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Stroke-direction preferences in drawing and handwriting *

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Abstract

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The aim of the present study is to examine the contribution of two independent spatial reference sytems in the manipulation of writing instruments. One system relates to the anatomical structure of the arm and the hand (resulting in preferences for oblique, i.e., diagonal movement directions) while the other corresponds with a more abstract, geometrical system (resulting in a bias favouring orthogonal, i.e., vertical and horizontal movement directions). Three experiments are reported in which the independence of these two reference systems is explored in drawing tasks in which subjects produced small back-and-forth movements in a variety of directions. The outcome of the first experiment showed that stroke-direction variability is larger in horizontal than in other directions. In experiment 2 it was predicted that when subjects are forced to choose repeatedly among a set of 16 different directions, a change of *arm position* would affect the pattern of preferences for oblique directions more than the pattern of preferences for orthogonal directions. The data confirm this hypothesis. In experiment 3 we analysed the changes in stroke-direction preferences as a function of variations in the *type* and the *size* of the movements to be produced as well as the effects of *visual control* of the motor task on the subjects' choice of movement directions. This last experiment provides additional evidence for the view that geometrical and anatomical reference systems must be distinguished. Finally, a frame-by-frame analysis of video-recordings of hand and finger movements indicates that the two anatomical subsystems cooperate consistently and predictably during the production of different movement directions.

Experiments on the perception, recall and production of movement directions have shown that subjects make use of a variety of reference

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systems to relate spatial to behavioural dimensions (cf. Shea and Zimny 1988). Egocentric, geocentric and anatomical reference systems have been proposed in the context of this intriguing phenomenon. Early research approaches related to this issue were, e.g., the studies in space orientation by Witkin and Asch (1968) and the development of a neurogeometric theory of human motion by Smith (1961a, 1961b). More recently, Rieser and Pick (1976) demonstrated, with regard to the perception of directions, that the orientation of tactile stimuli is interpreted with reference to body axes whereas haptic orientations are interpreted in terms of geocentric directions. In a developmental context Flanders (1976) discussed the superiority of up–down discrimination as compared to left–right discrimination. With respect to the recall of movement directions, Stelmach and Larish (1980) showed that the accuracy of limb positioning depends on whether the target positions lie within or outside an egocentric area. The production of movement directions has been investigated mainly in the context of graphic production, i.e. in drawing and handwriting tasks. Goodnow and Levine (1973) investigated the differential preference of orientations in sequencing aspects of the drawing of geometrical figures by children. Van Sommers (1984) reported that the 11 o'clock to 5 o'clock axis acts as a kind of dividing line, on the basis of which several syntactic characteristics of drawing can be predicted (e.g., stroke directions in free-line drawing and directions of rotation in the production of triangles, rectangles and circles). It appears from this literature that it depends on whether perception, recognition, recall or production of directions is involved which directions are used as reference axes in the control and coordination of behaviour.

In models of handwriting production two anatomical main axes are strongly represented (Teulings et al. 1989). In order to describe the spatial and the kinematic aspects of handwriting movements in a sufficient and parsimonious manner, most models of cursive stroke production (cf. Maarse 1987) imply the coordination of movements along two axes, corresponding to isolated hand and to isolated finger movements, respectively.

Anatomical model of movement directions

A simplified anatomical description of movement directions is depicted in fig. 1. The right arm of a right-handed subject is fixed at an

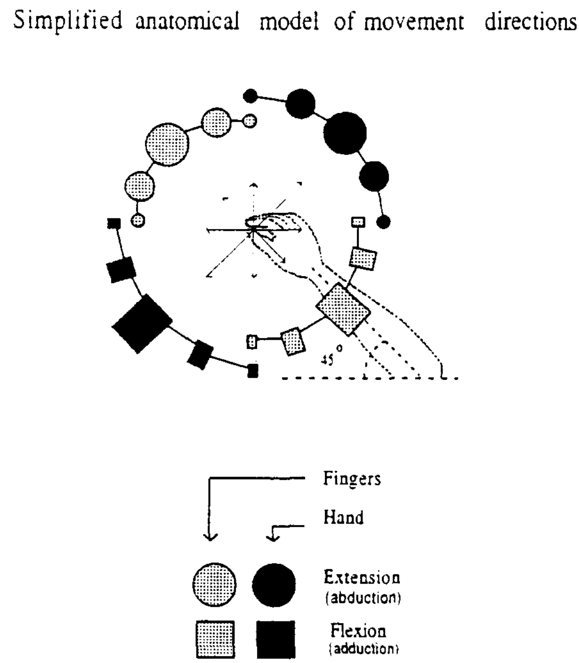

Fig. 1. Simplified model of the production of movement directions in drawing and handwriting. Black circles represent hand abduction, black rectangles hand adduction. Gray circles represent finger extension, gray rectangles finger flexion. The size of circles and rectangles reflects the degree of contribution of the involved system. Overlaps of two circles and two rectangles represent congruent coordination (in vertical directions) of hand and finger movements; overlaps of circles with rectangles represent incongruent coordination (in horizontal directions) of hand and finger movements. The length of the arrows extending from the centre indicates in Range Of Movement (ROM).

orientation of 45 degrees to the edge of the table. The maximum range of hand movements is larger than the maximum range of finger movements (Van Sommers 1984). In fig. 1 the latter is represented by the length of the arrows extending from the centre. Hand movements are needed to produce lines to the top-right and to the bottom-left. Finger movements are used to produce lines to the top-left and to the bottom-right. These diagonal (or oblique) lines thus require either hand or finger movements. Interposed directions, however, require the control of both hand and finger movements. Consequently, fewer degrees of freedom are involved in the oblique directions than in the interposed directions. Vertical directions are performed either by extending the hand and fingers (to the top) or by flexing both systems (to the bottom). Horizontal directions require either extension of the hand and flexion of the fingers (to the right) or flexion of the hand and extension of the fingers (to the left). We assume that the motor-control demands are lower for the vertical than for the horizontal directions because in the former direction, the hand and fingers are moving congruently, whereas they are moving incongruently in the latter direction (Van Sommers 1984). Elliot and Connolly (1984) refer to this distinction by using the terms simple versus complex synergies. In order to verify this anatomical description of the production of movement directions, we recorded a subject's hand and finger movements on video and conducted a frame-by-frame analysis to derive the displacement functions of the hand and finger movements separately. These data were obtained in the framework of experiment 1 below.

