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THE ROLE OF MANUAL DOMINANCE AND VISUAL FEEDBACK IN CIRCULAR DRAWING MOVEMENTS

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SUMMARY

Two studies are reported which investigated the role of manual dominance and visual feedback on a syntactical graphic motor rule described by Van Sommers (1984) for the drawing of circles: "the start-rotation principle" (SRP). This principle links together a starting position and the direction of the rotational drawing movement. In the first experiment, the subjects were free to select a starting position when they copied the circles, while fixed starting positions were imposed in the second experiment. In both studies, the subjects were asked to copy the circles in four successive conditions: right hand and normal visual condition, right hand without vision, left hand and normal visual condition, left hand without vision. Right-handed children aged from 4 to 10 years and right-handed adults participated in the experiments. Results showed that although already present at 4 years, the SRP gains in strength between 4 and 10 years, and takes different forms at the different ages. Interestingly, the behavior of children aged around 7 years appears more strictly "rule-based" than that of older children. A clear hand effect is also reported (a shift from a "mirror" to a "parallel" behavior of both hands during development), while the role of visual feedback seems less incisive. Results are interpreted within a cognitive developmental framework which integrates both a lower biomechanical level and a higher planning level of behavior analysis.

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INTRODUCTION

The study of macroscopic features of motor behavior is currently knowing a growing interest from researchers in the motor control domain (Rosenbaum & Jorgensen, 1992). Searching for general planning constraints also constitutes an important topic of investigation of graphic behavior (Thomassen & Teulings, 1979). After the seminal work by Goodnow & Levine (1973), several studies have been carried out to explore the potential effects of different factors on the degree to which subjects respect certain graphic rules when they draw. Among these studies, those realized by Van Sommers (1984) appear particularly ingenious and informative. One of the many observations described by Van Sommers concerns a powerful principle which governs the production of geometrical figures like circles, triangles and squares: the "start-rotation principle" (SRP). Consider in a circle a virtual axis between 11 o'clock and 5 o'clock; the principle states that if a subject selects a starting point located above this axis (between 12 and 4 o'clock), the rotational direction is counterclockwise while starting points located below this axis (between 6 and 10 o'clock) are associated with clockwise rotations. It is worth noting the generality of this principle which

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also seems to hold for transport movements taking place in a circular board (Van der Vaart, personal communication). If people are asked to grab a handle located at different positions on the circumference of a circular board, and to rotate it 180° (from 1 to 7 o'clock for instance), then the relationship between the starting position and the rotational direction is similar to the one observed in drawing circles. The present study aims at disentangling possible determinants of such a powerful principle.

Both components of the SRP (starting location and rotational direction) evolve with age. Several studies have revealed a developmental shift in rotational direction, from clockwise to counterclockwise movements (Blau, 1977; Haworth, 1970; Thomassen & Teulings, 1979), as well as a progressive migration of starting locations toward the top of figures (Gesell & Ames, 1946; Lurçat, 1974). Moreover, these changes happen to coincide in time in such a way that the relationship expressed by the SRP is, according to Van Sommers (1984), already present at a very young age. However, in a previous study (Meulenbroek, Vinter & Mounoud, 1993) we reported a significant age trend between 5 and 9 years in the SRP's strength, but this study was not originally devoted to the investigation of this specific question and our earlier findings therefore remain open for verification. Van Sommers also showed that the SRP holds for left-handers, but the virtual axis crossing through the circle and separating clockwise from counterclockwise movements is slightly modified for lefthanders: counterclockwise movements are associated with starting points located between 2 and 4 o'clock, whereas clockwise movements are produced when the subject starts between 6 o'clock and 12 o'clock. Van Sommers suggested to relate the fact that left-handers' SRP is a mirror-image of the right-handers' SRP for the circle's upper half part to the difference in location of the "natural resting point" of the drawing hand for both samples inducing the pentip to be positioned: near 11 o'clock for right-handers and near 1 o'clock for left-handers. Furthermore, he pointed out that in both cases the association between the starting location and the rotational direction of drawing movement is congruent with a natural preference to start a movement with an extension rather than a flexion (Thomassen & Teulings, 1979). However, he did not explain why the 5 o'clock position separates the rotational directions in the lower part of the circle for both left and right-handers. These observations clearly suggest that biomechanical constraints may be important determinants of the SRP, and it is worth exploring whether right-handers respect a mirror version of the SRP when they have to draw with their left hand.

However, biomechanical constraints are probably not sufficient for a complete understanding of the SRP. What may be the benefit of the changes in starting locations and in rotational direction during development? In our previous study, we suggested the following hypothesis: visual control of the drawing movement as reflected by the accuracy of the closure of circular movements is optimal when subjects obey the principle. This hypothesis is related to Rosenbaum's "end-state stability" hypothesis (Rosenbaum, 1987) in the sense that planning activities attached to the final part of the drawing movement may determine the initial conditions in which the circle drawing is started. Such determinants of higher cognitive level associated with planning and control activities of movements might also be possible determinants of the SRP. Suppressing visual feedback when subjects draw circles may be a good empirical way to explore the role of visual control in circle production. Finally, if clockwise movements may be related to natural "non-figurative" movements such as are used in scribbling and counterclockwise to a "figurative" control mode of drawing (Thomassen & Teulings, 1979), then the shift in rotational direction observed in development suggests the intervention of cognitive-like determinants on this component of the SRP. In particular, handwriting education may be held responsible for its reinforcement between 5 and 9 years as reported in our previous study.

