THE COGNITIVE CHRONOMETRIC ARCHITECTURE OF WORD AND PICTURE NAMING: EVIDENCE FROM ONSET RESPONSE TIME AND DURATION

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ABSTRACT

Reading is a fundamental skill for functioning in today's society. Given the breadth of activities that require reading, it is important to develop a comprehensive model of basic reading processes. Furthermore, considering that many pictures co-appear with words in everyday life, it is imperative to understand the nature of picture identification processes, as well as how they interact with reading processes. As such, the present thesis focuses on developing a model of reading and extending it to include picture processing. In the present research, experiments on word identification (Experiments 1 and 2) examined onset reaction time (RT) in a word naming task using an additive factors method. The pattern of additive and overadditive joint effects on naming RT among Instructions (INST: name all, name words), Word Frequency (WF: $\log_{10}$HAL), Semantic Neighbourhood Density (SND: Inverse Ncount), and Word Type (WT: regular, exception) supported a cognitive chronometric architecture consisting of at least two cascaded stages of processing, with the orthographic lexical system as the locus of the INST x WF and the INST x SND interactions, and the phonological output system as the locus of the WF x WT and the SND x WT interactions. Additivity between INST and WT supports the notion that these variables affect separable systems, and a WF x SND interaction supports a common locus of their effects. These results support a dual-route cascaded model over parallel processing models of basic reading. We also examined response duration (RD) in these data by recording and hand-marking vocal responses, which provides evidence that reading processes are ongoing even after the initiation of a vocal response, and supports the notion that the more lexically a word is read, the shorter the RD. As such, the effects of WT and INST on RD were opposite to their effects on RT. Given the dissociating effects between RT and RD, these results provide new challenges to all models of basic reading processes. Experiments on picture and word identification (Experiments 3 and 4) involved localizing common systems and connections between these processes, and served to extend the dual-route model of reading. These experiments examined naming RT and RD for exception and regular words, and their corresponding pictures. The pattern of joint effects on RT among Format (pictures, words), Picture-Orthography Agreement, WF, and WT (regular, exception) supported a triple-route cascaded model. The results suggest the orthographic lexical system is accessed for both picture and word naming, and demonstrated a dissociation between regular and exception words on RT versus RD, whereas pictures consistently yielded an exception item advantage for both measures.

Experiment 4 examined Arabic digits and their corresponding number words, and found that Arabic digits produce shorter RDs than number words. In general, the results suggest that the picture and word identification systems are strongly coupled between the picture memory system and the orthographic lexical system, particularly for items that rely on “whole-word” lexical representations. We argue that RD provides a wider window for exploring cognition, and a converging measure of lexical processing, which must be considered when studying basic identification processes of any stimulus type. The development of a comprehensive model of basic reading processes will help identify behavioural markers of normal reading processes, and will serve to advance research on basic word recognition. In addition, given that a broad definition of ‘literacy’ should include picture processing, the development of a model that includes picture processing will serve to advance research on how reading and picture processing interact with each other, which may be critical for individuals with low literacy skills.

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LIST OF ABBREVIATIONS

AFM	Additive factors method
CI	Confidence interval
EXC	Exception
GLM	General linear model
GPC	Grapheme-to-phoneme conversion
HAL WF	$\log_{10}$ HAL word frequency
INST	Instructions
NWs	Nonwords
O-P	Orthography-phonology
O-S-P	Orthography-semantics-phonology
PDP	Parallel distributed processing
POA	Picture-orthography agreement
RD	Response duration
REG	Regular
RT	Reaction time
SMA	Supplementary motor area
SND	Semantic neighborhood density
SUBTL WF	Subtitle word frequency
WF	Word frequency
WT	Word type

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CHAPTER 1

AN INTRODUCTION TO BASIC LANGUAGE PROCESSES INVOLVED IN WORD AND PICTURE IDENTIFICATION

This thesis is based on two journal manuscripts. The first section, *I. Word Identification*, is based on:

Gould, L., Cummine, J. & Borowsky, R. (2012). The cognitive chronometric architecture of reading aloud: Semantic and lexical effects on naming onset and duration. *Frontiers in Human Neuroscience, Special Section on Meaning in Mind: Semantic Richness Effects, 6*(287), doi:10.3389/fnhum.2012.00287

The second section, *II. Picture and Word Identification,* is based on:

Gould, L., Anton, K., & Borowsky, R. (submitted). Reading pictures: Interactions between picture and word naming. *Visual Cognition.*

Reading is a fundamental skill for functioning in today's society. There are many day-to-day activities that require sufficient reading skills, such as being able to read a bus schedule, a TV guide channel, directions for preparing food, labels on a roadmap, signage on streets, bills and bank statements, navigating the internet, or finding medication at a pharmacy. Given the breadth of activities that require reading, it is important to develop a comprehensive model of basic reading processes. Furthermore, considering that many pictures co-appear with words in everyday life, such as in advertising, newspapers, textbooks, social media, grocery labels, playing video games, and watching subtitled foreign films, it is imperative to understand the nature of picture identification processes, as well as how they interact with basic reading processes. As such, the present research focuses on developing a model of basic reading and extending it to include picture processing.

I. Word Identification

Our knowledge about word meaning is generally referred to as semantic knowledge. Semantic knowledge represents our worldly understanding of what things mean, how to interact with objects in our environment, how to interpret symbols and actions, as well as the meanings of words. As such, semantic knowledge is core to understanding not only language, but to understanding perception and cognition, and our world, in general. Although many years have been devoted to studying semantic knowledge, this concept has been a difficult one to elucidate due to its breadth. There are numerous ways to operationalize semantic processing, which provides multiple perspectives on the issue, but also broadens the problem space as opposed to narrowing it. However, as researchers have focused on and operationalized particular aspects of semantic knowledge, some substantial progress has been made (e.g., Balota, Yap & Cortese, 2006; Yap, Tan, Pexman & Hargreaves, 2011).

Yap, Pexman, Wellsby, Hargreaves, and Huff (2012) recently demonstrated that semantic variables such as semantic neighbourhood density (SND), number of features, semantic ambiguity (i.e., number of senses), imageability, and body-object interaction were reliable predictors of performance in several tasks of lexical processing. The only exceptions were the effects of SND and semantic ambiguity in the speeded pronunciation task. The null effect of semantic ambiguity in pronunciation has previously been argued to represent a lack of semantic influence in naming compared to lexical decision, for which there is an advantage for words with multiple meanings (Borowsky & Masson, 1996). Borowsky and Masson argued that the lexical decision task involves a monitoring of activation in orthographic, phonological, and semantic systems, thereby allowing for a familiarity-based lexical decision to benefit from multiple semantic representations (see also Balota & Chumbley, 1984; Chumbley & Balota, 1984), whereas naming can be accomplished without involvement of semantics and thus the lesser effect of semantic ambiguity in naming. It is possible that the effects of SND may behave similarly to the effects of semantic ambiguity, in that there may be an advantage for higher SND under conditions that encourage lexical access (see also Balota et al., 2004; Yap & Balota, 2009). One of the goals of the present research is to explore word naming behaviour under conditions where lexical access is either compulsory or not. Another goal is to expand the investigation of naming behaviour to more than just the onset of response, as has been done by Balota, Bolands, and Shields (1989). Balota et al., explored duration of vocalizations in a semantic priming paradigm, similar to Balota and colleagues' work with other basic reading tasks involving parameters beyond response onset (e.g., Abrams & Balota, 1991; Bangert, Abrams & Balota, 2012). As a general principle, going beyond the initial onset of response provides a larger window through which to view the effects of underlying cognitive processes. As perhaps the most ecologically valid basic reading task, the task of reading aloud is critical to explore in terms of both of our goals of manipulating lexical/semantic access and examining both response onset and duration.

Methodological Considerations in Reading Aloud

The measurement of vocal onset *reaction time* (RT) has been central to research on basic cognitive processes since the invention of the voice-key (Dunlap, 1913, Boder, 1933). Although many researchers had initially assumed that the initiation of a vocal response first requires the generation of a complete phonological code for the entire word, this assumption has been challenged in recent years (e.g., Hudson & Bergman, 1985; cf. Rastle, Harrington, Coltheart, & Palethorpe, 2000). Furthermore, research involving a delayed naming task (i.e., pronunciation is delayed until a cue is given) has demonstrated that the frequency effect still manifests in onset RT even after delays up to 1400 ms (Balota & Chumbley, 1985; see also Monsell, Doyle, & Haggard, 1989). As such, it appears that the influences of lexical variables such as word frequency are still having an effect even after sufficient time to prepare and initiate a response. Delayed naming evidence notwithstanding, it is unclear why it would be necessary to hold off the initiation of the vocal response until the entire word is decoded, especially given the typical instructions to name words as quickly and accurately as possible. Furthermore, several models of reading refer to: (i) a relatively slow serial grapheme-to-phoneme translation system, which allows for the naming of novel words in a serial/cascaded fashion, as well as (ii) a relatively fast lexical system, which allows words to be named in a "whole-word" manner (e.g., Coltheart et al., 2001, 2006; Borowsky et al., 2012). Nearly a century of research based on vocal onset RTs has been conducted to explore these and other basic reading processes. Given that cognitive processes could be operating beyond the initiation of vocal onset, it is important to explore measures of naming responses that go beyond measuring the onset. Another major goal of our present research involves exploring the *response duration* (RD) of vocal responses in addition to RT.

Research into the chronometric architecture of cognition also has a long history. Donders' (1868, 1969) subtractive logic provided the first method of examining when certain cognitive processes were occurring. For example, if one were to subtract the time that it takes to respond to the presence or absence of a flash of light, from the time that it takes to respond to a flash of light of a certain color, one could attribute the difference in time to color processing. However, this logic requires the untenable assumption of *pure insertion*, whereby more than just color processing has been inserted into the task (e.g., holding in memory the instructed target color). Sternberg (1969) argued that *pure insertion* was not a tenable assumption, and developed the Additive Factors Method (see also: Borowsky & Besner, 1993; Roberts & Sternberg, 1993; Stolz & Neely, 1995; Yap & Balota, 2007). By looking at the joint effects of the variables, this method allows for the examination of whether two variables are affecting the same system in time (i.e., rising overadditive interactive effects on RT) or separable systems in time (i.e., additive effects on RT). Another major goal of our present research involves exploring the joint effects of four variables that are known to reflect the operation of subsystems of basic reading processes: Semantic Neighbourhood Density (SND), Word Frequency (WF), Word Type (WT), and Instructions (INST).

Effects that Reflect the Operation of Lexical/Semantic Subsystems

As described earlier, semantic knowledge is core to any model of language processing. Semantic neighbourhood density has been shown to be a measure of semantic processing (Shaoul & Westbury, 2010). This measure reflects the number of words that co-occurred with a target word within a fixed distance threshold, as determined by an analysis of 57,153 words present in Wikipedia in April 2010 (a total of 971,819,808 occurrences). Words that have a large number of semantic neighbours show benefits relative to words that have a small number of semantic neighbours, as was shown by Yap et al., (2012) using the tasks of: lexical decision, go/no-go lexical decision, speeded naming, progressive demasking, and semantic classification. Semantic neighbourhood density could serve to facilitate semantic processing, as well as connections to other word-level systems such as the orthographic lexical system and the phonological output system, in that the higher the SND the higher the number of facilitative connections both within and between levels (as is typical of interactive activation architectures, McClelland & Rumelhart, 1981; Coltheart, 2006; Yap et al., 2012; see Figure 1).

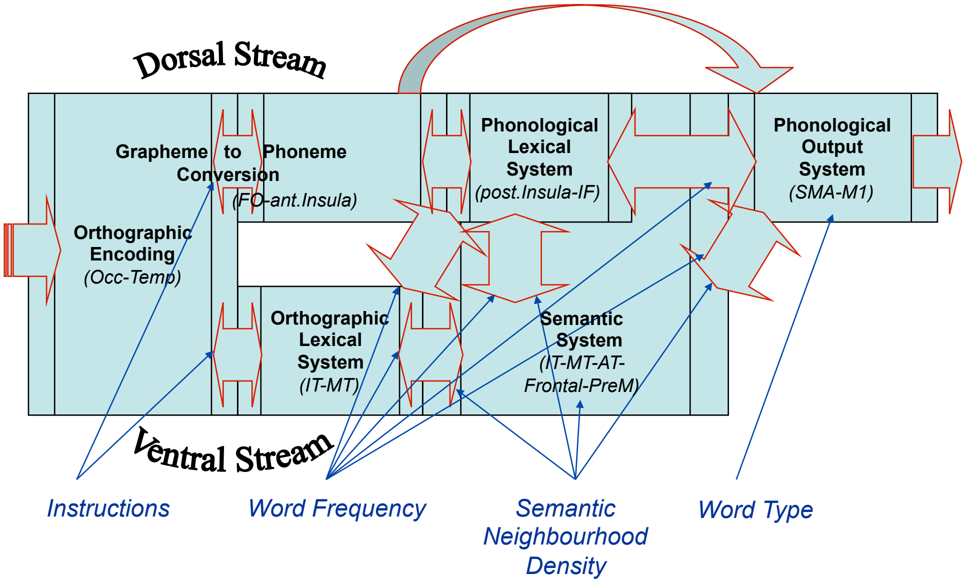

Figure 1: A dual-stream, ventral-lexical, dorsal-sublexical, cascaded processing framework for basic reading processes.

There are several models that propose that printed WF effects manifest in the lexical/semantic systems (e.g., Borowsky & Besner, 1993; McCann & Besner 1987; McClelland & Rumelhart, 1981; Morton, 1979; Reynolds & Besner, 2005). For example, WF could affect the connections between the lexical subsystems and semantic system, whereby the more frequently a word is read, the faster the rate of activation in these systems, and the faster the RT (see Figure 1; Borowsky & Besner, 1993). The WT (i.e., regular versus exception words) effect on RT is another effect that reflects basic reading processes. Given that regular words (REG words) can be pronounced correctly through both the sublexical grapheme-to-phoneme conversion (GPC) route (allowing the word to be "sounded out") or the orthographic lexical route (allowing the word to be read in a "whole-word" manner), these routes produce the same pronunciation at the phonological output system. Conversely, exception words (EXC words) must be processed via the orthographic lexical route to be pronounced correctly. Exception words produce a slower RT because the two routes produce conflicting pronunciations, and a single phonological output must ultimately be selected, particularly in the case of low frequency EXC words.

Word Type has also been found to interact with WF on naming RT, whereby EXC words produce slower RTs and elicit a greater WF effect, compared to REG words (e.g., Cummine, Sarty, & Borowsky, 2010; Monsell, Patterson, Graham, Hughes & Milroy, 1992). This same interactive pattern has been shown on the Blood Oxygenation Level Dependent function intensity in the supplementary motor area (SMA), which likely represents the phonological output system given that the SMA is the last cortical region prior to activating the motor cortex (see Figure 1; Cummine et al., 2010). Other reading route reliance effects have also been reported, whereby there is flexibility on route reliance depending on stimulus and task manipulations (e.g., Borowsky, Owen & Masson, 2002; Rastle & Coltheart, 1999; Reynolds & Besner, 2005; Zevin & Balota, 2000; see Balota, Yap, & Cortese, 2006 for a review). Given the proximity of SND effects to WF effects in the basic reading architecture, in that they both involve lexical/semantic systems, it seems reasonable that SND and WF should also interact due to these common influences.

Researchers have begun to explore the strategic effects of INST on reading. For example, Hino and Lupker (2000; Kinoshita & Woollams, 2002) presented participants with a list of words and nonwords (NWs), and used what we refer to as a *name words* condition and a *name all* condition. Instructions to *name words* required the participant to name a stimulus aloud only if it spells a word, which forces the participant to process the word via the orthographic lexical route, as they must first verify that the stimulus is in fact a word (see Figure 1). Cummine, Gould, Zhou, Hrybouski, Siddiqi, Chouinard, & Borowsky (2012) provided direct functional and behavioural evidence that INST to *name words* forces reliance on the orthographic-lexical route. We reported that INST to *name words* showed greater visible activation along the ventral-lexical stream, as well as produced greater WF effects on RT relative to INST to *name all* stimuli. There was no interaction between INST and WT (i.e., additivity), but there was an interaction between WF and WT under the normal *name all* instruction condition. When the Additive Factors Method (AFM) is employed, additive and interactive joint effects can reveal the loci of effects among the processing systems, and how many systems are involved in the cognitive chronometric architecture.

Additive Factors Method (AFM): Word Identification

The additive factors method proposes that if two variables produce a rising overadditive pattern on RT (i.e., overadditive and increasing from the point of origin, such as the WF x WT interaction described above, and from this point forward we will refer to this as a rising overadditive interaction), it is indicative of those variables affecting a common system of processing in time (see Figure 2). Also, the rising overadditive interaction between INST and

WF is indicative of these two variables affecting a common system (Cummine et al., 2012). In contrast, if two variables produce additive effects on RT, those variables are assumed to be affecting separable (even if they are cascaded; McClelland, 1979) systems of processing (see Figure 3). As such, the additive pattern found between INST and WT is taken to indicate that those variables are affecting separable systems of processing. Taken together, these joint effects support a cognitive chronometric architecture of at least two systems (see Figure 4), whereby INST and WF interact in a relatively early system that serves to gate the processing of words through the orthographic lexical route when the INST are to *name words* only (resulting in a lower threshold, see Figure 2 and 3), and WF and WT interact in the relatively late phonological output system in a similar fashion. The present research examines SND in addition to these variables in order to further constrain the architecture for basic reading processes. Given that WF and SND affect some common systems and connections, one would expect that SND should show similar joint effects with INST and WT as did WF (see Figures 1 and 4).

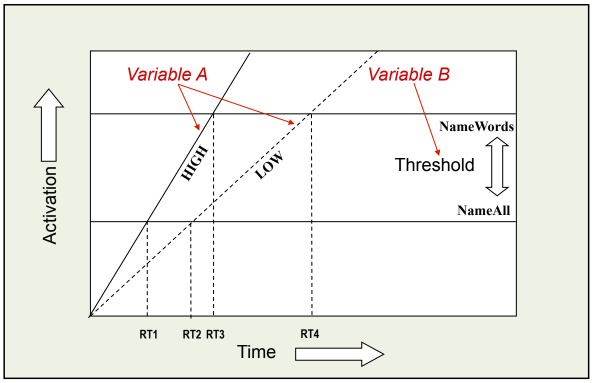

Figure 2: Overadditive interaction between INST and WF. An Additive Factors Method interpretation of this interaction is that both INST and WF are affecting a common system in time. If INST are assumed to affect the threshold for activation, and WF is assumed to affect the rate of activation over time, or vice versa, then the points in time when each rate crosses a threshold correspond to the average onset RTs. [(RT4 – RT2) > (RT3 - RT1)] and [((RT2 + RT4) / 2) > ((RT1 + RT3) / 2)]. WF and WT interact in a similar fashion.

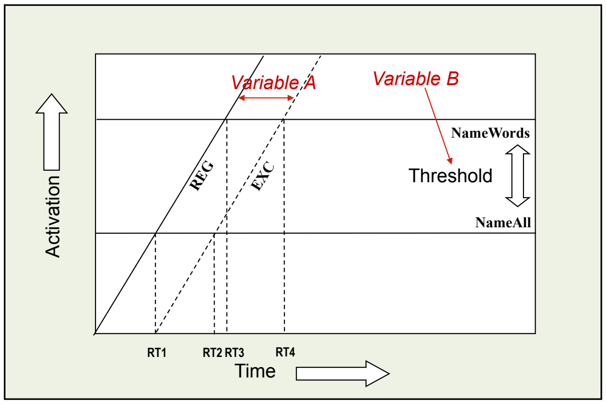

Figure 3: Additive joint effects between INST and WT. An Additive Factors Method interpretation of this additive effect is that INST and WT are affecting separable systems in time. If INST are assumed to affect the threshold for activation (i.e., the amount of time it takes to verify that a letter string spells a word), and WT is assumed to shift the rate of activation over time (i.e., the time it takes to choose among the competing phonological codes for EXC words), or vice versa, then the points in time when each rate crosses a threshold correspond to the average onset RTs. [(RT4 – RT2) = (RT3 - RT1)] and [((RT2 + RT4) / 2) > ((RT1 + RT3) / 2)].

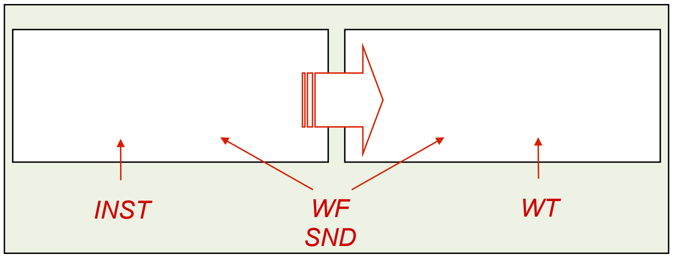

Figure 4: A cognitive chronometric architecture to account for the INST x WF, INST x SND, WF x WT, and SND x WT rising overadditive interactions, and INST + WT additivity.