At the basis of our predictions regarding subjects' choices of movement directions lies the assumption that the oblique directions are strong candidates for *principle axes* from a motoric viewpoint (cf. Maarse 1987) whereas the orthogonal directions are strong candidates from a perceptual viewpoint (cf. Shea and Zimny 1988; and Just and Carpenter 1985). In order to explore the independence of these two categories of movement directions as well as possible mechanisms underlying subjects' choices of stroke directions, three experiments were conducted, involving rapid back-and-forth movements in a large number of directions. [1]

The constraints that were imposed on the subjects' choice of movement directions gradually declined in experiments 1, 2 and 3, respectively. In experiment 1 the subjects were not allowed to choose a movement direction, i.e., in each trial they had to move in an indicated direction. In experiment 2 the subjects had to choose among 16 different directions at the beginning of each trial. Finally, in experiment 3 the choice of movement direction was completely free to the subjects. Furthermore, by using the same simple drawing task in the three experiments we were able to study systematically patterns of stroke-direction preferences and factors influencing these patterns of stroke-direction preferences. We therefore not only varied the con-

[1] The order in which the experiments are reported in this article was not the order in which they were conducted. Experiment 3 actually preceded experiment 2. The present sequence, however, reflects a gradual and logic change of the constraints imposed on the subjects' choices of movement directions.

straints with respect to the directional choice but also the experimental conditions in which the choices had to be made. These conditions were either related to the assumed independence of the anatomical and geometrical reference systems which were supposed to underly the subjects' choice of movement directions (i.e., manipulations of arm position and visual control in experiments 2 and 3, respectively) or to aspects of the anatomical description of movement directions as indicated in fig. 1 (i.e., increased motor control demands in horizontal movement directions and movement size in experiments 1 and 3, respectively). Because the hypotheses of the different experiments can be formulated more clearly after having defined the task constraints and experimental manipulations, we will first describe the experiments and subsequently specify our predictions in detail.

Method

Designs and procedures

The designs of the three experiments are shown in fig. 2. Common to all experiments was the task. Subjects had to produce rapid back-and-forth movements within a small stimulus circle within a limited period of time. In experiment 1, ten subjects performed two series of 16 trials. In each trial, lasting eight seconds, a prescribed, i.e. *forced*, direction had to be produced. These directions are indicated in fig. 2 by the numbers 1 to 16. The order of the 16 directions was counterbalanced across the two series of trials (i.e., 1 to 16 in one series and the reverse order in the other series) and counterbalanced across subjects. Each direction had to be produced at a high speed and as accurately as possible. Subjects wrote with a normal ballpoint pen on a plastic transparency sheet. The lower arm was fixed in a cuff to ensure that it remained at an angle of 45 degrees to the edge of the writing table.

In experiment 2, ten other subjects had to choose repeatedly and as arbitrarily as possible, among a set of 16 directions, always starting at the centre of the circle and moving back-and-forth to one of the 16 indicated radials. There were no numbers alongside the radials in this experiment. In each trial, back-and-forth movements of about 0.7 cm (between the centre and the circumference of the circle) had to be produced rapidly and accurately in the same direction. Subjects were

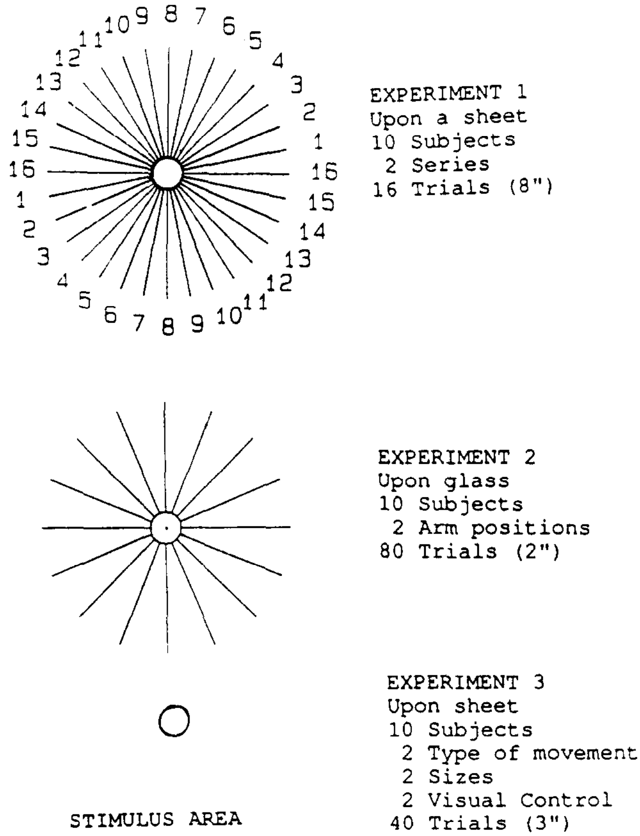

Fig. 2. Overview of the experimental designs of experiment 1, 2 and 3. Left-hand side: the stimulus material used in the three experiments. Right-hand side: indication of the experimental designs.

instructed to try to use all directions as often as possible without following a specific strategy. Between successive trials any systematic repetition, alternation or following the radials in a clockwise or counterclockwise fashion was to be avoided. Each subject performed two series of 80 trials, each trial lasting three seconds, the start and the end of the trial being indicated by the presentation of a high and a low tone, respectively. In one series of 80 trials the arm position was maintained at an angle of 30 degrees to the edge of the writing table, in the other series this angle was 60 degrees. Arm position was counterbalanced across subjects. In order to prevent the use of specific strategies, the task had to be performed on a rectangular piece of glass which was placed on top of the stimulus. Compared to the plastic transparency used in experiment 1, the piece of glass used in this experiment prevented, the subjects from being influenced by the grooves which appear on a plastic transparency as a result of a large number of back-and-forth movements. Furthermore, a ballpoint pen was used which left no traces of ink on the writing surface. This prevented the use of visual information which obviously could have influenced the subjects' choice of movement directions.

