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Latencies and kinematics reflect graphic production rules *

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Abstract

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Graphic production rules govern starting points, directions, and stroke order in copying and drawing. Recently, the authors proposed a working model and a quantitative specification of such rules for the copying of a well-defined set of geometrical patterns (Thomassen and Tibosch 1991). The present paper presents a reaction-time and kinematic analysis of the movements involved in reproducing these patterns. It shows that rule-governed copying is clearly reflected by the latency and kinematic measures. Movement sequences corresponding to graphic production rules are less variable, are generally preceded by shorter reaction times and are produced more rapidly due to shorter pen-up trajectories. An interpretation of these findings in terms of a hierarchical model of movement preparation shows that the rule-bound selection of a stroking sequence occurs at a relatively high level of preparation. As predicted, 'anchoring' constitutes a special rule, reflecting its advance planning by longer latencies and its precision features by higher accuracy and lower velocities of the involved movements. The latter results are also in agreement with the hierarchical model to the extent that, following the higher-level selection of an anchoring solution, the actual execution of anchored strokes is dealt with at a lower level in the hierarchy.

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Introduction

The graphic skills of writing, copying and drawing involve the efficient sequential production of the segments of the intended spatial patterns. The development of these skills is by no means trivial; a large number of factors have been highlighted in a recent conference on the development of graphic skills (Wann et al. 1991). The present paper intends to make a contribution to this area by looking at the latency and kinematic properties of copying movements. These are studied as a function of the opportunities that the patterns provide for the application of specific principles or rules [1] that appear to underlie the selection and execution of suitable stroking sequences by experienced adult writers.

The task of copying a geometrical pattern is one of 'linearizing' the instantaneously presented model, i.e., of transforming its graphical elements (to be called 'segments' in the present paper) into a temporal sequence of strokes. The subject of linearization of spatial patterns has been discussed by Levelt (1982) in the context of verbal descriptions. Although there is an interesting similarity with this domain, the principles and constraints are of course different from those of drawing and copying. Here the selection of a suitable (i.e., economic, accurate) sequence is highly constrained by a number of interacting cognitive, physiological and physical factors. These include (actual or generalized) preferences based on biomechanical effector properties, opportunities for visual guidance, prior learning and acquired skill in drawing and

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[1] The term 'graphic production rules' implies reference to production systems as proposed to model various kinds of cognitive behaviour, especially problem solving (see Newell and Simon 1972). Copying may indeed be described as problem solving and planning. Correspondingly, the action knowledge implied in the graphic production of copying may be represented in the form of production rules. A production rule consists of a condition and an action. The condition specifies the pattern of information that may be present in the situation, and the action specifies a possible performance. The rule states that if the condition is present, the action is performed. It may be questioned to what extent the rules referred to in the present paper are production rules rather than behavioural tendencies. Indeed, however strong the constraints imposed by the rules, across subjects there is not a full condition–action dependence. Apart from action knowledge, problem solving may also imply strategic knowledge which involves a form of planning. To the extent that a solution does not rely on highly practised, automatized routines or on an opportunistic strategy, planning is necessary. This involves the advance elaboration of a procedure without dependence on feedback from execution, and therefore the implementation of representation and processing systems in which, e.g., anticipation plays an essential role. All these elements seem to apply to copying as much as to any other tasks involving problem solving and planning.

handwriting, and factors associated with directionality in reading (see Thomassen et al. 1989).

The complexity of copying novel geometrical patterns composed of straight line segments may be illustrated as follows. Let us suppose that each segment is produced in a single graphical stroke. For a pattern with only one segment ($n = 1$) there are two copying solutions ($S = 2$): the copier may start at either side of the segment. With increasing n, the task soon becomes more complex. For $n = 2$ we have two segments with two possible starting points each and two possible orders of dealing with these segments, which yields eight solutions, or $S = 8$. The increase of the value of S as a function of n according to the general formula $S = (n!) \times 2(\exp)n$ is quite steep: for $n = 3$ it yields $S = 48$; for $n = 4$, $S = 384$. [2] These quantitative relationships make us aware of the fact that our ability to select a suitable stroking sequence forms an essential part of the copying skill. Various learnt biases, preferences and strategies, which have considerable general validity (Van Sommers 1984), guide and constrain us in our approach to a pattern and in our selection of suitable sequences from the huge number of alternatives. The developmental, educational, cultural, visual-control, and performance aspects of these preferences have been studied over the past two decades (Goodnow and Levine 1973; Lehman and Goodnow 1975; Lieblich et al. 1975; Nihei 1983; Ninio and Lieblich 1976; Simner 1981; Smyth 1989; Thomassen and Teulings 1979, 1983; Thomassen et al. 1989; Thomassen and Tibosch 1991; Van Sommers 1984).

