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The elaboration of motor programs for the automation of letter production

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ABSTRACT

We investigated how children learn to write letters. Letter writing evolves from stroke-by-stroke to whole-letter programming. Children of ages 6 to 9 (N = 98) wrote letters of varying complexity on a digitizer. At ages 6 and 7 movement duration, dysfluency and trajectory increased with stroke number. This indicates that the motor program they activated mainly coded information on stroke production. Stroke number affected the older children's production much less, suggesting that they programmed stroke chunks or the whole letter. The fact that movement duration and dysfluency decreased from ages 6 to 8, and remained stable at ages 8 and 9 suggests that automation of letter writing begins at age 8. Automation seems to require the elaboration of stroke chunks and/or letter-sized motor programs.

1. Introduction

Written language is omnipresent in everyday life. Despite its importance, there are not many studies on the cognitive components of handwriting production. The number of studies is even more limited for developmental research. This is surprising, since children spend at least 55% of their school time in motor tasks that involve writing (McHale & Cermak, 1992). The present study intends to gain more understanding on the psychomotor processes that lead the children – through practice – to the automation of grapho-motor production (Auzias & de Ajuriaguerra, 1986). During writing acquisition, children learn to follow a series of rules for letter production. It is a sort of "grammar of action" (Goodnow & Levine, 1973) that specifies where to start writing, in what direction to produce the movements and where to stop them. At the beginning of the learning processes, the application of these rules during letter production involves a strong cognitive load. Writing automation is achieved when this load decreases and letter writing becomes an instrument for communication. In other words, automation appears when the cognitive resources can be allocated to the other components of writing, namely spelling, sentence construction and text elaboration (Berninger & Winn, 2006; Hayes, 2012; Maggio, Lété, Chenu, Jisa, & Fayol, 2011; Pontart et al., 2013). The aim of this study was to deepen our understanding on how the cognitive load decreases with practice and letter writing becomes automatic. We investigated an aspect of writing automation that is related to the way motor information is coded and stored in long-term memory.

Handwriting derives from the intention of communicating in written language. It is a voluntary movement with a clearly specified goal. It requires two major phases. The first concerns motor planning which determines the temporal organization of action. It defines the hierarchy of the different sequences that lead to the goal of the action (Mazeau & Pouhet, 2014). The second phase is movement programming, which refers to the adjustments (size, amplitude, pressure, etc.) that the action requires in a given environment. This research focused on the elaboration of motor programs for letter production. A motor program is a sort of sensori-motor map that codes information on letter shape, the strokes that are needed for producing it and the direction of these strokes. Keele (1968) defined it as "a set of muscle commands that are structured before a movement sequence begins and that allows the entire sequence to be carried out uninfluenced by peripheral feedback." (p. 387). So a motor program is a procedural memory that stocks a chronologically and spatially organized motor sequence. It is activated each time an individual has to produce a letter. The activation of a motor program precedes movement production, irrespective of context and effector (Graham & Weintraub, 1996; van Galen & Teulings, 1983). At the beginning of writing acquisition, the children write letters stroke-by-stroke. With practice, they put the strokes together and writing becomes faster and smoother. In adult-like writing, each letter is represented as a single motor program irrespective of the number of strokes it is made up of (Teulings, Thomassen, & van Galen, 1983; van Galen, Smyth, Meulenbroek, & Hylkema, 1989). So the size of a motor program evolves from a stroke to a whole letter. How does this serial stroke-by-stroke pattern of activation become a global activation of the whole letter?

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1.1. Motor development for letter writing

Motor development for letter writing is a long process that takes place during the first years of elementary school (Chartrel & Vinter, 2004). Letter writing is achieved by learning rules that define manual actions on a writing instrument. Studies on general motor learning during the writing acquisition period shed some light into the understanding of how the children elaborate motor programs through practice. As Halsband and Lange (2006) point out, motor learning is both explicit and implicit. At the beginning, the movements are under explicit motor control. The elaboration of motor programs for letter production starts when the teachers explicitly tell the children how to proceed to produce them. Teachers define a "grammar of action" that guides the children on where to start writing and the path they should follow to write a given letter (Bara & Bonneton-Botte, 2015; Bruner, 1971; Goodnow & Levine, 1973). Goodnow and Levine (1973) defined seven hierarchical rules like "start at a leftmost and topmost point", "draw horizontal lines from left to right and vertical lines from top to bottom". Hence, the rules essentially specify onset and offset points to produce a geometrical model as well as stroke order and direction.