Experiment 3 was performed on a plastic transparency. A normal ballpoint pen was used which produced ink traces on the writing surface. Subjects were presented with a circle and had to produce rapid back-and-forth movements along a diameter of the circle. In each trial the orientation of the diameter had to be changed. No further constraints were placed upon the subject's choice of movement directions. Eight series of 40 trials were performed, each trial lasting four seconds. In four series, subjects had to produce pen jumps above the transparancy, in the other four, pen-down movements on the transparancy were required. When pen-jumps had to be produced, subjects had to position the pen-point somewhere on the circumference of the stimulus circle, subsequently lift the pen a few millimeters above the writing surface while moving towards the opposite position on the circumference of the circle. After touching this point with the end of the stylus, subjects had to return to the originally chosen position. By repeating this sequence they were actually *jumping* back-and-forth between two points on the circle.

In half the trials the circle had a diameter of 0.5 cm, in the other half a diameter of 1.5 cm. Finally, a third manipulation concerned the presence of visual feedback. In half the trials the subjects had to close their eyes whereas in the other half they were instructed to look at the penpoint. The three experimental variables (type of movement, size of movement and visual feedback) were presented in a fixed order of eight blocks of 40 trials. At the beginning of each trial, a high tone indicated to the subject that he or she was to select another movement direction. The four series in which the eyes had to be closed, the subjects were asked to do so before the first acoustic stimulus was presented. The experimenter visually controlled whether the subjects kept their eyes closed throughout these series. In all experiments the subjects were asked to maintain an upright head position. The latter was also checked visually by the experimenter.

Subjects

In each experiment ten different adult subjects volunteered as participants. All subjects were righthanded. This was verified by means of a 12-item questionnaire concerning hand preference on unimanual tasks such as throwing, drawing and writing, etc. (Annett 1967). Subjects were either paid for participation or they received credit corresponding to course requirements.

Hypotheses

We hypothesized that horizontal directions would be produced less accurately than vertical and oblique directions because the horizontal directions require a complex coordination of hand and finger movements (see fig. 1). This hypothesis (hypothesis 1) was tested in experiment 1. Since only *forced* movement directions had to be performed in this experiment, no further hypotheses regarding stroke-direction preferences were formulated here.

Furthermore, we predicted that the pattern of preferences for the oblique directions would change as a function of arm position (affecting the axes of the anatomical reference system) whereas this would not be the case for the orthogonal directions (the axes of the geometrical reference system). This hypothesis (hypothesis 2) was tested in experiment 2. It can be regarded as the main hypothesis of the experiments since it is directly related to the assumed independence of the two reference systems.

A different set of hypotheses was also formulated. Having to produce pen jumps just above the writing surface implies an increase of the degrees of freedom in movement as compared to the production of pen-down movements on the writing surface. In the former case movements have to be made in three dimensions and in the latter case only in two dimensions. With respect to the latter type of movements, our anatomical model of movement directions described that orthogonal directions involve movements with more degrees of freedom than oblique directions. We assumed that in producing pen jumps subjects would tend to keep the number of degrees of freedom low. The subjects would thus tend to select movements more in the oblique than in the orthogonal directions. This hypothesis (hypothesis 3) was tested in experiment 3. The size of the movements which had to be produced in this experiment varied between 0.5 and 1.5 cm. These values are rather large compared to the average stroke sizes used in cursive handwriting. The latter normally vary between 0.2 and 0.5 cm. We therefore hypothesized also that the larger movements in experiment 3 would be produced in those directions in which the Range Of Movement (ROM) of the anatomical subsystems involved is also relatively large, i.e., the directions corresponding to movements of the hand around the wrist (hypothesis 4; see fig. 1). Finally, we expected that in the absence of visual feedback a preference should emerge for diagonal rather than orthogonal directions (hypothesis 5). The opposite should be the case in the presence of visual control. At the basis of hypothesis 5 lies, again, the central assumption that the oblique directions are strong candidates for acting as main axes from a motoric viewpoint whereas the orthogonal directions are likely to serve as a perceptual reference system.

Data analysis

Pen-point movements were recorded by means of a digitizer (Calcomp 9240) with a sampling frequency of 100 Hz and a spatial accuracy of 0.1 mm. The data were stored on a VAX-11/750 computer. Subsequently, the *XY*-data were filtered with a high cut-off frequency of 12 Hz. Of each record, the filtered trajectory and the three corresponding velocity profiles were displayed for inspection (*X*, *Y* and tangential velocity). A sample of this procedure is displayed in fig. 3. A fixed number of strokes per record (twenty, ten and four in experiments 1, 2 and 3, respectively) was selected by means of a search procedure for successive minima in the tangential velocity function. The temporal and spatial accuracy of the analysis was increased by a quadratic interpolation of the time and speed values of the samples surrounding the selected minimum-velocity samples. Consequently, the angle, i.e., the orientation of each stroke relative to the digitizer (whose *X* axis remained parallel to the edge of the table throughout the experiments) could be determined with a precision of 1 degree. The frequencies at which the stroke directions occurred within each of the experiments, across and within experimental conditions were analyzed and plotted in polar frequency plots which clearly depict how often the