The general framework we adopt in the present study is that the SRP has some basic determinants grounded in the biomechanical system but that it gradually becomes a higher-order abstract motor rule in the course of development during which a complex dynamic interaction between bottom-up constraints (manipulated by hand dominance in the present study) and top-down constraints (manipulated by suppressing visual feedback) contributes to shape the SRP. In this perspective which sees the syntactical choices under two contrasting forces (Thomassen, 1992), we may expect a main effect of age which should confirm that the SRP is more than a basic "constitutional" constraint of circle production. Some predictions on hand and vision independently of the age effect may also be suggested. If the SRP is mainly biomechanically driven, then a mirror effect should be observed as a function of hand, especially when vision is suppressed. If, on the contrary, it is mainly driven by optimal visual control of starting or ending position, the SRP should be absent under non-vision conditions. But the "core" of our expectations is concerned with interactive effects between age and either vision or hand. The following hypotheses constitute the guidelines of the present study. A large hand effect in young children is expected, because the biomechanical determinants predominate at early ages, but a small visual effect should be observed, since the SRP is still not "re-written" or re-determined in terms of planning rules. Around the period of the shifts of the starting locations and of the rotational direction (which are seen here as cues of the establishment of new planning rules), the hand effect should decrease and the visual effect should increase. When the changes are stabilized, we expect only small and local effects of both variables. Finally, as the starting location "drives" the rotational direction in the SRP, the effects of our independent variables should be larger on the starting location than on the rotational direction.

Two experiments on circle production were conducted: in the first experiment, subjects were free to choose both the starting point and the direction of the rotation while copying circles. The spontaneous development of the SRP can be analyzed with such a "free circle production" design. In the second experiment, the starting points were imposed, and the syntactical choices of the subject were reduced to the direction of the rotational movement.

EXPERIMENT 1

The Start-Rotation Principle in a Free Circle Production Design

METHOD

Subjects

84 right-handed children participated in the experiment. They were divided into 6 age groups of 7 girls and 7 boys each: 4 yr (age range: 3;11 to 4;1), 5 yr (age range: 4;10 to 5;1), 6 yr (age range: 5;11 to 6;2), 7 yr (age range: 6;10 to 7;1), 8 yr (age range: 7;11 to 8;0) and 9 yr (age range: 8;10 to 9;1). Handedness of the youngest children (4 and 5 yr) was assessed by means of simple

tests drawn from Bryden (1977). 8 items were used, 4 were unimanual (drawing, throwing a ball, holding scissors and brushing one's teeth) and 4 were bimanual (shutting a bottle, hitting a nail with a hammer, lighting a match and wiping a plate with a linen). Only children who obtained a score equal or superior to 6 were selected. A sample of 16 right-handed adults (all volunteers) was also studied. The adults' group was made of 8 females (mean age=28.26, sd=8.15) and 8 males (mean age=34.50, sd=10.60). They all studied or worked at the University and were naive with respect to the aims of the study.

Material and Procedure

Each child copied a series of 9 circles (3 times 3 circles of different sizes) in 4 conditions. The adults copied the same models, but they had to repeat each circle 4 times. Diameters of the models were respectively of 1.4 cm, 1.9 cm and 2.5 cm. They were printed in black ink on a white card of 8 x 8 cm (1 model per card). The order of presentation of the 9 models was random but kept constant for each subject across the conditions. The models were presented one at a time in front of the subject who was instructed to copy it on a white sheet of paper of 15 x 21 cm (3 or 4 circles by response sheet), located in front of him. The bottom edge of the drawing paper was parallel with the edge of the table. The subjects were instructed to copy the models at a comfortable speed but without stopping i.e., in a single movement. They were also asked to pay attention to the regularity of the curvature and were encouraged to produce copies with a size similar to that of the model. The choice of the starting position as well as the direction of rotation were free. There were no time constraints and the next model was presented shortly after the previous one had been completed. A few practice trials were necessary for the younger children.

The 4 experimental conditions of copying were the following: right hand and normal visual conditions (RHV), right hand without vision of the drawing hand and the trace (RHNV), left hand and normal visual conditions (LHV), left hand without vision (LHNV). All subjects were tested in the 4 conditions which were always presented in the order just indicated. During the non-vision conditions, the subjects drew on the response sheet located under an opaque screen of 32 x 24 cm raised above the sheet at 15 cm and fixed on rigid supports located at the 4 corners.

The model was placed on the top surface of the screen during these trials. The screen prevented vision but did not affect the biomechanical conditions of movement execution. The subject's hand and drawing remained visible to the experimenter. For younger children (4 - 5 - 6 yr), the response sheet was replaced after each copy in the non-vision conditions to accomodate for possible orientation problems.

Data Analysis

The experimenter visually recorded for each circle the location of the starting point and the direction of rotation. Then an off-line analysis was performed by matching the curvature of the first half part of the circular drawing with circular templates on which 12 starting points at clock hours were marked. Starting points were measured in hours by selecting the closest hour location on the template. Recalling that the SRP requires to differentiate between 11.30 and 10.30 or between 4.30 and 5.30, this procedure was sensitive and reliable enough to ensure valid measures of the starting positions. The entire set of drawings was coded independently by 2 judges and their agreement was 91%. Drawings for which there was disagreement were re-examined by both judges working together.

Starting position and direction of rotation were analyzed and transformed into a new combined variable which reflected the presence or absence of the SRP. Means were computed across replications (3 for the children and 4 for the adults). Performance of a subject was thus characterized by 12 values (3 circles by 4 conditions) which varied between 0 (no respect of the SRP) and 1 (absolute respect of the principle). For the children's group, separate analyses were performed on the locations of starting points, the rotational directions (number of cases of counter-clockwise rotational movements), and the degree of respect of the SRP. Analyses consisted of ANOVAs for repeated measures with Age (n=6) and Sex (n=2) as between - subject factors and Hand (n=2), Vision (n=2) and Size of circles (n=3) as within-subject factors. As the cell entries were proportions, they were converted into arcsin measures to ensure normal distributions. Similar but separate ANOVAs for repeated measures (with Sex alone as between - subject factor) were performed for the adults' group. Additional ANOVAs with appropriate designs were performed if the data was pooled for some relevant reason. Results for the starting locations and the rotational movements will be presented first. The starting positions were grouped into 4 regions of identical sizes (top: 11 - 12 - 1 o'clock, right: 2 - 3 - 4 o'clock, bottom: 5 - 6 - 7 o'clock, and left: 8 - 9 - 10 o'clock), and their relative frequencies expressed in percentages were computed for each subject in each condition.

