the response. Even though this difference is small, especially in comparison to the observed effect of the visual component, it is consistent. Given the observation that visual enhancements, such as those applied by Zhai et al. (1997), can reduce the relative tracking error for the depth dimension, the contribution of the motor component to any error may become relatively higher. This would make it a more important and relevant factor in manual control tasks with three translational DOFs. The motor component should thus be taken into consideration in the design of handcontrollers with multiple DOFs. Therefore, it would be interesting to study the effect of the motor component for other DOFs, such as the X-axis and rotational axes, in a similar manner as done in the present experiment.

Conclusions

The results of both experiments show that spatial-motion mapping and reference-plane mapping are equally compatible with the visual-motor skills of the participants for tasks with three translational DOFs. This suggests that both mappings may be implemented in multiple DOF control tasks.

Regarding control of multiple DOFs, three factors were identified that may contribute to asymmetries in performance among the different DOFs: differences in the perceptual information, in information processing, or in psychomotor capabilities. From the two experiments reported here, we conclude that all three factors play a role in asymmetrical control performance. The poorer quality of the visual information for the depth dimension clearly affects control performance for that dimension in both experiments, and may be the largest contributor to asymmetrical performance. In the positioning task, the initial error in the depth dimension is consistently corrected subsequent to the initial error in the other visual dimensions, and the error in the tracking tasks is about 3.8 times larger in the depth dimension than in both the other dimensions. Providing more powerful depth cues may reduce this effect of visual quality (Kim et al., 1991; Gallimore & Brown, 1993; Hendrix & Barfield, 1995; Zhai et al., 1997).

We also observed effects of information processing on control performance in the two experiments. For instance, the error on the horizontal dimension was systematically corrected sooner than the error on the vertical dimension, although the difference was small. In addition, experience reduced the lags in correcting initial error. Since the quality of the visual information was the same for these two dimensions, these findings suggest an effect of attentional priority, in which relative more attention is paid to the horizontal dimension than to the vertical dimension in the initial phases of multiple DOF control. However, it should also be noted that Korteling et al. (1997) observed learning effects on the horizontal and vertical dimensions comparable to those found by Zhai et al. (1997), that is, more improvement on the vertical dimension than on the horizontal dimension between the first two phases. However, that study involved a one-DOF tracking task, which suggests that attentional priority may not be the only explanation for control differences between the horizontal and vertical dimensions in the initial phases of control tasks. In Experiment 2, we observed that the tracking performance in the depth dimensions improved during the course of the experiment, while this was not the case for the other two dimensions. Apparently, tracking in the horizontal and vertical dimension became more automatic, thereby leaving more attentional resources available for tracking in the depth dimension. This probably reflects a limited attentional capacity of the human operator, instead of a change in attentional priority between visual dimensions. As mentioned before, attentional priority effects may be best studied by analysing control input within a trial, as opposed to learning effects for control input over trials.

The results also showed effects of the psychomotor system on task performance. With the employed control device, tracking errors for the Z-axis were about 10% larger than the tracking errors for the Y-axis (i.e., fore-aft axis), regardless of the specific coupling with a visual dimension. Apparently, it is more difficult to accurately generate control inputs along the up-down axis, which can be ascribed to characteristics of the specific motor system that is used to generate these control inputs in combination with the mechanics of the handcontroller for the particular set-up studied. Consideration of the motor component in the design of multiple DOF systems is therefore recommended.

Taken together, these experiments showed that the use of multiple control-display mappings can be an effective way to investigate the relative contribution of the perceptual, cognitive and motor components to control performance with multiple DOFs. This is of relevance to the design of (tele-operation) systems that include multiple DOF handcontrollers.

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Table 1.
Summarised Results of the ANOVA on the Percentage of Trial Time Needed for Initial 10% Error Correction in the Positioning Task.

Source	df	F	p
Between subjects			
Mapping	1, 14	0.01	0.910
Within subjects			
Display	2, 28	2.03	0.150
Session	1, 14	0.93	0.352
Initial distance	2, 28	10.29	<0.001
Dimension	2, 28	14.31	<0.001
Session × Dimension	2, 28	3.36	0.049
Initial distance × Dimension	4, 56	7.52	<0.001

Note: Non-significant interactions and higher order interactions were omitted.

Table 2.
Summarised Results of the ANOVA on the RMS Tracking Error in the Tracking Experiments.

Source	df	F	p
Between subjects			
Mapping	1, 14	0.04	0.849
Within subjects			
Tracking task	1, 14	0.57	0.463
Display	2,28	5.29	0.011
Session	5, 70	7.50	<0.001
Axis	2, 28	8.30	0.001
Mapping × Axis	2, 28	22.41	<0.001
Mapping × Session × Axis	10, 140	4.58	<0.001

Note: Non-significant interactions were omitted.

Figure Captions

Figure 1. The two mapping principles and the nomenclature used in this paper for the control and display DOFs. The direction and striping of the arrows identify the specific coupling of the display dimensions and control axes for each mapping principle. The remarks between parentheses indicate the control axis (for display) or display dimension (for handcontroller) to which that particular DOF is coupled.

Figure 2. A schematic drawing of the three displays used in the present experiments, from top to bottom: 'no environment'; 'forward looking'; and 'downward looking'.

Figure 3. Mean percentage of trial time needed for initial 10% error correction as a function of initial distance and visual dimension, averaged over participants.

Figure 4. Mean percentage of trial time needed for initial 10% error correction as a function of session and visual dimension, averaged over participants.

Figure 5. Mean RMS tracking error (in cubesizes) as a function of mapping, session and control axis, averaged over participants.

Figure 6. Mean RMS tracking error (in cubesizes) as a function of visual dimension and control axis, averaged over participants. The interaction of mapping and control axis is also present in this figure: the letters in the bars indicate the specific mapping involved (S = Spatial-motion mapping; R = Reference-plane mapping).

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