In our earlier study, we looked at the stroke orders selected by right-handed subjects in the copying of a well-defined set of relatively simple geometrical patterns composed of straight segments only (Thomassen and Tibosch 1991). We found that a limited number of rules governed this selection. In particular, the 'grammar of action' proposed by Goodnow and Levine (1973) and several further principles as suggested by Van Sommers (1984) appear to involve graphic production rules. At the behavioural level, these rules are effective as tendencies which are moderated by various context variables and, naturally, they are subject to noise. As we will see, graphic production rules are to

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[2] For a slightly higher value of n, let us take a 'Chinese' example. We choose an average Chinese character consisting of ten strokes. If we would ask each of the 929 million people living in the People's Republic of China to select four unusual and different ways of drawing this character, all the resulting productions could be different in terms of stroking sequence, since for $n = 10$ we obtain $S = 3{,}715{,}891{,}200$.

some extent interdependent and they appear to be highly different in strength. Also, rule obedience shows considerable intersubject variation, part of which is related to age and handedness. As a consequence, any arbitrary geometrical pattern will result in a distribution of more and less frequently adopted stroking sequences.

In that study, we tested a probabilistic model simulating the distribution of the stroking sequences adopted for each pattern by 15 right-handed adult subjects. At first, the model was implemented with eight weighted rules. Even in its most elementary form, the model could predict 88 percent of the distributions. It appeared, moreover, that the model essentially comprised only five rules; three rules appeared not to contribute significantly to the proportion of correctly predicted distributions. In decreasing order of strength, as determined in our recent study, the five principal rules are the following:

(1) threading, i.e., drawing the successive segments with a continuous line, avoiding pen lifts;
(2) starting at the leftmost point of the pattern;
(3) anchoring, i.e., following a pen lift, starting a later segment from a position located on a segment drawn earlier;
(4) starting with a vertical segment;
(5) starting at the topmost point of the pattern.

The three additional rules contributing relatively little in the context of the five principal rules are:

(6) drawing vertical lines from top to bottom;
(7) drawing equally long parallel lines in immediate succession and in the same direction;
(8) drawing horizontal lines from left to right.
(Rules 5 and 6 are obviously interrelated, as are rules 2 and 8.)

No single pattern can be performed completely in agreement with all the rules. Some rules are mutually exclusive (rules 1 and 3); some may or may not be in conflict (rules 2 and 5). Some rules prevail over others; the rules higher in the above list tend to dominate over the ones listed lower. Finally, some rules simply do not apply to certain patterns. (In particular, any specific set of patterns may or may not favour the adoption of a rule.) There are, moreover, large differences between patterns as to the opportunity they provide for rule-bound performance. It will be clear from the examples in fig. 1 that pattern A may

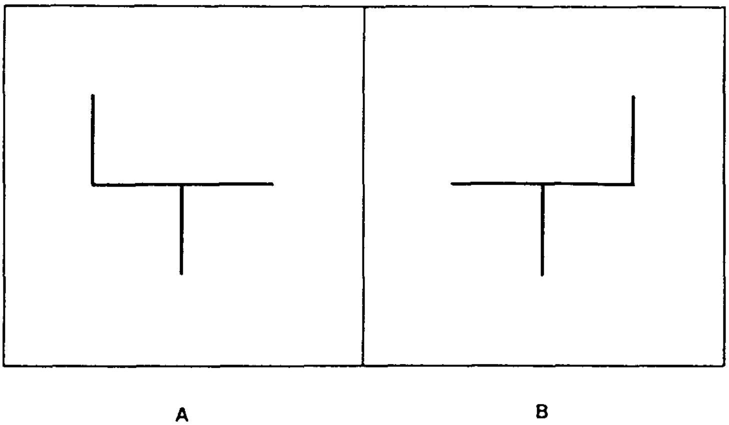

Fig. 1. Examples of three-segment patterns used in the experiment. (Each pattern is constructed in a 3×3 dot matrix of which in these examples only five locations are relevant. A is a 'non-conflicting' and B is a 'conflicting' pattern. A and B constitute a 'pair' as studied in the first analysis.)

be copied according to rules 1 (top segments), 2, 3 (bottom segment), 4, 5, 6, and 8. In pattern B, however, rule 1 is incompatible with the combination of rules 6 and 8; and rule 2 is incompatible with rules 4 and 5 and with the combination of rules 1 and 6.