Naming Response Duration

As previously mentioned, one major goal of our present research involves not only exploring measures of onset RT, but also the RD of vocalizations. Previous research on naming responses has almost solely relied on voice-key measures of *onset* RT. However, given that basic reading processes may still be operating while initiating a vocal response, onset RT measures may not be comprehensive enough. Examining the *duration* of vocal responses should serve as an important additional measure of word processing. Balota, Boland, and Shields (1989) showed that RD is an important converging measure of reading processing in that naming RDs are significantly shorter when a related word is presented. Given that their relatedness manipulation served to decrease RD, this supports the notion that manipulations that enhance lexical/semantic processing yield shorter RDs. Thus, one can predict that shorter RDs should reflect lexical "whole-word" reading, whereas longer RDs should reflect sublexical GPCs. Consistent with the view that RDs can reflect important aspects of cognitive processing post-onset RT, Kawamoto, Kello, Higareda, and Vu's (1999) research on onset and rime durations suggests that the criterion to initiate pronunciation is based on the initial phoneme and not the whole word. That said, RD effects could also reflect how familiar we are with a given word's pronunciation, whereby the more often we pronounce a given word, the shorter the RD could get as a function of the word being read more lexically over time.

Our present research also contributes a novel means of measuring RT and RD in word recognition, whereby one manually analyzes speech envelopes of verbal responses to objectively measure the onset and offset of a naming response. Previous studies have found that using voice-keys to measure onset RT may be quite unreliable. For example, a study by Rastle and Davis (2002) found that different types of voice-keys can produce different results, whereby the voice-keys were often triggered at different points in time following the actual onset of the naming response. They found that hand-marking the acoustic onset of each word using visual waveforms of intensity over time can produce less error than voice-keys, and thus suggest that visually investigating these waveforms may be an important way to check voice-key onsets. We also note that the proportion of errors that are due to voice-key problems can be quite substantial (e.g., Balota et al.,'s, 2007, large scale study of naming reported that nearly 13 percent of naming errors were due to voice-key problems). Our lab has begun to digitally record participants' vocal responses and then manually inspect each vocal response using PRAAT digital software (Boersma & Weenink, 2011). By using both visual and auditory cues to identify vocalization onset and offset, it allows us to precisely measure the onset RT and RD of each response. Given the potential for variability of voice-key measurements, in the present experiments we analyze the RTs obtained via hand-marking (Experiment 1), and RTs obtained via a voice-key (Experiment 2). Importantly, we also measure the RDs via hand-marking in both experiments, which has not been previously reported.

II. Picture and Word Identification

Over the past three decades, there has been a steady growth of empirical research dedicated to studying the cognitive processes involved in basic word recognition. This research has led to the development of advanced methods for examining the chronometric architecture of reading, and as a result, several dual-route models of basic reading processes have been proposed (Borowsky, Esopenko, Gould, Kuhlmann, Sarty & Cummine, 2012; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Cummine, Gould, Zhou, Hyrbouski, Siddiqi, Chouinard, & Borowsky, 2013; Gould, Cummine, & Borowsky, 2012). Likewise, there is a growing amount of empirical research dedicated to studying the cognitive processes involved in picture identification (e.g., Humphreys, Riddoch, & Quinlan, 1988; see review by Johnson, Paivio, & Clark, 1996). Despite all the attention paid to these well-studied areas of research, there has been much less attention paid to investigating the *connections* between the word recognition system and the picture identification system (e.g., Hennessey & Kirsner, 1999). 'Reading' today often involves a combination of information processing techniques, such as reading print and processing pictorial information (e.g., when using the internet to research a topic; when playing modern video games, Franceschini, Gori, Ruffino, Viola, Molteni, & Facoetti, 2013), and pictures and words often convey important information in many educational, occupational, and recreational activities. In addition, the presence of pictures in reading material has increased over the centuries, and thus, it is important that researchers begin to consider how picture identification processes may interact with basic reading processes, and investigate the connections between these two systems. As such, one of the major goals of the present study is to extend a dual-route model of reading to include picture identification processes.

The connection between pictures and words also has a long cultural history. Beginning in 1800 B.C. with the earliest known alphabetic inscriptions, our alphabet can be traced through the ancient Canaanites, Phoenicians, Greeks, and Romans, up through medieval Europe to the present day (Sacks, 2003). Egyptologist John Coleman Darnell recently made a remarkable discovery in the mid-1990s, and found two rare inscriptions on the cliffs of Wadi el-Hol, Egypt. These inscriptions contained 15 different signs, which were picture based. For example, there was a carving of an ox head, a human stick figure with raised arms, and wavy vertical lines. After a slow and methodical verification process, the pictographic writing system was indeed proved to be alphabetic. Darnell concluded that the inscriptions are probably the oldest alphabetic writing yet discovered. In addition, he determined that letters from the inscriptions were inspired by symbols in Egyptian hieroglyphics. For example, the inscription that contains four wavy vertical lines is without doubt the ancestor of the wavy-lined Phoenician M letter, named *mem* (water) and pronounced /m/, and thus is the ancestor of our present-day Roman M. This discovery was proved to be so remarkable because the inscriptions can point directly back to the invention of our present day alphabet, and suggest that the pre-Phoenician alphabetic writing was actually picture based. These findings suggest that the Canaanite alphabet consisted of pictures of real-world objects, whose phonetic decoding corresponded to the first phoneme of the object's pronunciation. Unfortunately, as the orthography was borrowed by other languages (e.g., Phoenicians, Greeks, and Romans), the meaning, and thus the pictorial basis of the letters was lost. Nevertheless, our cognitive ability to process alphabetic letters originated from our brain's ability to process familiar pictures.

Another related topic is the issue of how the human brain allows us to read, and whether the brain developed to read modularly, or if reading was developed as a shared adaptation from picture processing (Dehaene, 2009). One could argue that the human brain developed specific mechanisms for reading, whereby we have developed specialized cortical mechanisms exquisitely attuned to the recognition of written words. Indeed, some researchers have argued that the cortical mechanism for reading is located in identical brain regions in all humans (Cohen, Dehaene, Naccache, Lehéricy, Dehaene-Lambertz, Hénaff, & Michel, 2000; Cohen, Lehéricy, Chochon, Lemer, Rivaud, & Dehaene, 2002). However, one could also argue that there has not been enough time for the human brain to develop specialized reading circuits, and that there is a lack of evidence from activities or events during our evolution that could have resulted in reading-specific mechanisms. Given that the oldest alphabetic writing was found to be picture based, it would make sense that our brains have adapted to process pictures and words in the same region (see Price, 2012).

Researchers have begun to study the overlap between word and picture identification processes, but the results of these studies have led to a debate regarding the underlying nature of each process. Farah (1992) has described two hypotheses about visual object recognition. On one hand, Farah argues that the work of Marr (1982) and Beiderman (1987) has focused on models of visual stimuli, whereby a common set of mechanisms subserve all visual recognition. On the other hand, she points out that other researchers have argued that the visual system has evolved numerous specialized subsystems for recognizing different types of stimuli (e.g., Konorski, 1967), and that words and pictures activate separate 'modality-specific' subsystems (e.g., Potter & Faulconer, 1975), suggesting that words and pictures are processed by separate systems. She also describes evidence that suggests that the underlying impairment in pure alexia consists of an inability to recognize multiple shapes, resulting in the laborious letter-by-letter reading that pure alexia patients experience. For example, Kinsbourne and Warrington (1962) examined whether pure alexia patients exhibit impairments using both orthographic and picture-based stimuli, and found impairments for both types of stimuli. Thus, they concluded that patients who have pure alexia have an impairment in recognition of nameable items.

Researchers have also begun to examine the overlap between word and picture identification processes using functional magnetic resonance imaging, but the results of these studies provide support for both hypotheses, thereby continuing the debate underlying the nature of each process. On one hand, some researchers argue that words activate a specific region of the fusiform gyrus in the ventral visual processing stream specializing in word form identification, separate from the region specializing in picture identification (Dehaene & Cohen, 2011; Dehaene, Le Clec'h, Poline, LeBihan, & Cohen, 2002). On the other hand, other researchers argue that word and picture identification share a common region of the ventral stream (Price, 2012; Price & Devlin, 2003). However, these studies may be compromised by the fact that they did not control for the degree of ventral-lexical reliance in reading. Our present research involves examining how “whole-word” processing along the ventral-orthographic lexical route has either unique or shared activation loci relative to picture versions of the same referents by using stimuli that are known to rely on the orthographic lexical route (i.e., exception words, as described below, in contrast to regular words), thus controlling for the degree of lexical-based reading.

Model of Basic Reading and Picture Processing

As previously mentioned, our preferred cognitive architecture for basic reading processes, which is based on the Dual-Route Cascade model (Borowsky et al., 2012; Coltheart et al., 2001; Cummine et al., 2013; Gould et al., 2012), assumes that processing operates on two routes: a sublexical GPC route, which allows less familiar letter strings (including nonwords and novel words) and regular words (REG words; e.g., coin) to be “sounded out”, and a lexical route, which allows familiar words and exception words (EXC words; e.g., comb) to be read as “whole-words” (see Figure 1). It is well-known that high-frequency words and EXC words (which have to be read lexically given their inconsistent spelling-to-sound mappings) rely on the ventral-lexical stream, whereas REG words can rely on either or both (e.g., Borowsky et al., 2012; Gould et al., 2012). Furthermore, our lab has previously shown that instructions to only name letter strings that spell words also encourages reliance on the ventral-lexical stream (Cummine et al., 2013; Gould et al., 2012). These routes have been mapped onto the dorsal and ventral visual processing streams, respectively (Borowsky et al., 2012; Borowsky, Cummine, Owen, Friesen, Shih, & Sarty, 2006; Borowsky, Esopenko, Cummine, Sarty, 2007; Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Cummine, Sarty, Borowsky, 2010; Cummine et al., 2013; Herbster, Mintun, Nebes, & Becker, 1997; Hickok & Poeppel, 2007; Indefrey & Levelt, 2004; Jobard, Crivello, & Tzourio-Mazoyer, 2003; Joubert et al., 2004; Price & Devlin, 2003). This model also assumes that processing due to a particular stimulus is cascaded among the subsystems, specifically that the onset of activation in systems down-stream (e.g., phonological output system) has at least some delay relative to the onset of activation of an earlier system (e.g., orthographic lexical system). This assumption is necessary to account for additive effects, which will be described below in the *Additive Factors Method: Word & Picture Coupling* section.

Johnson, Paivio, and Clark (1996) provide an excellent review on picture naming (see also Paivio, 1986, 2007) and describe three generally accepted stages of naming a picture of an object: object identification (allows an object to be identified as a member of a particular class of objects), name activation (activates the appropriate name), and response generation (prepares and executes the phonology). A central concern for the present research is to determine the extent to which "name activation" involves the orthographic lexical system (i.e., the mental representation of the referent's spelling pattern). Paivio's dual-coding theory suggests that there is an additional nonverbal-to-verbal translation step for picture naming, which is not required in word naming, but it is not clear to what extent orthographic lexical representations are activated during picture naming. Borrowing from Paivio's work, the model of picture identification, which we are combining with the dual-route model of reading, assumes four stages (see Figure 5): (1) A visual feature encoding stage, which allows basic visual features such as vertical and horizontal elements, lines, edges, angles, and depth to be analyzed and encoded; (2) A shape encoding stage, which integrates the elementary aspects into an object (geometric) representation, and allows for basic shape to be identified; (3) A picture memory stage, which links the picture representation to previous memory, associations, and to the semantic and orthographic lexical systems, and lastly, (4) A nonverbal-to-verbal translation, whereby we suggest that orthographic-lexical, semantic, phonological-lexical, and phonological-output representations are activated, which allows the appropriate name to become activated and the picture to be verbally identified. These stages, similar to the word recognition system, may operate in a cascaded fashion. Most important for the concern of the present study is the *picture memory stage*, and how it interacts with the word recognition system.

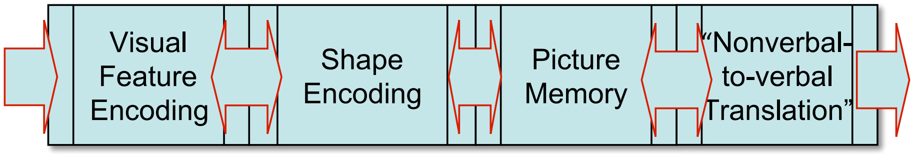

Figure 5: A four stage model of picture identification.

In the present study, EXC items (i.e., EXC words, and EXC pictures, which are pictures derived from EXC words), serve as optimal stimuli for studying whether there is a connection between picture processing and the orthographic lexical system, as it is well-known that EXC words must be processed through the orthographic lexical route. It is also known that EXC words show a larger WF effect compared to REG words (e.g., Cummine et al., 2010; 2013), which has been taken to reflect the greater involvement of the orthographic lexical route for reading EXC words. It follows then that if pictures have a strong connection to the orthographic lexical system, EXC pictures should show a larger WF effect compared to REG pictures (i.e., pictures derived from REG words). As mentioned above, one of the major goals of the present study is to further explore the interaction between word and picture identification processes, and to expand the dual-route model of basic reading accordingly. By using EXC words (which must be read via the orthographic lexical system given that their spelling-to-sound mappings consist of some exceptions to regular rules) and their corresponding pictures, we can begin to look at how "whole-word" processing along the orthographic lexical pathway may be different from, or similar to, picture processing.

Effects that Reflect the Operation of Lexical Subsystems

As described earlier, there are several models that propose that printed WF effects are manifest in the lexical/semantic systems (e.g., Borowsky & Besner, 1993; McCann & Besner 1987; McClelland & Rumelhart, 1981; Morton, 1979; Reynolds & Besner, 2005). For example, WF could affect the connections between the lexical subsystems and semantic system, whereby the more frequently a word is read, the faster the rate of activation in these systems, and the faster the RT. The WF effect on naming RT has been shown to be diluted (i.e., smaller) under conditions when more sublexical processing is occurring, and largest under conditions when more lexical processing is occurring (e.g., Borowsky, Owen, Masson, 2002; Cummine et al., 2013; Gould et al., 2012).

In order to better approximate everyday language exposure, New, Brysbaert, Veronis, and Pallier (2007) explored film and television subtitles as an alternative source of language use. This measure is based on subtitles from television series and films, and is thought to reflect the language of people in social interactions. Word frequency measures based on movie subtitles ($\log_{10}$ subtitle word frequency, SUBTL WF, from the E-Lexicon database, Balota et al., 2007) are also assumed to manifest in the lexical/semantic systems. Given the breadth of referents that are referred to in movies, SUBTL WF should elicit stronger WF effects than a WF measure that primarily reflects orthographic frequency (e.g., $\log_{10}$ HAL word frequency, HAL WF). As such, these two measures of WF will provide both a broad assessment of frequency sensitive connections (SUBTL WF), and a more focused assessment of frequency sensitive connections involving the orthographic lexical system (HAL WF).

The WT (i.e., REG words versus EXC words) effect on RT is another effect that reflects basic reading processes. Given that REG words can be pronounced correctly through both the sublexical route (allowing the word to be "sounded out") and the orthographic lexical route (allowing the word to be read in a "whole-word" manner), these routes produce the same pronunciation at the phonological output system. Conversely, EXC words must be processed via the orthographic lexical route to be pronounced correctly. Exception words produce a slower RT because the two routes produce conflicting codes at the phonological output level, and a single phonological output must ultimately be selected, particularly in the case of low frequency EXC words. Word Type and WF have typically been shown to interact on naming RT, whereby EXC words are slower on average, and elicit a greater WF effect, which has typically been accounted for in terms of dual-route models of reading (e.g., Andrews, 1982; Cummine et al., 2010; Monsell, Patterson, Graham, Hughes, & Milroy, 1992; Paap & Noel, 1991). Given that picture processing may also involve additional frequency-sensitive connections from the picture memory system to the orthographic lexical system, one might expect that they should produce larger WF effects than words.

Another way to examine the connection between the word recognition system and the picture identification system is to investigate the extent to which Picture-Orthography Agreement (POA) accounts for word naming performance. Assuming that the connections from the picture identification system to the orthographic lexical system can be measured by ratings of how well the orthography agrees with the picture, then we have a converging method for examining whether pictures serve to activate the orthographic-lexical system. We can also examine whether orthographic WF and POA affect a common system, or separable systems, as described in the *Additive Factors Method: Word & Picture Coupling* section below.

By systematically exploring these and other variables in terms of two-way interactions, a clearer sense of how various processing systems and connections are shared, or are separable, will be obtained. By employing the Additive Factors Method (AFM, Sternberg, 1969; Borowsky & Besner, 1991, 1993, 2000, 2006; Borowsky et al., 2012; Cummine et al., 2010, 2013; Gould et al., 2012; Yap, Balota & Tan, 2013), one can examine which variables affect which cognitive systems, the temporal arrangement of processes, and whether the nature of processing between the systems is staged or parallel.

Additive Factors Method (AFM): Word and Picture Coupling

The AFM proposes that if two variables interact in a rising overadditive pattern on RT, it is indicative of those variables affecting a common system of processing in time (see Figure 6). In contrast, if two variables produce additive effects on RT, those variables are assumed to be affecting separable (even if they are cascaded, McClelland, 1979) systems of processing. As such, additive effects between POA and WT would be taken to suggest that POA affects a separable system of processing than WT, whereas rising overadditive effects would be suggestive of POA and WT affecting a common system (see Figure 7). One major goal of the present research is to explore two-way joint effects in order to localize other systems and connections between basic reading and picture identification processes. Specifically, we will examine the two-way joint effects of Format (pictures versus words, which should have a relatively early influence), POA (which we hypothesize to reflect connections from the picture memory system to the orthographic lexical system), WF (including both HAL WF as a measure reflecting orthographic-based lexical connections, and SUBTL WF as a broader-based measure of lexical connections, both as continuous measures), and WT (EXC versus REG items, which is known to have an effect at the relatively later phonological output system, Cummine et al., 2010).

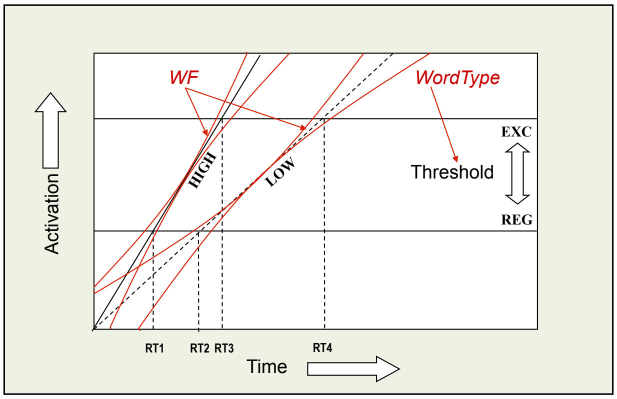

Figure 6: A rising overadditive interaction pattern between WF and WT. An Additive Factors Method interpretation of this interaction is that both WF and WT are affecting a common system in time. If WT is assumed to affect the threshold for activation, and WF is assumed to affect the rate of activation over time, or vice versa, then the points in time when each rate crosses a threshold correspond to the average onset RTs.

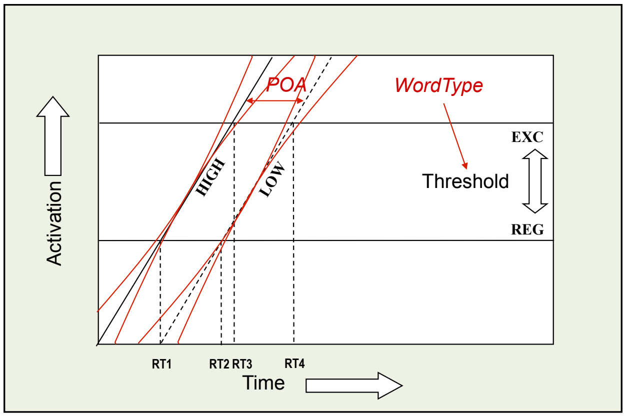

Figure 7: Additive joint effects between POA and WT. An Additive Factors Method interpretation of this additive effect is that POA and WT are affecting separable systems in time. If WT is assumed to affect the threshold for activation, and POA is assumed to shift the rate of activation over time, or vice versa, then the points in time when each rate crosses a threshold correspond to the average onset RTs. The red confidence intervals around the slopes allows for trial to trial variation as described by Masson and Kliegl (2013) and Gould et al., (2012), and thus we note that such variation is not problematic for applying the AFM and can be easily accommodated by cascaded stages of processing.