Results

1. Migration of Starting Positions Toward the Top and Role of Manual Dominance.

The migration of the starting locations toward the top during development is clearly illustrated by Figure 1. The Age trend is significant for the top region both when all drawing conditions are combined ($F(5,72)=9.553$, $p<0.001$) and when the RH-V condition is considered alone ($F(5,72)=14.755$, $p<0.001$).

The migration begins between 4 and 5 yr, and is evident between 5 and 6 yr when the RH is used. When the non - dominant hand is used, the migration is postponed, a bias for the selection of the top region not being established before 7 yr. In children, the Hand by Age interaction was significant for the top region ($F(5,72)=6.593$, $p<0.001$). For adults, Hand was significant for all regions but the bottom one (top: $F(1,14)=16.791$, $p<0.001$; right: $F(1,14)=80.362$, $p<0.001$, and left: $F(1,14)=5.814$, $p<0.05$). The competitively attracting region for starting locations in the LH condition is evidently the right one (2 - 3 - 4 o'clock), although a clear interacting age effect has to be pointed out. 4 and 5 yr-old children select more often the right than the top region when they draw with the LH, while it is the reverse for older children ($F(5,72)=2.912$, $p<0.01$). Similarly, 4 yr-old children select more often the left or bottom regions than the top when they draw with the RH, while the reverse is true for older children ($F(5,72)=3.232$, $p<0.01$). As expected in our main hypotheses, the Hand effect is indeed important at 4 yr (the RH starts at the left or at the bottom while the LH starts at the right or at the top), almost non existant at 7 yr (whatever the hand, the top region is selected), and small at 9 yr (the main behavior of both hands is similar at this age although the LH tends to start at the right in an appreciable number of cases). The adults' data is very close to that of the 9 yr-old children.

The role of visual information on the selection of starting location seems less important. It is never significant for the adults'

FIGURE 1: Effect of hand on the location of starting positions as a function of age (A: top or right located starting positions; B: bottom or left located starting locations).

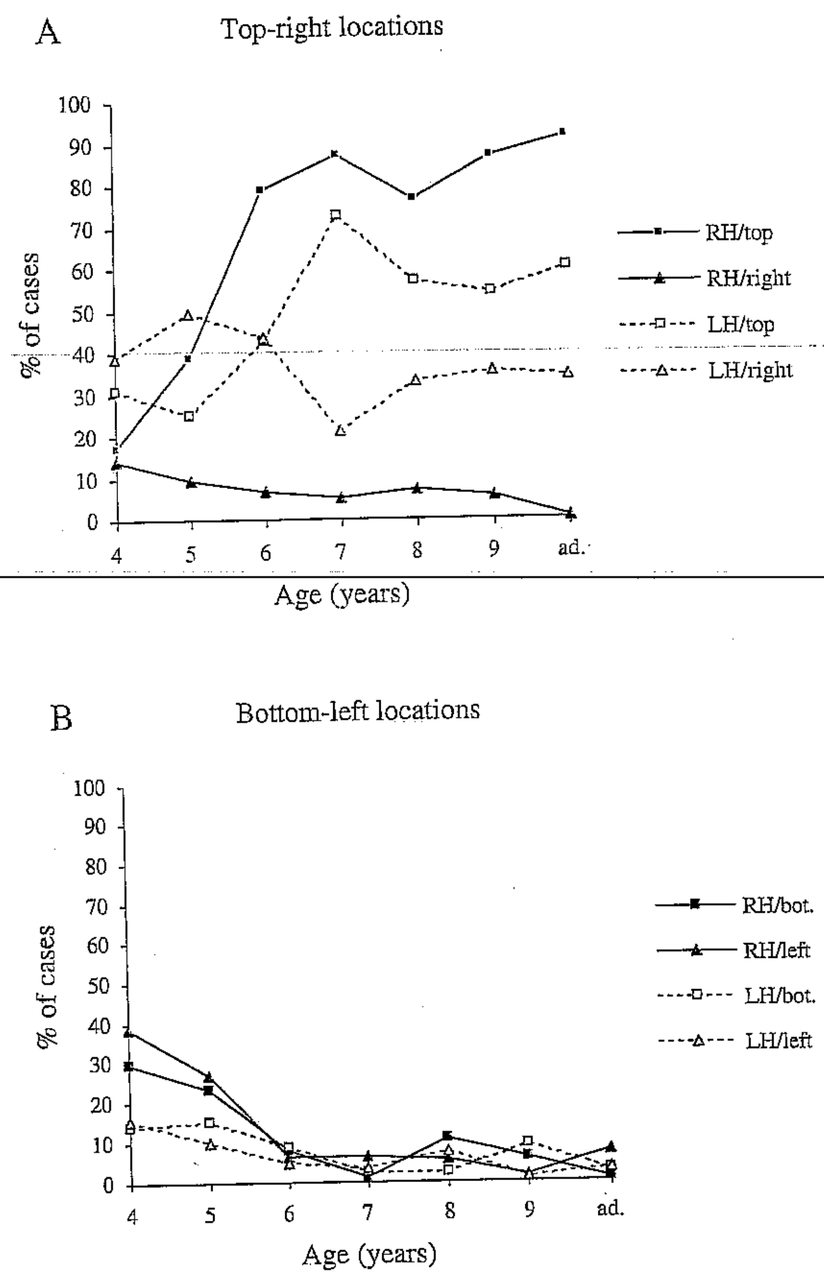


TABLE 1: Occurence of starting positions (in percentages) in top region (11-12-1 o'clock) and bottom region (5-6-7 o'clock) as a function of visual feedback and age.

	Vision Top region	Vision Bottom region	No-vision Top region	No-vision Bottom region
4 years	18.20	28.90	30.10	15.10
5 years	30.10	20.60	34.10	17.80
6 years	67.40	7.90	54.30	8.70
7 years	83.70	1.60	76.20	2.00
8 years	61.90	9.50	71.80	3.60
9 years	73.40	7.10	67.80	7.90

group. Table 1 shows this visual feedback effect as a function of age for the 2 regions where it happens to be significant for children (top: $F(5,72)=3.567$, $p<0.01$, and bottom: $F(5,72)=3.5$, $p<0.01$).