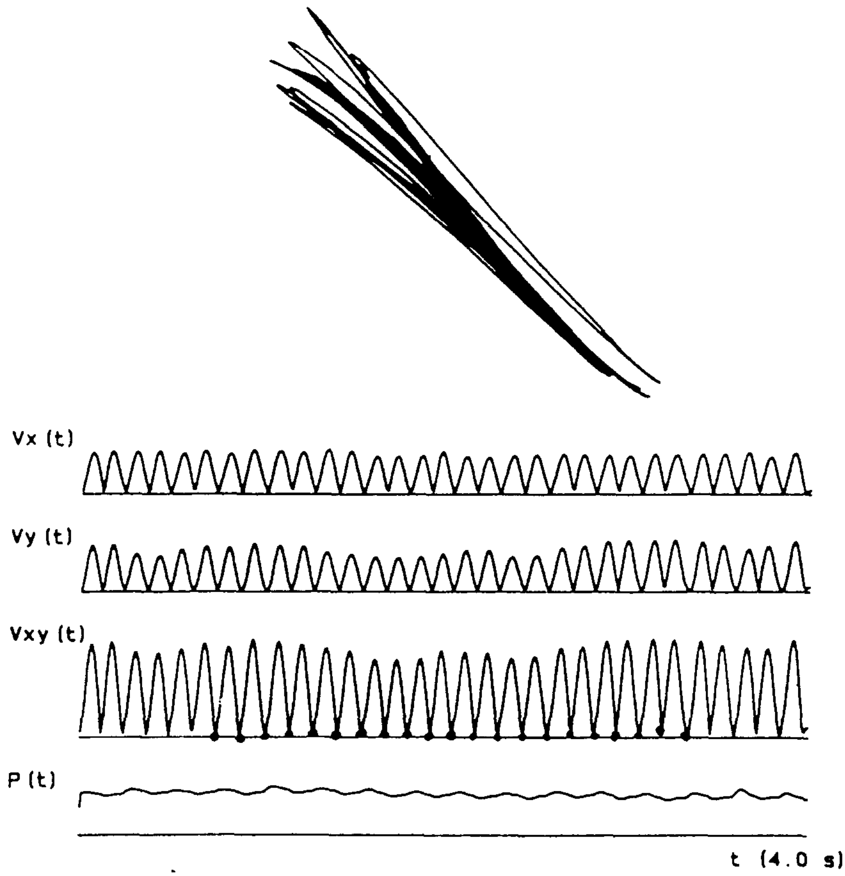

Fig. 3. A sample of the data-analysis procedure. The filtered XY-trajectory (cutt-off frequency of 12 Hz) and the corresponding velocity profiles, Vx, Vy and Vxy, as well as the axial pen pressure as a function of time (X-axis reflects 4 seconds) are depicted below the recorded pen-point movements.

subjects produced movements in each direction. Finally, of each selected stroke, the duration, the distance, and the pen-pressure variation were also calculated (Teulings and Maarse 1984). The means of these three dependent variables were displayed as a function of realized stroke directions. The latter polar plots were constructed for inspection and for comparisons with earlier results reported by Teulings et al. (1989). They were not analysed further, however, in the context of the present study, which is concerned with stroke-direction preferences.

Results

Fig. 4 depicts the overall results of experiment 1. The polar frequency plot shows that the subjects indeed tried to produce the prescribed 16 movement directions, i.e., a large number of lobes can be detected in this cumulative plot. Subjects succeeded more accurately in the vertical and oblique directions than in the horizontal directions, i.e., the lobes corresponding to the former directions are more distinct than the lobes corresponding to the latter directions. The mean stroke duration of the horizontal directions was longer than that of the vertical and oblique directions. Horizontal strokes tended to be smaller in size as well. These results are in agreement with the findings of Teulings et al. (1989). Pen pressure varied most in the top-left/bottom-right directions which, according to our anatomical description, corresponds to the direction of finger movements.

Whereas frequency and accuracy effects are confounded in the polar plots of fig. 4, fig. 5 reflects mainly accuracy effects. Fig. 5 depicts the 16 instructed stimulus directions (solid lines) together with the realized

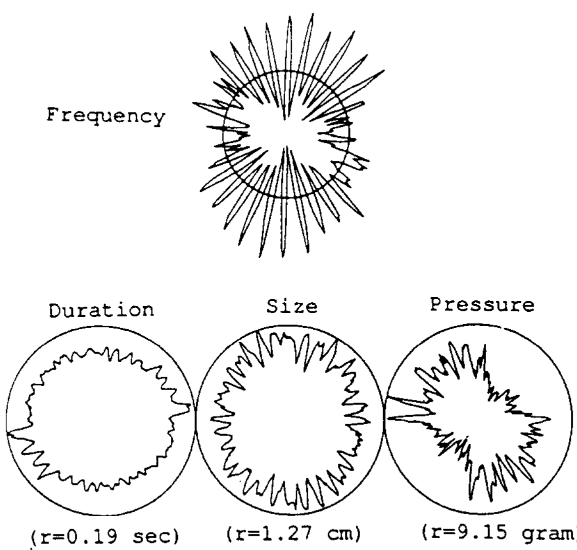

Fig. 4. Overall results of experiment 1. The polar frequency plot is depicted at the top (the circle reflects the expected frequencies if directions were chosen completely arbitrarily, i.e., 6,400 strokes/360 degrees). From left-to-right the polar plots of the mean stroke duration, stroke size and pen-pressure variation are depicted. The radii in these plots reflect the scaling in seconds, centimeters and grams, respectively.