Response Duration

Another major goal of the present research is to expand the investigation of naming behaviour to more than just the onset of response. Previous research on word and picture identification processing has almost solely relied on voice-key measures of *onset* RT. However, given that cognitive processes are still ongoing after the initiation of a vocal response, and that onset RT measures only reflect early aspects of processing, solely examining the onset RT may not be fully comprehensive. Gould, Cummine, and Borowsky (2012; see also Hennessey & Kirsner, 1999) propose that examining the *duration* of vocal responses serves as an important additional measure of naming, and opens a wider window into the underlying cognitive processes involved in identification.

Hennessey & Kirsner (1999) explored duration of vocalizations in a naming task that compared words and pictures, and examined whether the duration of naming is sensitive to variables that influence pre-production processes. They used picture naming as a baseline condition, as they assumed that producing a picture's name is based on direct retrieval of "whole-word" phonology from the lexical system. They argued that word naming responses should reveal duration lengthening, as these responses can reflect sublexical processing. In order to account for words having faster RTs, but longer RDs, they proposed that the sublexical route provides the initial part of the response before the full phonological code is available, rather than the whole response needing to be planned in advance of response initiation. However, Hennessey and Kirsner (1999) did not control for WT, which could be playing a role in modifying the effects reported in their study. Indeed, it appears that a majority of their stimuli are REG words and pictures (by our count, only about seven percent of their stimuli would be classified as EXC words).

Gould et al., (2012) examined the effect of WT on onset RT and RD in a word naming task using REG words, EXC words, and NWs as critical stimuli. We found that RDs were shortest for EXC words, which must be processed via the orthographic lexical route, and longest for nonwords, which must be processed via the sublexical route, while REG words elicited an intermediate RD, as they can be correctly processed through either route. Like Hennessey and Kirsner (1999), we proposed that shorter RDs reflect lexical "whole-word" reading, whereas longer RDs reflect sublexical "spelling-to-sound" mapping, as the sublexical pathway allows the phonology to be assembled in a piecemeal fashion to response production. Our results provided evidence that WT is a critical factor in examining RDs, and that basic reading processes are ongoing even after the initiation of a vocal response, supporting the notion that the more lexically a word is read, the shorter the RD.

The present study examines the RD of vocalizations for words and pictures, separately for EXC derived items and REG derived items, thereby controlling for WT. Given that EXC words are strategically biased towards the lexical route (e.g., Gould et al., 2012; Monsell et al., 1992), separately examining EXC items and REG items is important in order to properly control for the involvement of sublexical processing. In other words, Hennessey and Kirsner's results could be reflecting the state of affairs for REG items, whereas EXC items may show less of a RD difference between words and pictures. In the present research, Experiment 3 investigates the relationship between the word identification system and the picture identification system.

Another way to investigate the RD advantage for lexical "whole-word" items – a way that represents an ideal matching of stimuli – is by comparing Arabic digits (e.g., 3) and number words (e.g., three), as these two types of notation have the same meaning and phonology. Studies on patients with selective impairments to either word reading or Arabic digit identification (e.g., Cipolotti, Warrington, & Butterworth, 1995) support the notion that number words and digits are processed by separable systems, which are at least partly dissociable. Some researchers have argued that the naming RT for Arabic digits and number words are no different from each other (e.g., Ferrand, 1999), whereas others have shown an advantage for number words (e.g., Damian, 2004). Given that a RT advantage for Arabic digits is not ubiquitous in numerical cognition research, exploring RD effects in this context may provide for a more robust effect. To the extent that Arabic digits rely on a picture representation, and thus would refer to a "whole-word" representation to be pronounced correctly, they should show shorter RDs than their corresponding number words, which could be processed via involvement of the sublexical pathway. Given that number words and Arabic digits may also represent a "word versus picture" comparison of stimuli that are also perfectly matched on meaning and phonological output, Experiment 4 examines whether Arabic digits will demonstrate a RD advantage.

CHAPTER 2

AN EXAMINATION OF WORD AND PICTURE IDENTIFICATION PROCESSES

Experiments 1 & 2

As previously mentioned, one of the major goals of the present research involves exploring the joint effects of four variables that are known to reflect the operation of subsystems of basic reading processes: Semantic Neighbourhood Density (SND), Word Frequency (WF), Word Type (WT), and Instructions (INST).

Another major goal is to expand the investigation of naming behaviour to more than just the onset of response. As such, the present research involves exploring the *response duration* of vocal responses in addition to RT. As a general principle, going beyond the initial onset of response provides a larger window through which to view the effects of underlying cognitive processes. As perhaps the most ecologically valid basic reading task, the task of reading aloud is critical to explore in terms of both of our goals of manipulating lexical/semantic access and examining both response onset and duration.

Hypotheses

Our first set of hypotheses involves the joint effects of INST, WF, SND, and WT on onset RT (see Figure 1). We predict that: (i) *INST x WF* - to the extent that INST and WF are both affecting the orthographic lexical system, they should show a rising overadditive interaction on onset RT; (ii) *INST + WT* - because we are predicting that INST are having their effect early by gating processing towards the orthographic lexical system under *name words* INST, whereas WT has been shown to have its effect later at the phonological output system, these two variables should show an additive pattern on RT; (iii) *INST x SND* – to the extent that INST and SND are both affecting the orthographic lexical system, they should show a rising overadditive interaction on onset RT; (iv) *WF x SND* – to the extent that WF and SND are affecting the semantic system and connections to other word-level systems, they should also show a rising overadditive interaction on onset RT; (v) *SND x WT* – to the extent that SND and WT are affecting the phonological output system, they should also show a rising overadditive interaction on onset RT; and (vi) *WF x WT* – to the extent that WF and WT are affecting the phonological output system, they should produce the typical rising overadditive interaction under normal *name all* INST.

Our second set of hypotheses in regards to the RDs of vocal responses: *EXC RD < REG RD < NW RD* - given that EXC words must be processed as "whole-words" and read via the relatively fast lexical system in order to be pronounced correctly, they should produce the shortest RDs, despite the fact that EXC onset RTs are longer than REG onset RTs. Given that NWs must be processed through the relatively slow sublexical GPC system, they should produce the longest RDs. Finally, given that REG words can be processed through either route, they should elicit intermediate RDs relative to EXC words and NWs, despite having the fastest RTs[1]. With respect to INST, given that the *name words* condition also forces participants to rely on the orthographic lexical system, it should produce shorter RDs compared to the *name all* condition (*name words RD* < *name all RD*). Given Balota et al.'s demonstration of semantic priming having a facilitative effect on naming onset RT and naming RD, the SND effect should remain in the same facilitative direction for onset RT and RD in the present experiment. Furthermore, given that WF is considered to have its effects at the same semantic/lexical level as SND, the WF effect should also remain in the same facilitative direction for onset RT and RD.

In the experiments that follow, Experiment 1 (*n* = 20) was conducted in a MRI scanner (see Cummine et al. 2012), and Experiment 2 (*n* = 40) was conducted in a behavioral lab. Although the results of these experiments are presented separately, we will focus our discussion for these experiments on analyses that combine the data from Experiments 1 and 2.

Experiment 1

Method

Participants. Twenty participants responded to a local advertisement for a fMRI experiment at the University of Alberta (see Cummine et al., 2012 for details). The experiment was performed in compliance with the relevant laws and institutional guidelines, and was approved by the University of Alberta Health Research Ethics Board. The participants' consent was obtained according to the Declaration of Helsinki (1996). Inclusion criteria consisted of normal or corrected-to-normal vision and English as a first language. Eighteen participants were right-handed.

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[1] Following the interpretation of the WF x WT interaction within a dual-route framework (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) the initiation of a response is modulated by the consistency in the computed phonological codes from sublexical and lexical routes. On one hand, in the case of EXC words, while the onset RT may be delayed due to the competing phonological codes, the RD should be relatively short given that there is greater reliance on the lexical system. Regular words, on the other hand, have a relatively fast onset RT because there is no competition from the sublexical and lexical routes. However, information from both the sublexical and lexical systems can contribute to correct responding and thus the RD may be longer to accommodate the inclusion of the sublexical information.

Stimuli. One hundred and twenty-six pairs of monosyllabic REG words and EXC words matched for initial onset and length were used as critical stimuli (Patterson & Hodges, 1992). Semantic neighbourhood density, as described earlier in the introduction, was measured using inverse Ncount (Shaoul & Westbury, 2010), which is the inverse of the number of semantic neighbours + 1. These stimuli were well-matched on several of the characteristics available from the E-Lexicon Database (http://elexicon.wustl.edu/, Balota et al., 2007), as we found that WT (REG=0, EXC=1) did not correlate significantly with $\log_{10}$ HAL WF ($r = .036$, $p = .57$), bigram frequency by position ($r = .033$, $p=.60$), bigram mean frequency, ($r = -.051$, $p = .42$), bigram sum frequency ($r = -.036$, $p=.57$), number of morphemes ($r = .058$, $p = .357$), number of phonemes ($r = -.082$, $p = .20$), phonological neighborhood ($r = .081$, $p = .202$), or inverse Ncount ($r = -.031$, $p = .50$). These words can be considered to be of fairly high familiarity, as their mean WF is relatively high ($\log_{10}$ HAL WF mean = 9.63). A set of 128 pronounceable NWs were also generated from the critical words by changing one or two letters. The mean length of the NWs (4.48 letters) was well matched to the mean length of the words (4.51 letters for both the EXC words and REG words), $t(252) = 0.307$, $p = .759$. For each INST condition, a total of 190 stimuli were presented in two blocks (one block had 31 REG words, 32 EXC words, and 32 NWs, and the other block had 32 REG words, 31 EXC words, and 32 NWs), such that every participant was presented with each stimulus only once, and stimuli were cycled through INST conditions across participants so that each stimulus was presented equally often under each INST set.

Procedure and Apparatus. For the *name all* INST condition, participants were instructed to "read aloud each letter string, as quickly and accurately as possible." For the *name words* INST condition, participants were instructed to "only read aloud each letter string that spells a word, as quickly and accurately as possible." Letter strings were presented, and participants responded vocally, during a regular periodic gap in the image acquisition that followed the offset of each volume of images (i.e., a sparse-sampling, or gap, paradigm; Borowsky et al., 2005a, b, 2006, 2007, 2012; Cummine et al., 2010, 2012). That is, a letter string was presented for 1850ms during a silent gap, at the offset of a 1850ms acquisition of a volume of images, allowing participants to name aloud the letter string immediately and without gradient noise in the background. Letter strings were randomly selected, without repetition, and back-projected one at a time on a screen such that they were visible to the participants through the mirror on the head coil. A computer running EPrime software (Psychology Software Tools, Inc., http://www.pstnet.com) was used to trigger each image acquisition in synchrony with the presentation of visual stimuli. The longest words (6 characters in length) subtended a visual angle of 1.79° in height x 3.58° in width.

Vocal responses were recorded at 96KHz, 24bit, through the intercom using an Olympus LS11 digital recorder, during the acquisition gap. These recordings were then analyzed using PRAAT software (Boersma & Weenink, 2011), and the speech spectrograms and formants were used to localize vocalization onset RT and the RD. Given that the gradient noise associated with the final image acquisition in each volume coincided with the onset of the target stimulus, we were able to use it as an auditory and visual cue on the digital recording for identifying when the stimulus appeared on the screen (see Figure 8). By replaying the audio recording, we were able to code whether each participant's response was correct, incorrect, or a spoiled trial. By using PRAAT to analyze the speech spectrograms, and by replaying the audio recording, we were able to determine the exact time point for the onset RT and the RD.

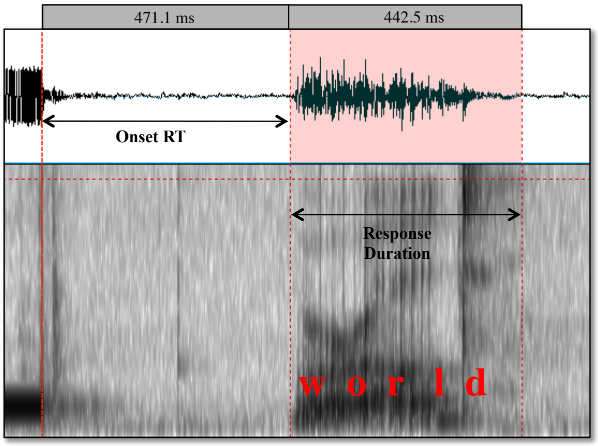

Figure 8: An example of using PRAAT to assist in localizing the onset RT and RD of the vocalization "world". Offset of gradient noise from the MRI can be seen and heard at the time point of the coarse red-dashed line (relevant for Experiment 1 only). The onset and offset of the vocalization can be seen and heard between the thin red-dashed lines, while the temporal distance between those lines (i.e., the RD) is indicated at the top. Visual inspection of both the spectrograms and the formants, as well as several replayings of the audio recording, allowed for precise measurement of the onset RT and RD.

Results

Word Naming Reaction Time. The naming onset RT data were first aggregated by participant as a function of INST (*name all, name words*) and WT (REG, EXC). Medians of the correctly named item RTs were submitted to a 2 X 2 general linear model (GLM) ANOVA, with WT and INST as repeated measures factors. The median naming onset RTs are presented in Figure 9. There were significant main effects of INST, $F(1,19) = 7.626$, $MSe = 4659$, $p = .01$, and WT, $F(1,19) = 4.97$, $MSe = 239$, $p = .04$, and no significant interaction, $F(1,19) = .049$, $MSe = 442$, $p = .83$.

Nonword Naming Reaction Time. The NW condition in the *name all* INST condition yielded a median onset RT of 687.7 ms (Loftus and Masson, 1994, repeated-measure 95% confidence interval, CI = ± 21.9).

Accuracy. The mean accuracy rates resulted in 100 percent accuracy in all cells, and thus there was no variance for a statistical analysis.

Figure 9: Median Naming RTs (in milliseconds) as a function of WT and INST in Experiment 1. The 95% C.I.s are presented as error bars using Loftus and Masson's (1994) method. Coefficients relating WF to RT (ms/$\log_{10}$HALWF) are presented in parentheses above each error bar, and coefficients relating SND to RT (ms/unit inverseNcount) are presented in parentheses below each error bar.

Word Frequency Effects on Reaction Time. In order to evaluate the effects of WF as a continuous variable, GLM regressions were conducted on each participant's correct onset RTs, with RT as the dependent variable, and WF as a continuous independent variable, separately for each combination of INST and WT. The resulting WF coefficients for each INST and WT set were then aggregated over participants (e.g., Borowsky et al., 2002), and submitted to a 2 X 2 GLM ANOVA, with WT and INST as repeated measures factors. This analysis allows one to generalize to both items and participants, in that items are treated as the unit of analysis in the regressions, and that participants are treated as the unit of analysis when the coefficients are being statistically tested. Given our use of the AFM and a focus on two-way joint effects, interaction effects were restricted to two-way joint effects in all the analyses reported here. Figure 9 shows the mean coefficients above the median RTs. There was a significant main effect of INST on the size of WF effect, $F(1, 19) = 15.5$, $MSe = 83.6$, $p = .001$, which represents an INST x WF interaction on naming RT, whereby the WF effects are greater under *name words* instructions. The main effect of WT on the size of WF effect was not significant, $F(1, 19) = 1.38$, $MSe = 115.2$, $p = .25$. An analysis of this WF x WT interaction for *name all* INST failed to show a significant effect, $t(19) = -1.27$, $SEM = 3.47$, $p = .22$.

Semantic Neighbourhood Density Effects on Reaction Time. In order to evaluate the effects of SND as a continuous variable, GLM regressions were conducted on each participant's correct onset RTs, with RT as the dependent variable, and SND as a continuous independent variable, separately for each combination of INST and WT. The resulting SND coefficients for each INST and WT set were then aggregated over participants, and submitted to a 2 X 2 GLM ANOVA, with WT and INST as repeated measures factors. Figure 9 shows the mean coefficients below the median RTs. There was a significant main effect of INST on the size of the SND effect, $F(1, 19) = 5.53$, $MSe = 1698.7$, $p = .03$, which represents an INST x SND rising overadditive interaction on naming RT, whereby the SND effects are greater under *name words* instructions. There was also a significant main effect of WT on the size of the SND effect, $F(1, 19) = 8.69$, $MSe = 1938.8$, $p = .008$, which represents a WT x SND rising overadditive interaction on naming RT, indicating that the SND effect is greater for EXC words than REG words.

Word Naming Response Duration. The naming RD data were aggregated by participant as a function of INST and WT. Medians of the correctly named item RDs were submitted to a 2 X 2 GLM ANOVA, with WT and INST as repeated measures factors. The median naming RDs are presented in Figure 10. There was a significant main effect of WT, $F(1, 19) = 152.06$, $MSe = 90.3$, $p < .001$. The main effect of INST showed a trend in the predicted direction but was not significant, *F*(1, 19) = 1.72, *MSe* = 749.25, *p* = .20, and no significant interaction, *F*(1, 19) = .710, *MSe* = 105.7, *p* = .41.

Nonword Naming Response Duration. The NW condition in the *name all* INST condition yielded a median RD of 587.9 ms (Loftus and Masson, 1994, repeated-measure 95% confidence interval, CI = ± 10.78).

Word Frequency Effects on Response Duration. We conducted analyses of WF effects on RD in the same way as our analyses on RT. Figure 10 shows the mean coefficients above the median RDs. There was a significant main effect of WT on the size of WF effect, *F*(1, 19) = 9.42, *MSe* = 16.1, *p* = .006, which represents a WT x WF interaction on naming RD, whereby the WF effects are greater for REG words. A main effect of INST on the size of WF effect approached significance, *F*(1, 19) = 3.67, *MSe* = 17.3, *p* = .07, whereby there was a tendency for an interaction, such that there were larger WF effects in the *name all* condition.

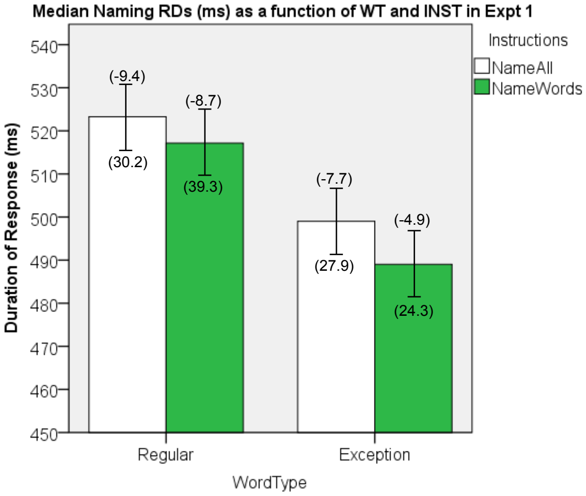

Figure 10: Median Naming RDs (in milliseconds) as a function of WT and INST in Experiment 1. The 95% C.I.s are presented as error bars using Loftus and Masson's (1994) method. Coefficients relating WF to RT (ms/$\log_{10}$HALWF) are presented in parentheses above each error bar, and coefficients relating SND to RT (ms/unit inverseNcount) are presented in parentheses below each error bar.

Semantic Neighbourhood Density Effects on Response Duration. We conducted analyses of SND effects on RD in the same way as our analyses on RT, and the mean coefficients are shown below the median RDs in Figure 10. There was no significant main effect of INST on the size of the SND effect, *F*(1, 19) < 1, *MSe* = 706.2, *p* = .99, nor was there a significant main effect of WT on the size of the SND effect, *F*(1, 19) = 2.15, *MSe* = 880.0, *p* = .16, which suggests there were no interactions between INST and SND, or WT and SND on RD.

Discussion

For onset RT there was a significant main effect of WT and INST, but no interaction. This additive pattern supports the notion of WT and INST affecting separable systems (see Figure 4). The onset RT analysis involving WF supports a rising overadditive interaction with INST. This pattern of interaction with WF supports the notion of INST affecting the same system as that affected by WF. Our analysis of the SND effect on onset RT showed a rising overadditive interaction between INST and SND, as well as between SND and WT. This pattern of interaction with SND supports the notion of INST and WT both affecting the same system as that affected by SND.

In keeping with our hypotheses regarding the RDs of vocal responses, the pattern of results supported: *EXC RD < REG RD < NW RD* – in that the main effect of WT was significant, and that the 95% CI for NWs did not overlap with any of the comparison cells. Furthermore, there was a trend for the *name words* INST condition to have shorter RDs than the *name all* INST condition.

Our analysis of the WF effect on RD revealed a very interesting pattern. Specifically, larger WF effects are associated with the longer RD cells (i.e., REG words), despite the fact that the opposite pattern was demonstrated for onset RT. As such, RD is shorter for the lexically read EXC words, which supports our hypotheses about shorter RDs being associated with lexically read items. Our analysis of the SND effect on RD showed no significant two-way interactions.