In the present study we posed the question whether the selection and application of graphic production rules can be traced in the reaction times and in the kinematic features of the movements of the writing instrument. In particular, we expected that the availability and applicability of rules would support the copying process and would therefore result not just in a strongly decreased variability of stroking sequences (due to the very constraints imposed by the rules themselves) but specifically in a more rapid start and in increased fluency and velocity. In the case of patterns that can be performed entirely in accordance with the rules mentioned, we hypothesized that less stroking variability would be observed and that – in general – shorter latencies, higher velocities and more fluency would be obtained than in the case of patterns whose performance implies the violation of at least one rule. We will refer to this hypothesis as the General Rule Hypothesis.

This general principle was expected to apply to the majority of the rules. In contrast, the application of rule 3, i.e., the rule of anchoring, should lead to a less rapid start and to a slower and less fluid mode of production. The latter hypothesis is based on the suggestion made by Van Sommers that anchoring 'involves control to achieve accuracy' (1984: 40). The intended spatial accuracy, or 'end control' requires that anchored segments are performed under increased guidance, which should lead to an extra delay as well as to decreased velocity and fluency. It should be noted that anchoring can only be the case following a pen lift. Since the strong threading rule lends priority to keeping the pen on paper, pen lifts are likely only in those cases where threading would lead to retracing or to undesirable stroke directions. Whether or not anchoring occurs when the pen is placed back on paper will depend on the intended accuracy and probably on a number of other factors as well. Indeed, anchoring may reflect a cognitive strategy of advance planning in which the subject anticipates the anchored stroke and creates the conditions for such anchoring. To the extent that anchoring reflects an accuracy strategy, it should naturally result in a relatively high degree of spatial precision of the locus where the anchoring occurs. This precision assumption will therefore be tested first. If such anchoring is also accompanied by a relatively high degree of control or guidance, anchored patterns should be drawn with less fluency and at a slower rate, not only on paper but also above it in view of the pen's replacement at the proper location. To this hypothesis we will refer as the Anchoring Hypothesis. The advance-planning strategy is not incorporated in this hypothesis; we will, however, return to it in the Results and Discussion sections.

It is to be anticipated that our results will also provide evidence as to when the planning involved in anchoring occurs. It is known from work in our laboratory (Van Galen et al. 1986) that the programming of graphic units is generally done in advance. The higher the hierarchical level of such units, the earlier its programming occurs in relation to the execution of the actual strokes. A dependent variable clearly reflecting such on-line programming is the duration of pen-up movements in between units. Any uncertainty during copying is likely to result in (anticipatory or random) movements above paper, so that the duration and length of their trajectories may be taken as negative evidence of advance planning. Now, according to the hierarchical model, graphic productions which are prepared in advance should result in longer RTs; and to the extent that strokes are prepared only during copying performance itself, they should result in pen-up movements with longer durations. On the same model, the lowest levels of control are reflected by effects on the kinematics during real-time performance of the current stroke.

In order to test the General Rule Hypothesis, comparisons were made between productions of 'non-conflicting' (NC) and 'conflicting' (C) patterns. A pattern was considered 'NC' if it could be drawn in accordance with the rules described above or if rules simply did not apply to that pattern. If one or more of these rules had to be violated, the pattern was considered 'C'. To prevent structural factors from influencing the results of our comparisons, matched comparisons involving structural constraints had to be made. Matching was also a desirable procedure with respect to the Anchoring Hypothesis. Here we made within-subject paired comparisons of 'anchored' (A) productions and 'non-anchored' (NA) productions of the same patterns. A production was considered 'A' if one of its later strokes, following a pen-up movement, started from a location on an earlier stroke. If the later segment ended at such a location, having started in 'free space', it was considered 'NA'.

Method

Subjects

Fifteen graduate students of the Department of Experimental Psychology (2 females, 13 males) took part in the experiment as unpaid volunteers. They were aged between 25 and 30 years and right-handed as determined by their preferred hand for writing and drawing. The subjects were unfamiliar with the topic of investigation and unaware of the purpose of the experiment.

Materials

The stimulus patterns were all the possible different patterns composed of one, two, or three connected, straight line segments that can be drawn in a virtual orthogonal 3 × 3 dot matrix, excluding oblique segments. Every pattern with its unique structural properties was adopted in all its different orientations and rotations. [3] The crossing of line segments could of course occur only in the middle of the virtual matrix. In this way, 4 one-segment patterns were adopted, 25 two-segment patterns, and 120 three-segment patterns, totalling 149 patterns.