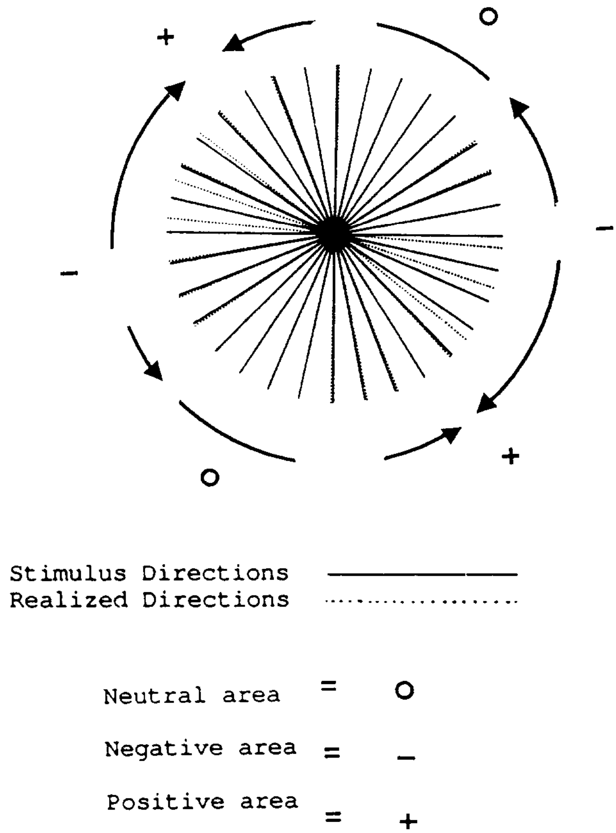

Fig. 5. A comparison of instructed stimulus directions (solid lines) and realized maximum-frequency directions (dotted lines) in experiment 1.

maximum-frequency directions (dotted lines). The latter directions were extracted from the frequency distribution after filtering this distribution with a rectangular filter of 6 degrees. This resulted, post hoc, in a reliable estimation of the maximum-frequency directions. Fig. 5 shows that, in general, the orientation of the maximum-frequency directions differed from the orientation of the instructed stimulus directions. A t-test on the absolute deviations confirmed the significance of this effect ($t = 3.72$; $p < 0.01$). Furthermore, the pattern of the deviations is strikingly similar to the findings reported by Van Sommers (1984: 12) with respect to the accuracy with which subjects copy straight lines of varying orientations. Van Sommers showed that sub-

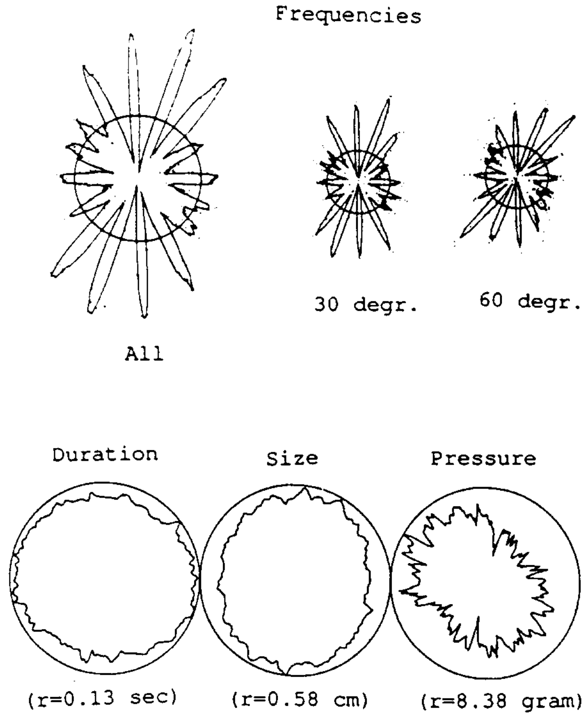

Fig. 6. Results of experiment 2. The overall polar frequency plot is depicted at the top on the left-hand side (total number of strokes amounting to 16000). At the right-hand side of this plot, the polar frequency plots of realized stroke directions in the 30-degree and 60-degree arm position are depicted (total number of strokes amounting to 8.000 strokes in each plot). Circles reflect expected frequencies if directions were chosen completely arbitrarily. At the bottom the polar plots of the mean stroke duration, stroke size and pen-pressure variation are depicted. The radii in these plots reflect the scaling in seconds, centimeters and grams, respectively.

jects have a tendency to rotate stroke directions towards a *positive area* (the 11 o'clock to 5 o'clock axis) and away from a *negative area* (almost orthogonally placed upon the former and therefore horizontal in orientation). An equally comparable result concerns the directions of the movements which were most accurate, viz., those in the bottom-left/top-right directions, the *neutral area* (indicated by the zero).

The top part of fig. 6 depicts the overall polar frequency plot of experiment 2 (left) and the polar plots of the 30-degree (middle) and 60-degree (right) arm-position conditions, separately. The results show that subjects succeeded in producing the 16 prescribed movement directions, i.e., 16 lobes in the polar frequency plot can be detected. As was the case in fig. 4, the polar plots of fig. 6 depict cumulative distributions reflecting not only frequency effects but also accuracy effects. In order to test our main hypothesis we analyzed these effects separately. With respect to frequencies it appeared that the number of strokes within each of the 12 lobes corresponding to the directions stemming from the anatomical reference system in the 30-degree arm-position condition correlated positively with these frequencies observed in the 60-degree arm-position condition ($Rxy = 0.89$; $p < 0.01$). Between the two arm-position conditions, the frequencies of the four directions stemming from the geometrical reference system, however, did not correlate significantly ($Rxy = 0.20$; $p > 0.10$). Further statistics

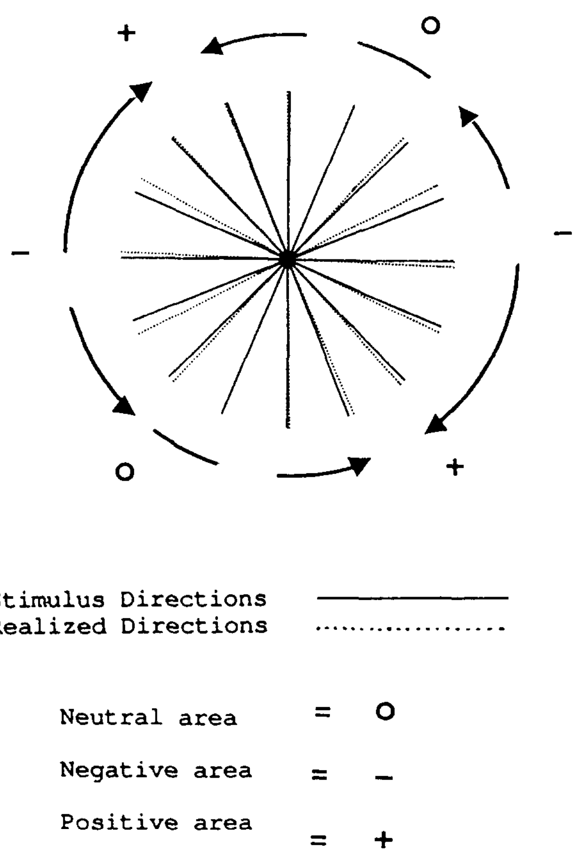

Fig. 7. A comparison of instructed stimulus directions (solid lines) and realized maximum-frequency directions (dotted lines) in experiment 2.