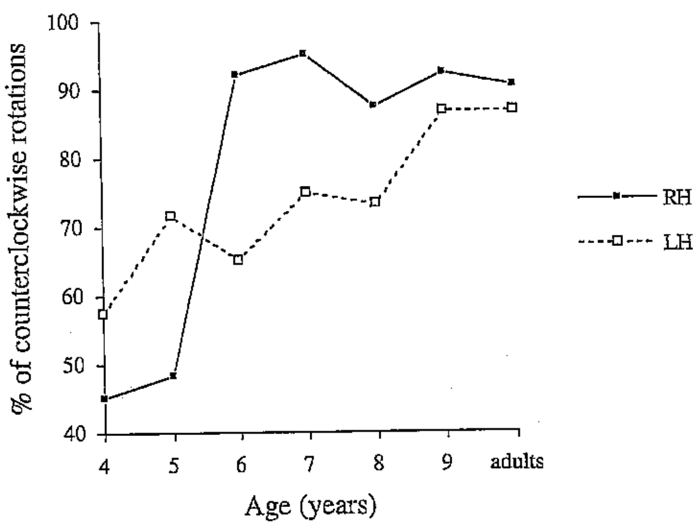
The interactions displayed in Table 1 are rather complementary: the bottom region is more frequented by young children (4-5 yr) when visual information is available than absent, and the top region is more often selected when vision is suppressed. By contrast, from 6 yr onwards, the top region is more often selected when the visual feedback is present (except at 8 yr). The results are thus more complex than formulated by our main hypotheses. The expected Age by Vision interaction depends on the starting location region. The availability of visual feedback affects the choice for bottom-located starting points for the youngest children, i.e. for locations which belong to their preferential choices, and it acts in the same sense for older children, affecting the selection of their preferential locations (the top region). Thus contrary to our hypothesis, the use of visual information does not differentiate younger from older children in a simple way, at least with regard to starting locations: the top migration is not simply due to ensure optimal use of visual feedback.

2. Convergent Changes in Rotational Directions

As shown by Figure 2, there is a significant increase of counterclockwise movements with age ($F(5,72)=6.934$, $p<0.001$). With regard to the dominant hand, the major change occurs between 5 and 6 yr, i.e. is contemporaneous to the top migration of starting locations. The oldest children produce essentially counterclockwise rotations, like the adults.

Post-hoc tests (Newman-Keuls test) carried out on Age revealed that 4 and 5 yr-old children produced significantly less counterclockwise movements than 6, 7 , 8 and 9 yr-old-children (t always >0.334, $p<0.05$ or $p<0.01$ for all comparisons). The youngest children tend to perform more clockwise than counterclockwise movements with the RH. The increase of counterclockwise movements is more smooth with the left than the right hand, but a similar preference for counterclockwise movements for both hands is progressively established, which has also been reported by Thomassen & Teulings (1979) for copying of letters and geometrical patterns. The effect of the use of dominant or non

FIGURE 2: Production of counterclockwise movements as a function of age and hand.



dominant hand on the production of counterclockwise movements depends on age, as indicated by the significant Hand by Age interaction shown in Figure 2 ($F(5, 72)=2.404$, $p<0.05$). Whereas at 4 and 5 yr, children perform more counterclockwise movements with the LH than with the right one, between 6 and 9 yr (and in adults), counterclockwise movements are more frequent with the RH. The Hand effect, however, was not significant (Newman-Keuls test) at 4, 8 and 9 yr ($p>0.05$). In sum, hands tend to function in mirror at 4 and 5 yr, while from 6 yr onwards, both hands tend to produce similar behavior as far as the rotational movement is concerned. Note that in the adults, main effects and interactions were not significant. We can now examine to what extent the SRP itself is sensitive to the experimental conditions, and to what extent it changes with age.

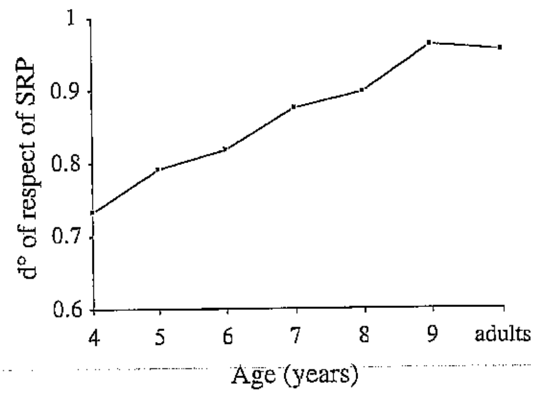
3. The SRP Evolves with Age.

As shown by Figure 3, more than 70% of the drawings performed by 4 yr-old children in different conditions of execution already follow the SRP.

Nevertheless, a significant developmental trend characterizes the evolution of this principle between 4 and 9 yr ($F(5,72)=6.166$, $p<0.001$). Post-hoc tests (Newman-Keuls tests) show that 4 yr-old children differ significantly from 7, 8 and 9 yr-old children (t always >0.257, $p<0.01$), 5 yr-old children from 8 and 9 yr-old children (t always >0.205, $p<0.05$) and 6 yr-old children from 9 yr-old children ($t=0.274$, $p<0.01$). Thus the principle increases in strength between 6 and 9 yr, which confirms the results obtained in our previous experiment (Meulenbroek et al, 1993). The degree of respect of the SRP by adults does not differ from the value obtained at 9 yr.

In adults, the Hand factor was significant ($F(1,14)=19.698$, $p<0.01$), the SRP being more applied when the subjects used the RH (98.8 %) than the LH (91.9 %). Whatever the age, the SRP is globally sensitive to hand also in children ($F(1,72)=24.412$, $p<0.001$) and to vision ($F(1,72)=6.545$, $p<0.01$) but these experimental conditions interact ($F(1,72)=3.961$, $p<0.05$): the suppression of visual information weakens the principle only when the LH is used (it decreases from 82.60% to 74.10%). With the dominant hand, there is no effect of vision (90,90% against 91%), which suggests a major role of handedness in comparison to vision on this graphic production rule, and

FIGURE 3: Evolution of the mean degree of respect of the SRP as a function of age.



