Cognition 136 (2015) 325–336

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

How does the interaction between spelling and motor processes build up during writing acquisition?

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ARTICLE INFO

Article history:
Received 7 January 2014
Revised 14 November 2014
Accepted 17 November 2014

Keywords:
Handwriting
Spelling
Motor production
Children
Cascade

ABSTRACT

How do we recall a word's spelling? How do we produce the movements to form the letters of a word? Writing involves several processing levels. Surprisingly, researchers have focused either on spelling or motor production. However, these processes interact and cannot be studied separately. Spelling processes cascade into movement production. For example, in French, producing letters PAR in the orthographically irregular word PARFUM (perfume) delays motor production with respect to the same letters in the regular word PARDON (pardon). Orthographic regularity refers to the possibility of spelling a word correctly by applying the most frequent sound-letter conversion rules. The present study examined how the interaction between spelling and motor processing builds up during writing acquisition. French 8–10 year old children participated in the experiment. This is the age handwriting skills start to become automatic. The children wrote regular and irregular words that could be frequent or infrequent. They wrote on a digitizer so we could collect data on latency, movement duration and fluency. The results revealed that the interaction between spelling and motor processing was present already at age 8. It became more adult-like at ages 9 and 10. Before starting to write, processing irregular words took longer than regular words. This processing load spread into movement production. It increased writing duration and rendered the movements more dysfluent. Word frequency affected latencies and cascaded into production. It modulated writing duration but not movement fluency. Writing infrequent words took longer than frequent words. The data suggests that orthographic regularity has a stronger impact on writing than word frequency. They do not cascade in the same extent.

1. Introduction

Writing is one of the most important communicational tools in humans. With the arrival of the internet, tablets and smartphones many people spend more time writing emails, chatting or communicating via Short Message System (SMS) than speaking. Despite the importance of writing in our society, the studies investigating written language production are very scarce. How do we recall a word's spelling when we need to write it? How do we produce the movements to form its letters? The answers to these questions are extremely limited. We know even less about how children learn to write. This study examined writing processes from a developmental perspective. We investigated how and when spelling and motor processes interact during writing acquisition.

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http://dx.doi.org/10.1016/j.cognition.2014.11.014
0010-0277/

1.1. Central and peripheral processing in written language production

Writing is a linguistic motor task that involves different processing stages. Surprisingly, researchers have either focused on spelling or motor production. The relationship between the two has hardly received any attention. Spelling refers to central processing. Movement production is instead related to peripheral processing. The distinction between central and peripheral processing levels comes from neuropsychological studies (e.g., Baxter & Warrington, 1986). Patients presenting central dysgraphia had difficulties with spelling processes. Case studies presenting peripheral dysgraphia exhibited difficulties with the motor aspects of writing. The clinical independence of these deficits led researchers to dissociate them. With the introduction of neuroimaging techniques the distinction was confirmed at the neural level (e.g., Beeson et al., 2003). Two recent meta-analyses reflect this view by examining the neural substrates of central and peripheral processing separately (Planton, Jucla, Roux, & Démonet, 2013; Purcell, Turkeltaub, Eden, & Rapp, 2011).

Central processes refer to spelling because word writing involves the selection and activation of orthographic representations (orthographic lexemes). This allows for the recall of the words' letter components and their organization (Caramazza & Miceli, 1990). Most researchers thought that spelling processes are complete before movement initiation. For this reason, they essentially presented latency data. Latency refers to the temporal lapse between word presentation and motor execution. It is informative about the processes involved in lexical access. Researchers investigated for example how letter-sound relationships affected spelling recall (Afonso & Álvarez, 2011; Bonin, Peereman, & Fayol, 2001; Qu, Damian, Zhang, & Zhu, 2011; Zhang & Damian, 2010). This approach elaborated *central* writing models. They included a low level processing "device" devoted to movement production. However, none of the models provided clear information on how writing movements were programmed and produced (e.g., Bonin et al., 2001; Caramazza, 1997). In addition, they did not consider any kind of interaction between the central and peripheral aspects of the writing process. Neuropsychological studies proposed similar models (e.g., Rapp, Epstein, & Tainturier, 2002). The data referred to writing errors produced by dysgraphic patients with impaired orthographic processing (Beaton, Guest, & Ved, 1997; Miceli, Benvengnú, Capasso, & Caramazza, 1997; Rapp, Benzing, & Caramazza, 1997).

On the other hand, research on handwriting production referred to *peripheral* processing. They investigated the selection and activation of motor programs (van Galen, Smyth, Meulenbroek, & Hylkema, 1989). Motor programs contain information on letter shape, stroke order and direction (Teulings, Thomassen, & Van Galen, 1983). These studies reported data on letter and symbol production, but not words. Latency was an indicator of motor program recall and movement preparation. Other measures like movement time and writing speed provided information on motor production *per se*. The idea was to gain understanding on movement control. They did not consider that writing has a communication function. They neglected the implication of higher order linguistic information such as word spelling. In this perspective, we produce one letter after another by activating its corresponding motor program. The movements to produce a letter should be identical, regardless of its spelling specifications.

In sum, most writing research ignored the relationship between central and peripheral processing. van Galen (1991) presented a handwriting model that integrated the two components of writing. He proposed higher order linguistic modules that initiate the writing process: activation of intentions, semantic retrieval and syntactical construction. They were taken from Levelt's (1989) model of speech production because these processes are common to all linguistic movements. He referred to previous speech research for descriptions on how each module functions. These three modules provide input into a spelling module. The information on how lexical selection and activation operated is rather limited. In contrast, he presented abundant details on the processing levels that follow spelling: selection of allographs, size control and muscular adjustment. The low level motor processes regulate the local aspects of letter production. van Galen's (1991) model postulated parallel processing from higher to lower level modules. The central high level modules are always active before peripheral low levels. This occurs because the higher level modules anticipate information on the following parts of the word. This points to the idea of an interaction between central and peripheral processing. Nevertheless, van Galen's model did not describe how the spelling and motor components of writing communicate.

Van Galen referred to dual-route conceptions of spelling. He did not adopt them because he argued that the independence of the two routes was under debate (e.g., Humphreys & Evett, 1985). He concluded the description of the spelling module by stating that "for reasons of simplicity" he preferred an "undifferentiated spelling module" (van Galen, 1991; p. 184). So, according to van Galen's (1991) model, to write a word we will activate its orthographic representation at the spelling module. The representation consists of a linear sequence of letters. It codes letter identity and order (e.g., $C_1A_2M_3E_4R_5A_6$; see Kandel, Peereman, Grosjacques, & Fayol, 2011 for a discussion on orthographic encoding). It is stored in the orthographic buffer until it can be "unwrapped" for serial production. It constitutes the input to the peripheral modules (i.e., allographs, size control and muscular adjustment).

1.2. The interaction between central and peripheral processing

Do central processes affect peripheral ones? Recent research on adult handwriting production suggests that spelling processes modulate the timing of motor processes. Delattre, Bonin, and Barry (2006) manipulated word frequency and orthographic regularity. Word frequency refers to the number of occurrences of a word. Orthographic regularity concerns the possibility of spelling a word correctly by applying the most frequent phoneme–grapheme conversion rules. For example, the French word PARDON (pardon, /paRdɔ~/) is an orthographically regular word. It is regular because the most frequent phoneme–grapheme