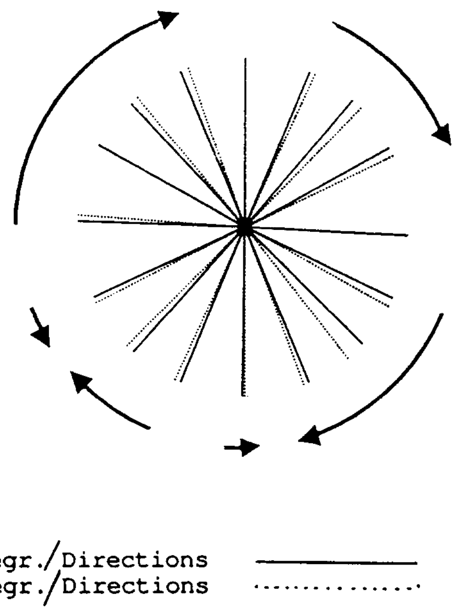

Fig. 8. A comparison of realized maximum-frequency directions in the 30-degree arm position condition (solid lines) and the realized maximum-frequency directions in the 60-degree arm-poisition condition (dotted lines) in experiment 2.

revealed no significant frequency effects as a function of arm position. A different picture emerged from the analysis of accuracy effects. Fig. 7 depicts the results with respect to the maximum-frequency orientations as compared to the 16 different stimulus directions among which subjects had to choose. The same pattern of results as described in experiment 1, depicted in fig. 5, appeared. The maximum-frequency directions deviated significantly from the instructed stimulus directions ($t = 4.81$; $p < 0.01$). Furthermore, when taking into account the direction of rotation of these deviations, it appeared that they tended to correlate positively with the deviations observed in experiment 1 ($n = 16$; $Rxy = 0.52$; $p < 0.05$).

Fig. 8 depicts the maximum-frequency directions in the 30-degree (solid lines) and in the 60-degree (dotted lines) arm-position conditions, separately. Wilcoxon tests confirmed our main hypothesis. When arm position changed from 30 to 60 degrees the oblique maximum-frequency directions significantly rotated 6.95 degrees clockwise in eleven cases and 1.50 degrees counterclockwise in one case ($n = 12$; $z = -2.94$;

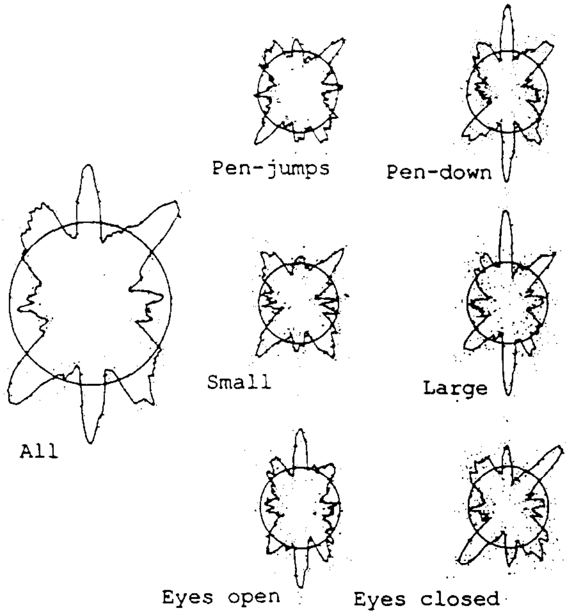

Fig. 9. Results of experiment 3. The overall polar frequency plot is depicted at the left-hand side (total number of strokes amounting to 12.800). The eight polar frequency plots on the right-hand side reflect the frequency distributions as a function of stroke orientation of pen-ups (top-left graph) versus pen-downs (top-right graph), small movements (middle-left graph) versus large movements (middle-right graph) and of the eyes-open condition (bottom-left graph) and eyes-closed condition (bottom-right graph). Circles reflect expected frequencies if directions were chosen completely arbitrarily.

$p < 0.01$). The orthogonal maximum-frequency directions, however, did not significantly rotate as a result of a change in arm position ($n = 4$; $z = -0.45$; $p > 0.10$). A change of arm position affected the accuracy with which directions stemming from the anatomical reference system were performed but did not affect the accuracy with which the directions originating from the geometrical reference system were performed. To summarize, the results of experiment 2 show that although arm position did not affect the pattern of preferences for stroke directions, it did influence the accuracy with which the frequently selected oblique stroke directions were produced.

In experiment 3 (fig. 9) subjects predominantly selected vertical, horizontal and diagonal movement directions having widths of about 30, 40 and 56 degrees, respectively. Since no stimulus directions were indicated in this experiment, it was likely that the experimental manipulations affected the pattern of preferences for stroke directions more clearly as compared to the first two experiments. By means of chi-square tests we compared observed and expected frequencies within the segments of the polar frequency distributions representing the preferences for oblique and orthogonal directions. When pen jumps had to be made, the subjects favoured the oblique directions above the orthogonal directions ($\chi^2 = 27.26$; $p > 0.01$). This was not the case when pen-down movements were made ($\chi^2 = 0.61$; $p > 0.10$). The small stimulus circle elicited more oblique than orthogonal directions ($\chi^2 = 102.92$; $p < 0.01$) whereas this was not the case with the large stimulus circle ($\chi^2 = 2.14$; $p > 0.10$). The same result appeared as a function of visual control. In the absence of visual control the oblique directions were preferred to the orthogonal directions ($\chi^2 = 79.38$; $p < 0.01$). This difference was not found in the presence of visual control ($\chi^2 = 1.86$; $p > 0.10$).

