Development of Differentiation Between Writing and Drawing Systems

Esther Adi-Japha and Norman H. Freeman
University of Bristol

When does a writing system emerge out of children's drawing to separate (a) script processing and production from (b) picture processing and production? And does one system's activation help or hinder the other system's operation? Children 4--12 years of age wrote repeated Os and Vs and drew matching shapes, in the contexts of script and of pictures. The technique elicits matching products in order to identify differences between production kinematics in different contexts. A transition occurred around age 6 in which (a) production was more fluent for writing than drawing and (b) activation of one system interfered with the other. Modeling the consolidation of both phenomena generated testable parameters for the slow approach to the adult steady state, involving increasing specialization and the waning of the need for suppression of the two systems' interference.

Within the graphic domain, writing and drawing form notation systems that fulfill different representational goals. Children need to differentiate these two graphic systems in order to become proficient producers of each (Ferreiro, 1986). It is not known at what age and under what conditions children firmly give up drawing their letters and start to recruit dedicated pathways for writing production. In this article we document how developmental differentiation between the notation systems manifests in real-time kinematics of fluent production. A model of the differentiation then serves to specify parameters that gradually approach the adult steady state as propounded by Adi-Japha and Freeman (2000), parameters that provide a metric against which to assess systematic replication.

Children's mastery of the graphic domain starts with drawing and the use of general hand coordination to produce largely smooth-curve scribbles. In their 3rd year, children typically attempt representational drawing, in which smooth curves become representationally differentiated from V-inflections (Adi-Japha, Levin, & Solomon, 1998). Even preliteracy children readily produce different output when asked, say, to draw a spoon and to write the word spoon (Karmiloff-Smith, 1992; Levin, Korat, & Amsterdam, 1996). Children's pretend writing contains many short strokes, whereas their drawing contains more smooth curves, attesting to the use of different action plans (Brenneman, Massey, Machado, & Gelman, 1996; see also Gelman & Greeno, 1989; Tolchinsky-Landsmann & Karmiloff-Smith, 1992). There are two possible developmental routes.

One possibility is that preschoolers generate both their drawing and writing action plans from a single undifferentiated graphic representational resource, thus drawing their letters by altering the frequency of curves and strokes in the output. The other possibility is that the preschoolers have already progressed toward generating the different action plans from distinguishable neural systems, each specialized for production within a different notation system. So the first research question is whether any systemic differentiation (a) occurs at all as early as the age of 4 years or (b) is a later outcome that occurs after a programmed writing system emerges that is due to writing practice. The second research problem that necessarily follows concerns the relation between the two systems whenever it is that they reliably differentiate. Do action plans for drawing reinforce action plans for writing (Glenn, Bradshaw, & Sharp, 1995; Meulenbroek, Vinter, & Mounoud, 1993), or does fluent writing actually demand suppression of drawing, as argued by Zesiger, Martory, and Mayer (1997)?

We report on a new method that provides evidence on the start of differentiation between the two production systems and on the relations between the differentiated systems. The evidence comes from studying production kinematics. It is not possible to rely on the literature for a direct comparison of the kinematics for drawing and the kinematics for writing. Some studies have been conducted on drawing and writing separately, in which case one cannot reliably compare them at the within-individual level to specify the ways in which the two systems' differences manifest themselves.

Other studies have been conducted on writing and drawing within individuals but have worked with the different products that emerge on the page, thus confounding production-process differences with product differences. A method is needed in which children can satisfy the requirements of both notation systems by producing exactly the same shapes when writing and when drawing so that unconfounded kinematic comparisons can be made.

Our choice of a target age range is based on the results of motor control studies on the nonlinear development of dexterity in Western schoolchildren. At age 6, children show fast ballistic movements; at ages 7--8, children tend to change to slower and visually guided movement; and at ages 9--10, children combine, after appropriate practice, the fast ballistic movement characteristic of adult production with visually guided movement, which they use to a lesser extent up to the age of 12 years (Hay, 1984; Meulenbroek & Van Galen, 1988; Smit-Engelsman, Van Galen, & Portier,
The target age range for kinematic comparisons is thus from 4 to 12 years. By tracking kinematic functions in producing written and drawn shapes, one can measure the degree to which a writing advantage (a dynamically more optimized production in writing than in drawing) emerges in standard measures such as increased velocity and fluency (defined later as scarcity of acceleration zero-crossings). If 4-year-olds’ drawing and writing action plans are already generated from differentiating systems, a small writing advantage should be detectable early on and should increase nonlinearly with age. It is conceivable, however, that a writing advantage will start to appear only later with the adoption of the visual-guidance strategy.