When the children follow the path the teachers instruct them, they are creating a link between sensory stimulation and a specific motor pattern (Wolpert, Ghahramani, & Jordan, 1995). They have to test or explore which movements produce the "best" letter shapes. The quality of the shape refers to its similarity with the model the teacher provided. The children proceed by trial and error learning. They have to generate a movement sequence that needs to be coded as a procedural memory. It integrates the best sensory-motor link. The elaboration of sensory-motor links is done in three stages. The stimulus is processed via sensory receptors. Then, the output is transmitted to the brain, which in turn interprets them to generate motor commands. The latter are transmitted to specific muscles that produce the motor output. This kind of motor learning is explicit in the sense that learning is the result of a *conscious* process that intentionally aims at creating this link. There are several types of sensori-motor links: Hand-eye coordination is necessary to make sure that the target has been reached; visuo-motor integration is involved in the adjustment of the movements to the location of the target; the fine motor skills of the hand control the dexterity required to hold the pen; and kinesthetic feedback is essential to verify that the correct movement has been produced. This multiplicity of sensori-motor links contributes to the construction and stabilization of the motor programs that will be activated for letter production. Poor writers often have deficient sensori-motor links (Bairstow & Laszlo, 1981; Cornhill & Case-Smith, 1996). At the beginning, the generation of these sensory-motor associations is extremely demanding in attentional processes (e.g., Atkinson, 1989; Petersen, Corbetta, Miezin, & Shulman, 1994; Shadmehr & Mussa-Ivaldi, 1994) and working memory (Deiber et al., 1997). This is difficult and time consuming, but is the basis for establishing the associations between letter shapes and the movement sequences required for writing them. Visuo-haptic exploration also participates to the generation of the sensori-motor maps (Bara, Fredembach, & Gentaz, 2010; James, 2010; James & Engelhardt, 2012). The children must select which sensory-motor link is the best for a given letter and decide to execute it. The execution is very demanding because the child has to keep the sensory-motor link active throughout the production and simultaneously process the resulting visual and kinesthetic feedback. This explains why at this stage the writing movements are extremely slow, visuo-motor coordination is difficult and the resulting shapes do not always mirror the model (e.g., Mojet, 1991; Wann, Wing, & Søvik, 1991). The processing of this feedback imposes a strong cognitive load that has an impact on movement accuracy and speed (Laszlo & Bairstow, 1984, 1985; Laszlo & Broderick, 1991; Meulenbroek & van Galen, 1986, 1988a; Søvik, 1974).

Through practice, motor learning will become progressively more implicit. Motor production will require less control and sensory feedback. When a motor sequence is completely learned and requires no explicit motor control at all, we can assume that the production is automatic. The storage in long-term memory of more and more accurate sensory-motor links allows the children to produce letters with less sensory control and intentionality (Meulenbroek & van Galen, 1986, 1988a, 1989). Movement control will improve to render the writing gestures fast, accurate and automatic. Automation is therefore linked to implicit motor learning of progressively more complex sensory-motor associations (Halsband & Lange, 2006). The improvement of motor control internalizes the sensory-motor links as learned actions. These sensory-motor links or maps refer to the same kind of concept writing researchers call a "motor program".

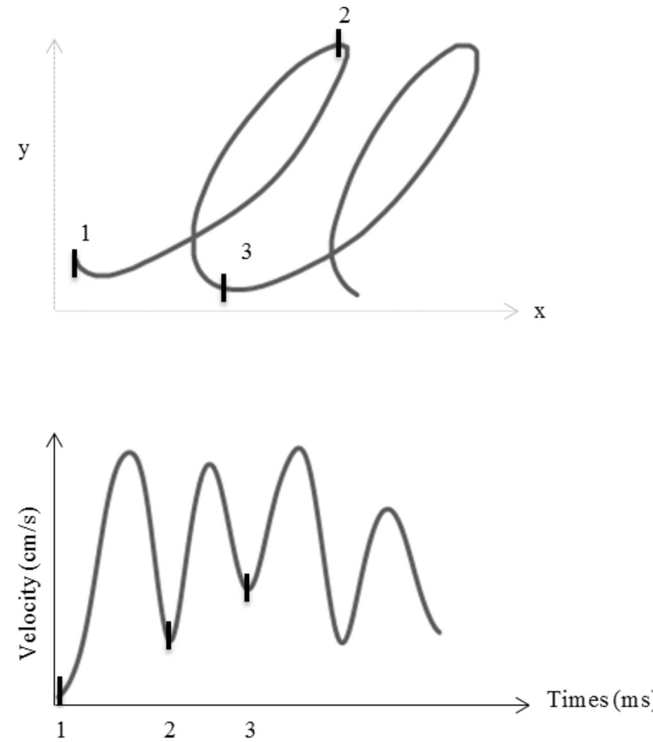

Fig. 1. Illustration of the concept of stroke. Example of segmentation of the first *l* of an *ll* motor sequence produced by an adult. Upper part: Stroke trajectory segmentation on the basis of geometric criteria (xy coordinates). Lower part: Velocity profile (tangential velocity as a function of time) and stroke segmentation on the basis of kinematic criteria (velocity minimum values).

1.2. Motor programs for letter writing

Learning to write a letter requires the memorization of a motor sequence in a given order. At the beginning of the acquisition process the children learn to produce strokes. A stroke is a motor sequence that is limited by two tangential velocity minima at maximum curvature (Meulenbroek & van Galen, 1990). Fig. 1 presents an example of how we segmented the strokes of letter *l*.

To write a letter the children generate it stroke by stroke. With practice and neuro-motor maturation, each letter becomes a sequence of strokes that is represented in long-term memory (Halsband & Lange, 2006). Automation is achieved when the representation has enough geometric and kinematic information to produce the letter with a fast, ballistic and smooth movement. In other words, automation occurs when the representation is "stable". Stability allows for fast retrieval, motor planning and writing execution. Schmidt (1975) called this kind of representation a motor "schema". Since this view of motor control was somehow restrictive, the concept evolved. Halsband and Lange (2006) called it a sensory-motor map. Several studies refer to it as a "motor program". A motor program is defined as "an abstract representation of movement that centrally organizes and controls the