Apparatus

The experiment was controlled by an Olivetti M280 personal computer. The pen-tip displacements in the writing plane (i.e., on paper) and above this plane were recorded by means of a digitizer (XY tablet; Calcomp 23180). The special laboratory-made pen and the recording and signal-analysis techniques have been described elsewhere (Maarse 1987; Teulings and Maarse 1984; Teulings and Thomassen 1979). Pen-pressure criteria were used to differentiate 'pen-down' movements on paper from 'pen-up' movements above the paper. The X and Y coordinates and axial pen force were sampled at a rate of 100 cps. A black-and-white EGA monitor, located about 50 cm before the seated subject, was used for the presentation of the stimulus patterns. Each pattern was presented in a square box of 24 × 24 mm in the centre of the monitor display. The size of the patterns within this box was limited to 12 × 12 mm, so that the 6-mm outer edge within the box was never used. The background of the monitor screen was white, the contour of the box was grey, and the pattern segments were black.

The patterns were copied on normal white A4 paper sheets taped onto the digitizer. In the top half of each sheet, a rectangle of 90 mm width and 36 mm height, divided into two rows of five boxes of 18 × 18 mm, was printed in thin, grey lines to match the grey lines of the boxes on the display. Just this limited region of the response sheets, allowing only ten responses to be entered in the boxes, was used to avoid large

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[3] An example may clarify the procedure of adoption of patterns. An L-shaped two-segment pattern with a long and a short segment can be drawn in the 3×3 matrix. It therefore belongs to the stimulus set. Moreover, it can be drawn in the left-hand part of the matrix as well as in its right-hand part. But since these patterns are identical, only one of these possibilities is (randomly) adopted in the set. The L pattern can be rotated in the writing plane in four orientations, which from a graphic point of view are different. This results in four L patterns in different orientations in the set. Similarly, an inverted L, which is different from any of the normal L's orientations, will have four representations in the set. However, an L shape with two equally long segments can only have four different representations altogether in the set; but there are two possible sizes of such an equilateral L shape. Thus there are 4 L shapes, 4 inverted L shapes, 4 large equal-legged L shapes and 4 small equal-legged L shapes in the set.

differences in arm and hand position as well as inconvenient positions due to a lack of resting space. Before the start of the session, the subject was free to rotate the digitizer, and to place it at a comfortable distance. The resulting orientation always had the horizontal sides of the response boxes at a slight angle with respect to the table edge. The boxes on each response sheet were used from left to right, the top row preceding the bottom row.

Procedure

The 149 patterns to be copied were presented twice in the same random order. There were two random orders, one for eight subjects, the other for the remaining seven subjects. Ten patterns were selected to serve as preliminary practice materials; these patterns occurred also among the experimental stimuli. The subject was required to hold the pen tip a few millimeters above the centre of the next box of the response sheet until the next model pattern was displayed, and then to copy it in that box immediately in approximately the same relation to the box. Response sheets were changed after every ten trials.

A trial consisted of three phases. First, an empty box was presented in the centre of the screen; its appearance was accompanied by a brief, high-pitched tone (50 ms, 2000 Hz). Then, 500 ms after the onset of this tone, the model pattern appeared in the box; the subject copied this pattern immediately. During the third phase, the subject moved the pen-tip above the centre of the next box. The next trial started 1500 ms after the pen-tip approached this point above the writing plane. Also during the third phase of each trial, the recorded pattern was automatically coded for the stroking-order analysis and compared with the presented model pattern. A reproduction was considered correct if two conditions were fulfilled. First, the pen-tip had to pass pen-down through (the neighbourhood of) all the appropriate locations of the virtual 3 × 3 matrix (9 × 9 mm) inside the 18 × 18 mm box. Second, the pen tip was not allowed to pass pen-down through (the neighbourhood of) any of the other, inappropriate matrix locations. The 'neighbourhood' of these locations was defined as a circular area with a radius of 2.25 mm around the matrix location.

Following each response, the subject was informed as to whether or not the production was correct in the above sense; the criteria themselves, however, were unknown to the subject. Non-correct attempts were followed not by the normal tone, but by a longer-lasting, lower-pitched tone (300 ms, 250 Hz) announcing the next trial. The subjects were told not to let themselves be discouraged by such negative feedback, but to try and draw more accurately in the next trial. Rejected trials were repeated automatically at the end of the session. A session, including the 10 practice trials, the 298 experimental trials and the repeated trials, lasted 30 to 45 minutes.