Detection of Neural System Differentiation by Output Main Effects

The first research question concerns the differences between the writing and drawing systems. Evidence for neural system differentiation comes from a degree of double dissociation that is manifest in adult neuropatients. Some patients almost lose the ability to write, whereas their drawing is not much impaired, and other patients exhibit the reverse (Anderson, Damasio, & Damasio, 1990; Baxter & Warrington, 1986; Silveri, 1996; Sparr, Jay, Drislane, & Venna, 1991). The assumption is that writing and drawing are controlled from cortical systems that do not entirely overlap even though the two systems must have much in common because they share a common output of hand movement. It would be economical for the brain to dedicate some separate areas to the control of writing and drawing output, because writing is a rule-bound combinatorial notation system with conventional units, and drawing is a compositional system in which lines become blended. When a circle or an oval appears in a page of script, it is most likely to represent the looped letter O; but a circle or oval in a drawing could represent many things via many projections in two or three dimensions (e.g., a ring, disk, hole, bump, or sphere) depending on its context (Freeman, 1980). Legible writing requires that output be constrained by stored letter shapes (A. W. Ellis, 1988; Margolin & Goodman-Schulman, 1992), whereas recognizable drawings need the producer to be more flexible in producing novel line compositions. Zesiger et al. (1997) modeled graphic production by positing (a) that drawing is controlled by a system that has very few constraints on hand movement and (b) that writing is controlled by a neural system that is highly constrained, which allows for practice to result in a high level of automaticity in accessing target shapes. The operating characteristics of the two output systems may be likened to the computational difference between (a) drawing from a drawing package that adjusts line-segment free parameters and (b) writing by using a word-processing package that summons letter shapes from specified fonts by relatively automated keystroke commands. It follows that if normal intact adults are asked repeatedly to write the letter O in order to complete script, the kinematics of their hand movement should differ from the kinematics of drawing the same shape in order to complete a picture. The more automated writing should be faster than drawing (Adi-Japha & Freeman, 1999), as we confirmed (Adi-Japha & Freeman, 2000). Accordingly, it should be possible to track the emergence of kinematic differences with age as an indicator of the gradual separation of the two control systems.

Detecting Relations Between Systems by Output × Context Interactions

The second research question concerns the relations between the two systems. A proposal concerning such relations has arisen from observations of coping strategies used by some neuropatients. Zesiger et al. (1997) argued that the labored writing acquired by some dysgraphic patients is the result of attempts to bypass a clinically impaired writing system by recruiting a partially spared drawing system in order to produce letters’ shapes. The model is one in which normal writing involves inhibition of drawing’s access to letters’ shape representations. Developmentally, writing initially depends on drawing skills but then emerges from drawing, so suppression should ensure that one set of action plans does not interfere with the other. If that is the case, a direct prediction can be made about what will happen if participants are required to produce writing under conditions in which the drawing system is also activated. Writing should slow down relative to when the drawing system is not activated. The new method needed can encompass such a condition, as follows.

When a participant is required to complete a word, the letters already on the page activate the reading system. Looking at script activates a processing system different from the one activated by looking at pictures (Perani et al., 1999; Vandenbergh, Price, Wise, Josephs, & Fracalowiak, 1996). Activation of a processing system prepares the person to generate output (R. Ellis & Humphreys, 1999; Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Jeanne-rud, 1999; Peschl, 1999), and the details of output movements can vary with processing contexts (Thomassen, Tibosch, & Maarse, 1989). In the electrophysiological experiment of Ganis, Kutas, and Sereno (1996), both of the processing systems were activated by having adults read a page of script with a picture rebus embedded at the end. That experiment stopped short of requiring output, but it would be a straightforward matter to replace the rebus with a blank space in which the participant would either have to produce a drawing or write some script. That would tell one whether the anatomically separable processing systems controlled output. Accordingly, in a previous study (Adi-Japha & Freeman, 2000), we used a design in which adults viewed either a picture or a page of script and either had to write or to draw on the page. The design compared (a) the kinematics of drawing portholes on a ship with (b) the kinematics of writing Os, instead of drawing portholes, to complete the name of the ship. Those tasks were cross-compared with (c) the kinematics of writing Os to complete a page of script and (d) the kinematics of drawing bookworm-shaped holes on the script. Here we shall maintain the different terminologies we used for the products and the processes of production. In depiction, the products are Pictures, and the process is drawing. So adding portholes to a ship is a Picture—drawing task. When the task is to insert circles between the letters N . . . N on the side of the ship, in order to show its name, that is a Picture—writing task. Because motor planning for overlearned letters is programmed, 12-year-olds should speed up when writing letter circles relative to when drawing porthole circles. Children who are in the process of differentiating writing from drawing should show less of an increase in their writing speed than in their drawing speed. The youngest testable children might show no effect. These two tasks are shown in the top two left-hand panels of Figure 1. Likewise, as shown in the top two right-hand panels of Figure 1, completing the
letters L...K to produce the word LOOK in a page of script is a Script-writing task, whereas drawing two holes in the page of script is a Script-drawing task. Twelve-year-olds should still write faster than they draw, children who are differentiating a writing system from a drawing system should certainly be helped in writing by the activation of script representation, and younger children who use drawing as a basis for writing might be hampered in writing.

Accordingly, in the present study we used a quasi-Stroop design in which the congruent conditions were writing within a script and drawing within a picture, and the incongruent conditions were writing within a picture and drawing within a script. Note that the only differences between the stimuli in the pairs of pictures, and in the pairs of scripts, are the local shapes that provide cues for the size of the pairs of circles and pairs of letter Os to be produced and that cannot simply be copied to produce O or V shapes. The only procedural problem involved making it completely clear even to the 4-year-olds that they were to draw circles for portholes or bookworm holes in between the rectilinear local shapes. In terms of the computational approach to drawing, a loop, as used for a circle or a letter O, is one of the graphic primitives into which pictures can be parsed (van Sommers, 1984; Willats, 1992). Another primitive is an extended line without closure. V-inflections appear in both writing and drawing. V-inflections are used in writing letters like V and W, or in drawing dinosaur teeth, as shown in the bottom two left-hand panels of Figure 1. For the purposes of this study, it is immaterial whether participants produce perfect circles or meticulously squared-off Vs to match the exemplar they are shown at the start of a trial; as long as the shapes produced are the same across trials, it is feasible to measure kinematics to detect differences in the production of spatially matched products in two notation systems.

In sum, one can give participants pictures and script and specify circles or V-inflections to be added. Differences in production kinematics between repetitious drawing and writing of both circles and V-inflections would show how far action plans have differen-
tiated to implement representations of the notation systems. One can study production kinematics in contexts that (a) activate a supportive notation system or (b) might require suppression of the two systems' interference to release fluent and fast output. Functionally differentiated programming of writing and drawing in 12-year-olds provides data for comparison with the data of younger children of varying ages and for identifying partial differentiation and the development of suppression. Those processes can then be modeled.