Experiment 2

Method

Participants. Forty undergraduate students participated for course credit in their introductory psychology class. The experiment was performed in compliance with the relevant laws and institutional guidelines, and was approved by the University of Saskatchewan Research Ethics Board. Inclusion criteria consisted of normal or corrected-to-normal vision and fluency in English. Thirty-eight participants were right-handed.

Stimuli, Procedure and Apparatus. These were identical to Experiment 1, with the following exceptions: Testing was done in a sound attenuated behavioral lab, stimuli were presented on a 15 inch Samsung CRT monitor connected to a PC running EPrime software, participants initiated each trial by pressing a button on the PST serial response box, which was also connected to a microphone that was interfaced with the voice-key for detecting vocalization onsets. Response duration was measured in the same way as Experiment 1 (see Figure 8).

Results

The same analyses were conducted as in Experiment 1. One participant elicited error rates that were in excess of three standard deviations below the mean of all participants, and was thus excluded from the analyses.

Word Naming Reaction Time. The median naming onset RTs are presented in Figure 11. There were significant main effects of INST, $F(1,38) = 26.5$, $MSe = 2260.5$, $p < .001$, and WT, $F(1,38) = 4.96$, $MSe = 686$, $p = .03$, and no significant interaction, $F(1,38) = .463$, $MSe = 242$, $p = .96$.

Nonword Naming Reaction Time. The NW condition in the *name all* INST condition yielded a median onset RT of 750.8 ms (Loftus and Masson, 1994, repeated-measure 95% confidence interval, CI = ± 14.7).

Accuracy. The mean proportion accuracy rates are presented in Figure 12. There was a significant main effect of INST, $F(1, 38) = 15.62$, $MSe = .003$, $p < .001$, and WT, $F(1, 38) = 11.44$, $MSe = .001$, $p = .002$, and there was no significant interaction, $F(1, 38) = 2.64$, $MSe = .001$, $p = .11$. The NW accuracy in the *name all* INST condition yielded a mean proportion of .90 (Loftus and Masson, 1994, repeated-measure 95% confidence interval, CI = ± .017).

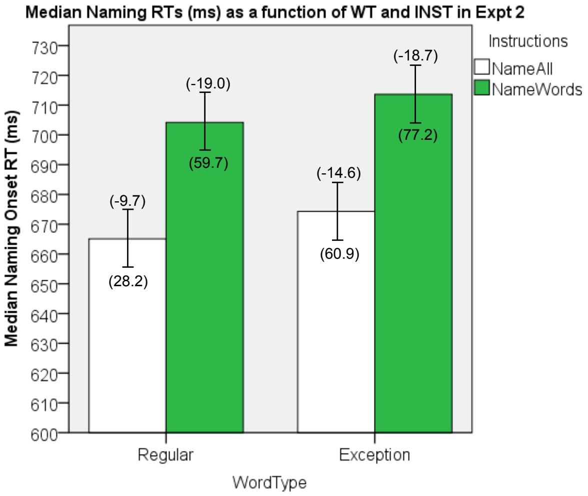

Figure 11: Median Naming RTs (in milliseconds) as a function of WT and INST in Experiment 2. The 95% C.I.s are presented as error bars using Loftus and Masson's (1994) method. Coefficients relating WF to RT (ms/$\log_{10}$HALWF) are presented in parentheses above each error bar, and coefficients relating SND to RT (ms/unit inverseNcount) are presented in parentheses below each error bar.

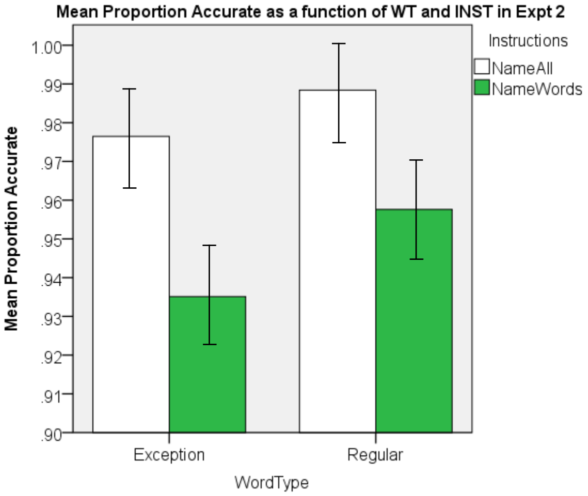

Figure 12: Mean Proportion Accurate as a function of WT and INST in Experiment 2. The 95% C.I.s are presented as error bars using Loftus and Masson's (1994) method.

Word Frequency Effects on Reaction Time. We conducted analyses of WF effects on RT in the same way as our analyses in Experiment 1. Figure 11 shows the mean coefficients above the median RTs. There was a significant main effect of INST on the size of the WF effect, $F(1, 38) = 11.28$, $MSe = 154.7$, $p = .002$, which represents a INST x WF interaction on naming RT, whereby the WF effects are greater for *name words* instructions. The main effect of WT on the size of the WF effect (i.e., the WF x WT interaction) did not reach significance, *F*(1, 38) = 1.78, *MSe* = 114.1, *p* = .19, however, an analysis of this WF x WT interaction for the normal *name all* INST showed a significant effect, *t*(38) = -2.13, *SEM* = 2.30, *p* = .04.

Semantic Neighbourhood Density Effects on Reaction Time. We conducted analyses of SND effects on RT in the same way as our analyses in Experiment 1. Figure 11 shows the mean coefficients below the median RTs. There was a significant main effect of INST on the size of the SND effect, *F*(1, 38) = 5.67, *MSe* = 3933.8, *p* = .02, which represents an INST x SND rising overadditive interaction, whereby the SND effect is larger for the *name words* INST condition. There was also a significant main effect of WT on the size of the SND effect, *F*(1, 38) = 4.46, *MSe* = 5534.5, *p* = .04, which represents a SND x WT rising overadditive interaction, whereby the SND effect is larger for EXC words than for REG words.

Word Naming Response Duration. The median naming RDs are presented in Figure 13. There was a significant main effect of WT, *F*(1, 38) = 140.29, *MSe* = 210.2, *p* < .001, which was in the predicted direction with EXC words showing shorter RDs. The main effect of INST approached significance, *F*(1, 38) = 2.7, *MSe* = 1187.8, *p* = .10, which was also in the predicted direction, and there was no significant interaction, *F*(1, 38) = .766, *MSe* = 186.3, *p* = .39.

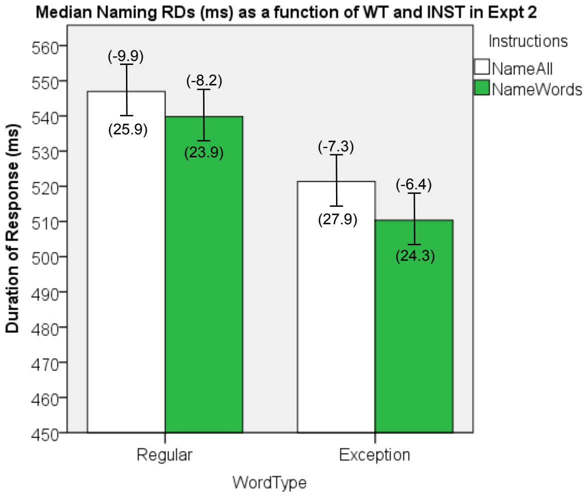

Figure 13: Median Naming RDs (in milliseconds) as a function of WT and INST in Experiment 2. The 95% C.I.s are presented as error bars using Loftus and Masson's (1994) method. Coefficients relating WF to RT (ms/log$_{10}$HALWF) are presented in parentheses above each error bar, and coefficients relating SND to RT (ms/unit inverseNcount) are presented in parentheses below each error bar.

Nonword Naming Response Duration. The NW condition in the *name all* INST condition yielded a median RD of 561.5 ms (Loftus and Masson, 1994, repeated-measure 95% confidence interval, CI = ± 7.65).

Word Frequency Effects on Response Duration. We conducted analyses of WF effects on RD in the same way as our analyses in Experiment 1. Figure 13 shows the mean coefficients above the median RDs. There was a significant main effect of WT on the size of the WF effect, $F(1, 38) = 4.28$, $MSe = 45.2$, $p = .045$, which represents a WT x WF interaction on naming RD, whereby the WF effects are greater for REG words. There was no main effect of INST on the size of WF effect, $F(1, 38) = 1.42$, $MSe = 44.2$, $p = .24$, although we note that the direction of the effects was consistent with Experiment 1.

Semantic Neighbourhood Density Effects on Response Duration. We conducted analyses of SND effects on RD in the same way as our analyses in Experiment 1. Figure 13 shows the mean coefficients below the median RDs. There was no significant main effect of INST on the size of the SND effect, $F(1, 38) = .17$, $MSe = 1826.0$, $p = .69$, nor was there a significant main effect of WT on the size of the SND effect, $F(1, 38) = .08$, $MSe = 652.1$, $p = .78$.

Discussion

Our first set of hypotheses involved the joint effects of INST, WF, SND, and WT on onset RT. Consistently in both Experiments 1 and 2, we showed that: (i) *INST x WF* – the rising overadditive INST x WF interaction was significant, supporting the notion that these variables are affecting the orthographic lexical system; (ii) *INST + WT* - these two variables showed an additive pattern on RT, supporting the notion that they are affecting separable systems, namely the orthographic lexical system and the phonological output system, respectively; (iii) *INST x SND* - the rising overadditive INST x SND interaction was significant, supporting the idea that the orthographic lexical system is affected by both variables; (iv) *SND x WT* – the rising overadditive SND x WT interaction was also significant, which is congruent with SND and WT both affecting the phonological output system; (v) *WF x WT* - the WF x WT rising overadditive interaction under the normal *name all* instructions was significant, supporting the notion that these variables affect the phonological output system.

Our RD analyses showed a similar pattern as Experiment 1. Consistent with Experiment 1, there was a main effect of WT whereby RD is shorter for the lexically read EXC words (*EXC RD* < *REG RD*), and approaches significance for INST (*name words RD* < *name all RD*), further supporting our hypotheses about shorter RDs being associated with lexically read items. Larger WF effects were again associated with the longer RD cells (i.e., REG words), despite the fact that the opposite pattern was demonstrated for onset RT. Our analysis of the SND effect on RD showed no significant effects.

The consistency in the results between Experiment 1 and 2 is reassuring, given that a voice-key was used to collect onset RT in Experiment 2, whereas hand-marking of onset RT was used in Experiment 1 (see Figures 9 and 11; cf. Rastle & Davis, 2002). Given that Experiment 1 was conducted in a MRI, we could not use a voice-key, but the gradient noise from the MRI scanner served as an effective auditory cue for identifying stimulus onset on the recording in that it was synchronized to appear coincidently with the last image acquisition prior to the gap for responding. In Experiment 2, we used a voice-key for detecting onset RT as we did not include an auditory cue for stimulus onset. Further discussion of these experiments will be considered in the Chapter 3: General Discussion.

Analysis of Combined Experiment 1 and 2 Data

Results

Word Naming Reaction Time. The data from the two experiments were combined, and the results were analyzed for all participants together ($n = 59$). The median naming onset RTs are presented in Figure 14. There were significant main effects of INST, $F(1,58) = 31.7$, $MSe = 3009.1$, $p < .001$, and WT, $F(1,58) = 8.6$, $MSe = 528.2$, $p = .005$, and no significant interaction, $F(1,58) = .03$, $MSe = 303.5$, $p = .85$.

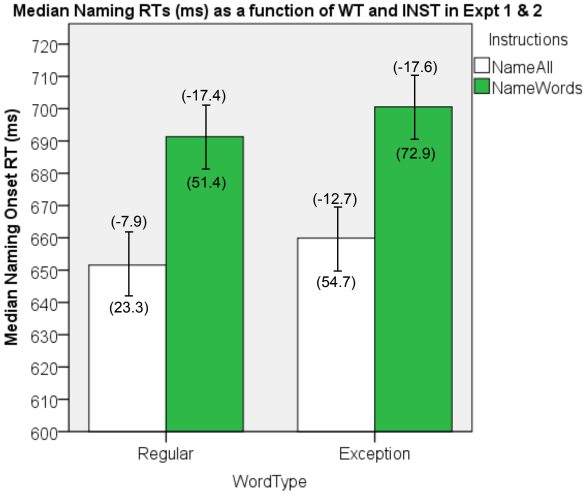

Figure 14: Median Naming RTs (in milliseconds) as a function of WT and INST in the combined analysis of Experiments 1 and 2. The 95% C.I.s are presented as error bars using Loftus and Masson's (1994) method. Coefficients relating WF to RT (ms/$\log_{10}$HALWF) are presented in parentheses above each error bar, and coefficients relating SND to RT (ms/unit inverseNcount) are presented in parentheses below each error bar.

Nonword Naming Reaction Time. The NW condition in the *name all* INST condition yielded a median onset RT of 729.4 ms (Loftus and Masson, 1994, repeated-measure 95% confidence interval, CI = ± 12.1).

Accuracy. Given that there was no variance in Experiment 1 accuracy data, we did not perform a combined analysis of the Experiment 1 and Experiment 2 data.

Word Frequency Effects on Reaction Time. We conducted analyses of WF effects on RT in the same way as our analyses in Experiments 1 and 2. Figure 14 shows the mean coefficients above the median RTs. There was a significant main effect of INST on the size of WF effect, $F(1, 58) = 23.4$, $MSe = 129.2$, $p < .001$, which represents an INST x WF rising overadditive interaction on naming RT, whereby the WF effects are greater under *name words* instructions. The main effect of WT on the size of the WF effect approached significance, *F*(1, 58) = 3.18, *MSe* = 112.6, *p* = .08, which suggests a WT x WF rising overadditive interaction on naming RT averaging over both levels of the INST manipulation, whereby the WF effects are greater for EXC words than for REG words. More importantly, the analysis of this interaction under the normal *name all* INST condition yielded a significant effect, *t*(58) = -2.49, *SEM* = 1.91, *p* = .02[2].

Semantic Neighbourhood Density Effects on Reaction Time. We conducted analyses of SND effects on RT in the same way as our analyses in Experiments 1 and 2. Figure 14 shows the mean coefficients below the median RTs. There was a significant main effect of INST on the size of the SND effect, *F*(1, 58) = 10.08, *MSe* = 3134.9, *p* = .002, which represents an INST x SND interaction on naming RT, whereby the SND coefficients are greater in the *name words* INST condition than in the *name all* condition. There was also a significant main effect of WT on the size of the SND effect, *F*(1, 58) = 9.70, *MSe* = 4264.6, *p* = .003, which represents a SND x WT interaction on naming RT, whereby the SND coefficients are greater for EXC words than for REG words.

Word Frequency and Semantic Neighbourhood Density Joint Effects on Reaction Time. A GLM regression was conducted on each participant's correct onset RTs, with RT as the dependent variable, and SND and WF as continuous independent variables, separately for each combination of INST and WT. Given that this constitutes a multiple regression, we note that, here and in later multiple regression analyses, the issue of multicolinearity was handled by using a tolerance threshold set at .0001, and there were no situations whereby this threshold was exceeded. Multivariate outliers were assessed using Malhalanobis distance, and there were no multivariate outliers exceeding the threshold of $\chi^2(2) = 13.816$, *p* < .001. The resulting WF x SND

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[2] We are concentrating on two-way interactions in this research given the focus on the Additive Factors Method. A reviewer had pointed out an interesting potential three-way interaction whereby the WF x WT interaction was only significant in the *name all* condition, but not the *name words* condition. Given that the WF effects are consistently negative for all of the conditions, any such three-way interactions would be ordinal (i.e., not a cross-over interaction), which are notoriously difficult to detect (i.e., all effects are in the same general direction). Nonetheless, we did examine tests for three-way interactions under the conditions in our study that had the most power to detect such interactions. We tested the WF x WT x INST interaction on RT on pg. 23 that the reviewer referred to, and it yielded the following result, *F*(1,38) = 1.67, *MSe* = 160.40, *p* = .204. We also examined the corresponding interaction in the item analyses, and also found a non-significant result, *F*(1,248) = .43, *MSe* = 2057.89*,* *p* = .51.

coefficients for each INST and WT set were then tested against zero using one-sample *t*-tests. The WF x SND coefficients were significantly different from zero for REG words in the *name all* INST condition, *t*(58) = -2.40, *SEM* = 7.96, *p* = .02, and for REG words in the *name words* INST condition, *t*(58) = -2.11, *SEM* = 8.46, *p* = .04. The WF x SND coefficients for EXC words in the *name words* INST condition approached significance, *t*(58) = -1.77, *SEM* = 8.65, *p* = .08, and the coefficients for EXC words in the *name all* INST condition were not significant, *t*(58) = -1.21, *SEM* = 5.76, *p* = .23.

Word Naming Response Duration. The median naming RDs are presented in Figure 15. There was a significant main effect of WT, *F*(1, 58) = 257.6, *MSe* = 167.7, *p* < .001, and of INST, *F*(1, 58) = 4.39, *MSe* = 1023.9, *p* = .04, and no significant interaction, *F*(1, 58) = 1.39, *MSe* = 156.6, *p* = .24.

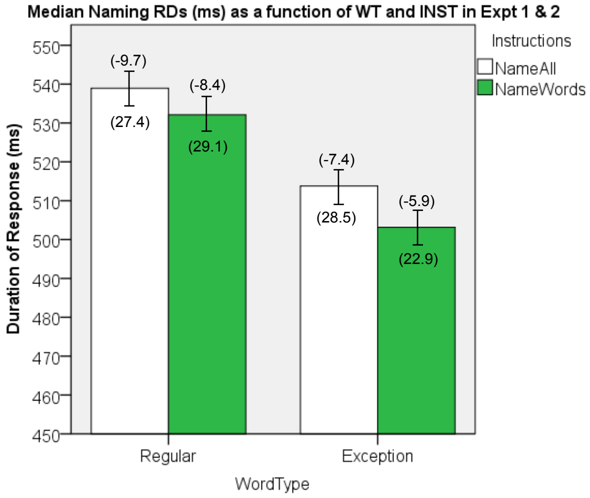

Figure 15: Median Naming RDs (in milliseconds) as a function of WT and INST in the combined analysis of Experiments 1 and 2. The 95% C.I.s are presented as error bars using Loftus and Masson's (1994) method. Coefficients relating WF to RT (ms/$\log_{10}$HALWF) are presented in parentheses above each error bar, and coefficients relating SND to RT (ms/unit inverseNcount) are presented in parentheses below each error bar.

Nonword Naming Response Duration. The NW condition in the *name all* INST condition yielded a median RD of 570.4 ms (Loftus and Masson, 1994, repeated-measure 95% confidence interval, CI = ± 6.72).

Word Frequency Effects on Response Duration. We conducted analyses of WF effects on RD in the same way as our analyses in Experiments 1 and 2. The main effect of INST on the size of WF effect approached significance, *F*(1, 58) = 3.55, *MSe* = 34.7, *p* = .065, which suggests a

INST x WF interaction on naming RD, whereby the WF effects are greater for the *name all* INST condition. The main effect of WT on the size of WF effect was significant, *F*(1, 58) = 9.77, *MSe* = 35.0, *p* = .003, which represents a WT x WF interaction on naming RD, whereby the WF effects are greater for REG words. Figure 15 shows the mean coefficients above the median RDs.

Semantic Neighbourhood Density Effects on Response Duration. In order to evaluate the effects of SND as a continuous variable, GLM regressions were conducted on each participant's correct RDs, as in Experiments 1 and 2. Figure 15 shows the mean coefficients below the median RDs. There was no significant main effect of INST on the size of the SND effect, *F*(1, 58) = .145, *MSe* = 1429.3, *p* = .70, nor was there a significant main effect of WT on the size of the SND effect, *F*(1, 58) = .509, *MSe* = 742.5, *p* = .48.

Word Frequency and Semantic Neighbourhood Density Joint Effects on Response Duration. A GLM regression was conducted on each participant's correct RDs, with RD as the dependent variable, and SND and WF as continuous independent variables, separately for each combination of INST and WT. The resulting WF x SND coefficients for each INST and WT set were then tested against zero using one-sample *t*-tests. The WF x SND coefficients were significantly different from zero in the *name all* INST condition, for both EXC words, *t*(58) = -6.80, *SEM* = 2.74, *p* < .001, and REG words, *t*(58) = -3.12, *SEM* = 8.28, *p* = .003. The WF x SND coefficients for EXC words in the *name words* INST condition approached significance, *t*(58) = -1.94, *SEM* = 3.82, *p* = .057, and the coefficients for REG words in the *name words* INST condition were not significant, *t*(58) = -1.13, *SEM* = 4.44, *p* = .26.

