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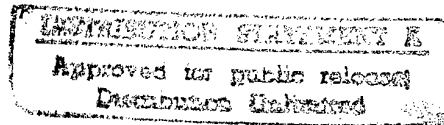
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title
**Control-Display mapping in a
3D positioning task**

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27 November 1996



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Wanneer de specifieke koppeling tussen een besturingsmiddel (control) en een display overeenstemt met de verwachtingen van mensen ten aanzien van deze koppeling is er sprake van een compatibele relatie tussen dit besturingsmiddel en display. Ten opzichte van minder compatibele of zelfs incompatibele relaties, wordt er beter gepresteerd. Zo is er minder training nodig om een bepaald prestatie-niveau te bereiken, is de reactiesnelheid hoger, worden er minder fouten gemaakt en is de mentale belasting lager bij compatibele control-display relaties. Control-display (C-D) compatibiliteit is dus van grote invloed op de taakuitoefening.

Een bepaalde vorm van C-D compatibiliteit betreft bewegingscompatibiliteit, wat te maken heeft met de specifieke koppeling van een bewegingsrichting van het bedieningsmiddel aan bewegingsrichting in het display. Met betrekking tot bewegingscompatibiliteit is veel onderzoek verricht naar compatibiliteit tussen besturingsmiddelen en displays met één of twee vrijheidsgraden. De huidige studie richt zich op de compatibiliteit tussen besturingsmiddelen en displays met drie of meer vrijheidsgraden.

Om de effecten van bewegingscompatibiliteit tussen dergelijke 3D-besturingsmiddelen en displays te onderzoeken, werd een experiment verricht. Hierbij is alleen gekeken naar C-D compatibiliteit ten aanzien van translaties langs de x-, y- en z-as. Door middel van een positioneringstaak werden twee principes beschouwd waarop deze compatibiliteit gebaseerd kan zijn. Als eerste werd spatiële mapping onderscheiden, waarbij de richting van een beweging met het 3D-besturingsmiddel (ruimtelijk gezien) altijd gelijk was aan de richting van de beweging in het perspectivische display. Een translatoire beweging met het 3D-bedieningsmiddel van de bestuurder af bijvoorbeeld, resulteerde ook in het display altijd in een translatie van de bestuurder af. Als tweede principe werd referentievlak mapping gedefinieerd. Hierbij werd het vlak waar het 3D-besturingsmiddel in was geplaatst (het tafelblad), gebruikt als referentie voor bewegingen in het beeldschermvlak van het display. Zo resulteerde een translatoire beweging met het besturingsmiddel van de bestuurder af, in een opwaartse beweging van de stimulus in het display, wanneer het schermvlak in een hoek van 90° stond ten opzichte van het besturingsmiddelvlak. Met spatiële mapping zou, in deze situatie, ook de stimulus zich van de bestuurder af hebben bewogen (in de diepte-dimensie van het display) in plaats van opwaarts. Een 2×2 tussen subjects factorieel design werd gebruikt om de aan- en afwezigheid van beide vormen van control-display mapping te evalueren. Uit de resultaten van het experiment kwam steeds een hoofdeffect van referentievlak mapping naar voren, terwijl er geen hoofdeffect van spatiële mapping of een interactie tussen beide werd gevonden. Hierbij werd de experimentele taak sneller uitgevoerd en werd er minder afstand afgelegd in de positioneringstaak wanneer er sprake was van referentievlak mapping. Daarnaast werd er eerder een constant (en beter) prestatie-niveau bereikt bij de referentievlak mapping. Deze resultaten geven aan dat bewegingscompatibiliteit tussen besturingsmiddelen en displays met drie of meer vrijheidsgraden hoofdzakelijk bepaald wordt door de bewegingsrichting van stimulus en respons ten opzichte van een vlak in plaats van de 3D-ruimte als zodanig (volume). De bewegingen ten opzichte van een bepaald vlak met een 3D-besturingsmiddel worden als het ware geprojecteerd op een vlak in het display.

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SUMMARY

Subjects have certain expectations about the mapping of motion directions of the control device on those of the controlled object on the accompanying display. When the actual mapping is according to this expectation, the relation is compatible. Compared to less compatible or even incompatible relations, less training is required, reaction times are faster, less errors are made, and mental workload is lower in compatible control-display relations.

Concerning this mapping of motions of device and controlled object (motion compatibility), a lot of research is conducted on configurations with only one or two degrees of freedom, in contrast with devices and displays with three or more degrees of freedom.

Motion compatibility in 3D may be based on two different principles: spatial-motion mapping, and reference-plane mapping. In the first principle, motions of the device in space are always parallel to the motions of the object in the display. In the second, the plane of the device was used as reference plane for the display, and projected on the display as such. The present experiment investigates the effects of presence and absence of both mapping principles in a 3D positioning task.

The results showed a positive main effect of reference-plane mapping, while no main effect of spatial-motion mapping, nor an interaction between both was found. The experimental task was executed faster and more efficient, and the task was learned faster in the reference-plane mapping conditions. These results indicate that that motion compatibility between control and display with three degrees of freedom is mainly determined by motions in relation to (different) planes, and not to the 3D space as such. Motions in relation to the plane of the device are projected onto the plane of the display.

Control-Display compatibiliteit in een 3D positioneringstaak

J.B.F. van Erp, A. Oving en J.E. Korteling

SAMENVATTING

Mensen hebben een bepaalde verwachting over de koppeling van de bewegingsrichting van een besturingsmiddel (control) en van het object op een bijbehorend display. Wanneer een specifieke koppeling overeenstemt met deze verwachting is er sprake van een compatibele relatie. Ten opzichte van minder compatibele of incompatibele relaties, is er minder training nodig, is de reactiesnelheid hoger, worden er minder fouten gemaakt en is de mentale belasting lager. Control-display (C-D) compatibiliteit is dus van grote invloed op de taakuitoefening.

Met betrekking tot bewegingscompatibiliteit is veel onderzoek verricht bij besturingsmiddelen en displays met één of twee vrijheidsgraden, in tegenstelling tot onderzoek naar besturingsmiddelen en displays met drie of meer vrijheidsgraden.