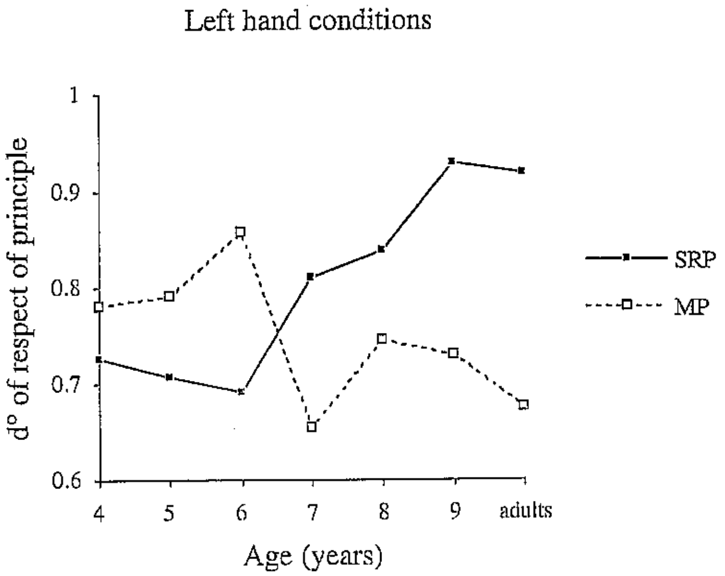
eliminates the hypothesis of a SRP purely visually determined. However if the RH is globally superior to the LH with regard to the SRP, it may be due to the fact that the LH responds better to the "mirror-principle" in which the 11-5 o'clock axis is modified into a 1-7 o'clock axis. We may expect young children to be more sensitive to the mirror-principle than older children, as in the latter both hands tend to behave in a similar way.

Testing for the Mirror Principle in the Left Hand Conditions

Data obtained in the LH conditions was recoded with regard to the mirror-principle (MP) and the degree of respect of either the SRP or the MP was considered as a within-subject factor in an ANOVA for repeated measures carried out with Age (in children) or Sex (in adults) as between-subjects factor, Principle and Vision as within-subjects factors. Figure 4 shows the evolution with age of the degree of respect of both principles.

As expected, the MP fits better the data of the 4 to 6 yr-old children, while the SRP becomes superior at 7 yr. The Age by Principle interaction is indeed significant ($F(5,78)=3.667$, $p<0.01$). In adults, the degree of fit of the data by the MP is lower than at 9 yr, which suggests a further reinforcement of the SRP for the LH after 9 yr. The SRP is clearly superior to the MP for adults ($F(1,14)=26.954$, $p<0.001$). Unexpectedly however, a clear superiority effect of the MP on the SRP is better observed at 6 yr than at 4-5 yr. Post-hoc tests (Newman-Keuls test)

FIGURE 4: Evolution with age of the degree of respect of the SRP and MP for the LH conditions.



revealed a significant difference between both means (SRP and MP) at 6 yr, 7 yr and 9 yr (p always <0.05). It is further worth noting that the non-significant effect of the Principle factor ($F(1,78)=0.579$, $p<0.44$) rules out a pure biomechanical account of the SRP. The SRP seems thus sensitive to handedness between 4 and 6 yr, although the developmental trend characterizing this period is rather counterintuitive. And from 7 yr onwards, the SRP nicely holds for the LH, indicating indeed a relative independence of this syntactical rule from handedness. Note however that the lack of a significant superiority effect at 4 yr may be simply due to the children's choices for starting locations mainly outside (see Figure 1) of the critical regions (top and bottom) which differentiate the SRP from the MP. As a matter of fact, the mirror behavior of both hands observed at that age is such that no incidence on the SRP/MP comparison can be expected: the RH rather mainly obeys the clockwise version of the SRP (on the overall percentage of cases of respect of the SRP by the RH, around 65% are produced with a clockwise rotation), while the LH tends to conform to the counterclockwise version (the advantage of the counterclockwise version for the LH is however not strong, 57% against 43% for the clockwise version). A mirror-hand effect on the SRP is thus present at 4 yr, but takes this specific form. The SRP/MP confrontation becomes pertinent as the starting locations migrate toward the top, between 5 and 6 yr.

Some questions are left open with Experiment 1 and require a control experiment before the results can be discussed. As most of the major changes happen between 5 and 6 yr (in Experiment 1, 6 yr corresponds to the first primary grade), we may explore the impact of handwriting learning on the evolution of the SRP. Experiment 2 allows us to appreciate this role by modifying the matching between chronological age and school level. Further, Experiment 1 showed that a systematic selection of starting locations occurs during development in such a way that entire portions of the circle's circumference are no longer chosen by children. Do older children still respect the SRP when they have to start at the bottom of the circle for instance? An appropriate investigation of the existence of the SRP should establish that this principle holds whatever the starting location imposed to the subject. In Experiment 2, therefore, fixed starting points located all around the circle's circumference are imposed to the subject. As unpractised movements are required from the subject, a general underestimation of the strength of the SRP may be expected in Experiment 2, whatever the age. Nevertheless children should progressively respect the SRP more with increasing age, whatever the starting location imposed.

Experiment 2

The Start-Rotation Principle in a Fixed Starting Locations Design

Method

Subjects

120 right-handed children participated in the experiment. They were divided into 6 age groups of 10 girls and 10 boys each: 5 yr (age range: 4;11 to 5;1), 6 yr (age range: 5;11 to 6;0), 7 yr (age range: 6;11 to 7;1), 8 yr (age range: 7;11 to 8;1), 9 yr (age range: 9;0 to 9;1) and 10 yr (age range: 9;11 to 10;0). As in the first experiment, the distribution of the subjects according to chronological age was redundant with a repartitioning according to a school level criterion, each age group corresponding

respectively to one level, but the correspondence between age and school level was modified in the sense that older children (7 yr-old instead of 6 yr-old) were observed within the first primary grade. The precise correspondence was the following: 5 yr (medium kindergarten class: kd2), 6 yr (last kindergarten class: kd3), 7 yr (first primary grade: g1), 8 yr (second grade: g2), 9 yr (third grade: g3) and 10 yr (fourth grade: g4). Handedness of the youngest children (5 yr) was assessed by very simple tests (see Experiment 1) drawn from Bryden (1977), and the same criterion of selection was considered.