Item Analyses

Word Naming Reaction Time. An item analysis was performed on the combined data from Experiments 1 and 2. Median onset RTs for both *name all* and *name words* INST were treated as repeated measure dependent variables, and regressed on WT and INST using a repeated measures GLM. Given that our measure of WF was moderately correlated with our measure of SND, *r* = -.674 when we use the inverse Ncount measure, as we have in these analyses (*r* = .861 when the non-inverse Ncount measure is used), we chose to analyze the effects of WF and semantic density in separate regression models, as well as together in a subsequent model so that we could assess all of the two-way joint effects.

In the regression model that included WF but not SND, there was a significant main effect of INST, *F*(1,248) = 113.38, *MSe* = 2057.9, *p* < .001, and a main effect of WT, *F*(1,248) = 4.53, *MSe* = 3896.8, *p* = .03. There was also a significant main effect of WF, *F*(1,248) = 104.33, *MSe* = 3896.8, *p* < .001. There was no significant interaction between INST and WT, *F*(1,248) = 0.289, *MSe* = 2057.9, *p* = .59. There was a significant INST x WF interaction, *F*(1,248) = 50.05, *MSe* = 2057.9, *p* < .001. The WT x WF interaction approached significance by a one-tailed test, *F*(1,248) = 2.53, *MSe* = 3896.8, *p* = .057.

In the regression that included SND but not WF, there was a significant main effect of INST, *F*(1,248) = 118.50, *MSe* = 2176.0, *p* < .001. There was no significant main effect of WT, *F*(1,248) = 0.27, *MSe* = 4562.7, *p* = .60. There was a significant main effect of SND, *F*(1,248) = 51.45, *MSe* = 4562.7, *p* < .001. There was no significant interaction between INST and WT, *F*(1,248) = 1.24, *MSe* = 2176.0, *p* = .26. There was a significant interaction between INST and SND, *F*(1.248) = 34.0, *MSe* = 2176.0, *p* < .001. There was a significant WT x SND interaction, *F*(1,248) = 4.13, *Mse* = 4562.7, *p* = .043.

In the regression that included both WF and SND, there was a significant main effect of INST, *F*(1,245) = 24.89, *MSe* = 2034.2, *p* <.001. There was no main effect of WT, *F*(1,245)= .01, *MSe* = 3757.9, *p* = .94. There was a significant main effect of SND, *F*(1,245) = 9.38, *Mse* = 3757.9, *p* = .002, and a significant main effect of WF, *F*(1,245) = 27.83, *MSe* = 3757.9, *p* < .001. There was no significant interaction between INST and WT, *F*(1,245) = .01, *Mse* = 2034.2, *p* = .93. There was a significant interaction between INST and SND, *F*(1,245) = 4.23, *Mse* = 2034.2, *p* = .041. There was a significant interaction between INST and WF, *F*(1,245) = 10.01, *Mse* = 2034.2, *p* = .002. The WT x SND interaction approached significance, *F*(1,245) = 3.43, *Mse* = 3757.9, *p* = .065 (which, given the significant interaction in our earlier analyses, could be assessed by a one-tailed test with *p* = .0325). There was no significant WT x WF interaction, *F*(1,245) = .01, *Mse* = 3757.9, *p* = .93. There was a significant interaction between SND and WF, *F*(1,245) = 8.24, *Mse* = 3757.9, *p* = .004.

Word Naming Response Duration. An item analysis was performed on the combined data from Experiments 1 and 2. Median RDs for both *name all* and *name words* INST were treated as repeated measure dependent variables, and regressed on WT and INST using a repeated measures GLM.

In the regression model that included WF but not SND, there was a significant main effect of WF, *F*(1,248) = 20.9, *Mse* = 5249.7, *p* < .001. There were no other significant main effects or interactions.

In the regression model that included SND but not WF, there was a significant main effect of INST, *F*(1,248) = 9.21, *Mse* = 1043.1, *p* = .003, a significant main effect of WT, *F*(1,248) = 7.21, *Mse* = 5518.0, *p* = .008, and a significant main effect of SND, *F*(1,248) = 7.83, *Mse* = 5518.0, *p* = .006. There were no significant two-way interactions.

In the regression that included both WF and SND, the only significant main effect was WF, *F*(1,245) = 6.75, *MSe* = 5230.4, *p* = .01, and the main effect of SND approached significance, *F*(1,245) = 3.10, *MSe* = 5230.4, *p* = .08. The only two-way interaction that approached significance was between SND and WF, *F*(1,245) = 3.56, *MSe* = 5230.4, *p* = .06. There were no other significant main effects or interactions.

Discussion

Our hypotheses for Experiments 1 and 2 involved the joint effects of INST, WF, SND, and WT on onset RT. Taken together, the by-participants analyses, the by-item-by-participant regression analyses, and the by-item analyses, support our hypotheses such that: (i) *INST x WF* – the INST x WF rising overadditive interaction was significant, supporting the notion that these two variables are affecting the orthographic lexical system; (ii) *INST + WT* - given that INST should be having its effect in the early stages of word processing, whereas WT has previously been shown to have its effect at a later stage of processing, this additive pattern was also consistent with our previous research (Borowsky et al., 2012; Cummine et al., 2010, 2013), and supports the notion that INST are affecting an orthographic lexical system that is temporally separable from the phonological output system that is affected by WT; (iii) *INST x SND* – the INST x SND rising overadditive interaction was significant, supporting a common locus of the orthographic lexical system for their effects; (iv) *WF x SND* – the WF x SND rising overadditive interaction supports the notion that these two variables are affecting the semantic system and the connections to other word-level systems; (v) *SND x WT* – the SND x WT rising overadditive interaction was significant, supporting a common locus of the phonological output system for their effects; and (vi) *WF x WT* - the WF x WT rising overadditive interaction under the normal *name all* instructions was significant in Experiment 2 and the combined analyses, supporting the notion that these variables affect the phonological output system.

Our second set of hypotheses involved the RDs of vocalizations: *EXC RD < REG RD < NW RD* - given that EXC words must be processed as "whole-words" and read lexically in order to be pronounced correctly, they produced the shortest RDs, despite the fact that EXC onset RTs are longer than REG onset RTs. Given that NWs must be processed through sublexical GPCs, they produced the longest RDs. Finally, given that REG words can be processed through either route, they elicited intermediate RDs relative to EXC words and NWs, despite having the fastest onset RTs. The results supported the prediction that *name words RD < name all RD* in that the more lexically a word is read, the shorter the RD. The WF effect also remained in the same facilitative direction for onset RT and RD, which is consistent with it having its effects at the same lexical/semantic level as SND. Further discussion of these experiments will be considered in the Chapter 3: General Discussion.

Experiment 3

As mentioned in Chapter 1, there is a lack of empirical research dedicated to examining the *connections* between the word recognition system and the picture identification system, despite the fact that reading often involves a combination of information processing techniques. As such, one of the major goals of the present study is to extend a dual-route model of reading to include picture identification processes. The present research involves exploring two-way joint effects in order to localize systems and connections between basic reading and picture identification processes. Specifically, by examining the two-way joint effects of Format (pictures versus words, which should have a relatively early influence), POA (which we hypothesize to reflect connections from the picture memory system to the orthographic lexical system), WF (including both HAL WF as a measure reflecting orthographic-based lexical connections, and SUBTL WF as a broader-based measure of lexical connections, both as continuous measures), and WT (EXC versus REG items, which is known to have an effect at the relatively later phonological output system, Cummine et al., 2010).

Another goal of the present research is to expand the investigation of naming behaviour to more than just the onset of response. Previous research on word and picture identification processing has almost solely relied on voice-key measures of *onset* RT. However, given that cognitive processes are still ongoing after the initiation of a vocal response, and that onset RT measures only reflect early aspects of processing, solely examining the onset RT may not be fully comprehensive. Gould, Cummine, and Borowsky (2012; see also Hennessey & Kirsner, 1999) propose that examining the *duration* of vocal responses serves as an important additional measure of naming, and opens a wider window into the underlying cognitive processes involved in identification.

Hypotheses

Our first set of hypotheses involves naming onset RT, and the joint effects of HAL WF, SUBTL WF, POA, and WT on onset RT. We predict that: (1) As illustrated in Figure 16, there should be rising overadditive interactions between: *WF x WT for words* - to the extent that WF and WT are affecting the phonological output system (Cummine et al., 2010; Gould et al., 2012); there should also be *Format x WF, POA x WF, and Format x POA* rising overadditive interactions – to the extent that these variables all reflect connections involving the orthographic lexical system, and given that additional frequency-sensitive connections would be involved between the picture identification system and word identification system during nonverbal-to-verbal translation; and there should be additivity between: *Format + WT and POA + WT* – to the extent that these variables are affecting separable systems; (2) *Picture naming RT > Word naming RT* - Picture naming RT should be longer than word naming RT, supporting the notion that there is an additional nonverbal-to-verbal translation step for picture naming, which is not required in word naming (Paivio, 1986, 2007), and has typically been found in the literature (e.g., Cattell, 1886; Fraisse, 1969; Hennessey & Kirsner, 1999; Potter & Faulconer, 1975); (3) *HAL WF effect on picture and word naming RT* - there should be a significant orthographic HAL WF effect on picture naming RT, as well as for EXC words as typically reported in the literature, suggesting that naming pictures and words both involve the activation of the orthographic lexical system; and (4) *HAL WF effects for pictures* - there should be a significant frequency effect for both REG and EXC pictures, which should be stronger for EXC pictures if they have greater access to the orthographic lexical system.

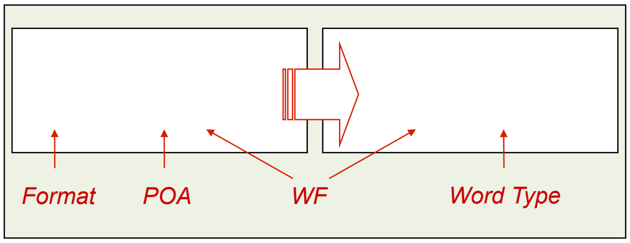

Figure 16: A cognitive chronometric architecture to account for the rising overadditive interactions between Format x WF, POA x Format, POA x WF, and WF x WT, and the additive patterns between Format + WT and POA + WT.

Our second set of hypotheses involve the RDs of vocal responses (Gould et al., 2012): (1) *EXC RD < REG RD* - given that reading EXC words must be based on “whole-word” (lexical) retrieval and read via the relatively fast lexical system in order to be pronounced correctly, they should produce the shortest RDs, despite the fact that EXC onset RTs are longer than REG onset RTs; (2) *Picture RD < Word RD* - given that word naming can involve sublexical processing, words should show longer RDs compared to picture naming responses particularly for REG words (which can be assembled sublexically), suggesting that duration is lengthened with the involvement of sublexical processing (Hennessey & Kirsner, 1999).

Method

Participants. Forty undergraduate students participated for course credit in their introductory psychology class. The experiment was performed in compliance with the relevant laws and institutional guidelines, and was approved by the University of Saskatchewan Research Ethics Board. Inclusion criteria consisted of normal or corrected-to-normal vision and fluency in English.

Stimuli. Sixty monosyllabic words (30 EXC, 30 REG) and their corresponding pictures (taken from Google Images, see Appendix A) were used as critical stimuli. These stimuli were matched on several of the characteristics available from the E-Lexicon Database (http://elexicon.wustl.edu/, Balota et al., 2007), as we found that WT (REG=0, EXC=1) did not correlate significantly with $\log_{10}$ HAL WF ($r = .029$, $p = .83$), $\log_{10}$ SUBTL WF ($r = -.026$, $p = .84$), bigram frequency by position ($r = .023$, $p = .88$), bigram mean frequency, ($r = .023$, $p = .86$), bigram sum frequency ($r = -.032$, $p = .81$), and number of phonemes ($r = .052$, $p = .70$). These words can be considered to be of fairly high familiarity, as their mean HAL WF ($\log_{10}$ HAL WF mean = 8.69) and SUBTL WF ($\log_{10}$ SUBTL WF mean = 2.86) are relatively high.

Each participant was presented with two blocks of words, which were counterbalanced by WT. After each block of words, participants were presented with two blocks of pictures, which were also counterbalanced by WT. After the blocks of pictures, participants completed the POA ratings, which asked participants to rate how well the picture matches the corresponding word. The counterbalance order cycled through conditions such that every participant was presented with each stimulus once in word format and once in picture format.

Procedure and Apparatus. For the word condition, participants were instructed to “read aloud each letter string, as quickly and accurately as possible”, and for the picture condition, participants were instructed to “name aloud the picture of the object, as quickly and accurately as possible.” Letter strings were randomly selected, without replacement, and participants initiated each trial by pressing a button on the PST serial response box, which was also connected to a microphone that was interfaced with the voice-key, although this was not relied on for detecting vocalization onsets (see below). Testing was done in a sound attenuated behavioral lab, and stimuli were presented on a 15 inch Samsung CRT monitor using EPrime software (Psychology Software Tools, Inc., http://www.pstnet.com). The longest words (“bridge” and “brooch”), subtended a visual angle of 1.79° in height x 3.58° in width, and the tallest picture (hook), subtended a visual angle of 5.96° in height x 3.58° in width.

Following Gould et al., (2012), vocal responses were recorded at 96KHz, 24bit, using an Olympus LS11 digital recorder. These recordings were then analyzed using PRAAT software (Boersma & Weenink, 2011), and the speech spectrograms and formants were used to localize vocalization onset RT and the RD. A tone was programmed to coincide with the onset of the target stimulus, thereby allowing us to use it as an auditory and visual cue on the digital recording for identifying when the stimulus appeared on the screen (see Figure 8). By replaying the audio recording, we were able to code whether each participant's response was correct, incorrect, or a spoiled trial. By using PRAAT to analyze the speech spectrograms, and by replaying the audio recording, we were able to determine the exact time point for the onset RT and the RD.

Results

By-Subject Analyses

Word and Picture Naming Reaction Time. The naming onset RT data were first aggregated by participant as a function of Format (word, picture) and WT (REG, EXC). Medians of the correctly named item RTs were submitted to a 2 X 2 GLM ANOVA, with Format and WT as repeated measures factors. The median naming onset RTs are presented in Figure 17. There was a significant main effect of Format, $F(1,39) = 612.66$, $MSe = 6094.7$, $p < .001$, whereby words are named faster than pictures. There was no significant main effect of WT, $F(1,39) = .30$, $MSe = 2509.27$, $p = .59$, and there was a significant Format x WT interaction, $F(1,39) = 16.09$, $MSe = 2555.90$, $p < .001$, which did not take the form of a rising overadditive interaction and thus cannot be interpreted as these two variables affecting the same stage of processing. Instead, this interaction on naming RT suggests that the advantage for REG words compared to EXC words is accompanied by a disadvantage for REG pictures compared to EXC pictures. The 95% repeated-measure confidence intervals (CIs; Loftus & Masson, 1994) for RT was calculated and is shown in Figure 17, confirming the REG word advantage and REG picture disadvantage.

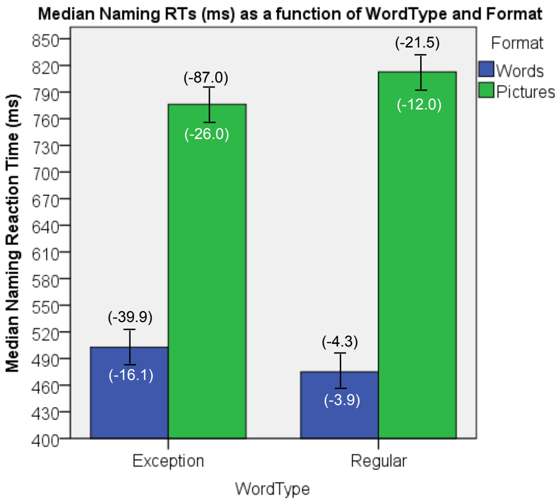

Figure 17: Median Naming RTs (in milliseconds) as a function of WT and Format for the by-subjects analyses in Experiment 3. The 95% CIs are presented as error bars using Loftus and Masson's (1994) method. Coefficients relating HAL WF to RT (ms/$\log_{10}$HALWF) are presented in parentheses below each error bar, and coefficients relating SUBTL WF to RT (ms/$\log_{10}$SUBTLWF) are presented in parentheses above each error bar.

HAL Word Frequency Effects on Reaction Time. In order to investigate the effects of HAL WF as a continuous variable, GLM regressions were conducted on each participant's correct onset RTs, with RT as the dependent variable, and HAL WF as a continuous independent variable, separately for each combination of WT and Format. The resulting HAL WF coefficients for each WT and Format set were then aggregated over participants (e.g., Borowsky et al., 2002; Gould et al., 2012), and submitted to a 2x2 GLM ANOVA, with WT and Format as repeated-measures factors. This analysis allows one to generalize to both items and participants, in that items are treated as the unit of analysis in the regressions, and that participants are treated as the unit of analysis when the coefficients are being statistically tested (Cummine et al., 2013; Gould et al., 2012). Given our use of the AFM, interaction effects were restricted to two-way interactions in all the analyses reported here. Figure 17 shows the mean coefficients below the median RTs. There was a significant main effect of WT on the size of the HAL WF effect, $F(1, 39) = 9.02$, $MSe = 756.85$, $p = .005$, which represents a WT x HAL WF rising overadditive interaction on naming RT, whereby the HAL WF effects are greater for EXC derived items. The main effect of Format on the size of the HAL WF effect approached significance, $F(1, 39) = 3.97$, $MSe = 813.57$, $p = .053$ ($p = .027$ one-tailed, justified given this is a predicted effect), whereby there was a rising overadditive interactive pattern, such that there were larger HAL WF effects for pictures than for words.

The 95% repeated-measure CIs for HAL WF effects on RT was calculated to be ± 10.16 ms/lg unit HAL WF. The coefficients reported below the error bars on Figure 17 exceed this CI (with the exception of the REG word condition), and thus are significantly different from zero. As such, when applied to the HAL WF coefficients for word RTs in Figure 17 (-16.1 versus -3.9), there is a significant rising overadditive WT x HAL WF interaction. When applied to the HAL WF coefficients for picture RTs in Figure 17 (-26.0 versus -12.0), there is a significant WT x HAL WF interaction, but not of the rising overadditive type. The average of the HAL WF coefficients for REG and EXC words is -10.03, and the average for the HAL WF coefficients for REG and EXC pictures is -19.02. Although the difference between these coefficients does not exceed the 95% CI, the pattern is consistent with the rising overadditive interactive pattern described above.

Subtitle Word Frequency Effects on Reaction Time. The same analyses were conducted on SUBTL WF as for HAL WF. Figure 17 shows the mean coefficients above the median RTs. There was a significant main effect of WT on the size of the SUBTL WF effect, $F(1, 39) = 21.75$, $MSe = 4697.19$, $p < .001$, which represents a SUBTL WF x WT interaction on naming RT, whereby the SUBTL WF effects are greater for EXC derived items. There was also a main effect of Format on the size of the SUBTL WF effect, $F(1, 39) = 14.36$, $MSe = 2895.65$, $p = .001$, which represents a Format x SUBTL WF rising overadditive interaction on naming RT, whereby the SUBTL WF effects are greater for pictures than for words.

The 95% repeated-measure CIs for SUBTL WF effects on RT was calculated to be ± 19.33 ms/lg unit SUBTL WF. The coefficients reported above the error bars on Figure 17 exceed this CI (with the exception of the REG word condition), and thus are significantly different from zero. As such, when applied to the SUBTL WF coefficients for word RTs in Figure 17 (-39.9 versus -4.3), there is a significant SUBTL WF x WT interaction. When applied to the SUBTL WF coefficients for picture RTs in Figure 17 (-87.0 versus -21.5), there is also a significant SUBTL WF x WT interaction. The average of the SUBTL WF coefficients for REG and EXC words is -22.1, and the average for the SUBTL WF coefficients for REG and EXC pictures is -54.0. The difference between these coefficients exceeds the 95% CI, and the pattern is consistent with the rising overadditive interactive pattern described above.

Picture-Orthography Agreement Effects on Reaction Time. Picture-orthography agreement ratings were aggregated by items over participants, and used as average ratings in the analyses reported here. In order to ensure that POA ratings are not confounded with WT (i.e., REG versus EXC), a point-by-serial correlation was computed and found to be $r = -.084$, $p = .52$. The same analyses were conducted on POA as for HAL WF and SUBTL WF. The mean coefficient relating: POA to EXC word RT was -31.78 ms/unitPOA, POA to EXC picture RT was -443.51 ms/unitPOA, POA to REG word RT was -2.99 ms/unitPOA, and POA to REG picture RT was -450.17 ms/unitPOA. There was a significant main effect of Format, $F(1, 39) = 293.0$, $MSe = 25178.24$, $p < .001$, which represents a Format x POA rising overadditive interaction. There was no significant main effect of WT, $F(1, 39) = .259$, $MSe = 18953.53$, $p = .61$.