Koppeling van bewegingsrichting van control en bestuurd object kan op basis van twee verschillende principes: spatiële mapping, en referentievlak mapping. Bij het eerste principe zijn bewegingen met het 3D-besturingsmiddel ruimtelijk gezien altijd gelijk aan de bewegingen van het object in het display, bij het tweede principe werd het vlak waar het 3D-besturingsmiddel in was geplaatst (het tafelblad), gebruikt als referentie voor bewegingen in het beeldschermvlak van het display. Het effect van aan- en afwezigheid van beide mapping principes werd onderzocht in een positioneringstaak.

Uit de resultaten van het experiment kwam alleen een positief hoofdeffect van referentievlak mapping naar voren, terwijl er geen hoofdeffect van spatiële mapping of een interactie tussen beide principes werd gevonden. Hierbij werd de experimentele taak sneller uitgevoerd en werd er minder afstand afgelegd, en werd er eerder een constant (en beter) prestatieniveau bereikt in de referentievlak mapping situaties. Deze resultaten geven aan dat bewegingscompatibiliteit tussen besturingsmiddelen en displays met drie of meer vrijheidsgraden hoofdzakelijk bepaald wordt door de bewegingsrichting van stimulus en respons ten opzichte van een vlak in plaats van de 3D-ruimte als zodanig (volume). De bewegingen ten opzichte van een bepaald vlak met een 3D-besturingsmiddel worden hierbij geprojecteerd op een vlak in het display.

1 INTRODUCTION

1.1 Control-display compatibility

Control-Display compatibility (or Stimulus-Response compatibility) plays an important role in perceptual motor tasks. Central issue is the specific relation between characteristics of the control device (i.e. enabled moves, or location of the device), and the characteristics of the display. A compatible relation is defined as the similarity between the true relation, and the expected relation, or population stereotype. A population stereotype is the C-D relation as expected by a specific proportion of the population, the strength of the population stereotype is enlarged as this proportion becomes larger (Fitts & Seeger, 1953; Kornblum, Hasbroucq & Osman, 1990).

With a compatible relation, performance will be better than with a less compatible, or even incompatible, relation. This is expressed in decreasing reaction times, decreasing number of errors, and faster learning (i.e. Duncan, 1977; Beringer & Worringham, 1992; Fitts & Deininger, 1954; Fitts & Seeger, 1953; Miller, 1985; Wayman, 1993). Furthermore, with incompatible relations, performance is more sensitive to increased workload (Loveless, 1962; Andre & Wickens, 1992; Wayman, 1993). This may eventually lead to operators applying the expected relation between control and display.

Concerning C-D compatibility, one can distinguish between spatial and motion compatibility (Sanders & McCormick, 1992; Wickens, 1992). Both principles will be discussed in the next Sections.

1.2 Spatial and motion compatibility in 2D

Spatial compatibility

Spatial compatibility concerns static elements of the C-D compatibility, including location. Spatial compatibility can be acquired by the principle of co-location (Wickens, 1992), resulting in locating the control device as close as possible to the display. An example of co-location is a touch screen, in which location of display and control are identical. Applying the principle of co-location is not always possible, for instant because of lack of space. However, realizing spatial compatibility is also possible by congruence between a group of displays and a group of controls: pattern of responses is equal to the pattern of stimuli, although both groups are physical separated. Fitts and Seeger (1953) already showed that tasks are executed faster, and with less errors.

Motion compatibility

Motion compatibility concerns the (direction of) motions of the control device, and the (direction of) motions of the controlled object on the display (Kornblum, Hasbroucq & Osman, 1990).

Concerning linear controls and displays in 2D, a compatible mapping means that motions of stimulus and response are parallel (Fitts & Deininger, 1954; Loveless, 1962; Andre & Wickens, 1992; Simon, 1969). However, applying this principle is not always possible, or

does not always lead to a preferred relation. For example, position of both display and control in relation to the human operator act on compatibility. Beringer and Worringham (1992) investigated three kinds of compatibility, in which the position of the operator was varied in relation to control and display. First factor was defined as muscle synergy, in which wrist extension resulted in a leftward motion of the object (see Fig. 1a, in which the thumb is pointed downwards). In Fig. 1a, extension of the wrist makes the object move rightward, although the control moves leftward. Second factor was defined as compatibility on the basis of the virtual visual field. Motions of the object in the visual field are motions of the control when looked at (see Fig. 1b). Third factor was defined as geographical C-D compatibility, in which motions of the control resulted in a parallel motion of the object, despite position and orientation of the operator (see Fig. 1c). Research showed that compatibility on the basis of the virtual visual field is the only factor (positively) influencing performance. Beringer and Worringham (1992) called this the “self-reference effect”, in which operators base relations between control and display on the view from their own position.

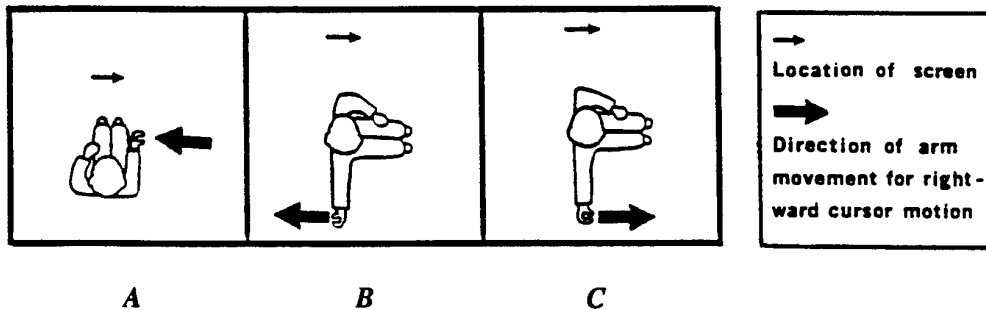


Fig. 1 Three principles of compatibility, as defined by Beringer and Worringham (1992).

When control and display differ in orientation, it is not always possible to make all motions of control and display parallel. Spragg, Finck and Smith (1959) used two different C-D relations for two different orientations between joystick and display, in which the display was always oriented in the vertical plane in front of the operator. The joystick could be positioned in the vertical or horizontal plane (because of reasons of comfort, the joystick was not exactly positioned vertical (Spragg, Finck & Smith, 1959). Fig. 2 shows a schematic representation.

Best performance was reached when control and display were in the same plane, and direction of response was equal to the direction of the stimulus (Fig. 2a). When joystick and display were not positioned in the same plane, performance was slightly (but not significant) better in the forward-up configuration (Fig. 2d), than in the forward-down configuration (Fig. 2c). However, in a more recent study, the forward-up configuration did score significantly better (Wayman, 1993). When control and display are orientated different, a direct mapping of the control plane with the display plane leads to better performance. A possible explanation for this is the advantage of less mental rotation for this configuration, which may also lead to less mental effort.