Let us briefly summarize the results with respect to the hypotheses. The results of experiment 1 confirmed our first hypothesis. Vertical and oblique directions were performed more accurately than horizontal directions. Hypothesis 2, our main hypothesis with respect to the independence of the geometrical and anatomical reference systems, was only partially confirmed in experiment 2. The predicted differential effects of variations in arm position on the subjects' patterns of preference for stroke directions were clearly present in the accuracy data but absent in the frequency data. The frequency effects found in experiment 3 were almost completely in agreement with our last three predictions. Having to produce pen-jumps resulted in a preference for oblique directions (hypothesis 3) and the absence of visual control over task performance elicited a preference for oblique movement directions as well (hypothesis 5). The instruction to produce relatively large movements, however, induced a bias favouring vertical directions. Hypothesis 4, therefore, was not confirmed because it was predicted that large movements would be produced mainly in the top-right bottom-left directions (corresponding to movements of the hand).

Finally, the verification of our anatomical model of the production of stroke directions by means of video recordings is depicted in fig. 10 in which of each of the 16 trials in experiment 1 the individual displacement functions of hand and finger movements of one subject are depicted. The Pearson-product-moment correlation between each pair of displacement functions is printed on the right-hand side of each

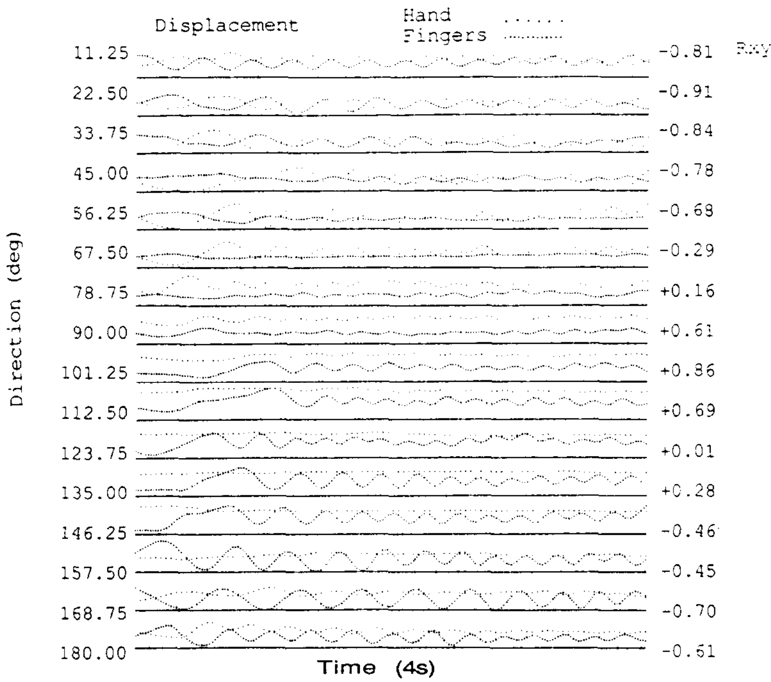

Fig. 10. Thirty-two displacement functions (X-axes reflect 4 seconds of time) derived from a frame-by-frame video-analysis on the basis of recordings of the hand and finger movements of a subject performing the 16 different movement directions in experiment 1. Infrequently interrupted lines reflect the displacement functions of a point on the hand which was located between the index finger and thumb. Frequently interrupted lines reflect the displacement functions of the most distal point on the index finger relative to the former reference point on the hand. Stimulus directions are printed at the left-hand side, Pearson-product-moment correlations between the displacement functions are printed at the right-hand side.

profile. It can be seen that hand movements are absent in the top-left/bottom-right directions and that finger movements are absent in the bottom-left/top-right directions. Flat displacement functions imply that there is no activity of the corresponding subsystem while the penpoint is moving in the indicated direction. In the vertical direction hand and fingers are moving in a congruent fashion, as reflected by a high positive correlation (the displacement functions are in phase), whereas in the horizontal directions the movements of the two anatomical subsystems are incongruent, as reflected by the strong negative correlations (the displacement functions are out of phase).

Discussion

Three different experiments have shown that subjects use a restricted set of movement directions when they repeatedly have to make rapid back-and-forth movements with a writing stylus. Strong preferences exist for horizontals, verticals and diagonals. Our investigation of changes in the patterns of preferences for movement directions as a function of arm position (experiment 2) and type of movement, movement size and visual control (experiment 3) has shown that it is likely that two independent reference systems are involved. On the one hand, a perceptual reference system seems to underly the subjects' frequent choice of orthogonal directions. On the other hand, an anatomical reference system, which is more directly related to the directions of isolated hand and isolated finger movements, is probably effective as a bias favouring oblique movement directions. Within the orthogonal reference system, the vertical direction is preferred to the horizontal direction probably because of the differences in motor control demands which emerge when the latter direction is being produced. Vertical directions are performed by a congruent, but horizontal directions by an incongruent coordination of the subsystems of hand and fingers. Pen jumps are predominantly produced in oblique movement directions in which the control demands are relatively low. It must be mentioned, however, that the production of pen jumps not only implied a different type of movements as compared to the production of straight lines but also influenced the amount of visual feedback in the sense that no ink traces resulted from these jumps. A confounding of the increase in the degrees of freedom (having to move in three dimensions instead of two) and the reduction of visual feedback (no traces of ink were left on the transparency) actually occurred in the pen-jump condition. Consequently, this part of experiment 3 cannot be considered as the most solid test of the predictions regarding the independence of the anatomical and geometrical reference systems. We assumed that large movement sizes are produced by an anatomical subsystem with a relatively large range of movement (the hand). The results show, however, that subjects prefer to produce larger movements in vertical directions. Apparently, large movements elicited a preference for a congruent cooperation of hand and finger movements in vertical directions. This cooperation of hand and fingers apparently results in a larger ROM than an incongruent cooperation of these subsystems or an isolated contribution of the subsystem with the largest ROM (the hand). Further research is needed before conclusive statements on this issue can be made. Subjects also avoid using orthogonal movement directions when they are unable to monitor their movements visually, suggesting that the geometrical reference system may indeed have a closer relationship to the perceptual system than to the motor system. Again this interpretation must be made with some caution because the manipulation of visual control in experiment 3, in which a transparancy was used and a stylus that produced ink traces on the surface cannot be compared completely with the use of a piece of glass and a pen which left no trace of ink as was the case in experiment 2.