Finally, let us look briefly at our previous modeling of adult data (Adi-Japha & Freeman, 2000). The adult data conformed to the modeling used by Ghahramani and Wolpert (1997), Harris and Wolpert (1998), and Wolpert, Ghahramani, and Jordan (1995). Time-based means for the two mixed conditions, Script-drawing and Picture-writing, were an averaged function of the means for the two single-system conditions, Picture-drawing and Script-writing. That is, the data were modeled to show that adults did not need to suppress drawing in order to write. But we expected children to need to do so because of the early dependence of writing on drawing skills. Accordingly, the apposite modeling below is one that sets parameters for suppression strengths with age. The modeling has the advantage that systematic replication is then free to vary input conditions (e.g., to increase the number of words in the script context in order to increase activation of the writing system) and to use modeling to extract suppression parameters to compare with the estimates reported below. There were two other kinematic measures we used with adults (Adi-Japha & Freeman, 2000) that we also looked at here in children. One measure was production time for each separate shape from when the pen hit the page to when the pen was finally lifted (shape time). The other measure was how many times the pen decelerated and accelerated again during shape time (acceleration alternations), that is, the extent of the interruptions to perfectly fluent movement (interruptions indicate dysfluency, as in Meulenbroek & Van Galen, 1988). We hypothesized that there would be (a) a difference in both measures between the outputs of drawing and writing, with age, and (b) an Output X Context interaction in which the simultaneous activation of two processing systems would slow down output and induce dysfluency.

Method

Participants

Sixty-four urban middle-class participants were divided into the following four age groups (each with 8 boys and 8 girls): 4-year-olds (M = 53 months, range = 49–57 months), 6-year-olds (M = 79 months, range = 71–86 months), 9-year-olds (M = 112 months, range = 109–117 months), and 12-year-olds (M = 148 months, range = 143–154 months).

Materials

Each stimulus in Figure 1 was reproduced in a set of four on A3 (42 cm × 29.7 cm) paper so as to set the space for production within a simultaneously presented context (as a further development of the method of Ganis et al., 1996).

Design and Procedure

Before completing each page of four stimuli, participants were shown the shape to produce (instructions are described below). In conditions in which circle drawing was required, target shape and size were specified by showing the participants a 1-cm-diameter circle and having them complete each stimulus on a digitized graphics tablet (WACOM, sampling rate 150 Hz, nominal accuracy of 0.02 mm) by producing pairs of circles to depict either porpoises or bookworm-shaped holes in the delimited production space between the local cues that reminded participants of the size of the targets. In conditions in which O writing was required, the participants were shown a 1-cm-diameter circular O and were asked to complete a set of stimuli by writing diagrams to make either LOOK or NOON. In the other half of the conditions, the target was a V, and the task was to write pairs of letters or to draw pairs of teeth for the dinosaur.

The instructions for the O Script-writing condition were as follows. The experimenter pointed to the displayed O and said, "Two of these could be made here [the experimenter put two fingers in the production space on the upper left stimulus] to make the word LOOK." After completion, the procedure was repeated for the lower left stimulus and then for the remaining two right-hand stimuli if the participant did not spontaneously complete them. With appropriate minor modifications, the same instructions served for each page. The presentation order of two copies of each stimulus sheet in Figure 1 was counterbalanced except that (a) writing and drawing tasks were grouped, and (b) within writing and drawing tasks, Os and Vs were grouped.

Each shape produced yielded two target kinematic measures consisting of (a) shape production time (measured in seconds) and (b) number of acceleration alternations (above the minimal four) per unit of length as a measure of fluency (i.e., number per centimeter, Meulenbroek & Van Galen, 1988), along with two subsidiary kinematic measures of (c) velocity and (d) pause time between shapes (seconds taken for the movement between the pair of shapes in a string), which are included in Figures 2 and 3 for normative purposes. Each shape produced also yielded three spatial measures consisting of (e) curve length of shapes (in millimeters), (f) their y-axis/x-axis ratio scaling, and (g) spacing between shapes (in millimeters), all of which were essential for checking whether participants were producing comparable shapes across the conditions.

Results

First, we present an analysis centered on the kinematic output main effects that distinguish writing from drawing across ages. Second, we consider the role of picture versus script context in its interaction with writing versus drawing. These steps for the kinetic measures of production are then repeated for the spatial measures of the products. The parallel forms of analyses for the kinematic and spatial measures then make it easy to collate the results for the two. Finally, we perform model fitting by collating parameter estimates from the output effect with parameter estimates from the Context × Output effect.

The data were collected after the warm-up trial (one on each page of stimuli from Figure 1). Each measure was subjected, separately for Os and for Vs, to a 4 × 2 × 2 multivariate analysis of variance (MANOVA) on Age (4, 6, 9, and 12 years) × Output (writing vs. drawing) × Context (picture vs. script). This was followed by a second round of analyses involving a separate 2 × 2 (Output × Context) MANOVA on each age group. Testing the hypotheses advanced in the introduction involves concentrating on output main effects and Context × Output interactions.

Kinematic Measures

The first question of how drawing differs from writing is answered wherever the output variable (drawing vs. writing) appeared in main effects and in interactions. The second question of
relations between Picture-drawing and Script-writing systems is answered wherever output appeared in interactions with context (Picture vs. Script).