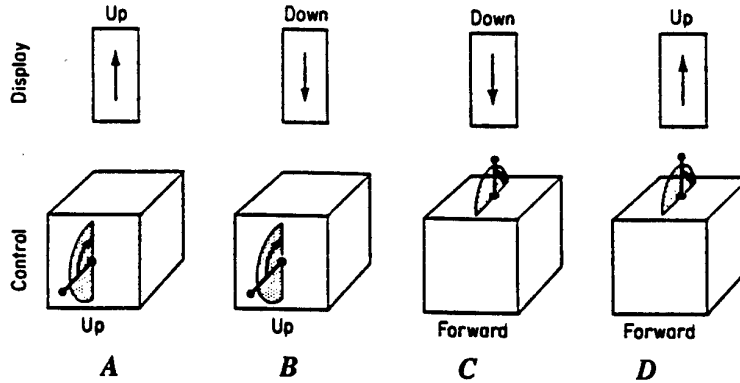


Fig. 2 Four control display configurations used by Spragg, Finck and Smith (source: Sanders & McCormick, 1992, Figure 10-7).

1.3 Motion compatibility in 3D

Control devices in existent man-machine systems often have only one or two degrees of freedom, like volume knobs on radios, or handles of a bulldozer. A degree of freedom, in this instance, is a translation along the x, y, or z axis, or a rotation around one of them. By integrating the required degrees of freedom in one control device (and accompanying display), task performance may be improved. The control order of the DOF's must be the same (i.e. Chernikoff & Lemay, 1963; Fracker & Wickens, 1989). A control device in which three or more DOF's are integrated may be advantageous in tasks in which objects with three or more DOF's must be controlled. Tasks in which these 3D control devices can be used are for example the control of unmanned platforms and robot-arms, and remote medical surgery.

The field of motion compatibility between 3D control devices and (2D) displays knows little research. Question is whether the results of experiments on 2D tasks may be applied to 3D tasks. For example, in 3D tasks, it is always possible to implement a configuration in which all motions are parallel, despite the orientation of both control and display. Moving the control forward results in a forward motion on the display (motion away from the operator), and moving the control upward results in a upward motion of the object on the display. This configuration is in conformance with the principle of motion compatibility, and is analogous to the principle of geographical compatibility in Beringer & Worringham's research (1992), and condition A in the research of Spragg, Finck and Smith (1959).

A second possibility for C-D mapping is the use of the plane in which the control is located and the plane in which the display is located. If both planes have the same orientation, motions of control and display are parallel. If both planes do not have the same orientation (for example control device in a horizontal plane, and monitor in a vertical plane), one can use the optimal configuration in the 2D configuration (Fig. 2d), and add the third dimension. A forward motion of the device results in an upward motion on the display, a downward motion of the device results in a object motion into the depth.

Concerning motion mapping between 3D control device and 2D display, one can distinguish the above mentioned mapping principles. In the first, the plane of the control device is used as reference for the plane of the display. We call this *reference-plane mapping*. The second is on the basis of geographical compatibility: motions of control device and target are always parallel. We call this *spatial-motion mapping*. If both planes have the same orientation, both principles result in the same mapping, when both planes do not have the same orientation, this will lead to different mappings.

The present experiment investigates which of both principles is most determinative for motion compatibility. Subjects had to position an object (cursor) in 3D space at a target location. In a full factorial between subjects design, above mentioned mapping principles were varied, leading to four groups. When both principles are present or absent, control device and display are located in the same plane, see Fig. 3.

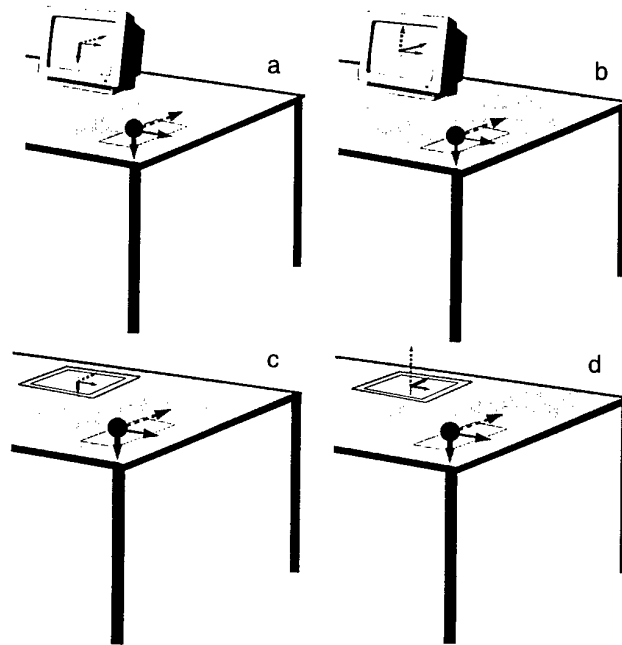


Fig. 3 The four C-D configurations used in the present experiment. a: spatial-motion mapping; b: reference-plane mapping; c: spatial-motion and reference-plane mapping present; d: spatial-motion and reference-plane mapping absent.

2 METHODS

2.1 Subjects

40 subjects participated: 20 male, and 20 female (mean age 22.8, sd 3.7 years). All subjects were right-handed, and had normal or corrected-to-normal vision. None of the subjects reported a colour deficiency. Subjects were paid for their participation.

Because of possible differences in ability on spatial tasks between males and females (Anastasi, 1958; Gleitman, 1991), both sexes were balanced across four C-D configurations. Furthermore, subjects were allocated on the basis of their score on the WAIS substitution subtask, seeing to a well-balanced distribution of scores (Salthouse, 1985).

2.2 Experimental task, stimuli, and instrumentation

Experimental task

The experimental task used was a positioning task (only translations), in which subjects were instructed to move a cursor as fast as possible to a target position, using a so-called 3D mouse. A 3D mouse is a control device, with which a cursor is controlled in three dimensions at the same time.

Both the controlled object and the stationary target were squares of the same size, the cursor was coloured red, the target white. Two depth cues were available: relative size and interposition [closest square would cover (part of) the other square].