Material and Procedure

Each subject copied a series of 8 circles in 4 conditions twice. As Experiment 1 did not reveal any effect of the size of the model, only 1 size was selected in Experiment 2: the circles had a diameter of 2.0 cm, and they were printed in black ink on white cards of 8 x 8 cm. The major difference with Experiment 1 was that, to induce a starting location at pre-determined positions, we used one of the techniques elaborated by Van Sommers (1984): the model had a small gap (of around 1.5 mm) located at fixed points on the circumference. 8 starting locations were selected (4 above the 11-5 o'clock axis, 4 under this axis): at 12, 1, 3, 4, 6, 7, 9, and 10 o'clock. The order of presentation of the 8 models was random but kept constant for each subject across the conditions. The 5 and 11 o'clock positions were excluded because as they are free with regard to the direction of the rotational movement, they would certainly increase the entropy of the measures of sensibility to the principle. The 2 and 8 o'clock locations were also suppressed because of the duration of the experiment for young children: a mean duration of 35 minutes was necessary for the copying of 64 circles.

The procedure was similar to that adopted in Experiment 1, but the subject was told to copy the model by starting his drawing at the point where the model presented the gap. The experimenter checked whether subjects obeyed the instructions with regard to the imposed starting position. A number of trials were necessary for children before they understood and respected the instructions. The 4 experimental conditions (within-subject design) were the same as in Experiment 1: RH-V, RH-NV, LH-V and LH-NV, and the non-vision condition was obtained by means of the same display.

Data Analysis

The experimenter visually recorded for each circle drawn the direction of rotation of the movement. The respect of the SRP was then assessed for each copying. Means were computed for the 2 trials of the copying of each circle. A subject obtained 32 scores comprised between 0 and 1 (8 starting locations by 4 conditions). A series of ANOVAs for repeated measures (expressed in arcsin measures) was carried out with Age ($n=6$) as a between-subject factor, Hand ($n=2$) and Vision ($n=2$) as within-subject factors for each starting location. A separate ANOVA was also performed on the general mean degree of respect of the principle with Age and Sex as between-subject factors. Furthermore, general means of respect of the SRP obtained by each subject in Experiment 1 and in Experiment 2 were compared to one another in order to test for possible differences induced by the modification in the matching between age and school-level.

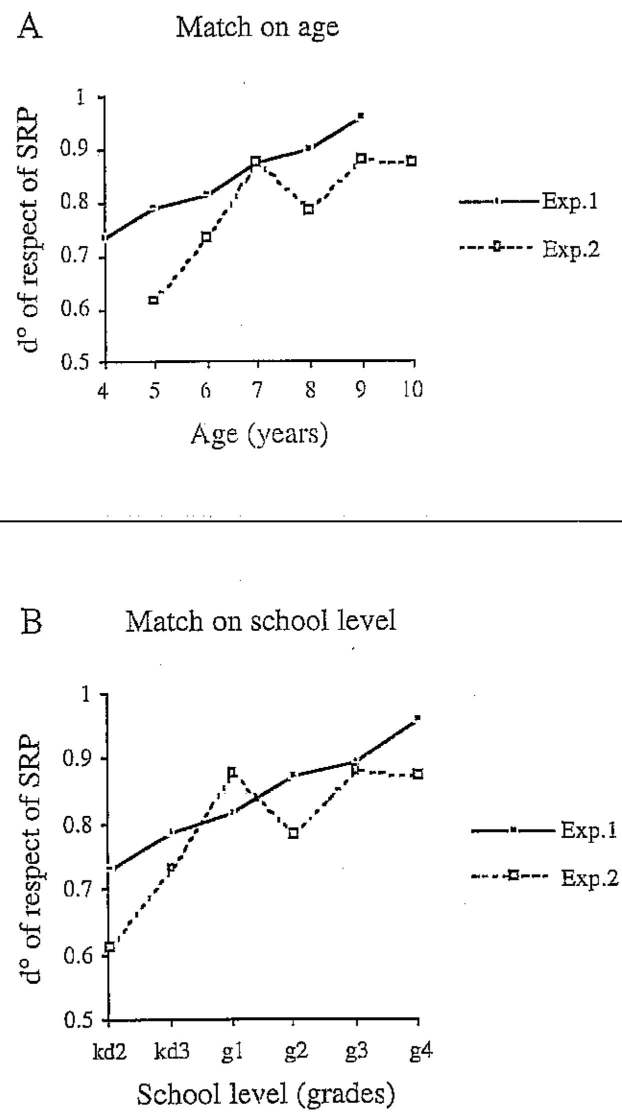
RESULTS

1. The SRP Develops: But Does Handwriting Training Play any Role?

The ANOVA carried out on the general means of the SRP in Experiment 2 confirmed again a significant Age effect ($F(5,114)=9.503$, $p<0.001$). However, a slight decrease of the SRP's strength was observed at 8 yr, but no post-hoc significant differences between 7 and 8 yr or between 8 and 9 yr were found ($p>0.05$). Figure 5 shows the SRP's evolution obtained in Experiment 2 and confronts two kinds of matching between the first and second experiment, either on the basis of chronological age (left panel) or on the basis of school level (right panel).

Figure 5 confirms our hypothesis according to which the SRP would be underestimated by the procedure adopted in Experiment 2. Except once, whatever the matching made between both experiments, the degree of respect of the SRP obtained in Experiment 2 is constantly inferior to that reported in Experiment 1. But as indicated by the F-values of the ANOVAs, the difference between both experiments is greater when the match is performed with respect to age ($F(1,130)=17.454$, $p<0.001$) than to school level ($F(1,130)=5.328$, $p<0.05$). A series of t-tests for independent samples were carried out on these data. When the

FIGURE 5: Comparisons between the evolution of the mean degree of respect of the SRP in both experiments (A: matching on age; B: matching on school level).