The 95% repeated-measure CIs for POA effects on RT was calculated to be ± 45.72 ms/unitPOA (i.e., ms per unit increase in picture-orthography agreement rating). Thus, the coefficients for EXC pictures and REG pictures are significantly different from zero. When the 95% CI is applied to the POA coefficients for word RTs (-31.78 versus -2.99), there is no significant POA x WT interaction. When applied to the POA coefficients for picture RTs (-443.51 versus -450.17), there is no significant POA x WT interaction. The average of the POA coefficients for REG and EXC words is -17.36, and the average for the POA coefficients for REG and EXC pictures is -446.84. The difference between these coefficients exceeds the 95% CI, which represents a Format x POA rising overadditive interaction.

In order to investigate whether POA interacts with an orthographic lexical variable, GLM regressions were conducted on each participant's correct onset RTs, with RT as the dependent variable, and POA and HAL WF as continuous independent variables, separately for each combination of WT and Format. The resulting POA x HAL WF coefficients for each WT and Format set were then aggregated over participants, and submitted to one-sample *t*-tests against zero. Given that this interaction represents a difference score in the slope of one variable as a function of the other, and given the negative slopes for each of these variables overall (i.e., WF has a negative relationship with RT, and POA has a negative relationship with RT), the positive coefficient for the interaction reflects a decreasing negative difference, and thus maps onto a rising overadditive pattern when the fastest RT point is plotted closest to the origin. The only significant POA x HAL WF rising overadditive interaction was for EXC words (12.59 ms/unitPOAxHAL WF, $t(38) = 2.69$, $SEM = 4.68$, $p = .011$).

We conducted the same analyses on POA x SUBTL WF, and found no significant rising overadditive interaction patterns, supporting the notion that SUBTL WF may not be as specific of a measure reflecting processing in the orthographic lexical system as HAL WF.

Error Rates. The mean error rate percentages are presented in Figure 18. There was a significant main effect of Format, *F*(1, 39) = 128.65, *MSe* = 60.9, *p* < .001, no significant main effect of WT, *F*(1, 39) = 1.76, *MSe* = 30.9, *p* = .192, and a significant Format x WT interaction, *F*(1, 39) = 19.59, *MSe* = 36.9, *p* < .001. The 95% repeated-measure CIs for error rates was calculated and is shown in Figure 18. Given that at the by-subjects level, the errors are binary (correct or incorrect, with the majority correct) for individual trials, it is not possible to run regressions for the WF effect on percent error, and thus, we only performed these regressions in the by-item analyses (see below).

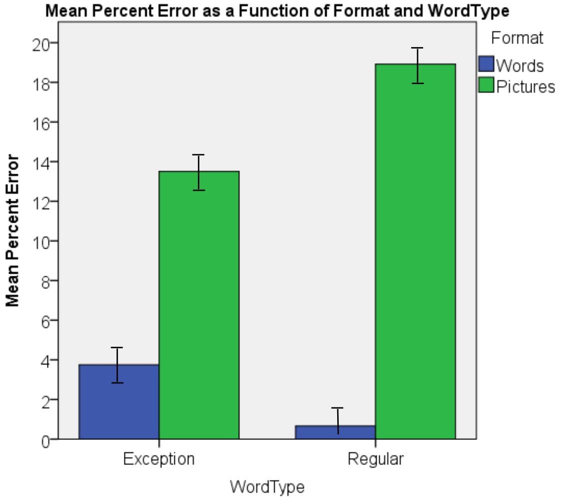

Figure 18: Mean Percent Error as a function of Format and WT for the by-subjects analyses in Experiment 3. The 95% CIs are presented as error bars using Loftus and Masson's (1994) method.

Word and Picture Naming Response Duration. The naming RD data were aggregated by participant as a function of Format and WT. Medians of the correctly named item RDs were submitted to a 2 X 2 GLM ANOVA, with Format and WT as repeated measures factors. The median naming RDs are presented in Figure 19. There was a significant main effect of WT, *F*(1, 39) = 37.61, *MSe* = 427.28, *p* < .001, whereby EXC items have shorter durations than REG items, no main effect of Format, *F*(1, 39) = .003, *MSe* = 932.28, *p* = .96, and the Format x WT interaction did not reach significance, *F*(1, 39) = 2.86, *MSe* = 560.20, *p* = .09. The 95% repeated-measure CIs for RD was calculated and is shown in Figure 19.

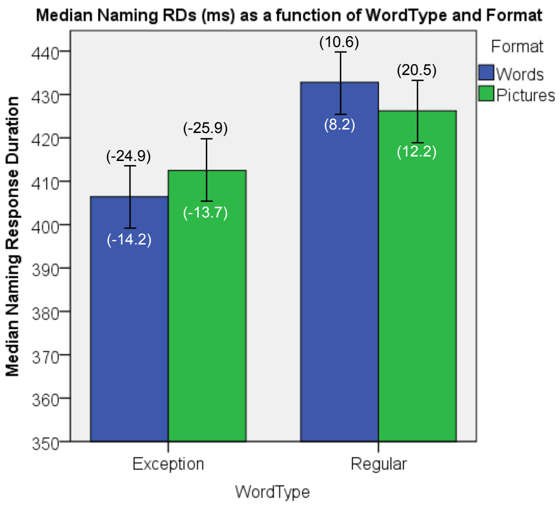

Figure 19: Median Naming RDs (in milliseconds) as a function of WT and Format for the by-subjects analyses in Experiment 3. The 95% CIs are presented as error bars using Loftus and Masson's (1994) method. Coefficients relating HAL WF to RT (ms/$\log_{10}$HALWF) are presented in parentheses below each error bar, and coefficients relating SUBTL to RT (ms/$\log_{10}$SUBTL WF) are presented in parentheses above each error bar.

HAL Word Frequency Effects on Response Duration. In order to investigate the effects of HAL WF on RD, we conducted the same analyses as for onset RT. Figure 19 shows the mean coefficients below the median RDs. There was a significant main effect of WT on the size of the HAL WF effect, $F(1, 39) = 203.59$, $MSe = 114.77$, $p < .001$, which represents a HAL WF x WT interaction on naming RD, whereby the HAL WF effects are greater for EXC items. The main effect of Format on the size of the HAL WF effect did not reach significance, $F(1, 39) = 2.91$, $MSe = 69.89$, $p = .09$, whereby there was a tendency for an interaction, such that there were larger HAL WF effects for words than for pictures.

The 95% repeated-measure CIs for HAL WF effects on RD was calculated to be ± 2.77 ms/lg unit HAL WF. The coefficients reported below the error bars on Figure 19 exceed this CI, and thus are significantly different from zero. As such, when applied to the HAL WF coefficients for word RDs in Figure 19 (-14.2 versus +8.2), there is a significant HAL WF x WT interaction. When applied to the HAL WF coefficients for picture RDs in Figure 19 (-13.7 versus +12.2), there is also a significant HAL WF x WT interaction.

Subtitle Word Frequency Effects on Response Duration. In order to investigate the effects of SUBTL WF on RD, we conducted the same analyses as for HAL WF. There was a significant main effect of WT on the size of the SUBTL WF effect, $F(1, 39) = 110.84$, $MSe = 605.01$, $p <$

.001, which represents a SUBTL WF x WT interaction, whereby the SUBTL WF effects are greater for EXC items. There was no significant main effect of Format, $F(1, 39) = 1.79$, $MSe = 436.77$, $p = .18$.

The 95% repeated-measure CIs for SUBTL WF effects on RD was calculated to be ± 6.71 ms/lg unit SUBTL WF. The coefficients reported above the error bars on Figure 19 exceed this CI, and thus are significantly different from zero. As such, when applied to the SUBTL WF coefficients for word RDs in Figure 19 (-24.9 versus +10.6), there is a significant SUBTL WF x WT interaction. When applied to the SUBTL WF coefficients for picture RDs in Figure 19 (-25.9 versus +20.5), there is also a significant SUBTL WF x WT interaction.

Picture-Orthography Agreement Effects on Response Duration. The same analyses were conducted on POA as for HAL WF and SUBTL WF. The mean coefficient relating: POA to EXC word RD was 9.27 ms/unitPOA, POA to EXC picture RD was -4.18 ms/unitPOA, POA to REG word RD was -13.58 ms/unitPOA, and POA to REG picture RD was -15.55 ms/unitPOA. There was a significant main effect of WT, $F(1, 39) = 7.88$, $MSe = 1485.37$, $p = .008$, which represents a POA x WT interaction, and there was no significant main effect of Format, $F(1, 39) = 2.16$, $MSe = 1102.98$, $p = .15$.

The 95% repeated-measure CIs for POA effects on RD was calculated to be ± 12.64 ms/unitPOA. Thus, the coefficients for REG words and REG pictures are significantly different from zero. When the 95% CI is applied to the POA coefficients for word RDs (9.27 versus -13.58), there is a significant POA x WT interaction. When applied to the POA coefficients for picture RDs (-4.18 versus -15.55), there is no significant POA x WT interaction. The average of the POA coefficients for REG and EXC words is -2.16, and the average for the POA coefficients for REG and EXC pictures is -9.86. The difference between these coefficients does not exceed the 95% CI.

Item Analyses

Word and Picture Naming Reaction Time. The naming onset RT data were first aggregated by item as a function of Format (word, picture) and WT (REG, EXC). Medians of the correctly named item RTs were submitted to a 2 X 2 GLM ANOVA, with Format as a repeated measures factor and WT as a between-items factor. The median naming onset RTs are presented in Figure 20. There was a significant main effect of Format, $F(1, 58) = 208.46$, $MSe = 22431.7$, $p < .001$, no significant main effect of WT, $F(1, 58) = .045$, $MSe = 27259.3$, $p = .83$, and no significant

Format x WT interaction, *F*(1, 58) = 1.43, *MSe* = 22431.7, *p* = .25. The 95% repeated-measure CIs for RT was calculated and is shown in Figure 20.

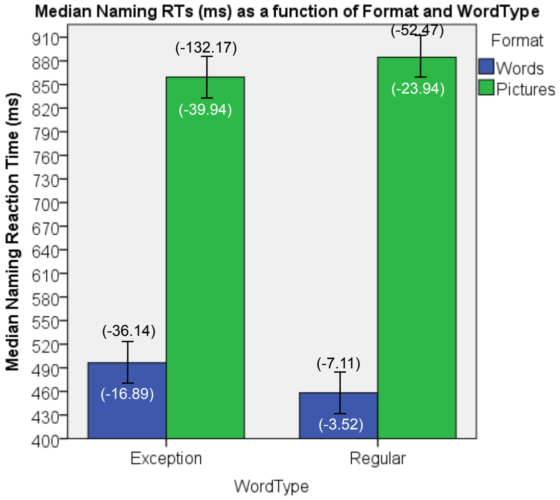

Figure 20: Median Naming RTs (in milliseconds) as a function of WT and Format for the by-items analyses in Experiment 3. The 95% CIs were calculated using Loftus and Masson's (1994) method for EXC and REG items separately, as these items can be paired up by Format in a repeated measures manner, and are presented as error bars around the median RTs, whereas WT is a between-items factor. Coefficients relating HAL WF to RT (ms/$\log_{10}$HALWF) are presented in parentheses below each error bar, and coefficients relating SUBTL WF to RT (ms/$\log_{10}$SUBTLWF) are presented in parentheses above each error bar.

HAL Word Frequency Effects on Reaction Time. Separate GLM regressions were conducted on EXC and REG stimuli in order to test coefficients that relate HAL WF to RT (below the CI bars in Figure 20). *T*-tests showed that the coefficient relating HAL WF to EXC word onset RT (-16.89 ms/unitlgWF) was significant, *t*(58) = -2.976, *SEM* = 5.67, *p* = .006, and approached significance for EXC picture onset RT (-39.94 ms/unitlgWF), *t*(58) = -1.83, *SEM* = 21.88, *p* = .08. The coefficient relating HAL WF to REG word onset RT (-3.52 ms/unitlgWF) was not significant, *t*(58) = -.84, *SEM* = 4.18, *p* = .40, nor was the coefficient relating HAL WF to REG picture onset RT (-23.94 ms/unitlgWF), *t*(58) = -.83, *SEM* = 28.65, *p* = .41. The significant coefficient that relates HAL WF to EXC word naming RT, but not to REG word naming RT, is in accord with the commonly reported WF x WT rising overadditive interaction reported in the literature. In order to investigate the effects of HAL WF, we added it as a variable to the GLM. This analysis yielded a significant main effect of HAL WF, *F*(1, 57) = 6.42, *MSe* = 24931.2, *p* = .014, and there was no significant Format x HAL WF interaction, *F*(1, 57) = 1.66, *MSe* =

22179.2, *p* = .20. When the HAL WF x WT interaction was added to the GLM there was no significant interaction, *F*(1, 56) = .60, *MSe* = 25106.1, *p* = .44.

Subtitle Word Frequency Effects on Reaction Time. Separate GLM regressions were conducted on EXC and REG stimuli in order to obtain coefficients that relate SUBTL WF to onset RT (shown above error bars in Figure 20). *T*-tests showed that the coefficient relating SUBTL WF to EXC word onset RT (-36.14 ms/unitlgSUBTL WF) was significant, *t*(58) = -2.47, *SEM* = 14.61, *p* = .02, and to EXC picture onset RT (-132.17 ms/unitlgSUBTL WF), *t*(58) = -2.56, *SEM* = 51.62, *p* = .01. The coefficient relating SUBTL WF to REG word onset RT (-7.11 ms/unitlgSUBTL WF) was not significant, *t*(58) = -.81, *SEM* = 8.73, *p* = .42, or to REG picture onset RT (-52.47 ms/unitlgSUBTL WF), *t*(58) = -.88, *SEM* = 59.81, *p* = .38. The significant coefficient that relates SUBTL WF to EXC word naming RT, but not to REG word naming RT, is also in accord with the commonly reported WF x WT rising overadditive interaction reported in the literature. In order to investigate the effects of SUBTL WF, we added it as a predictor in the GLM similar to how HAL WF was analyzed above. This analysis yielded a significant main effect of SUBTL WF, *F*(1, 57) = 8.32, *MSe* = 24203.4, *p* = .006. The Format x SUBTL WF interaction approached significance, *F*(1, 57) = 3.52, *MSe* = 21495.7, *p* = .06 (*p* = .03 by one-tailed test). When the SUBTL WF x WT interaction was added to the GLM there was no significant interaction, *F*(1, 56) = 1.73, *MSe* = 23897.2, *p* = .19.

Error Rates. The mean error rate percentages are presented in Figure 21. There was a significant main effect of Format, *F*(1, 58) = 63.38, *MSe* = 260.48, *p* < .001, no significant main effect of WT, *F*(1, 58) = 67.33, *MSe* = 373.67, *p* = .55, and the Format x WT interaction that approached significance, *F*(1, 58) = 3.64, *MSe* = 260.48, *p* = .06. The 95% repeated-measure CIs for error rates are presented in Figure 21.

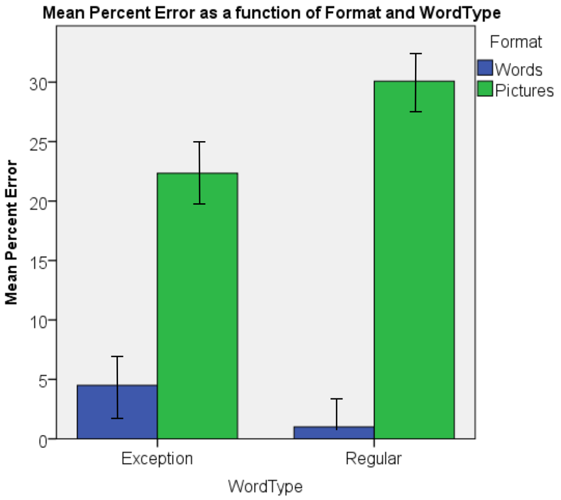

Figure 21: Mean Percent Error as a function of Format and WT for the by-items analyses in Experiment 3. The 95% CIs were calculated using Loftus and Masson's (1994) method for EXC and REG items separately, as these items can be paired up by Format in a repeated measures manner, and are presented as error bars around the median RTs, whereas WT is a between-items factor.

HAL Word Frequency Effects on Percent Error. Separate GLM regressions were conducted on EXC and REG stimuli in order to obtain coefficients that relate HAL WF to percent error. *T*-tests showed that the coefficient relating HAL WF to EXC word percent error (-2.08 ms/unitlgWF) was significant, *t*(58) = -3.06, *SEM* = .68, *p* = .005, and was also significant for EXC picture percent error (-5.87 ms/unitlgWF), *t*(58) = -2.56, *SEM* = 2.28, *p* = .01. The coefficient relating HAL WF to REG word percent error (-.11 ms/unitlgWF) was not significant, *t*(58) = -.54, *SEM* = .21, *p* = .59, nor was the coefficient relating HAL WF to REG picture percent error (-3.41 ms/unitlgWF), *t*(58) = -1.02, *SEM* = 3.32, *p* = .31. We added HAL WF to the item analysis GLM. This analysis yielded a significant main effect of HAL WF, *F*(1, 57) = 9.21, *MSe* = 327.32, *p* = .004. The Format x HAL WF interaction approached significance, *F*(1, 57) = 3.97, *MSe* = 247.78, *p* = .051. When HAL WF was added to the GLM there was no significant HAL WF x WT interaction, *F*(1, 56) = 1.05, *MSe* = 327.03, *p* = .31.

Subtitle Word Frequency Effects on Percent Error. Separate GLM regressions were conducted on EXC and REG stimuli in order to obtain coefficients that relate SUBTL WF to percent error. *T*-tests showed that the coefficient relating SUBTL WF to EXC word percent error (-5.26 ms/unitlgSUBTLWF) was significant, *t*(58) = -3.15, *SEM* = 1.67, *p* = .004, and to EXC picture percent error (-8.82 ms/unitlgSUBTLWF), *t*(58) = -3.62, *SEM* = 5.19, *p* = .001. The coefficient relating SUBTL WF to REG word percent error (-.56 ms/unitlgSUBTLWF) was not significant, *t*(58) = -1.30, *SEM* = .43, *p* = .20, or to REG picture percent error (-8.46 ms/unitlgSUBTLWF), *t*(58) = -1.23, *SEM* = 6.88, *p* = .23. We added SUBTL WF as a predictor in the GLM, and this analysis yielded a significant main effect of SUBTL WF, *F*(1, 57) = 13.84, *MSe* = 305.94, *p* < .001, and a significant Format x SUBTL WF interaction, *F*(1, 57) = 7.29, *MSe* = 234.97, *p* = .009. When the SUBTL WF x WT interaction was added to the GLM there was no significant interaction, *F*(1, 56) = 2.67, *MSe* = 297.23, *p* = .11.

Picture-Orthography Agreement Effects on Reaction Time. The same analyses were conducted on POA as HAL WF and SUBTL WF. The mean coefficient relating: POA to EXC word RT was -39.42 ms/unitPOA (*t*(58) = -2.03, *SEM* = 19.42, *p* = .052), POA to EXC picture RT was -339.56 ms/unitPOA (*t*(58) = -9.25, *SEM* = 36.72, *p* < .001), POA to REG word RT was -8.06 ms/unitPOA (*t*(58) = -.75, *SEM* = 10.82, *p* = .46), and POA to REG picture RT was -349.08 ms/unitPOA (*t*(58) = -9.80, *SEM* = 35.61, *p* < .001). We added POA as a predictor in the item analysis GLM, and this analysis yielded a significant main effect of POA, *F*(1, 57) = 180.31, *MSe* = 7010.56, p < .001, and there was a significant Format x POA interaction, *F*(1, 57) = 128.58, *MSe* = 7010.56, p < .001. When the POA x WT interaction was added to the GLM there was no significant interaction, *F*(1, 56) = .16, *MSe* = 6762.48, p = .69.

Word and Picture Naming Response Duration. The naming RD data were aggregated by item as a function of Format and WT. Medians of the correctly named item RDs were submitted to a 2 X 2 GLM ANOVA with Format as a repeated measures factor and WT as a between-items factor. The median naming RDs are presented in Figure 22. There was a significant main effect of Format, *F*(1, 58) = 7.69, *MSe* = 322.07, *p* = .007, whereby pictures have shorter durations than words. There was no significant main effect of WT, *F*(1, 58) = 1.26, *MSe* = 5989.4, *p* = .26, and no significant Format x WT interaction, *F*(1, 58) = .791, *MSe* = 322.07, *p* = .38. The 95% repeated-measure CIs for RD was calculated and is shown in Figure 22. The CIs indicate that the word and picture conditions differ from each other within each WT.