Kinematic differences between drawing and writing. We focus first on output, reporting as appropriate on the structural variable of age, to answer the first question of whether writing kinematics did differ from drawing kinematics. The output main effect, for both Os and Vs, in dysfluency, \( F(1, 60) = 15.58 \) and \( 14.37, ps < .001 \), respectively, and in shape time, \( F(1, 60) = 15.58 \) and \( 14.37, ps < .01 \) and .05, respectively, showed that writing was more fluent and took less time than drawing. That writing advantage appeared from age 6 onward. A glance at the start of each curve in Figure 2 shows that there were no significant differences between 4-year-olds' writing and drawing anywhere.

Dysfluency. Figure 2A shows the writing advantage for Os at ages 6, 9, and 12, \( F(1, 15) = 5.06, 17.66, \) and \( 10.53, ps < .04, \) .001, and .01, respectively, with a significant advance between ages 6 and 9, correlated \( r(15) = 2.14, p < .05. \) Figure 2B shows a similar function for Vs, with a writing advantage absent at age 4, nonsignificant at age 6, \( F(1, 15) = 4.13, p < .06, \) and significant at age 9 and age 12, \( F(1, 15) = 9.13 \) and \( 10.87, ps < .01. \)

![Figure 2. Kinematic output effects (means and standard deviations) across ages. *p < .05. **p < .01.](image-url)
**Shape time.** The writing advantage for Os appeared from age 6 onward: \( F(1, 15) = 5.12, 14.3, \) and 8.30, \( p < .04, .01, \) and .02, for ages 6, 9, and 12 respectively. Between ages 6 and 9, the shape-time increase for writing was less than that for drawing, \( t(15) = 2.49, p < .03. \) Figure 2D shows a similar function for Vs for ages 9 and 12, \( F(1, 15) = 8.70 \) and 19.17, \( p < .01 \) and <.001, respectively, but with the interesting complication of a reversal between the age of 4 and all other age groups. A post hoc test for independent groups, on the shape-time gap between writing and drawing, was nonsignificant between the ages of 4 and 6, \( t(30) = 1.82, p < .08, \) and significantly different between age 4 and ages 9 and 12, \( t(30) = 2.90 \) and 2.60, \( p < .01 \) and .02, respectively. Between ages 4 and 6, a shape-time writing advantage started to emerge, \( t(15) = 2.69, p < .02. \)

In summary, the indication is that 4-year-olds drew their shapes throughout. Age groups 6, 9, and 12 showed a writing advantage in all measures.

**Kinematic Context \( \times \) Output interactions.** The importance of congruence is shown by the Context \( \times \) Output \( \times \) Age interactions for Os and Vs dysfluency, \( F(1, 60) = 6.01 \) and 4.13, \( p < .01, \) respectively, and for Vs pause time, \( F(1, 60) = 6.99, p < .001 \) (shape times revealed no significant three-way interaction).

Figure 3A shows a cross-over with Os dysfluency. The difference between ages 4 and 6, \( t(30) = 2.78, p < .01, \) was that 4-year-olds were less dysfluent in incongruent conditions, \( F(1, 15) = 4.95, p = .04, \) and 6-year-olds were less dysfluent in congruent conditions, \( F(1, 15) = 4.57, p < .05, \) like the 12-year-olds, \( F(1, 15) = 6.02, p = .03, \) who also significantly differed from the 4-year-olds, \( t(30) = 3.06, p < .01. \) Figure 3B, for Vs dysfluency, is similar in that dysfluency differed between 4-year-olds and the two oldest groups, \( t(30) = 1.99, 2.13, \) and 2.59, \( p < .06, .04, \) and .02, for ages 6, 9, and 12, respectively, even though there was no significant congruence effect at age 4, \( F(1, 15) = 3.59, p = .08. \)

Figure 4D shows a cross-over with Vs pause time; 4-year-olds paused more for Vs in congruent conditions, \( F(1, 15) = 5.95, p < .03, \) whereas the other age groups showed congruence effect. There were significant differences between ages 4 and 6 and between ages 4 and 12, \( t(30) = 2.80 \) and 2.66, \( p < .01 \) and .02, respectively.

In summary, the age 4 group stood out as not benefiting from the activation of a processing system that was congruent with output. In fact, the reverse occurred in dysfluency for these preliterate children (we defer consideration of this matter to the Modeling Systems Development section).

**Spatial Measures**

Whereas kinematic measures reveal how shapes are produced, spatial measures describe the actual products. The purpose of the design was to elicit the same target shapes for both writing and drawing, so we hoped for null results from the spatial analyses (apart from chance positives from multiple analyses) or minor effects to be dealt with later when collating the results of the spatial and kinematic analyses.

Each spatial measure was analyzed as each kinematic measure had been, with a \( 4 \times 2 \times 2 \) MANOVA (Age \( \times \) Output \( \times \) Context), separately for Os and for Vs, followed by a \( 2 \times 2 \) MANOVA (Output \( \times \) Context) for each age group. We focus first on output, reporting as appropriate on the structural variable of age, to answer the first question of whether the spatial product of writing did differ from that of drawing.

**Spatial differences between drawing and writing.** A main effect of output appeared only once, for Vs curve length, \( F(1, 60) = 9.31, p < .01, \) whereby drawn Vs tended to be smaller than written Vs, as can be seen in Figure 5. Here the large variance at age 4 leaps to the eye, and a large variance occasionally appeared at age 6; but ages 9 and 12 show rather small variance.

**Spatial Context \( \times \) Output interactions.** Context and output never appeared together in an interaction. There were no significant outcomes from analyses involving congruent Picture-drawing and Script-writing conditions compared with incongruent Picture-writing and Script-drawing conditions (Figure 5). The contrast with the significant kinematic interactions makes it interesting to proceed to the collation of the kinematic and spatial data.