The most important results of the present three experiments are considered to be the results depicted in figs. 6 and 8. Although arm position did not affect the pattern of preferences for movement directions insofar as frequencies were concerned, it could be shown that arm position differentially affected the orientation of the maximum-frequency directions. This result confirmed our main hypothesis which stated that obliques would be more affected by a change in arm position than horizontals and verticals. However, it might be argued that hand position differentially obstructed the view of movement directions. Because all subjects were righthanded, the fingers or pen might have occluded the bottom-right part of the stimulus circle and not its top-left part. This factor could have influenced the subjects' choices of movement directions. However, the instruction to the subjects to try to use all directions as much as as possible were given while the stimulus circle was in complete view. The radials that extended from the circle were relatively large as compared to the required size of the movements which ensured that bottom-right directions remained visible to some extent throughout task performance. Furthermore, the findings with respect to the pattern of preferences for movement directions as well as with respect to the changes in this pattern as a function of arm position are not restricted to the bottom-right directions. We also found avoidances of movement directions which are unlikely to have been obstructed by either the hand, the fingers or the pen (e.g., horizontally to the left).

In view of recently developed models of drawing (Van Sommers 1989), handwriting (Van Galen et al. 1989) and psychomotor behaviour in general (e.g., Laszlo and Bairstow 1985) the present findings might be related to the distinction between *action planning* and *motor programming*. In planning motoric actions (in three-dimensional space) subjects are assumed to make decisions with respect to (1) the point in space where a movement sequence will begin and, (2) the direction in which the sequence will proceed. Subsequent to this planning process, a motor programming process is hypothesized in which an internal representation of the movement sequence is retrieved from long-term motor memory whenever this representation is available. In the case of handwriting, motor programmes (which presumably represent the movement sequences of individual graphemes or letters) are stored in memory during the acquisition phase of the skill (Van Galen et al. 1989; Meulenbroek and Van Galen 1988). For drawing, however, a recurring necessity might exist for constructing a plan for action. This action plan can be conceived of as an internal procedure which contains a number of motor programmes, each representing the primitives of the drawing act (e.g., lines, circles, dots). Besides retrieving the correct number of programmes corresponding to the number of different primitives which have to be drawn, the programmes will also have to be executed in a proper order corresponding to the results of the decision-making process. In view of the findings by Teulings et al. (1989) who showed that at a peripheral level of preparation, two anatomical main axes can be distinguished, it might be argued that the anatomical reference system is active at a lower level of motor-programme execution whereas the geometric spatial reference system is likely to be involved in the decisions being made during a higher-order process of action planning.

It may seem rather speculative to suggest that the geometrical reference system is active during action planning and the anatomical reference system during a more peripheral phase of motor preparation. However, this line of reasoning may contribute to the understanding of as yet unexplained aspects of graphic behaviour. An example may be the differential complexity of copying squares and diamonds. Children as well as adults have more problems and are less accurate in copying diamonds than in copying squares (Piaget and Inhelder 1956; Abercrombie 1965; Naeli and Harris 1976; Freeman 1980; Laszlo and Bairstow 1985). Broderick and Laszlo (1987) showed that (1) a partial or complete loss of visual control of the production of these geometrical figures affects the orientation accuracy of the figures but not the angular accuracy of the individual line segments, (2) subjects use external alignment cues to orient geometrical figures in space and, (3) diamonds are more accurately orientated on a rectangular piece of paper (incongruent frame) than on a round piece of paper (neutral frame). Especially this latter result can be understood by assuming that the geometrical reference system, bearing a closer relationship to the perceptual system than the anatomical reference system, is active during action planning (from which follows the orientation accuracy of the complete figure) but not during motor programming (which results in the angular accuracy of the individual line segments).

The present study should not be related directly to the search for main axes in cursive handwriting as conducted by, e.g., Teulings et al. (1989). The latter authors studied in detail the invariances of the duration, the size and the spatial variability of strokes performed in various directions. They showed that wrist-joint and finger-joint movements have both high accuracies but that the former are produced at a higher speed than the latter. Movements requiring a coordination of both joints were found to be reasonably fast but least accurate in space. The latter results correspond to the present findings. The analyses of Teulings et al. contribute to the issue of how the motor system coordinates and controls economically the production of ballistic strokes at a peripheral level, which, of course, is a very important topic in motor theory. At the same time, however, the authors stress that their data do not provide evidence for the view that handwriting movements are represented by means of only two axes when a higher internal level of motor control is concerned. The present study, although it is restricted to the level of directional preference, is aimed just at the latter issue. We investigated stroke-direction preferences across subjects under a variety of conditions and could show that at the level of direction choice, anatomical, but also geometrical factors play an active role. Of course, individual differences in patterns of stroke-direction preferences were not the object of our study and were neglected by restricting our analyses to the cumulative frequency distributions across subjects. Further research on these latter issues is needed.

A final remark concerns the video analysis of the performance of one subject in experiment 1. It resulted in separate, relative displacement functions of hand and finger movements producing a variety of movement directions. Although these findings may not be generalized, they provided supporting evidence for those *anatomical* models of handwriting production which assume that two (almost) orthogonal subsystems are coordinated at a peripheral level of movement production (e.g., Vredenbregt and Koster 1971; Dooijes 1983; Hollerbach 1981; Morasso and Mussa Ivaldi 1982). Empirical evidence of the type presented here was thus far lacking.

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