Stimuli

For each trial, different initial positions for cursor and target were generated by choosing an arbitrary point on a sphere as initial position for the target. The point of reference of the display was chosen as centre of the sphere, initial position of the cursor was found by projecting the position of the target through this centre. Radius of the sphere was varied, leading to initial distances between target and cursor of 28.0, 23.8, and 19.6 cm.

Additional restriction for generating initial positions of target and cursor was the minimum distance of 4.0 cm between coordinates on each axis. This leads to a minimum required control action on all axis, and prevents interposition in the initial position. Furthermore, taken over all trials, the total distance to travel was equal in every dimension. Finally, to balance the direction of the required motion on each axis, initial positions of target and cursor were switched, and added to the list of trials.

For each initial radial distance, 30 stimuli pairs were generated, leading to a total of 90 initial positions. These 90 trials were order balanced for every block and subject.

Instrumentation

Two 14" LIJN/RC (18A) SVGA colour monitors (maximum refresh rate 60 Hz) were used to display the positioning task. A LIJN 80486-66 PC was used for image generation. The control device was connected to a second LIJN 80486-66 PC, which was connected to the image generator. This PC registered stimulus data, and mouse input, and stored the data. A third LIJN 80486-33 PC was used as clock; update and sample frequency of the total system was set at 20 Hz. The area of the screen was 25 cm (H) \times 19 cm (V). Vertical viewing angle was 60° to acquire a stronger perspective, which may lead to better detection of motions in the depth dimension. This was reached by placing the centre of projection 16.45 cm from

the screen (McGreevy & Ellis, 1986). Distance between point of projection and point of reference was 16.45 cm as well. The point of reference was used as origin of the coordinate system. Size of both the target and cursor was 2×2 cm. Margins around the target were set by a sphere around the centre of the target with radius 0.75 cm.

As control device in the experiment, a commercial 6 degree of freedom space mouse[®] was used (see Appendix I). This device consists of a flat knob, mounted on a stationary platform. By subjecting force/torsion on the knob, one moves the object. This also results in small postponement of the knob in relation to the platform: 1.5 mm for translations, 4° for rotations. The knob of the spacemouse is spring-centred. Because of the availability of proprioceptive feedback, with such a elastic control, one performs better than with an isometric device (Zhai & Milgram, 1993; Zhai, 1993). Force/motion relation is 3N/mm for translations. The cursor was controlled with linear speed control (first order), maximum speed (in 3D) was 6 cm/s. In each of the conditions, the mouse was located 5 cm from the right side of the monitor.

2.3 Statistical design

Dependent variables

During the experiment, x, y, and z coordinates of the controlled cursor were recorded (20 Hz sampling frequency). From this raw data, two dependent performance measures were extracted: total positioning time per trial, and total distance travelled. This last variable is a measure for task efficiency (see Van Erp, Kappé & Korteling, 1996). Scores per subject were based on the mean of 30 replicas per initial distance and block. Correct positioning was defined as keeping the cursor for .5 s within an area around the target. If a subject could not complete a trial within 60 s, the trial was interrupted, and the next started. In this case, 60 s was taken as score.

Independent variables

As mentioned in the Introduction, one can distinguish two principles on which motion mapping between a 3D control device and a 2D display can be based: *spatial-motion mapping*, and *reference-plane mapping*. A factorial combination of both principles leads to four C-D configurations. In all four configurations, the control device was located in the horizontal plane, the display either in the horizontal or vertical plane (see Fig. 3). To ensure a good view on the display, and because of reasons of comfort, the horizontal plane used to place the monitor in was actually installed under an angle of 15° . When the display was under an angle of 90° with the control device, the horizontal plane was exactly horizontal. To avoid reflections, the experiment was run with dimmed, indirect light.

It may be expected that with compatible relations, tasks are acquired faster (Fitts & Seeger, 1953; Wayman, 1993). To test this, every subject completed four blocks of 90 trials. This repetition was introduced as factor in the analysis of variance.

Because of the possible asymmetrical training effects between different C-D configurations, the four C-D configurations were varied in a between subjects design (Knight, 1987; Poulton, 1974). Initial distance between cursor and target (three levels), and block (four levels) were varied within subjects.

Results were analyzed by a 2 (spatial-motion mapping) \times 2 (reference-plane mapping) \times 4 (block) \times 3 (initial distance) ANOVA. The analysis of variance was conducted with the statistical package SPSS/PC + (4.0), all post-hoc test (Tukey's HSD, $p \leq .05$) were executed with the statistical package STATISTICA (5.0).

2.4 Procedures

Subjects came in pairs: one could rest, while the other participated in the experiment. The experiment consisted of four blocks of the same 90 experimental trials. Order of the trials was randomized, time between two consecutive trials was 1.5 s (screen was turned black). After arrival, subjects received instructions for the WAIS substitution task (see Appendix II). After the instructions, subjects executed the task, and were assigned to a group on basis of age, sex, and test results.

Before the first block, subjects received a written explanation of the positioning task, the control device, and the aims of the experiment (see Appendix III). Consecutively, every subject was able to try the control device for one minute with a white (cursor) square. Directly afterwards, 6 training trials were presented, two trials for every initial distance. During the experiment, no training was given.

3 RESULTS

This Chapter presents the results for the two dependent variables separately (complete results are presented in Appendix IV). Section 3.1 presents the results on mean positioning time, Section 3.2 on mean distance travelled. Before analysis, distribution of both dependent variables was examined with a Kolmogorov-Smirnov goodness of fit test ($p \leq .05$). Both distributions did not deviate from the expected normal distribution.

3.1 Mean positioning time

Control-Display mapping

The main effect of reference-plane mapping was significant for the mean positioning time [$F(1,36)=30.81$, $p < .001$]. Means indicated that subjects needed less time in the conditions in which the plane of the control device could be mapped on the plane of the display (present: 5.2 s, absent: 7.8 s). The main effect of spatial-motion mapping did not show a significant effect, neither did the interaction with reference-plane mapping.

Block

The within subjects factor block showed a significant effect on mean positioning time [$F(3,108)=95.84$, $p<.001$]. Means per level revealed that subjects needed less time in consecutive blocks. A post-hoc test showed that the difference between block three and block four is not significant, which indicated that subjects reached asymptote.