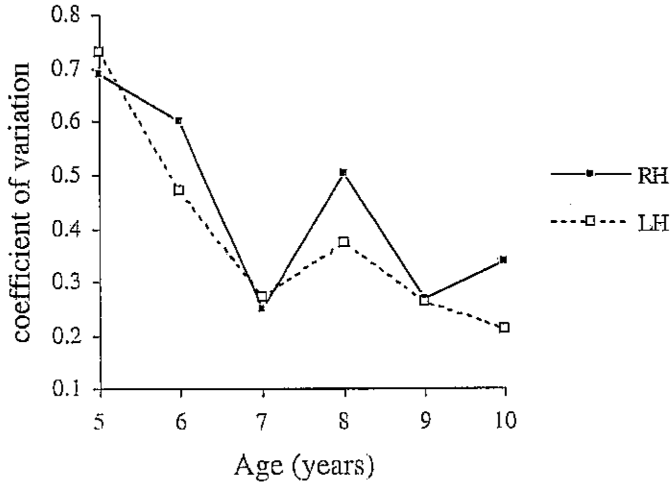
matching was based on age, 2 comparisons of means were significant: at 5yr ($t=-3,659$, $p<0.01$) and at 8yr ($t=-2,145$, $p<0.05$), while they are nearly significant ($p<0.09$) at 6 and 9 yr. When it is established on the basis of school level, only 1 comparison is significant: for the 4th grade ($t=-2,491$, $p<0.05$) although it is nearly significant for the 2nd grade ($p < .073$). It thus appears reasonable to suggest that a matching based upon school level is more appropriate, which provides some support to the hypothesis that an active role of handwriting learning and practice on the development of graphic rules cannot be ruled out.

2. Do Children Equally Respect the SRP whatever the Starting Location ?

If children progressively come to respect the SRP better, we may wonder if they also tend, with age, to be more independent of the effects induced by the starting locations. To explore the intra-individual variability in the degree of respect of the principle, a coefficient of variation of the different values obtained by each subject across the starting locations was computed as a function of hand and vision. An ANOVA for repeated measures was performed on these coefficients of variation and revealed a significant Age effect ($F(5,114)=9.80$, $p<0.001$), Hand effect ($F(1,114)=3.966$, $p<0.05$) and Age by Hand interaction ($F(5,114)=2.851$, $p<0.01$). Figure 6 shows the evolution with age of the mean values of intra-individual variability in the degree of respect of the principle as a function of hand.

The variability clearly decreases with age, which means that the 10yr-old children tend to respect the principle equally whatever the starting location, while younger children appear sensitive to the starting location. As a matter of fact, the 5yr-old children do not follow significantly this principle, neither at 4 o'clock (mean degree of SRP respect of .48) nor at 10 o'clock (.46). The theoretical frontiers which separate clockwise from counterclockwise movements are not well established at this age. Note that the decrease of variability is more regular and faster with the LH than with the RH. In particular, at 10yr, a higher variability with regard to the respect of the principle is linked to the RH than to the LH. A more precise look at the data shows in fact that at this age, the RH responds to a kind of "gradient" of respect of the principle along the different starting locations (the range of respect of the SRP going from .70 to .99), with 2

FIGURE 6: Evolution of the intra-individual variability as a function of age and hand.



symmetrical peaks, one at 3 o'clock (.94), the other at 9 o'clock (.99). This "flexible" behavior of the RH contrasts with a more "rigid" behavior produced by the LH (the range of respect of the SRP going from .82 to .95), although the highest values are again observed in 2 symmetrical positions, at 12 and 7 o'clock. As a matter of fact, the slight superiority of the RH on the LH for starting positions on a horizontal/oblique axis (3-4/9-10 o'clock) and that of the LH on the RH on a mirror vertical/oblique axis (12-1/6-7 o'clock) seems rather general whatever the age. Only at 7-8 yr are the differences between both hands very reduced. An ANOVA for repeated measures revealed indeed a significant Age by Hand by Zone interaction ($F(5,114)=4.603$, $p<0.001$). It is further important to point out that these results globally confirm our hypothesis with regard to the Age by Hand interaction: the Hand effect is large at early ages, almost absent between 7 and 9 yr, and moderate at 10 yr, which is congruent with data reported in Experiment 1.

Discussion

Both experiments confirm that, although already present at 4 yr to a considerable extent, the SRP gains in strength between

4 and 9-10 yr, a period during which the starting locations migrate toward the top and the incidence of counterclockwise rotations increases. If we turn back to our main hypotheses, in both experiments, significant Age by Hand interactions are observed: the Hand effect is large at young ages, reduced at around 6-7 yr, and moderate later. But the expected Age by Vision interaction (small, then large and finally a local visual effect) does not appear in our studies. The suppression of visual information affects the selection of a starting position in the sense that young children select less often bottom-located starting positions and older children less often top-located starting points. Finally, as expected, the starting position is a more sensitive variable to the experimental conditions than the rotational direction.

How can we account for the SRP's development, which benefits from the starting locations migration and from the increase of counterclockwise rotations? Different explanations may be proposed. As shown by the confrontation between Experiment 1 and 2, a role of the school training in handwriting, also suggested by Goodnow et al (1973), seems very probable. A second explanation would state that the SRP's development results from the evolution of motor planning activities. Not only the SRP increases in strength, but it takes different forms during development. With regard to the RH, 2 main forms of SRP were observed. At early ages, children start at the bottom or the left and turn clockwise. If we look at the movement in terms of the ending conditions, an optimal visual control of the ending movement to insure an accurate circle's closure is possible (the entire beginning of the drawn trace is visible), but the ending hand posture is not optimal: the drawing movement ends at 6-7-8 o'clock, with highly flexed fingers, far from the "natural resting point" of the RH located around 11 o'clock (Van Sommers, 1984). Later, children and adults start at the top and turn counterclockwise. Again in terms of ending conditions, the visual monitoring of the ending movement is optimal, as well as the final hand posture since the movement ends at 11-12 o'clock. We suggest indeed that the SRP's development is dependent of how children through practice learn to plan their drawing movement with respect to the ending conditions, which corresponds to Rosenbaum's "end-state comfort" effect (Rosenbaum, 1987, 1991).