Data analysis

In the Results section, we will first report the results of two matched comparisons concerning the General Rule Hypothesis with respect to the conflicting (C) and non-conflicting (NC) patterns. In the first analysis, the comparisons were made with respect to pairs of patterns consisting of either two or three strokes. Each of the pairs comprised an NC pattern that could be (and in fact was) performed ‘lawfully’ according to the rules described above. There were 27 such patterns in the set. The matched C patterns were the mirrored counterparts of these NC patterns. Mirroring in this case was, somewhat arbitrarily, achieved by rotating the pattern around the Y axis. Mirroring of an NC pattern always resulted in a C pattern involving conflict between rules. We thus analysed 27 NC–C pairs; 14 of these were pairs of two-segment patterns, and 13 were pairs of three-segment patterns.

The second analysis to be reported is concerned with three-segment patterns only, and it involved comparisons within quadruplets. Every NC pattern adopted in this comparison was now contrasted with three C patterns having the same structure but a different orientation. This largely obviated the arbitrariness of the choice of only one mirrored configuration in the previous analysis. The three matching C patterns were (1) the NC pattern’s horizontal mirror image (rotation around the Y axis), (2) the NC pattern’s vertical mirror image (rotation around the X axis), and (3) the NC pattern’s image after a 180-degree orientation shift in the writing plane (equivalent to rotation around both the X and the Y axis). If one of these rotations was identical to the original NC pattern, the pattern was not adopted in the comparison. Thus, a selection of 13 NC patterns remained, each of which was compared to the three corresponding C patterns. In fact, the patterns and their counterparts sub 1 contributed to the pairs analysis described above.

The analysis regarding the Anchoring Hypothesis is mainly concerned with t-tests on a number of variables studied in paired comparisons between anchored (A) and non-anchored (NA) productions of the same patterns. As mentioned, each subject copied every pattern twice. There were 39 cases, all involving three-segment patterns, in which a subject happened to reproduce exactly the same pattern once with an anchoring strategy and once without. These 2×39 cases were entered in a paired comparison using t-tests in which patterns and subjects were held constant.

Dependent variables

The following dependent variables were studied.

Variability, or the mean number of different stroking sequences observed across the 30 productions (2 by 15 subjects) of each pattern.

Reaction time (RT), or the duration between the appearance of the model pattern on the screen and the start of the pen-down trajectory. It thus includes both the latency during which the subject still holds the pen above the centre of the appropriate box on the response sheet, and the pen-up movement toward the starting position on paper.

Movement time (MT), or the summed duration either of the pattern segments produced on paper (MTdown) or of the intermittent movements of the pen above the paper during the production of the pattern (MTup). The latter definition thus excludes any pen-up movements preceding the first segment and following the last segment of the pattern.

Distance covered (DC), or the distance travelled by the pen tip either during MTdown (DCdown) or during MTup (DCup). The latter variable was measured as the perpendicular projection of the pen movements onto the writing plane.

Mean velocity (MV), or the averaged absolute velocity of the pen tip, either in pen-down (MVdown) or in pen-up (MVup) trajectories.

Dysfluency (DF), or the number of peaks in the absolute-velocity profile corresponding to either pen-down (DFdown) or pen-up (DFup) movements after low-pass filtering with a cut-off frequency of 12 cps.

Results

With respect to the General Rule Hypothesis, we will primarily report the results of analyses of variance. We performed a separate analysis of variance for each of the dependent variables with pairs/quadruplets, conditions, and replications as factors and subjects × conditions as error term. The other analyses of variance which we also performed, namely with subjects, conditions, and replications as factors and pairs/quadruplets × conditions as error term, yielded almost the same results; they will not be reported in this paper.

General Rule Hypothesis: Pairs

Not surprisingly, the stroking variability of the C patterns was much larger than that of the NC patterns. For the two-segment C patterns, the mean number of production 'solutions' was 4.00, whereas for the NC patterns it was 1.07. For the three-segment patterns these figures were 6.77 and 1.69, respectively. For the total set of 27 pairs the mean for C was 5.70, while for NC it was 1.37, or less than a quarter of the former figure. The results of the analyses of variance with respect to the 27 pairs were as follows. There was a tendency for reaction time (RT) to be shorter under NC patterns (RT(NC) = 913 ms) than under C patterns (RT(C) = 951 ms); ($F(1, 26) = 3.32$; ($p = 0.077$). Highly significant effects were obtained for the duration of the pen movements above the paper (MTup) during the production of the patterns. These were of a shorter duration under the NC condition (MTup(NC) = 317 ms) than under the C condition (MTup(C) = 382 ms); ($F(1, 26) = 15.29$; ($p < 0.001$). The distance travelled above the paper (DCup) was also significantly shorter for NC patterns (DCup(NC) = 0.699 cm) than for the corresponding C patterns (DCup(C) = 0.825 cm); ($F(1, 26) = 5.25$; $p = 0.029$). The further analyses of variance did not show statistically significant effects.