**Collation of Kinematic and Spatial Data**

The collation conforms to the order that was used before—namely, dealing first with differences between writing and drawing and then with the context by output interaction. It may be recalled that there were no significant differences anywhere for scaling of shapes and for spacing between shapes, which is reasonable given the constrained tasks. These null outcomes contrast with the greater fluency and with the lesser pause time of writing compared with drawing, which were reported in the Kinematic Measures section. For both Os and Vs, kinematics revealed a writing advantage from age 6 onward (see Figure 2). For Os, there were no drawing versus writing differences in spatial measures, and for Vs one such difference was significant only at age 12 in curve length (see Figure 4). The kinematic Context \( \times \) Output \( \times \) Age interactions that appeared both for Os and Vs did not appear for spatial curve length or \( y/x \) scaling. The indication is that the kinematics measures picked up systemic effects that the spatial measures did not pick up, thus achieving the design target of eliciting the same shapes for writing and drawing.

Kinematic measures revealed a cross-over whereby 4-year-olds were more fluent in incongruent conditions than congruent conditions, and then a reversal began that continued a trend up to age 12. There were no spatial effects at all here, with context and output remaining noninteractive. That leaves the kinematic cross-over as an index of relations between processing systems and production systems.

Finally, we conducted three checks on whether spatial differences could explain the kinematics. First, following Viviani and Schneider (1991), we calculated the slope between curve length and production time, and it confirmed the isochronic principle that movement duration is only weakly dependent on movement extent. For Os, the slope-value means (and SEs) were 0.023 (0.015), 0.020 (0.008), 0.023 (0.012), and 0.052 (0.008) for ages 4, 6, 9, and 12, respectively. The question is whether dysfluency output and congruence effects are reducible to curve-length
differences. For Os, output effects were significant for ages 6, 9, and 12, but the corresponding correlation in Table 1 was low for age 6 ($r = −.18$) and effectively zero for ages 9 and 12. At age 12 was where a particularly strong congruence effect had been found for dysfluency, so again the kinematics results cannot be reduced to spatial effects. For Vs, output effects were significant for ages 9 and 12, yet age 9 showed a virtually zero correlation value, whereas 12-year-olds showed a moderate correlation ($r = −.32$). For Vs, a congruence effect was significant at age 12 and cannot be seen at age 6, yet both groups had precisely the same correlation value. So spatial correlation magnitude is not predictive of kinematics.

Finally, we performed micro-analyses on number of segments per page and on starting position for each shape (following Thomsassen et al., 1989). As expected, there was an age effect whereby 4-year-olds produced more segments and, for Os, started less far along on the y-axis, compared with all other groups. But no significant output effect or Context X Output effects emerged; differential segmentation did not explain the kinematics data.

**Overall Data Summary**

Kinematics revealed the gradual emergence of a writing advantage from age 6 onward. Performance in congruent conditions
revealed dysfluency reversal between age 4 and the older ages whereby the 4-year-olds not only failed to benefit from congruent conditions but showed the reverse. Spatial measures for O shapes revealed no main effect of output (except for a tendency for Vs to be smaller in drawing than in writing) and no spatial output by context interaction to match that found in the kinematic measures. Finally, collation of kinematic and spatial measures data did not reveal any points that needed special consideration for modeling. The overall conclusion is that after age 4, an emergent writing advantage that is seen at age 6 then differentiates such that congruence effects become particularly strong by age 12.

**Figure 4.** Spatial output effects (means and standard deviations) across ages. **p < .01.

**Modeling Systems Development**

Modeling has to encompass the strength of the output differences between drawing and writing and the interaction of output with context. The present model involves estimates from fluency data extracted from the dysfluency measure, because dysfluency was sensitive to both sources of evidence, so a model based on both will have the greatest generality. The model takes up where Zesiger et al. (1997) left off. The contents are two knowledge stores, one for picture shapes and one for script shapes, connected to procedural knowledge stores of how to draw and how to
We suggest that literacy involves (a) strengthening the Script-writing link and (b) suppressing interference by the Script-drawing link when writing is required. The stronger the Script-writing link is, the weaker the activation of the Script-drawing link.

Modeling was done in two steps. First, we conducted a transform on the data so as to track changes in the Script-writing and Script-drawing tasks for each age at both group and individual levels. The assumption was that as a result of the strengthening of the Script-writing link, performance on the Script-writing task would improve with age, and that as a result of the weaker activation of the Script-drawing link, concomitant with higher activation of the specialized links of Picture-drawing and Script-writing, suppression of the Script-drawing task would decline with age. That made it interesting to extend the model, suggested in Adi-Japha and Freeman (2000) for adults, to include the early-childhood Script-drawing link. Model fitting yielded values for suppression caused by activation of the Script-drawing link in the Script-drawing task. As will be seen, parameter estimates fell into a series in which suppression declined with age (contrary to the Zesiger et al., 1997, model). The model provides a metric against which to assess systematic replication and to vary input conditions;

Figure 5. Spatial congruence effects (means and standard deviations) across ages.
Table 1
Correlation of Curve Length With Each Within-Shape Kinematic Measure for Os and Vs

<table>
<thead>
<tr>
<th>Age</th>
<th>Os</th>
<th></th>
<th></th>
<th>Vs</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Age</td>
<td>Shape time</td>
<td>Velocity</td>
<td>Dysfluency</td>
<td>Shape time</td>
<td>Velocity</td>
</tr>
<tr>
<td>4 years</td>
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<td>0.80</td>
<td>-0.35</td>
<td>0.00</td>
<td>0.48</td>
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</tr>
<tr>
<td>6 years</td>
<td>0.28</td>
<td>0.29</td>
<td>-0.18</td>
<td>0.07</td>
<td>0.59</td>
<td>-0.32</td>
</tr>
<tr>
<td>9 years</td>
<td>0.39</td>
<td>0.03</td>
<td>-0.01</td>
<td>0.24</td>
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</tr>
<tr>
<td>12 years</td>
<td>0.20</td>
<td>-0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.33</td>
<td>-0.32</td>
</tr>
</tbody>
</table>

we assume that the richer the context, the higher the activation of associated links.