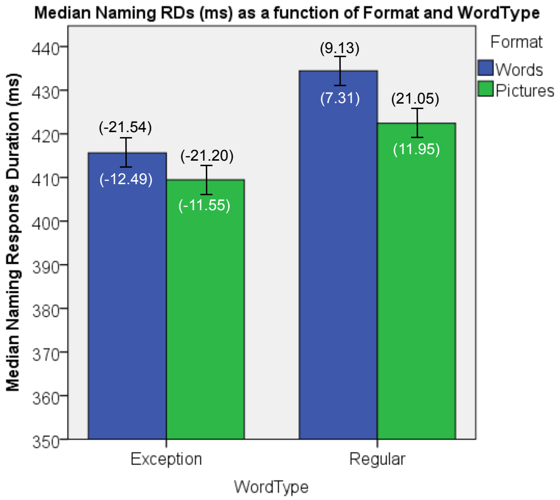

Figure 22: Median Naming RDs (in milliseconds) as a function of Format and WT for the by-items analyses in Experiment 3. The 95% CIs were calculated using Loftus and Masson's (1994) method for EXC and REG items separately, as these items can be paired up by Format in a repeated measures manner, and are presented as error bars around the median RDs, whereas WT is a between-items factor. Coefficients relating HAL WF to RT (ms/$\log_{10}$HALWF) are presented in parentheses below each error bar, and coefficients relating SUBTL WF to RT (ms/$\log_{10}$SUBTLWF) are presented in parentheses above each error bar.

HAL Word Frequency Effects on Response Duration. Separate GLM regressions were conducted on EXC and REG stimuli in order to obtain coefficients that relate HAL WF to RD (shown below CI bars in Figure 22). *T*-tests showed that the coefficient relating HAL WF to EXC word RD (-12.49 ms/unitlgHALWF) approached significance, *t*(58) = -1.95, *SEM* = 6.41, *p* = .06, and also approached significance for EXC picture RD (-11.55 ms/unitlgWF), *t*(58) = -1.94, *SEM* = 5.97, *p* = .06. The coefficient relating HAL WF to REG word RD (7.31 ms/unitlgWF) was not significant, *t*(58) = 1.16, *SEM* = 6.28, *p* = .25, and approached significance for REG picture RD (11.95 ms/unitlgWF), *t*(58) = 1.90, *SEM* = 6.26, *p* = .06. In order to investigate the effects of HAL WF, we added it to the GLM. This analysis yielded no significant main effect of HAL WF, *F*(1, 57) = .83, *MSe* = 6007.3, *p* = .37. There was no significant Format x HAL WF interaction, *F*(1, 57) = 1.24, *MSe* = 320.72, *p* = .27. When the WT x HAL WF interaction was added to the GLM there was a significant interaction, *F*(1, 56) = 5.96, *MSe* = 5526.25, *p* = .02.

Subtitle Word Frequency Effects on Response Duration. Separate GLM regressions were conducted on EXC and REG stimuli in order to obtain coefficients that relate SUBTL WF to RD (shown above CI bars in Figure 22). *T*-tests showed that the coefficient relating SUBTL WF to EXC word RD (-21.54 ms/unitlgSUBTLWF) was not significant, *t*(58) = -1.31, *SEM* = 16.44, *p* = .20, nor to EXC picture RD (-21.20 ms/unitlgSUBTLWF), *t*(58) = -1.39, *SEM* = 15.23, *p* = .17. The coefficient relating SUBTL WF to REG word RD (9.13 ms/unitlgSUBTLWF) was not significant, *t*(58) = -.68, *SEM* = 13.33, *p* = .49, nor to REG picture RD (21.05 ms/unitlgSUBTLWF), *t*(58) = 1.58, *SEM* = 13.33, *p* = .12. In order to investigate the effects of SUBTL WF on RD, we added it as a predictor in the GLM. This analysis yielded no significant main effect of SUBTL WF, *F*(1, 57) = .23, *MSe* = 6070.06, *p* = .63. The Format x SUBTL WF interaction was not significant, *F*(1, 57) = 1.36, *MSe* = 320.08, *p* = .25. When the WT x SUBTL WF interaction was added to the GLM the interaction approached significance, *F*(1, 56) = 3.18, *MSe* = 5846.29, *p* = .08.

Picture-Orthography Agreement Effects on Response Duration. We conducted the same analyses on RD as on onset RT, and found no significant main effects or interactions.

Discussion

Our first set of hypotheses involved (1) the joint effects of Format, POA, WF, and WT on onset RT. Taken together, our results support the hypotheses such that we predicted rising overadditive interactions between: *WF x WT for words* - our results consistently showed significant HAL WF x WT and SUBTL WF x WT rising overadditive interactions on RT (i.e., larger WF effects for EXC words than REG words), replicating the pattern reported in the literature and supporting the notion that these variables affect the phonological output system (Cummine et al., 2010; Gould et al., 2012); *Format x WF, POA x WF, and Format x POA*– these interactions were also obtained (although the HAL WF x Format interaction in the by-subjects analyses was significant only by a one-tailed test *p* = .027) and support the notion that these variables all reflect connections involving the orthographic lexical system, and that additional frequency-sensitive connections are involved between the picture identification system and word identification system during nonverbal-to-verbal translation. We also predicted additivity between: *Format + WT and POA + WT* – additivity was obtained between POA and WT, reflecting the extent that these variables are affecting separable systems.

(2) *Picture naming RT > Word naming RT* – our results consistently showed a Format effect, whereby words have a faster onset RT (and lower error rate) compared to pictures of the same referents (Cattell, 1886; Fraisse, 1969; Hennessey & Kirsner, 1999; Potter & Faulconer, 1975),

supporting the notion that there is an additional nonverbal-to-verbal translation step for picture naming, which is not required in word naming (Paivio, 1986, 2007).

(3) *HAL WF effect on picture and word naming RT* - there was a significant orthographic WF effect on EXC word naming RT as is commonly reported, as well as for picture naming RT, supporting the notion that naming pictures and words both involve the activation of the orthographic lexical system. Similar results were found for SUBTL WF as well.

(4) *HAL WF effect for pictures* – as predicted, there was a significant frequency effect for both REG and EXC pictures, that was stronger for EXC pictures suggesting that they have greater access to the orthographic lexical system. These findings clearly converge on the idea that picture identification involves the orthographic lexical system. Similar results were found for SUBTL WF effects as well.

Our second set of hypotheses were in regards to RDs of vocalizations. We predicted that:

(1) *EXC RD < REG RD* - given that reading EXC words must be based on "whole-word" (lexical) retrieval, they produced shorter RDs, despite the fact that EXC word onset RTs are longer than REG word onset RTs (Gould et al., 2012). Furthermore, naming EXC pictures also produced shorter RDs than REG picture RDs, which extends the RD advantage to the picture format.

(2) *Picture RD < Word RD* - given that REG word naming can involve sublexical processing, REG words showed longer RDs compared to picture naming responses suggesting that duration is lengthened with the involvement of sublexical processing (Hennessey & Kirsner, 1999). However, this pattern on RD was only robust for REG items, whereas for EXC items it was significant only in the item analyses, and the pattern reversed in the subject analyses.

Experiment 4

As described in the Introduction, Arabic digits and number words are completely matched for meaning and phonology, and thus serve as an ideal condition for examining RD effects. Several researchers in the field of numerical cognition suggest that number words and Arabic digits are processed via separable pathways, which are at least partly dissociable, as evidenced by patients with selective impairments to either word or Arabic digit identification (e.g., Cipolotti et al., 1995). Although the results of studies examining naming RT for Arabic digits and words have been inconsistent, there is some research supporting an RT advantage for number words in naming (Damian, 2004). However, upon closer inspection of Damian's results, it appears that the advantage for number words is mainly driven by the number words 'zero' and 'seven', which we do not have in our stimulus set, as these words are multisyllabic. Given that RT effects may not be robust, we also examine RD effects and hypothesize that, to the extent that Arabic digits rely on a representation that may be akin to a picture representation, and thus refer to a "whole-word" representation to be pronounced correctly, they should show shorter RDs than their corresponding number words, which could be processed via involvement of the sublexical pathway.

Method

The same subjects participated in Experiment 4, and the method was the same as Experiment 3 with the following exception. Ten monosyllabic numbers (1-12, excluding 7 and 11 as these are multisyllabic) in word format and digit format were used as critical stimuli. Each number was presented randomly three times in a block for a total of 30 trials per block, and each participant was presented with two blocks of numbers, which were counterbalanced by Notation Format (word, digit).

Results

The naming onset RT and RD data were first aggregated by participant as a function of Notation Format (word, digit). The median naming onset RTs are presented in Figure 23, and the median naming RDs are presented in Figure 24. The 95% repeated-measure CIs for word and digit RT was calculated to be ± 9.62 ms, and for word and digit RD was calculated to be ± 5.90 ms. As such, when applied to the RT data there is no significant effect of Notation Format, whereas when applied to the RD data there is a significant effect supporting an advantage for digits (Digit: 363.42 ms versus Word: 371.50 ms). The response accuracy was at ceiling for both conditions (i.e., 100% accuracy).

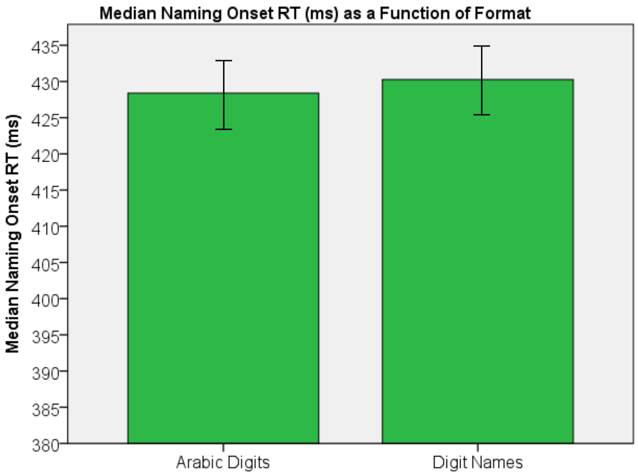

Figure 23: Median Naming RTs (in milliseconds) as a function of Format in Experiment 4. The 95% CIs are presented as error bars using Loftus and Masson's (1994) method.

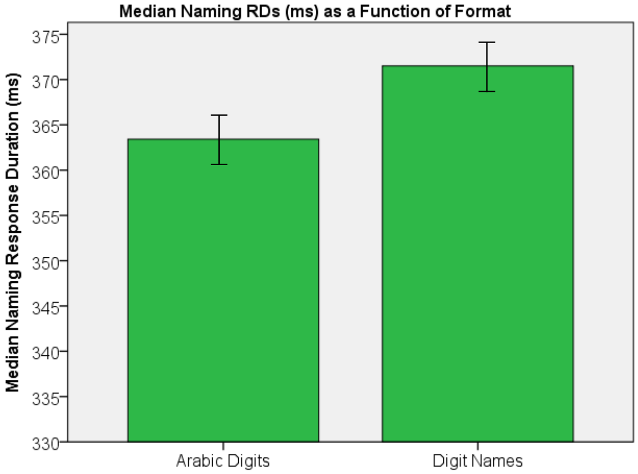

Figure 24: Median Naming RDs (in milliseconds) as a function of Format in Experiment 4. The 95% CIs are presented as error bars using Loftus and Masson's (1994) method.

Discussion

In Experiment 4, we hypothesized that Arabic digits, which must rely on lexical "whole-word" processing to the extent that they are processed as pictures, showed shorter RDs compared to their matched number words, which can rely on sublexical processing and showed longer RDs, should show shorter RDs compared to their corresponding number words, which could be processed via involvement of the sublexical pathway. Our results support our hypothesis such that the RD data revealed a significant effect supporting an RD advantage for digits. Furthermore, we did not find a reliable RT advantage for Arabic digits, supporting the idea that the RT difference between these conditions is not very robust. These results provide further support for the notion that items that must be processed lexically produce shorter RDs, whereas items that can be processed sublexically produce longer RDs.

CHAPTER 3

GENERAL DISCUSSION

I. Word Identification: A Summary of the Findings from Experiments 1 and 2

As described in the introduction, our hypotheses for Experiments 1 and 2 involved the joint effects of INST, WF, SND, and WT on onset RT. Taken together, the by-participants analyses, the by-item-by-participant regression analyses, and the by-item analyses, support our hypotheses such that: (i) *INST x WF* – the INST x WF rising overadditive interaction was significant, supporting the notion that these two variables are affecting the orthographic lexical system; (ii) *INST + WT* - given that INST should be having its effect in the early stages of word processing, whereas WT has previously been shown to have its effect at a later stage of processing, this additive pattern was also consistent with our previous research (Borowsky et al., 2012; Cummine et al., 2010, 2013), and supports the notion that INST are affecting an orthographic lexical system that is temporally separable from the phonological output system that is affected by WT; (iii) *INST x SND* – the INST x SND rising overadditive interaction was significant, supporting a common locus of the orthographic lexical system for their effects; (iv) *WF x SND* – the WF x SND rising overadditive interaction supports the notion that these two variables are affecting the semantic system and the connections to other word-level systems; (v) *SND x WT* – the SND x WT rising overadditive interaction was significant, supporting a common locus of the phonological output system for their effects; and (vi) *WF x WT* - the WF x WT rising overadditive interaction under the normal *name all* instructions was significant in Experiment 2 and the combined analyses, supporting the notion that these variables affect the phonological output system.

Our second set of hypotheses involved the RDs of vocalizations: *EXC RD < REG RD < NW RD* - given that EXC words must be processed as "whole-words" and read lexically in order to be pronounced correctly, they produced the shortest RDs, despite the fact that EXC onset RTs are longer than REG onset RTs. Given that NWs must be processed through sublexical GPCs, they produced the longest RDs. Finally, given that REG words can be processed through either route, they elicited intermediate RDs relative to EXC words and NWs, despite having the fastest onset RTs. The results supported the prediction that *name words RD < name all RD* in that the more lexically a word is read, the shorter the RD. The SND effect remained in the same facilitative direction for onset RT and RD, which is consistent with Balota et al.'s (1989) finding with semantic priming. The WF effect also remained in the same facilitative direction for onset RT and RD, which is consistent with it having its effects at the same lexical/semantic level as SND.

Response Duration

By developing a new measure of RD for reading aloud**,** we have an additional and more comprehensive measure of basic reading processes. Given that basic reading processes are still ongoing after the initiation of a vocal response, measures of onset RT may only reflect early aspects of processing (e.g., in terms of only *partially* reflecting lexical access, or the resolution of conflicting phonological codes). Our results provide evidence that systems that are influenced by such variables as INST, WF, SND, and WT are still affecting the duration of the reading response, even after these variables have already influenced onset RTs. In addition, our results support the notion that the more lexically a word is read (e.g., EXC words, or *name words* INST), the shorter the RD, in the face of longer onset RTs for such conditions (see Figures 25 and 26). To our knowledge, this is the first demonstration of a dissociation between RT and RD, as a function of the degree of lexical-based reading. This dissociation is particularly powerful given that it has been demonstrated by both a within-item (i.e., INST) and between-item (i.e., WT) manipulation. Although Balota et al. (1989) showed that semantic priming had an effect on both RT and RD in their study, whereby both were shorter for the related condition, WT and INST in the present study are clearly showing a dissociation between onset RT and RD. Interestingly, neither SND nor WF effects reversed between RT and RD (i.e., inverse Ncount coefficients remained positive, while WF coefficients remained negative in all conditions), and thus seem to be behaving in a manner consistent with semantic priming effects (Figure 26).

Perhaps SND and WF effects (similar to Balota et al.'s 1989 finding with semantic priming) can be thought of as consistently reflecting the core lexical/semantic aspects of processing, in that they both facilitate the speed of lexical/semantic access and thus affect onset RT and RD in the same way. Instruction effects might best be thought of as reflecting a front-end gating manipulation, whereby INST to *name words* serves to increase reliance on the orthographic lexical route, relative to INST to *name all*. Reaction time is higher for *name words* INST given the time required to verify the word's lexical status, whereas RD is shorter in this condition given that once the word's lexical status has been verified, the phonological code is also lexical-based and thus more rapidly produced. However, it is clear that EXC words are showing different RDs for the two INST conditions, suggesting that there is ‘room to move’ for EXC words to have even shorter RDs under the *name words* INST condition compared to the *name all* INST condition. Perhaps under *name all* INST, EXC RDs are produced with some hesitation due to the greater overall reliance on sublexical GPCs under *name all* INST (e.g., for naming the NWs, and perhaps REG words some of the time). Word Type effects might best be thought to reflect a back-end convergence effect, whereby both routes produce converging phonological codes for REG words, relative to EXC words whereby both routes produce conflicting phonological codes. Reaction time is shorter for REG words given an early assessment of the phonological codes for the word’s onset, allowing a participant to quickly initiate their response, whereas RD is longer given the slower sublexical contribution to completing the entire word’s pronunciation.

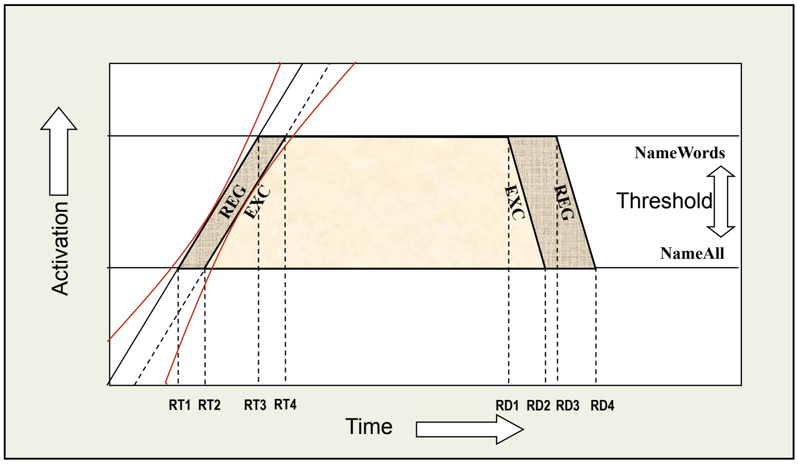

Figure 25: Additive joint effects on RT and RD between INST and WT. An Additive Factors Method (AFM) interpretation of the additive effect on RT is that INST and WT are affecting separable systems in time. If INST are assumed to affect the threshold for activation (i.e., the amount of time it takes to verify that a letter string spells a word), and WT is assumed to shift the rate of activation over time (i.e., the time it takes to choose among the competing phonological codes for EXC words), or vice versa, then the points in time when each rate crosses a threshold correspond to the average onset RTs (the left side of each trapezoid). The red confidence intervals around the slopes allow for trial to trial variation as described by Masson and Kliegl (2013), and thus we note that such variation is not problematic for applying the AFM, and can be easily accommodated by cascaded stages of processing. The effects of INST and WT on RD represent a dissociation when compared to RT. The right side of each trapezoid represents the RD and illustrates the dissociation.

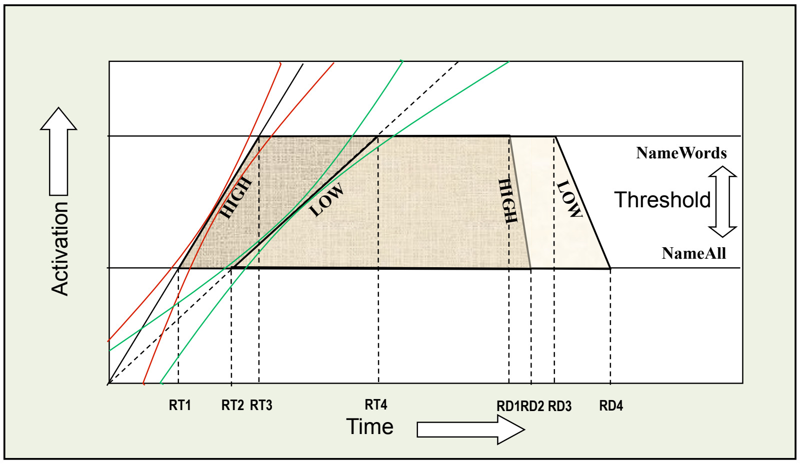

Figure 26: Overadditive interaction on RT between INST and WF. An AFM interpretation of this interaction on RT is that both INST and WF are affecting a common system in time. If INST are assumed to affect the threshold for activation, and WF is assumed to affect the rate of activation over time, or vice versa, then the points in time when each rate crosses a threshold correspond to the average onset RTs (the left side of each trapezoid). WF and WT interact on RT in a similar fashion. The red and green confidence intervals around the slopes allow for trial to trial variation. The effects of WF on RD remain negative when compared to RT. We note that SND effects can be accounted for in a similar manner. The effects of INST on RD represent the dissociation when compared to RT. The right side of each trapezoid represents the RD and illustrates this dissociation.