General Rule Hypothesis: Quadruplets

Also in this data set, stroking variability in the C patterns was much larger than that of the NC patterns. The mean number of different production 'solutions' of the 39 three-segment C patterns was 5.10, whereas for the 13 NC patterns it was 1.69, or only one third of this figure. The results of the analyses of variance concerning the 13 quadruplets are as follows. There was a significant effect of reaction time (RT), with the shortest mean RT of 924 ms for the NC condition and means of 1015, 955, and 965 ms for the corresponding C conditions ($F(3, 36) = 3.79$; $p = 0.018$). Also the amount of time that the pen was above the paper (MTup) was shortest for the NC condition (353 ms) and longer for all the other conditions with means of 466, 453, and 394 ms. This effect was highly significant ($F(3, 36) = 9.90$; $p < 0.001$). Finally, the distance travelled by the pen-up movements above the paper (DCup) was significant, with the shortest distance for the NC condition (0.712 cm) and longer distances (0.971, 0.958, and 0.818 cm) for the three C conditions ($F(3, 36) = 6.24$; $p = 0.002$). Further comparisons did not yield significant effects. [4]

Taking the two data sets together we may conclude that, along with a strongly decreased variability, shorter reaction times tend to occur in the graphic production of non-conflicting patterns. The execution of these patterns is, moreover, characterized by pen-up movements of much shorter mean durations covering somewhat smaller trajectories. Since the latter movements are signs of on-line planning in graphic production (Van Galen et al. 1986), we may conclude that the abstract rules governing graphic production facilitate not only the preliminary selection of economic stroking sequences at higher hierarchical levels, but also their intermittent further planning in between the real-time execution of the individual segments.

Anchoring Hypothesis

Anchored strokes were produced in all four possible directions, thereby following preferred or non-preferred directions. It was assumed that there were no systematic differences between anchored and non-anchored movements in this respect. With respect to the Anchoring Hypothesis, the accuracy expectation was tested as follows. All selected patterns, giving rise to an anchoring and a non-anchoring production,

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[4] Among the three-stroke patterns NC patterns were a minority (13 out of 120). Mirror images and rotations by definition changed the relationships between the original starting points and preferred stroke directions. In some cases, one of the orientations (especially the one sub 4) happened to generate another NC pattern involving different starting points and new stroke directions. Because of the small number of analysable quadruplets, this imperfection was not considered serious enough to discard the quadruplet altogether. The result, however, was that the post-hoc tests did not always separate the NC condition sharply from its three rotations. For the three significant effects reported in this paragraph, the following significant gaps (Student-Newman-Keuls test; alpha = 0.05) were observed, respectively. RT: (1, 3, 4) (3, 4, 2); MTup: (1) (4) (3, 2); DCup: (1, 4) (3, 2).

involved the anchoring of the later segment from the middle of an earlier segment. (For example, the vertical bottom segments in fig. 1 divide the horizontal segments in two equal parts.) Accuracy of anchoring could thus be estimated by measuring the deviation with which the later, anchored segment started from exactly the middle of the earlier segment. This deviation was expressed as a proportion of the length of the earlier segment. The same estimate was made for the corresponding non-anchored segment whose endpoint reached the earlier segment in approximately the same position. It was found that the anchored segments started slightly more precisely from the midpoint of the earlier segments (mean deviation of 5.60 percent from the middle) than where the non-anchored segments arrived (mean deviation of 6.82 percent from the middle). This difference was in the predicted direction and it occurred significantly in the majority of the cases (Sign test: $N = 37$; $x = 12$; $z = 2.14$; $p = 0.016$). The measured velocities clearly indicate that guidance and control during performance are indeed more likely under anchoring peformance. This holds significantly for pen-down movements (MVdown(A) = 2.170 cm/s; MVdown(NA) = 2.502 cm/s; $t(38) = 2.10$; $p = 0.021$) as well as for pen-up movements (MVup(A) = 2.193 cm/s; MVup(NA) = 2.546 cm/s; $t(38) = 1.80$; $p = 0.040$). Thus, non-anchoring movements are made at significantly higher rates than anchoring movements.