We started by tracking changes in the strength of the Script-writing and Script-drawing task performance. To minimize the effect of developmental change in movement strategy (Hay, 1984; Meulenbroek & Van Galen, 1988; Smit-Engelsman et al., 1994; Viviani & Schneider, 1991), we used the Picture-drawing task for a baseline measure on each age group, normalizing each measure with respect to the Picture-drawing task. For each individual, the strength of the Script-writing task was computed as the ratio of (a) the difference between Picture-drawing and Script-writing to (b) Picture-drawing. The wider the difference, the better the Script-writing task was performed. The strength of the Script-drawing task was computed as the ratio of (a) the difference between Script-drawing and Picture-drawing to (b) Picture-drawing. The assumption was that any extra dysfluency in Script-drawing over Picture-drawing for ages 6–12 would be explained by suppression caused by the activation of an early-childhood Script-drawing link. As a result of the suppression, the Script-drawing task was (on average) performed the worst of all four tasks. Group and individual values were computed to minimize the distance between the overall value, and values were extracted over repetitions.

We noted early on that 4-year-olds had the same output dysfluency when writing and when drawing. The suggestion was that preliterate children generate both script and pictures via a drawing route. Although the children’s stored knowledge of pictures and of script are distinguishable in action plans for drawing and for pretend writing (Brenneman et al., 1996; Gelman & Greeno, 1989; Levin et al., 1996; Tolchinsky-Landsmann & Karmiloff-Smith, 1992), both sets of knowledge have access to procedural knowledge of how to draw. That is denoted in the first diagram of Figure 6. Turning to the Context × Output interaction, we noted

![Figure 6](image_url)

*Figure 6.* Developmental model for the differentiation between writing and drawing, with production routes as arrows. Values in the figure depict the fluency of tasks relative to the Picture-drawing task (e.g., 1.43 is a relative 43% suppression). The lesser the value, the greater the fluency.
that age 4 dysfluency was less in incongruent conditions (in contrast to the performance of the older groups). The assumption was that incongruent conditions interfered with the generation of different action plans for writing and drawing (Brenneman et al., 1996), so the children treated the incongruent tasks with less care, spending significantly less shape time on line and thus giving less opportunity for acceleration zero-crossings to occur, while treating the Script-writing task, with its relatively new letters’ shapes, with extra care. At age 4, 11 of 16 children (binomial, ns) were more fluent in Picture-writing than in Picture-drawing, and 10 of 16 (binomial, ns) were more fluent in Script-drawing than in Script-writing. The Script-writing task showed (on average) the worst performance of all four tasks, with 12 of 16 children (binomial, $p < .04$) more fluent in Picture-drawing than in Script-writing.

By age 6, a writing-specific production route emerged. Script-writing fluency was about the same as Picture-drawing fluency. With two processing systems and two production systems, context-to-output congruence facilitated production. An efficient link between the script context and the writing system required the suppression of the early-stage Script-drawing link. With 12 of 16 children ($p < .04$) performing better at Picture-drawing than at Script-drawing, the 43% suppression value (see Figure 6) was the highest among the different age groups. So, if participants are required to draw in a script context under suppression of the Script-drawing link, their drawing worsens relative to when they draw in a picture context. The accompanying suppression of writing in the picture context relative to writing in the script context cannot be detected at this age, presumably because there is no significant difference between writing and drawing, so integration of drawing actions while writing does not make a difference. Thus, the contribution to the Output X Context effect comes mainly from Script-drawing versus Picture-drawing.

At age 9, a writing-specific production route was well differentiated. Picture-drawing fluency was less than Script-writing fluency. The relative strengthening of the Script-writing link at age 9 is shown by two arrows between the script and writing boxes in Figure 6. With a stronger Script-writing linkage, weaker suppression is needed. Any accompanying suppression of writing in the picture context cannot be detected at this age, presumably because of the combined ballistic and feedback-guided strategy noted earlier, which reduces the effect of context on writing. At this age, differentiation between writing and drawing was consolidated by (a) differences between Script-writing and Picture-writing in 12 of 16 children ($p < .04$), (b) differences between Picture-writing and Picture-drawing in 13 of 16 children ($p < .02$), (c) a significant difference between Script-writing and Script-drawing in 14 of 16 children ($p < .01$), and (d) a significant difference between Picture-writing and Script-drawing in 15 of 16 children ($p < .001$).

At age 12, Picture-drawing fluency was less than script-writing fluency, and suppression of the Script-drawing link was maintained (12 of 16 children, $p < .04$). Now that a clear distinction was established between the Picture-drawing and Script-writing links, and a ballistic strategy was being reused, when participants were required to write in the picture context, their writing worsened relative to when they wrote in the script context because of unwanted integrated drawing action plans. The suppression accompanying writing in the picture context relative to writing in the script context was 0.12 ($SD = 0.03$) and applied to 12 of 16 children ($p < .04$). Thus, with two suppressive processes of similar strength, the Context X Output interaction strongly appears. As at age 9, differentiation between writing and drawing was consistent, with differences (a) between Script-writing and Picture-drawing (14 of 16 children, $p < .01$), (b) between Picture-writing and Picture-drawing (13 of 16 children, $p < .02$), (c) between Script-writing and Script-drawing (13 of 16 children, $p < .02$), and (d) between Picture-writing and Script-drawing (13 of 16 children, $p < .02$).