Block showed a significant interaction with reference-plane mapping [$F(3,108)=32.40$, $p<.001$]. Fig. 4 shows that the positive effect of reference-plane mapping became smaller during the experiment. The positive effect was significant for the first three blocks, and almost reached significance in the last block ($p=.058$). Concerning the effect of block in relation to reference-plane mapping absent versus present, the post-hoc test showed that the absent group reached asymptote between the third and fourth block, and the present group reached asymptote between the first and second block.

The interaction of block with spatial-motion mapping is also significant [$F(3,108)=4.06$, $p<.01$], see Fig. 4. The post-hoc test showed that a positive effect of spatial-motion mapping was only present in the first block. Concerning the effect of block, the post-hoc test indicated that with spatial-motion mapping absent reaching asymptote took a little longer (significant difference between the first block and all others, and between the second and the third), than in the conditions with spatial-motion mapping present (only a significant difference between the first block and all others).

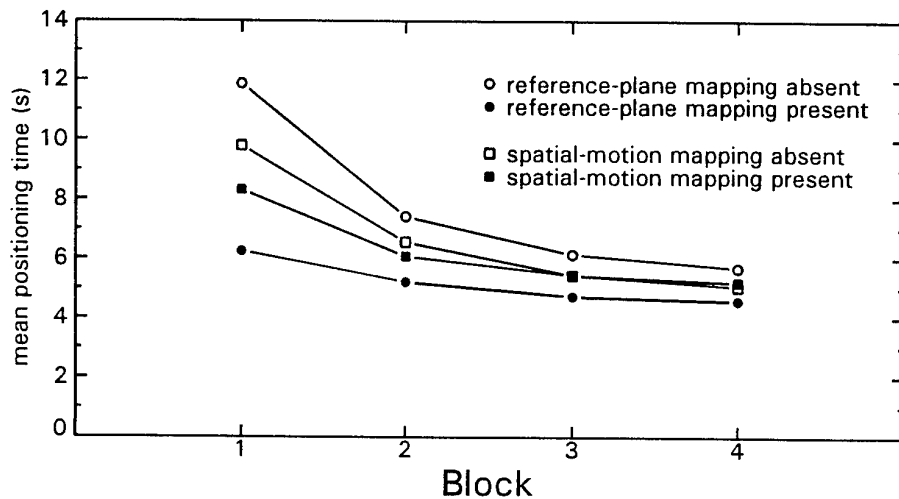


Fig. 4 Interaction of reference-plane mapping and spatial-motion mapping with block on the mean positioning time.

Initial distance

The main effect of initial distance was significant on mean positioning time [$F(2,72)=151.96$, $p<.001$]. The post-hoc test showed significant differences between all three conditions. As expected, a smaller initial distance resulted in a smaller mean positioning time.

The interaction initial distance \times reference-plane mapping was significant [$F(2,72)=3.55$, $p < .05$], and showed a larger positive effect of reference-plane mapping with larger initial distances. The interaction initial distance \times block was significant as well [$F(6,216)=6.48$, $p < .001$]. The post-hoc test only revealed the pattern of a positive learning effect in the first three blocks, and reaching asymptote between the third and fourth block for all three initial distances.

A post-hoc Tukey test on the third order interaction reference-plane mapping \times block \times initial distance [$F(6,216)=3.60$, $p < .01$] showed that with reference-plane mapping present better scores are present in every block and initial distance, but that this positive effect is relatively large with inexperienced subjects and large initial distances.

3.2 Mean distance travelled

Control - Display mapping

Again, only reference-plane mapping showed a significant main effect on the mean distance travelled [$F(1,36)=23.07$, $p < .001$]. Means showed that subjects controlled their target more efficiently in the conditions with reference-plane mapping present (present: 25.6 cm, absent: 18.6 cm). There was no main effect of spatial-motion mapping, and there was no significant interaction between both mapping principles.

Block

Block showed a main effect on distance travelled [$F(3,108)=37.69$, $p < .001$], which showed that subjects became more efficient during the experiment. Significant effects were present between the first and all other blocks, and between the second and fourth block, which indicated that subjects reached asymptote after the first three blocks.

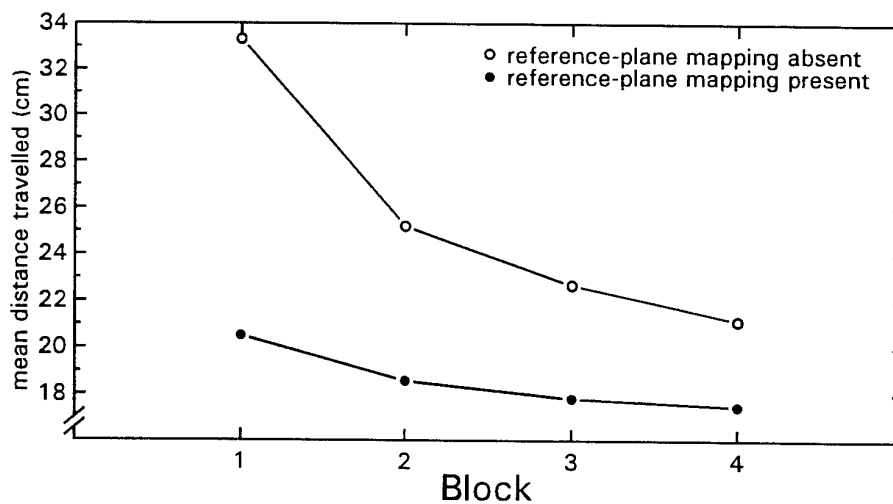


Fig. 5 Interaction of reference-plane-compatibility and block on mean distance travelled.

The interaction between reference-plane mapping and block was significant [$F(3,108) = 13.52, p < .001$], see Fig. 5. The post-hoc test showed that the positive effect of reference-plane mapping was present in all four blocks. Concerning the learning effects within conditions, the post-hoc Tukey test revealed that a learning effect was only present with reference-plane mapping absent (difference between the first and all other blocks, and between the second and the fourth block). In the conditions with reference-plane mapping present, there was no difference between the blocks. This indicated that with reference-plane mapping present, subjects immediately reached a high and stable performance level compared to the conditions without reference-plane mapping, and that this effect was still present after subjects reached asymptote.

The interaction spatial-motion mapping \times block was not present for the variable mean distance travelled. This interaction was present for the variable mean positioning time, which indicates that this effect was caused by the speed of the cursor, not by the distance travelled.