Does the hypothesis hold for the LH? 3 different types of deviations from the SRP are observed for the LH. The first one is presented by the youngest children (4 yr) who start at the right and turn counterclockwise. The visual monitoring of the ending phase is not good in this case because the fingers of the LH may prevent vision of the beginning of the drawn trace. As the movement ends at around 2-3 o'clock, the final hand posture is quite good, since the natural resting point of the LH is located at around 1 o'clock (Van Sommers, 1984). The second type corresponds to the MP and is observed essentially at around 6 yr: children start at the top and turn clockwise. In terms of ending conditions, the MP is an optimal solution both with regard to visual control and to hand posture, but this solution is not stabilized through development. The third type characterizes the drawing movements of older children and adults with the LH: they start at the top-right (1-2 o'clock) and turn counterclockwise which is very similar to the solution adopted by the RH. However, though comfortable in terms of final hand posture, this last form of SRP is not optimal with regard to the visual ending conditions (but recall that accurate drawing movements are rarely needed from the non-dominant hand). Does it mean that the late development of the SRP with regard to the non-dominant hand is under the control of the dominant hand, as if a kind of transfer from the right to the left hand were realized at around 7-8 yr? The SRP would become at this moment a common abstract motor rule guiding circular drawing movements. Data related to the Hand effect on the SRP's components in Experiment 1 is congruent with this framework. They illustrate a shift from a "mirror" behavior of both hands in younger children to a "parallel" behavior in older children, also commonly reported in bimanual studies either related to drawing tasks (Abercrombie, 1970) or to other kinds of motor tasks (Corbetta, 1989; Fagard, 1987, 1990). At early ages, both hands respond to similar but mirror biomechanical constraints with regard to the starting location and to the rotational direction when, later, they obey common general rules. It is usually suggested that maturation of interhemispheric communication may be responsible for the progressive decrease of mirror movements (Yakolev & Lecours, 1967; Preilovski, 1972). The latter may be also responsible for the emergence of the last type of SRP's deviation observed for the LH.

The role played by visual information on the SRP seems rather weak. With regard to syntactical aspects of movements, Smyth (1989; Smyth & Silvers, 1987) mainly showed an increase of threading progression strategy in adults when they had to copy patterns without vision. Remembering spatial locations of movements and pencil repositioning were thus minimized. In our study, subjects were asked to draw the figure in one single movement, which makes it understandable that in adults and the oldest children at least, the effect of the suppression of visual feedback was limited. Experiment 1 showed however that the selection of starting locations in the top region decreased when vision was lacking in children aged between 6 and 9 yr. This result provides some support to the hypothesis exposed above on the SRP's development: if the top migration of the starting locations is linked to accuracy requirements, this region should be sensitive to the manipulation of visual information.

Our experiments suggest that the SRP is determined not only by biomechanical constraints but also by determinants which necessitate learning. From this point of view, the SRP may be compared to other motor principles, like the Isochrony Principle for instance which undergoes a significant developmental trend though being present at an early age (Viviani & Schneider, 1991; Vinter & Mounoud, 1991). The fact that this principle characterizes the drawing movements of young children who select starting locations and rotational directions differently than older children reinforces the hypothesis of a strong "constitutional" basis which may consist in the fact that a sequence of movements in which an extension of the fingers preceeds a flexion is conserved, as suggested by Thomassen & Teulings (1979). But, if Experiment 2 showed that the SRP is progressively established whatever the starting location imposed to the subject, it also revealed that a greater intraindividual variability may exist at older ages for the dominant hand. The behavior of the 7-8 yr-old children globally appears more strictly "rule-based" than that of older children, which is congruent with the theoretical perspective developed by Karmiloff-Smith (1990) with respect to graphic routines or linguistic rules. At older ages however, the less practiced hand (the non-dominant hand) remains largely rule-based. This point suggests two lines of discussion around which further experiments may be constructed. Firstly, motor rules like syntactical rules differ from those like the

Isochrony or Isogony Principles in the sense that they do not define theoretical limits toward which some behavioral variables tend, but rather they constitute some kind of "fuzzy" events, of which presence is fundamentally entached of uncertainty. Exploring the contextual or individual factors which affect this uncertainty may be a fruitful line of research (Vinter, 1993). Secondly, if a decrease of behavioral variability clearly appears during development, development may also by contrast produce variability, because a high degree of practice and expertise in a domain (the graphic domain here) may lead to some autonomy with regard to rules. From this point of view, a strictly rule-based graphic behavior may indicate both a high level of cognitive control on the behavior, or on the contrary, a high level of automatization, if the economical advantage of the rule for the control of behavioral and task parameters is taken into consideration.

In conclusion, the experiments showed that the syntactical rules of graphic behavior constitute an interesting research topic for the study of interacting effects between lower order biomechanical constraints and higher order planning constraints, especially when a developmental perspective is adopted. In this perspective, both experiments suggest that biomechanical constraints predominate early in development, the hand effect being important between 4 and 6 yr. Then higher constraints linked to motor planning activities seem to predominate between 6 and 7 - 8 yr, a period during which the role of manual dominance is reduced and drawing behavior becomes largely rule-based. Finally, both kinds of constraints seem to intervene in older children and in adults in which a sensitivity to manual dominance is again observed with regard to starting locations. Studying how planning constraints emerge during development or during learning is an important topic of research in motor behavior. Experiments currently in progress explore to what extent the results reported here with regard to manual dominance and visual information are specific to circular movements or, on the contrary, can be generalized to the drawing of rectilinear geometrical figures.

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