In sum, tracking the Script-writing and Script-drawing tasks with dysfluency data explains the development of a writing system and the effect of picture and script contexts on writing and drawing kinematics. At age 4, children generate both writing and drawing via a drawing route but are more fluent (a) in Picture-drawing than in Script-writing and (b) in incongruent conditions (Picture-writing and Script-drawing), which they distinguish from congruent display and may treat with less care. At age 6, a writing-specific route emerges, necessitating the suppression of drawing when writing is required. The data reveal heavy suppression in Script-drawing. By ages 9 and 12, both Script-writing and Picture-writing production are significantly better than Script-drawing and Picture-drawing production, and we attribute these effects to Script-writing facilitation. With a stronger Script-writing system, weaker use of the early-phase Script-drawing link is needed, but it is not until age 12 that the accompanying suppression of writing in the picture context becomes significant within a symmetrical Context X Output interaction.

The second step of the modeling was aimed at extracting values for suppression caused by the activation of the Script-drawing link in the Script-drawing task. Following our previous formulation (Adi-Japha & Freeman, 2000), the general model for parameter estimation can be formulated as

$$m = P_{pd} * m_{pd} + P_{sw} * m_{sw} + P_{sd} * (m_{pd} + m_{sw}),$$

where $m$ is a dysfluency measure, $m_{pd}$ is the dysfluency output of the Picture-drawing link (Equation 1, the subscript $Pd$), and $m_{sg}$ is the dysfluency output of the Script-writing link ($Sw$). The corresponding $P$s represent the probabilities that the links will be activated. All $P$s and $m$s change with age. The first term in Equation 1, $P_{pd} * m_{pd}$, represents the activation of the Picture-drawing system. The second term, $P_{sw} * m_{sw}$, represents the activation of the Script-writing system. The third term, $P_{sd} * (m_{pd} + m_{sw})$, originates in the early-childhood activation of the Script-drawing link in the absence of a Script-writing system, and $m_{sd}$ represents extra dysfluency with respect to the output of the Picture-drawing system. The Picture-drawing task is represented by $P_{pd} = 1$, $P_{sd} = P_{sw} = 0$; for age 4, $P_{Sw} = 0$; and at any time, $P_{pd} + P_{sd} + P_{sw} = 1$.

For age 6, $m_{sw} \approx m_{pd}$, and Equation 1 is reduced to $m = m_{pd} + P_{sd} * m_{sd}$. Substituting $m_{sd}$, we find that the Script-drawing suppressive term $P_{sd} * m_{pd}$ in the Script-drawing task has the value of 0.43 ($SD = 0.19$). For ages 9 and 12, we reduce Equation 1 to $m = P * m_{pd} + (1 - P) * m_{sw} + P_{sd} * m_{sw}$, where $P = (P_{pd} + P_{sw})$, and compute the Script-drawing suppressive term $P_{sd} * m_{pd}$ in the Script-drawing task by minimizing the distance between $m_{sd}$ and $P * m_{pd} + (1 - P) * m_{sw} - P_{sd} * m_{sw}$ over repetitions. Minimization was done over the two values ($P, P_{pd} * m_{pd}$) using the direct search method provided by the Matlab package. For age 9, $P_{sd} * m_{pd}$ has the value of 0.26.
These data show that suppression related to the activation of the Script–drawing link declines with age.

The data for Vs present a similar picture, with the age 4 Script–writing task showing the worst performance of all four tasks at this age group, an age 6 Script–writing link strength ratio of 0.04 (SD = 0.16; 11 of 16 children, ns), an age 9 ratio of 0.13 (SD = 0.10; 11 of 16 children, ns), and an age 12 ratio of 0.14 (SD = 0.04; 13 of 16 children, p < .02), along with respective Script–drawing suppression values of 0.32 (SD = 0.13; 12 of 16 children, p < .04), 0.13 (SD = 0.11; 12 of 16 children, p < .04), and 0.17 (SD = 0.07; 11 of 16 children, ns). As with Os, the suppression of Picture–writing relative to Script–writing is detectable at age 12 and has the value of 0.08 (SD = 0.05; 12 of 16 children, p < .04). Using Equation 1, the suppressive term P_{sd} * m_{Gd}/m_{pd} in the Script–drawing task for age 6 has the value of 0.34 (SD = 0.13); for age 9 the value is 0.18 (SD = 0.10); and for age 12 the value is 0.20 (SD = 0.07).

Discussion

The main results are that a writing-specific route emerges, presumably as a result of practicing writing around age 6, and that the emergence of the route gives rise to a production advantage in congruent conditions that link processing and production. Writing in a script context and drawing in a picture context are more fluent than writing in a picture context and drawing in a script context. Prior to the emergence of the writing-specific route, nursery-school age children do differentiate congruent from incongruent displays, but they fail to benefit from such congruence.

Though the new design we used had been tried in a pilot study, it is unlikely that it was optimal for its purposes at this stage of knowledge. One question concerns the contexts.

The most common practice in production studies is to minimize context so as to ensure that full attention is given to the emerging product. Such a practice is useful in studying differences between processing and action systems (Milner, 1998). However, most production takes place in rather rich contexts; it is only the first letter of script that is produced on a blank page, usually with neuromuscular warm-up, and our aim was to study relations between action and processing. The most common practice in processing studies is to supply a rich context for target stimuli to ensure a clearly activated processing system. Thus, to compare picture with script systems activation, Ganis et al. (1996) supplied a page of text with a pictogram in the terminal focal position. We adapted that practice by using rich contexts with a production space in the terminal focal position. It would have been possible to have zero-context conditions for writing and for drawing, but that would have been premature for this particular experiment. Extreme relaxation of control over processing would render the data ambiguous, especially those of the younger children. There would be no guarantee that their comprehension of the task would tally with that of older participants, who might access either writing or drawing systems on verbal request. Had zero-context conditions been included in the randomization, there might have been interference; had these conditions been reserved for the posttest position, cross-comparison would have been jeopardized.