As regards latency, the anchoring results do show a slightly longer mean RT for anchored patterns. The 50 ms difference is, however, not significant (RT(A) = 962 ms; RT(NA) = 912 ms; $t(38) = -0.95$; $p = 0.174$). This implies that there is at best a tendency to prepare anchored patterns more in advance. Looking at the duration of pen-up movements during copying, we see that there is an opposed tendency: non-anchored patterns tend to be planned more during copying. Again, however, this tendency does not reach significance (MTup(A) = 333 ms; MTup(NA) = 395 ms; $t(38) = 1.52$; $p = 0.068$). Taking these two latter results together, however, we believe we may regard the two opposed tendencies as an indication that anchored movements involve slightly more advance planning than non-anchored movements. This evidence reflecting a somewhat decreased structural uncertainty during the actual copying performance of anchored patterns may gain further strength by the significantly shorter pen-up trajectories in anchored patterns (DCup(A) = 0.702 cm; DCup(NA) = 0.903 cm; $t(38) = 2.49$; $p = 0.009$).

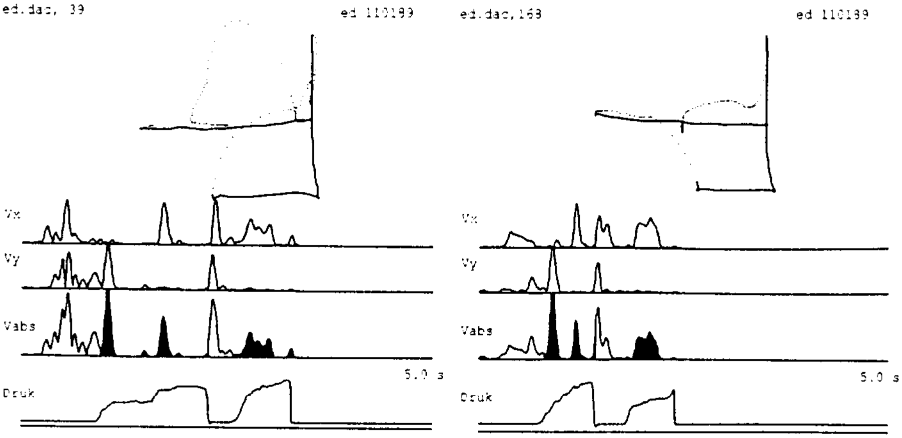

Fig. 2. Anchored (left-hand panel) and non-anchored (right-hand panel) productions of the same pattern by the same subject. (Dotted lines represent pen-up trajectory segments; *Vx*, *Vy*, and *V*abs are horizontal, vertical and absolute-velocity distributions over time; the area under pen-down distributions is black; Druk = axial pen force.) The figures illustrate some typical differences: The anchored production shows greater spatial accuracy, longer-lasting and more anticipatory movements, and more pen-down velocity peaks. The pen-up trajectory, starting near the centre of the figure displays 'exploratory' movements anticipating the directions of later strokes and 'marking' a position on the vertical segment near the location of the start (left-hand panel) or of the stop (right-hand panel) of the final, large horizontal stroke.

The fluency measures also show confirming tendencies. Pen-down movements are on average very similar in anchoring and non-anchoring (DFdown(A) = 3.019; DFdown(NA) = 2.991); pen-up movements, however, tend to be more fluent in anchoring (DFup(A) = 2.718; DFup(NA) = 3.359). Although the latter difference is not significant ($t(38) = 1.47$; $p = 0.076$), in its contrast to the pen-down similarity, this pen-up difference is in agreement with the general pattern of results following which pen-up movements reflect on-line planning under non-anchoring conditions.

Some of the general findings with respect to anchoring may be illustrated nicely by the trajectories and the kinematic data of an anchored and a non-anchored production of the same pattern by the same subject (see fig. 2). The left-hand figure (anchoring) shows a longer latency and more preparatory pen-up movements preceding the first pen-down stroke. Moreover, more guidance is visible here in the multiple-peak pen-own velocities (in black). In contrast, the right-hand figure (non-anchoring) displays a bimodal velocity distribution of the pen-up movement preceding the start of the final stroke, indicating more response uncertainty. The resulting trace has less spatial accuracy than that following anchoring.