Initial distance

Initial distance showed a main effect on mean distance travelled [$F(2,72) = 277.60, p < .001$]. As expected, less distance was travelled when the initial distance between cursor and target was smaller. Initial distance \times reference-plane mapping was significant as well [$F(2,72) = 4.72, p < .05$], showing a positive effect of reference-plane mapping on all initial distances, which is largest with the largest initial distance.

The interaction between initial distance and block [$F(6,216) = 6.09, p < .001$] revealed that subjects reached asymptote in the fourth block for all initial distances. Finally, the three way interaction reference-plane mapping \times block \times initial distance was significant [$F(6,216) = 4.70, p < .001$]. The post-hoc Tukey test showed that with reference-plane mapping present, subject performed better in every block and for every initial distance, and that subjects sooner reached asymptote (only significant difference between first and fourth block with reference-plane mapping present, significant difference between the first three blocks with reference-plane mapping absent). This means that with reference-plane mapping present, subjects reached higher performance levels, and that they reached them sooner. Finally, the three way interaction showed that differences in performance on the different initial distances was larger in the first block, which is analogue to the results on mean positioning time.

4 DISCUSSION

The present study was carried out to investigate the possible mappings between 3D control devices and (2D) visual displays. For this mapping, two different Control-Display (C-D) mapping principles are distinguishable: *spatial-motion mapping*, and *reference-plane mapping*. The first refers to a mapping in which control device and controlled object motions are parallel in space (Fitts & Deininger, 1954; Loveless, 1962; Andre & Wickens, 1992; Simon, 1969). The second refers to a mapping in which the plane of the control device is used as frame of reference, and as such mapped on the plane of the display. Only

when control and display are in parallel planes, both principles lead to the same C-D mapping.

The experiment tests both mapping principles in a 3D positioning task. Both principles are varied between subjects in a full factorial design. Experimental task was to position an object or cursor as fast as possible at a target location in 3D space. As control device, a space mouse with 3 integrated translational DOF was used. Depth cues in the visual display were relative size and (partial) occlusion. Dependent variables analyzed were mean positioning time, and mean distance travelled.

The results showed a significant positive main effect of reference-plane mapping, and significant interactions with all other factors, both on mean positioning time, and mean distance travelled. Spatial-motion mapping, however, did not show any main effect, and only one interaction with block.

Compatibility of a C-D mapping is reflected in better performance and faster learning. Both indications were only manifested with reference-plane mapping present. This points out that reference-plane mapping is the compatible C-D mapping in the present experiment. Despite the fact that learning effects in the reference-plane mapping absent conditions were stronger, the difference was still present after reaching asymptote. One can conclude that motion compatibility between a 3D control device and a 2D display is predominantly based on the mapping of the planes of control device and display.

A possible explanation for the advantage of reference-plane mapping may be found in the claim that subjects use a *spatial reference frame* to determine the orientation of objects and themselves in space (Logan, 1995). This frame is a simple description of the 3D space, on the basis of which (relative) distances and orientations can be determined. This reference frame is important to coordinate motions as well. Concerning the present study, one can state that in reference-plane-compatible conditions, an external, visible frame of reference is present which supported subjects by coordinating control motions. In conditions without this external reference frame, subjects had to create an internal reference frame, compatible with the mapping between control and display. In this situations, external visual support is weak or absent, and constructing an internal reference frame will be time consuming and therefore enlarge workload, leading to slower learning and lower performance levels.

A possible explanation for the decreasing difference between reference-plane-compatible and incompatible conditions is the shift from closed-loop to open-loop control as a result of increasing experience. Control behaviour becomes less dependent on feedback, and relies more on an internal motor program (i.e. Zhai & Milgram, 1993). A more efficient motor program leads to more efficient control in the reference-plane-incompatible conditions as well. Therefore, the importance of an external reference frame throughout the blocks decreases, but not dissipates.

In the present experiment, in the reference-plane mapping conditions, only mapping on the display plane was possible. We did not include the possibility of mapping the control plane on a plane which was depicted in the display, because no environmental cues were provided. However, in a study of Buiel and Breedveld (1995) after optimal C-D mapping, a plane was provided which was parallel to the display. Best performance was found with a mapping according to the reference-plane mapping. Angle between display (including the depicted

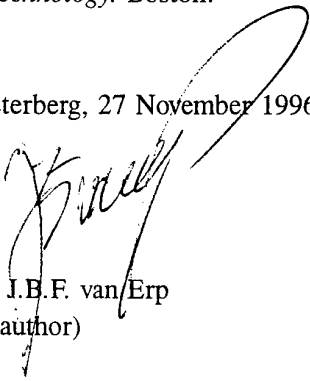
plane) and control plane was 90° (control moving forward resulted in an upward motion of the cursor on the display, which is corresponding the condition “reference-plane mapping present/spatial-motion mapping absent”) One of the reasons subjects mentioned in favour of this configuration is the fact that the depicted plane appeared to be downward oriented, which imposed a looking down sensation. The plane was experienced as a ground plane on which a specific task had to be executed. The way in which the orientation of the environment of a perspective display is interpreted has important consequences for the optimal mapping of control and display (i.e. Ellis, Tyler, Kim & Stark, 1991). It is recommended to conduct research on this phenomenon.

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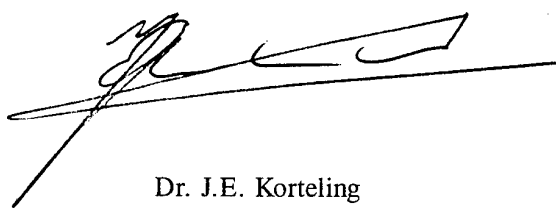
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Soesterberg, 27 November 1996



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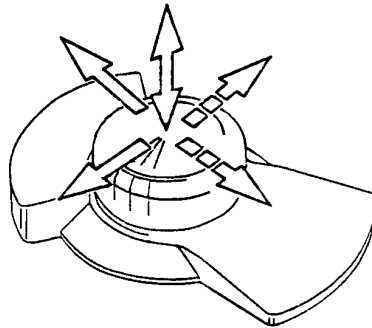


Dr. J.E. Korteling
(project manager)

APPENDIX I Technical specifications SPACE MOUSE®

Measuring system	optical
Size (L×B×H)	165 mm, 112 mm, 40 mm
Weight	670 g
Stiffness	3 N/mm
Translation range	±1,5 mm
Rotation range	±4°
Diameter knob	65 mm
Weight knob	25 g
Connector	9 pins (female) D-Sub connector (IBM PC serial slot connector)
Power supply	RS232 handshake lines RTS en DTR (6,5 V, 9 mA)
RS232 interface	2D mode only 1200 BAUD transmission, Logitech M+ protocol, 3D mode receiving and sending 9600 BAUD, 8 databits, 2 stopbits
Cyclus tijd	60 ms (shortest interval between 2 consecutive data packets), 17 data- packets per seconde (fastest data transmission time).