We suggest that the present design lays the basis for converging scaling of contexts. The rich contexts were devised to provide comparable pixel coverages and comparable numbers of lexemes in inputs. It is now straightforward to devise reductions of contexts and to measure whether estimated suppression parameters are a function of the strength of processing-system activation. Doing so would permit a test between an all-or-nothing switching mechanism and a strength-of-activation decision gating. It will be useful to go on to a split-screen design in which both script and picture appear in the visual field but only one of them has to be acted on. Such a design accords with a traditional progression from sequential to simultaneous contrast. It is thus conceivable that stronger results will arise from split-screen presentation, but not enough is known about the two systems’ relations to be sure. This matter is noted again below in our discussion of the modeling of suppression.

The second design feature concerns sampling of products. Production studies either narrow actions to a single shape such as a reiterated loop or allow products to vary so that kinematics cannot be studied, as we noted in our introduction. The design was a compromise between constraining shapes and sampling widely. Extremes were chosen: Os, which become highly automated before the age of 10 years (Vinter & Perruchet, 1999), and effortful linear Vs. Dysfluency phenomena reassuringly applied to both. The growth point is to enlarge sampling within and between linear and curved products. Vs can encompass the letters W, X, Y, and Z, for which there is no reason to expect anything other than replication of the dysfluency data. More interesting are curved shapes. First, consider the aspect of effortfulness. A Q is an O with focal attention needed for the second stroke, similar to a G compared with a C. It will be interesting to discover whether such shapes remove some of the complex differences between O and V in the present data. Second, there may be differences in production kinematics when selecting shapes that are both curved and linear, as with D, P, and R. Enlarged sampling should yield better developmental estimates.

The third design feature concerns ages. Age 4 was chosen to provide as near to floor effects as possible. Kinematic measures fulfilled that aim in the major respect that age 4 differed from the other ages in having no output main effect favoring writing. The suggestion was that 4-year-olds always drew their letters, congruent with the developmental route, noted in the introduction, of having only one representational base for the graphic domain. The suggestion had been that the alternative action plans noted by Brenneman et al. (1996), Gelman and Greeno (1989), Levin et al. (1996), and Tolchinsky-Landsmann and Karmiloff-Smith (1992) were generated from that single representational base. Certainly, neither for Os nor for Vs did 4-year-olds find the script context facilitating writing or the picture context facilitating drawing, unlike the other age groups. In fact, the reverse tended to occur for 4-year-olds. However, caution should be exercised with the youngest group, because both their kinematic and their spatial variances tended to be large, as one might expect for such an early phase of dexterity. By age 6, performance seemed more controlled. All those children had had enough literacy training to be familiar with whole lexemes. Thus at this age it is desirable to investigate relations between age, dexterity, and practice at both reading and writing.

The most secure and crucial finding for a developmental explanation was the emergence of congruence as a facilitator, a positive Context × Output interaction confined to kinematics. We suggest that the phenomenon is worth becoming the target of study. A positive congruence effect is evidence for the integration of pro-
cessing and action into an effective system. That is where it was crucial for the design to compare and contrast two systems. Questions arise concerning relations between the differentiated systems.

The model of Zesiger et al. (1997) posited that normal adults achieve writing optimization by suppressing the Picture–drawing system. But the present modeling led to the suggestion that increasing system differentiation makes suppression progressively less necessary as systemic facilitation develops. According to this view, suppression is a tool for encouraging developing systems to differentiate rather than a gating mechanism operative between differentiated systems. The question can be empirically resolved by modeling parameter estimates from scaled contexts, as noted earlier. But there is reason to believe that in normal adults, whose system differentiation is complete, a reintegration occurs whereby kinematic means become predictable from averaging the characteristic operating velocities of the two systems (Adi-Japha & Freeman, 2000). That reintegration reinforces the suggestion that suppression is a developmental device rather than a characteristic of the steady state.

Finally, there may be applied implications. As noted in the introduction, current research suggests that activation of a processing system prepares the person for output. Let us first consider the importance of fluent writing and conditions that facilitate it. Jones and Christensen (1999) established a highly reliable relation between automaticity in handwriting and the ability to generate written text for expressing ideas at the ages of 6 and 7 years. The magnitude of the effect was surprising. When the effect of reading was controlled, writing speed and accuracy accounted for 67% of the variance in written expression. This finding highlights the importance of early writing practice and the differentiation of a proficient writing-specific route at those transitional ages. We suggest that the use of mixed writing and drawing conditions in the practice of writing, as in writing the word cow in response to a picture of a cow or vice versa, should be reconsidered. We do not doubt that children learn a great deal at the level of lexemes from mixing processing systems, but mixing served only to retard automaticity in the present experiment. As for drawing, our study highlights strong Script–drawing suppression for 6-year-olds. We suggest that even though the children knew they were about to draw, the script context activated writing readiness, which led to suppression of drawing action plans. It will be interesting to discover whether the effect generalizes beyond input-triggered processing systems. That is, asking children to draw with a pen, which they associate with writing, or to draw on the type of page they regard as part of a writing book, might arouse unconscious writing readiness and hamper drawing production. Maybe, to encourage children to draw more and to elicit fluent production, a different graphic apparatus should be used for drawing and for writing.

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Received December 6, 1999
Revision received August 25, 2000
Accepted September 13, 2000