Summing up the anchoring results, we conclude that the reaction-time data in combination with those on the trajectories provide evidence for more advance planning in anchored than in non-anchored pattern productions. Consequently, anchored patterns may be regarded as being planned earlier at a higher hierarchical level, so that there is less uncertainty with respect to their sequencing. But there appears to be more lower-level control during the actual execution of their individual segments, as reflected by the lower pen velocities both on paper and above it, resulting in the observed greater spatial precision.

Discussion

The results show that the question posed in the introduction to this article, whether latency and kinematic data reflect the application of graphic production rules, may be answered affirmatively. From the data we may conclude that the applicability of these rules generally facilitates the planning and preparation as well as the actual execution of drawing movements. We have thus linked the constraints which have so far been described in the abstract terms of biases, preferences or rules, to concrete behavioural and trajectory features. The anchoring results show that anchored productions tend to be planned hierarchically in advance. By definition, an anchored segment is never produced as the first segment, and yet anchored patterns as a whole tend to have longer reaction times and shorter pen-up trajectories. This brings us to the following issue. The present analysis does not differentiate between the kinematic features of the individual strokes producing the segments of the patterns. Such a more detailed analysis might indicate more exactly the locus of the events taking place during graphic production. The circumstance that for most patterns there are a number of different stroke orders, and that the performances of the individual segments thus have to be searched in the raw data, has thus far prevented us from conducting such an analysis.

When discussing the above results we did not pay much attention to some non-significant effects, either expected or unexpected. Of course, the pen-down trajectories in matched patterns should have similar lengths under all the compared conditions; this was confirmed by the data. But the fact that the velocity and fluency measures did not differentiate at all between conflicting and non-conflicting patterns may have been a surprise. The explanation we offer is that the straight segments of the patterns were in general easy to produce so that, once started, the strokes themselves had similar kinematic features irrespective of their being part of conflicting or non-conflicting patterns. (Only under the presumed precision strategy during anchoring did we establish effects of reduced velocity.) As with other graphic tasks, a considerable amount of uncertainty appears to be solved during the time that the pen is above the paper, either before or intermittently with the pen-down production of the strokes. This explanation is in agreement with our hierarchical interpretation following which only the higher-order preparatory aspects of conflicting sequences should be reflected by latency and kinematic measures. In contrast, the anchoring movements may be regarded as being dealt with, according to the hierarchical model, at lower levels to the extent that the anchored strokes are to be performed with great spatial accuracy.

A note should be made with respect to our finding of shorter pen-up trajectories in anchored productions. We looked into the possibility that the geometrical distance in the models between the end of the preceding segment (where the pen was lifted) and the start of the subsequent segment (where the pen was put on paper again) was shorter in the anchored than in the non-anchored productions of the same patterns. This appeared to be the case in a majority of the 39 pairs analysed, although there were a number of pairs where anchoring bridged a larger gap than non-anchoring, or where no difference in geometrical distance existed. All cases were therefore inspected separately. It was found that geometrical distance was only a portion of the total distance travelled during pen-up movements in both conditions, and that this portion tended to be smaller under non-anchoring. This is in line with our expectations of more random or anticipatory pen-up movements under non-anchoring and with the results as summed up above. This is also confirmed by the fact that the absolute distances travelled in conflict versus non-conflict patterns (0.923 vs. 0.712 cm) were highly similar to those in non-anchored vs. anchored productions (0.903 vs. 0.702 cm), suggesting similar effects of uncertainty at the structural level. The longer pen-up trajectories under non-anchoring may be related to the phenomenon to be discussed in the final paragraph.

A special feature of planning in graphic production appears to be what could be called the 'exploration' of trajectories. This phenomenon has been observed frequently in our laboratory. When a trajectory is prepared for graphic production, the pen tip may anticipate the direction or the shape of the trajectory above the writing plane, or 'mark' a specific point there. This high-speed exploration, reflecting a specific form of planning, is often visible in the pen-up trajectory (see fig. 2). Now, if a position on an earlier segment serves as an anchoring point, this position will by definition have received some marking in graphic space when it was passed pen-down. This could provide an essential advantage favouring anchoring over non-anchoring, where such a marking would require an extra pen-up exploratory movement. These favourable conditions may thus contribute to the factors that make anchoring such an attractive production strategy, even to the extent that it balances the disadvantage of drawing segments in leftward or upward directions, which are awkward for righthanders and in conflict with the set of other rules studied in this paper. Such a trade-off between levels of control may well be a general characteristic of a grammar of action also outside the domain of graphic behaviour.

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