Source: Space Mouse® User's Manual.



APPENDIX II WAIS substitution task: Instructions (in Dutch)

Om de snelheid van informatieverwerking van de proefpersonen te bepalen, werd een subtaak van de Nederlandse versie van de WAIS afgenomen. Dit betrof de zogenaamde substitutietaak waarbij bepaalde symbolen corresponderen met getallen. De bedoeling van deze taak was om binnen 90 s zoveel mogelijk symbolen in corresponderende getallen om te zetten. Het aantal correct omgezette symbolen gold hierbij als score. Hieronder staat de instructie behorende bij deze taak weergegeven, en is een voorbeeld van het test- of scoreformulier te vinden.

Hieronder ziet u in de bovenste helft een teken staan en een cijfer in de onderste helft. Onder elk teken staat een ander cijfer. Ze horen op deze manier bij elkaar. Daarbeneden ziet u dat de bovenste hokjes tekens hebben, maar de onderste hebben geen cijfers. U moet nu in elk van die hokjes het cijfer zetten dat bij het teken hoort. Bij het eerste teken (↓) moet u dus het cijfer 2 invullen en bij het volgende teken (=) zet u een 1. Bij het daarop volgende voorbeeld (⇒) hoort het cijfer 3. Als u dit begrepen heeft kunt u de voorbeelden afmaken.

VOORBEELD

↓	↓	⇒	L	U	O	Λ	X	=
1	2	3	4	5	6	7	8	9

↓	=	⇒	Λ	↓	L	X	=	U	L
2	1	3							

Op de volgende bladzijde staat hetzelfde voorbeeld en een aantal lege hokjes die op dezelfde manier moeten worden ingevuld. Pas als de proefleider zegt dat u kunt beginnen slaat u deze bladzijde om en vult u zoveel hokjes in als u kunt, zonder er een over te slaan.

APPENDIX III Instructions (in Dutch)

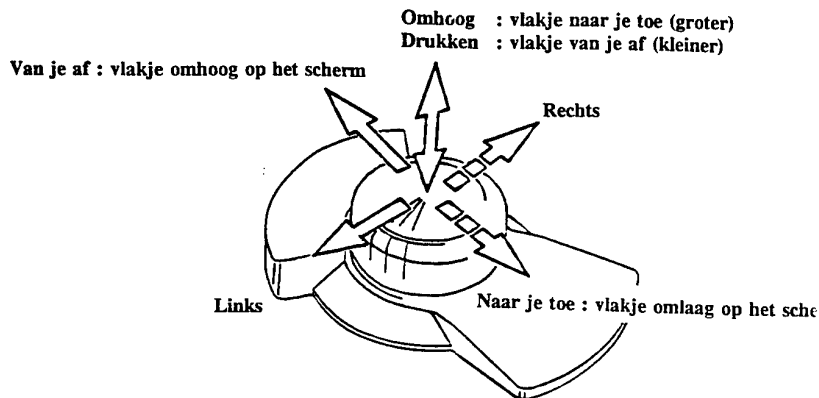
Conditions I and III

In dit experiment is het de bedoeling dat je zo *snel mogelijk* met een muis een vlakje op een beeldscherm bestuurt.

Er verschijnen twee gekleurde vlakken op het beeldscherm: een rood en een wit vlakje. Het witte vlak kun je besturen met de muis, het rode vlak blijft stilstaan. Bedoeling van de taak is dat je het witte vlak zo snel en zo dicht mogelijk naar het rode vlak stuurt.

Hierbij kun je in de links-rechts en omhoog-omlaag richting van het scherm bewegen. Daarnaast kun je ook in de diepte-richting bewegen. Welk vlakje van de twee verder van je af ligt (meer in de diepte), kun je zien doordat dit vlak dan kleiner is. Daarnaast kan het vlak dat dichterbij ligt (dus groter is), het andere vlak geheel of gedeeltelijk afdekken, waardoor dit laatste vlak maar gedeeltelijk of helemaal niet is te zien.

Wanneer je de knop van de muis naar links beweegt, beweegt ook het witte vlak naar links en beweeg je de knop naar rechts dan gaat ook het vlak naar rechts. Om het vlak in de diepte te sturen (kleiner te maken) druk je de knop naar beneden. Om het vlak naar je toe te halen (groter te maken) trek je de knop omhoog. Om het vlak omhoog te sturen op het scherm, beweeg je de knop naar voren (van je af). En om het vlak omlaag te bewegen op het scherm, beweeg je de knop naar je toe.



Op het scherm zie je nu de volgende boodschap staan: "Wacht op start !Niet aan muis komen!". Zodra de test gestart wordt, verdwijnt dit bericht en komt er "Start over 2 seconden" op het scherm te staan. Je kunt nu je hand bij de knop leggen. Na deze 2 seconden verschijnen dan de twee vlakken en begint de test.

Om te wennen aan de muis, krijg je eerst alleen een wit vlakje te zien. Je kunt nu de verschillende bewegingen een minuut lang even uitproberen. Direct daarna krijg je 6 oefeningen, waarbij je het witte vlak dus naar het rode vlak moet sturen. Vervolgens gaat dan de test beginnen.

De bedoeling is: het witte vlak zo *snel* en zo goed mogelijk naar het rode vlak sturen!!

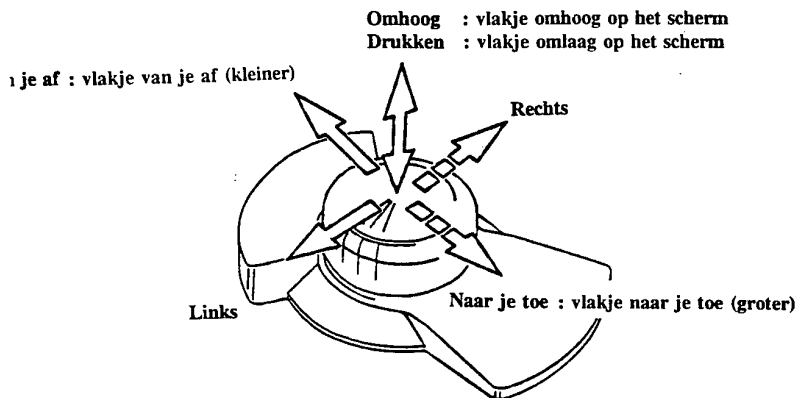
Conditions II and IV

In dit experiment is het de bedoeling dat je zo *snel mogelijk* met een muis een vlakje op een beeldscherm bestuurt.

Er verschijnen twee gekleurde vlakken op het beeldscherm: een rood en een wit vlakje. Het witte vlak kun je besturen met de muis, het rode vlak blijft stilstaan. Bedoeling van de taak is dat je het witte vlak zo snel en zo dicht mogelijk naar het rode vlak stuurt.

Hierbij kun je in de links-rechts en omhoog-omlaag richting van het scherm bewegen. Daarnaast kun je ook in de diepte-richting bewegen. Welk vlakje van de twee verder van je af ligt (meer in de diepte), kun je zien doordat dit vlak dan kleiner is. Daarnaast kan het vlak dat dichterbij ligt (dus groter is), het andere vlak geheel of gedeeltelijk afdekken, waardoor dit laatste vlak maar gedeeltelijk of helemaal niet is te zien.

Wanneer je de knop van de muis naar links beweegt, beweegt ook het witte vlak naar links en beweeg je de knop naar rechts dan gaat ook het vlak naar rechts. Om het vlak in de diepte te sturen (kleiner te maken) beweeg je de knop naar voren (van je af). Om het vlak naar je toe te halen (groter te maken) beweeg je de knop naar je toe. Om het vlak omhoog te bewegen op het scherm, trek je de knop omhoog. En om het vlak omlaag te bewegen op het scherm, druk je de knop naar beneden.



Op het scherm zie je nu de volgende boodschap staan: "Wacht op start !Niet aan muis komen!". Zodra de test gestart wordt, verdwijnt dit bericht en komt er "Start over 2 seconden" op het scherm te staan. Je kunt nu je hand bij de knop leggen. Na deze 2 seconden verschijnen dan de twee vlakken en begint de test.

Om te wennen aan de muis, krijg je eerst alleen een wit vlakje te zien. Je kunt nu de verschillende bewegingen een minuut lang even uitproberen. Direct daarna krijg je 6 oefeningen, waarbij je het witte vlak dus naar het rode vlak moet sturen. Vervolgens gaat dan de test beginnen.

De bedoeling is: het witte vlak zo *snel* en zo goed mogelijk naar het rode vlak sturen!!

APPENDIX IV Complete statistical results

Dependent variable: time

effect	DFeffect	MSeffect	DFerror	MSerror	F	p-level
1 reference-plane	1	806.7	36	26.2	30.81	.000
2 spatial-motion	1	24.8	36	26.2	0.95	.337
3 initial distance	2	92.8	72	0.61	151.96	.000
4 block	3	384.1	108	4.01	95.84	.000
1 × 2	1	62.3	36	26.2	2.38	.132
1 × 3	2	2.17	72	0.61	3.55	.034
1 × 4	3	129.9	108	4.01	32.40	.000
2 × 3	2	1.28	72	0.61	2.10	.130
2 × 4	3	16.3	108	4.01	4.06	.009
3 × 4	6	3.53	216	0.54	6.48	.000
1 × 2 × 3	2	1.66	72	0.61	2.71	.073
1 × 2 × 4	3	7.55	108	4.01	1.88	.137
1 × 3 × 4	6	1.96	216	0.54	3.60	.002
2 × 3 × 4	6	0.58	216	0.54	1.07	.380
1 × 2 × 3 × 4	6	0.61	216	0.54	1.12	.349

Dependent variable: distance travelled

effect	DFeffect	MSeffect	DFerror	MSerror	F	p-level
1 reference-plane	1	5874.6	36	254.7	23.07	.000
2 spatial-motion	1	37.2	36	254.7	0.15	.705
3 initial distance	2	1914.2	72	6.90	277.60	.000
4 block	3	1379.6	108	36.6	37.69	.000
1 × 2	1	564.1	36	254.7	2.21	.145
1 × 3	2	32.5	72	6.90	4.71	.012
1 × 4	3	494.9	108	36.6	13.52	.000
2 × 3	2	10.2	72	6.90	1.48	.234
2 × 4	3	39.9	108	36.6	1.09	.356
3 × 4	6	24.4	216	4.00	6.09	.000
1 × 2 × 3	2	15.0	72	6.90	2.17	.121
1 × 2 × 4	3	14.9	108	36.6	0.41	.748
1 × 3 × 4	6	18.8	216	4.00	4.70	.000
2 × 3 × 4	6	5.40	216	4.00	1.35	.236
1 × 2 × 3 × 4	6	5.82	216	4.00	4.00	.195

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11. AUTHOR(S) J.B.F. van Erp, A. Oving and J.E. Korteling		
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14. SUPPLEMENTARY NOTES		
15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE) Subjects have certain expectations about the mapping of motion directions of the control device on those of the controlled object on the accompanying display. When the actual mapping is according to this expectation, the relation is compatible. Compared to less compatible or even incompatible relations, less training is required, reaction times are faster, less errors are made, and mental workload is lower in compatible control-display relations. Concerning this mapping of motions of device and controlled object (motion compatibility), a lot of research is conducted on configurations with only one or two degrees of freedom, in contrast with devices and displays with three or more degrees of freedom. Motion compatibility in 3D may be based on two different principles: spatial-motion mapping, and reference-plane mapping. In the first principle, motions of the device in space are always parallel to the motions of the object in the display. In the second, the plane of the device was used as reference plane for the display, and projected on the display as such. The present experiment investigates the effects of presence and absence of both mapping principles in a 3D positioning task. The results showed a positive main effect of reference-plane mapping, while no main effect of spatial-motion mapping, nor an interaction between both was found. The experimental task was executed faster and more efficient, and the task was learned faster in the reference-plane mapping conditions. These results indicate that that motion compatibility between control and display with three degrees of freedom is mainly determined by motions in relation to (different) planes, and not to the 3D space as such. Motions in relation to the plane of the device are projected onto the plane of the display.		
16. DESCRIPTORS Display Man-Computer Interface Man-Equipment Compatibility Mouse (device)		IDENTIFIERS
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