The present RD results also bear on the question of the degree to which reading processes are still occurring post-vocalization onset. Given the significant effects of INST, WF, SND, and WT on RD, there is clearly a substantial amount of processing occurring post-vocalization onset. These post-vocalization onset effects clearly support the utility of an RD measure for investigating reading processes.

Additive Factors Method (AFM) and Models of Reading

The AFM allows for the investigation of whether two or more variables are affecting common or separable systems in time, whereby two variables that interact in a rising overadditive pattern on RT are considered to affect a common system, whereas two variables that are additive on RT are considered to affect separable systems. We selected four lexical/semantic variables known to affect basic reading processes, and examined their joint effects so as to delineate the sequence of systems involved in reading aloud. We manipulated: INST as a variable that would serve to gate processing towards the lexical route when participants were to *name words* only; WF as a variable whose effects reflect lexical/semantic connections; SND as a semantic variable whose effects reflect associations among semantic neighbours and their lexical/semantic connections; and WT as a variable whose effects reflect the convergence of the sublexical and lexical routes, in that REG words can be pronounced correctly through either route, whereas EXC words create conflicting phonological codes through the two routes. The INST x WF and INST x SND rising overadditive interactions support the notion that these variables are affecting a common and relatively early system in time, namely the orthographic lexical system (see Figure 1). The WF x WT and SND x WT rising overadditive interactions support the notion that these variables affect a common and relatively later system in time, namely the phonological output system. The INST + WT additive joint effects support the notion that they are affecting the orthographic lexical and phonological output systems, respectively. Taken together, these joint effects clearly support a model where the orthographic lexical system and phonological output system are cascaded in time (Figure 1), and not operating in parallel (cf., Plaut & Booth, 2000; Seidenberg, Petersen, MacDonald & Plaut, 1996).

The issue of the naming task being less sensitive to semantic effects, as described in Chapter 1 (Yap et al., 2012; Borowsky & Masson, 1996), is also addressed with the present results. By instructing readers to pronounce words only after lexical verification (i.e., the *name words* INST condition), and thus requiring them to read lexically, there was a larger SND effect than when they were instructed to name without encouraging reliance on the lexical route (i.e., the *name all* INST condition). As such, the INST x SND rising overadditive interaction supports the notion that semantic influences on naming behaviour can occur under conditions that encourage lexical access. The SND x WT rising overadditive interaction also supports this notion, whereby EXC words, which must be processed via the orthographic lexical route, showed a larger SND effect than REG words[3].

Ventral-lexical, dorsal-sublexical, model of basic reading processes

Our preferred cognitive architecture for basic reading processes, which is based on the Dual-Route Cascade model (Coltheart et al., 2001), assumes that processing operates on two

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[3] In response to a reviewer's query about SND effects under the *name all* INST condition, we conducted one-sample *t*-tests on the coefficients that relate SND to RT and to RD. All SND coefficients were found to be significantly different from zero (all t's(58) > 4.25, p's < .001). We also examined WF effects in the same way, and found that all WF coefficients were significantly different from zero (all t's(58) > |-7.06|, p's < .001). These results support the previously described idea that both SND and WF effects consistently reflect the core lexical/semantic aspects of processing, in that they both facilitate the speed of lexical/semantic access and thus affect onset RT and RD in the same way.

routes: a sublexical GPC route, which allows less familiar letter strings (including NWs and novel words) to be "sounded out", and a lexical route, which allows familiar words to be read as "whole-words" (see Figure 1). These routes have been mapped onto the dorsal and ventral visual processing streams, respectively (Borowsky et al., 2012, 2006, 2007; Cohen et al., 2008; Cummine et al., 2010, 2012; Herbster et al., 1997; Hickok & Poeppel, 2007; Jobard et al., 2003; Joubert et al., 2004; Indefrey & Levelt, 2004; Price & Devlin, 2003). This model also assumes that processing is cascaded among the subsystems.

The ventral-lexical route is relied on for reading familiar REG words and EXC words. The dorsal-sublexical route is relied on for reading NWs, novel words, and less familiar REG words. The convergence of these two routes can be facilitative in the case of reading REG words (where the phonological codes would be the same from both routes), or conflicting in the case of reading EXC words (where the phonological codes would be different from both routes), which has been described earlier in the context of the interaction between WF and WT (see also Cummine et al., 2010). Given that WF and SND have their effects in the lexical/semantic systems, including the orthographic lexical system, their influences are early enough to interact with the effects of INST, which can gate processing through the lexical route under the *name words* condition. In order to allow for novel words that lack any lexical representation to be read aloud, there is also a pathway from GPC to phonological output (see also Borowsky, Owen, & Masson, 2002).

It is worth noting that the ventral-lexical, dorsal-sublexical, multiple stage model and the effects of INST and WT that we are describing here are also consistent with other findings in the literature that have underscored the necessity of multiple stages and attentional control in basic reading models. For example, Reynolds and Besner (2005) showed that participants took longer to name both words and NWs when the item on the preceding trial was from the other lexical category, relative to when the preceding item was from the same lexical category, which is similar to our account for why EXC words show different RDs under the two INST conditions (see also Reynolds & Besner, 2006, for a multiple stage account of attention and reading processes). Furthermore, Reynolds and Besner (2011) have also showed changes in the WF effects as a function of list context when reading pseudohomophones aloud (see also Borowsky, Owen, & Masson, 2002).

Single-mechanism models

Single-mechanism parallel distributed processing (PDP) models (e.g., Plaut & Booth, 2000) are challenged by the current results. Such models have been developed to account for the basic effect of WT (REG, EXC), and the WF by WT interaction, on RT by a ‘division-of-labor’ between an Orthography–Phonology (O–P) pathway and an Orthography–Semantics– Phonology (O–S–P) pathway (e.g., Harm & Seidenberg, 2004, although ‘‘pathway’’ may be misleading given that these models subscribe to parallel processing across the entire network). Larger WF effects for EXC words are thought to occur due to the additional WF-sensitive connections involved in the O–S–P pathway, compared to the O–P pathway that REG reading is thought to rely on. There is no distinct orthographic lexicon in these models, unlike the dual-stream models, and so instructions to read by first checking the orthographic lexicon (name words, based on spelling) raises a challenge in and of itself. Waiting (to any degree) for the O units to settle on the word’s pattern of activation and using that information to gate processing in the S and P units might be a solution, but such ‘‘stage-like’’ or ‘‘cascaded’’ processing is counter to the *parallel* definition of these models (Plaut & Booth, 2000; and see the debate by Borowsky and Besner, 2006, Plaut and Booth, 2006, and Besner and Borowsky, 2006, for additional discussion of these issues, and see Ziegler, Perry & Zorzi, 2009, for a more recent hybrid computational model that has implemented thresholds or “stages of processing” in order to account for some additive effects). Perhaps most challenging is the presence of additive effects on RT (i.e., INST and WT) in the same range of RTs that also show rising overadditive interactions. Although a sigmoid activation function within a single-mechanism PDP model has been explored as a means to account for both additivity and rising overadditive interactions (Plaut & Booth, 2000), this approach is problematic as additive effects can only arise equidistant from the center of the sigmoid input–output function, yet additive effects occur regularly within the very same range of RTs as rising overadditive effects, as demonstrated in the research reported here, and elsewhere (see Borowsky & Besner, 2006 and Cummine et al. 2012 for a review).

Additive effects in the same range of RTs as rising overadditive effects are still best accounted for by the AFM. Additive effects of two variables are easily accounted for by implementing the effects of the two variables at two different time points in processing (i.e., two systems with stage-like processing). These systems may be in cascade (e.g., Borowsky & Besner, 1993; Coltheart et al., 2001; McClelland & Rumelhart, 1981) – all that is necessary is at least some delay between the initiation of activation in one system compared to the other. Such a delay is parsimonious with the known behaviour of real neural networks, and thus it can also be argued to be a necessary characteristic in all neurobiological models. Overadditive effects of two variables can be accounted for by implementing the effects of the two variables within the same system of processing (e.g., by affecting its activation rate, threshold, or baseline activation level, see Borowsky & Besner, 2006 and 1993 for discussion about how these parameters can be modeled to account for additivity and overadditivity). Dual-stream models of reading can readily handle the rising overadditive interactions as long as cascaded processing (i.e., some degree of delay of activation in systems downstream) is assumed.

Advantages of the present method

Despite the amount of time that goes into hand-marking each vocalization, the benefits from this approach far outweigh the costs (see also Rastle & Davis, 2002). Not only does hand-marking provide a new set of empirical data (RD) for testing models of reading processes, it also provides the following advantages. The traditional definition of a spoiled trial in a naming experiment includes a substantial proportion of trials when the voice-key failed to trigger – in the present experiments, the proportion of spoiled trials is quite low, given that replaying the audio is an important part of zeroing-in on the onset and offset, which is not done when one relies on a voice-key. Recording and hand-marking of vocal responses also allows for the collection of overt naming behavioral data in the MRI environment. Experiment 1 was conducted in the context of a fMRI study, and by simply recording through the intercom and synchronizing stimulus onset with an image acquisition, we were able to clearly detect onset and durations of vocal responses. By also using sparse sampling (i.e., a gap in image acquisition), the participants' vocal response was made in a relatively noise-free time period, which was also helpful. As such, recording and hand-marking of vocal responses will be of great benefit to researchers who do fMRI experiments involving vocalization responses. We note that there has been some computer software developed to analyze for onset and duration (e.g., Kello & Kawamoto, 1998), but such an approach would not be as effective as hand-marking and replaying vocal responses with respect to detecting spoiled responses and individual differences in intensity of vocalization, especially in noisy environments such as an MRI.

II. Picture and Word Identification: A Summary of the Findings from Experiments 3 and 4

In order to develop a model based on robust effects, our conclusions of Experiment 3 focus on effects that are consistent across by-subjects and by-items analyses. As previously described, our first set of hypotheses involved:

(1) Naming onset RT and the joint effects of Format, POA, WF, and WT on onset RT. Taken together, our results support the hypotheses such that we predicted rising overadditive interactions between: *WF x WT for words* - our results consistently showed significant HAL WF x WT and SUBTL WF x WT rising overadditive interactions on RT (i.e., larger WF effects for EXC words than REG words), replicating the pattern reported in the literature and supporting the notion that these variables affect the phonological output system (Cummine et al., 2010; Gould et al., 2012); *Format x WF, POA x WF, and Format x POA*– these interactions were also obtained (although the HAL WF x Format interaction in the by-subjects analyses was significant only by a one-tailed test $p = .027$) and support the notion that these variables all reflect connections involving the orthographic lexical system, and that additional frequency-sensitive connections are involved between the picture identification system and word identification system during nonverbal-to-verbal translation. We also predicted additivity between: *Format + WT and POA + WT* – additivity was obtained between POA and WT, reflecting the extent that these variables are affecting separable systems. However, our results demonstrated a significant underadditive interaction (i.e., when plotting the fastest condition near the origin) between Format and WT, which can be accounted for via separable stages of processing, as will be discussed later.

(2) *Picture naming RT > Word naming RT* – our results consistently showed a Format effect, whereby words have a faster onset RT (and lower error rate) compared to pictures of the same referents (Cattell, 1886; Fraisse, 1969; Hennessey & Kirsner, 1999; Potter & Faulconer, 1975), supporting the notion that there is an additional nonverbal-to-verbal translation step for picture naming, which is not required in word naming (Paivio, 1986, 2007).

(3) *HAL WF effect on picture and word naming RT* - there was a significant orthographic WF effect on EXC word naming RT as is commonly reported, as well as for picture naming RT, supporting the notion that naming pictures and words both involve the activation of the orthographic lexical system. Similar results were found for SUBTL WF as well.

(4) *HAL WF effect for pictures* – as predicted, there was a significant frequency effect for both REG and EXC pictures, that was stronger for EXC pictures suggesting that they have greater

access to the orthographic lexical system. These findings clearly converge on the idea that picture identification involves the orthographic lexical system. Similar results were found for SUBTL WF effects as well.

Our second set of hypotheses were in regards to RDs of vocalizations. As described in Chapter 1, an additional major goal of the present research was to investigate naming behaviour beyond just the onset of response, specifically, by examining RD. Response duration provides useful information about basic reading processes, in addition to RT and error rates, to reveal the cognitive chronometric architecture of processing during naming (Gould et al., 2012). We had hypothesized:

(1) *EXC RD < REG RD* - given that reading EXC words must be based on "whole-word" (lexical) retrieval, they produced shorter RDs, despite the fact that EXC word onset RTs are longer than REG word onset RTs (Gould et al., 2012). Furthermore, naming EXC pictures also produced shorter RDs than REG picture RDs, which extends the RD advantage to the picture format.

(2) *Picture RD < Word RD* - given that REG word naming can involve sublexical processing, REG words showed longer RDs compared to picture naming responses suggesting that duration is lengthened with the involvement of sublexical processing (Hennessey & Kirsner, 1999). However, this pattern on RD was only robust for REG items, whereas for EXC items it was significant only in the item analyses, and the pattern reversed in the subject analyses. The results of the present study support our earlier findings (Gould et al., 2012) in that they demonstrate a dissociation between REG word and EXC word RT and RDs. This WT effect on RD is a critical finding because it implies that we cannot say that pictures always have shorter RDs than words. It is important to note that Hennessey and Kirsner did not control for WT, and they used mainly REG words as critical stimuli. Clearly, it is imperative to examine the effect of WT on naming RD since we have reported that the dissociation between RT and RD effects on pictures is only robust for REG items.

In Experiment 4, we hypothesized that Arabic digits, which rely on a "whole-word" lexical representation to be pronounced correctly, should show shorter RDs compared to their corresponding number words, which could be processed via involvement of the sublexical pathway. Our results support our hypothesis such that the RD data revealed a significant effect supporting an RD advantage for digits. Furthermore, we did not find a reliable RT advantage for

Arabic digits, supporting the idea that the RT difference between these conditions is not very robust.

Word Type Effects

The WT effect on word naming RT was used a measure to reflect the convergence of the sublexical and lexical routes, whereby REG words (which can be pronounced correctly through either the sublexical route or the orthographic lexical route), produced faster RTs, whereas EXC words (which must be processed via the orthographic lexical route to be pronounced correctly), produced slower RTs. Our results are consistent with previous research that proposes that REG words are named faster because the two routes produce the same pronunciation at the phonological output system, whereas EXC words are named slower because the two routes produce conflicting pronunciations at the phonological output system and a single pronunciation must be selected (Cummine et al., 2010, 2013; Gould et al., 2012).

The WT effect on word naming RD supports the notion that the more lexically a word is read, the shorter the RD, whereby EXC words produced shorter RDs than REG words, despite the longer RTs for EXC words. These results replicate our previous findings (Gould et al., 2012), which showed that EXC words produced shorter RDs compared to REG words (and nonwords). Gould et al. suggested that words that must be read lexically (i.e., EXC words) produce the shortest RDs, whereas words that can be read sublexically (i.e., REG words) produce the longest RDs.

Interestingly, our results also demonstrate a WT effect on RT for pictures, whereby EXC pictures produced faster RTs than REG pictures, which is the opposite effect than what is consistently reported for words (REG words are typically named faster than EXC words). In addition, our results demonstrate a WT effect on RD for pictures, whereby EXC pictures produced shorter RDs than REG pictures, which is the same effect as reported for words. Taken together, these findings suggest that RD is shorter for items that are identified lexically as “whole-words”, and longer for items that involve sublexical processing, and that a WT effect on picture processing supports the notion that pictures (particularly EXC pictures) must activate their corresponding orthographic representations.

Format Effects

The present results are also consistent with previous research that has shown that picture naming RT is longer than word naming RT, supporting the notion that there is an additional nonverbal-to-verbal translation step for picture naming, which is not required in word naming (e.g., Cattell, 1886; Fraisse, 1969; Hennessey & Kirsner, 1999; Paivio, 1986, 2007; Potter & Faulconer, 1975).

Furthermore, the RD results show that pictures (which must be processed lexically) produce shorter RDs than words (which can be processed via the orthographic lexical system or the sublexical system, particularly for REG words). These results replicate the results of Hennessey & Kirsner (1999), which demonstrated a RD disadvantage for words, suggesting that sublexical processing increases RD. However, our study demonstrated that it is only the REG items that consistently showed a RD disadvantage for words compared to pictures, whereas EXC items only demonstrated the RD disadvantage for words in the by-items analyses.

The results from Experiment 4 provide further support for the notion that items that must be processed lexically produce shorter RDs, whereas items that can be processed sublexically produce longer RDs. We found that Arabic digits, which must rely on lexical "whole-word" processing to the extent that they are processed as pictures, showed shorter RDs compared to their matched number words, which can rely on sublexical processing and showed longer RDs. Given that these items represent an ideal matching of stimuli (i.e., perfectly matched for meaning and phonology), the significant differences found between the two types of notation clearly reflect a benefit on RD due to lexical processing, and/or a cost due to sublexical processing.

Additive Factors Method (AFM): Word and Picture Coupling

As described in Chapter 1, the AFM is a behavioural technique from cognitive psychology that allows for the investigation of whether two variables are affecting a common or separable system(s) of processing in time, and whether the nature of processing between the systems is staged or parallel (Borowsky & Besner, 1991, 1993, 2000, 2006; Sternberg, 1969; Yap et al., 2013). By 'separable', the two systems need not be discrete serial stages of processing, but the onset of activation in the second system must be delayed relative to the onset of activation in the first system. The AFM proposes that if two variables are affecting a common system of processing, they should yield a rising overadditive interaction on RT, whereas if two variables are affecting separable systems of processing, they should yield additive effects on RT. We examined the two-way joint effects of Format (pictures versus words), picture-orthography agreement (POA, reflecting the connections from the picture memory system to the orthographic lexical system), Word Frequency (including HAL WF as a measure reflecting orthographic lexical connections, and SUBTL WF as a broader measure of lexical connections), and Word Type (EXC versus REG items, which is known to have an effect at the relatively later phonological output system) in order to localize the systems and connections between basic reading and picture identification processes. The Format x WF rising overadditive interaction (significant for SUBTL WF, and significant one-tailed for HAL WF) supports the notion that these variables are affecting a common, and relatively early system in time, given that Format can be assumed to affect the front end of the system. We believe this relatively early system is the orthographic lexical system given that WF is known to have its effect at that level (see Figure 27). The Format x POA and POA x HAL WF (for EXC words) rising overadditive interactions support the notion that these variables are also affecting the orthographic lexical system. Given that WF x WT rising overadditive interactions have been demonstrated to occur relatively late (i.e., the phonological output system in the SMA; Cummine et al., 2010), the HAL WF x WT and SUBTL WF x WT rising overadditive interactions further support the notion that these variables affect the phonological output system. The Format + WT and POA + WT additive effects support the notion that they are affecting separable systems, whereby Format and POA affect the orthographic lexical system and WT affects the phonological output system. Taken together, these joint effects clearly support a model where the stages of processing are cascaded in time (Figure 27), and not driven by a single stage or mechanism (cf., Seidenberg, Petersen, & MacDonald, 1996; Plaut & Booth, 2000).

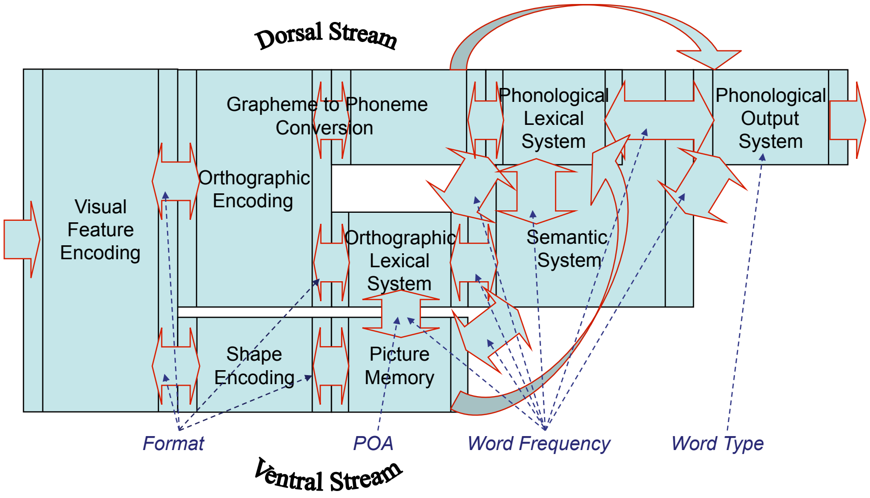


Figure 27: A Triple Route Model of Basic Reading and Picture Processing.

The Triple Route Model of Basic Reading and Picture Processing

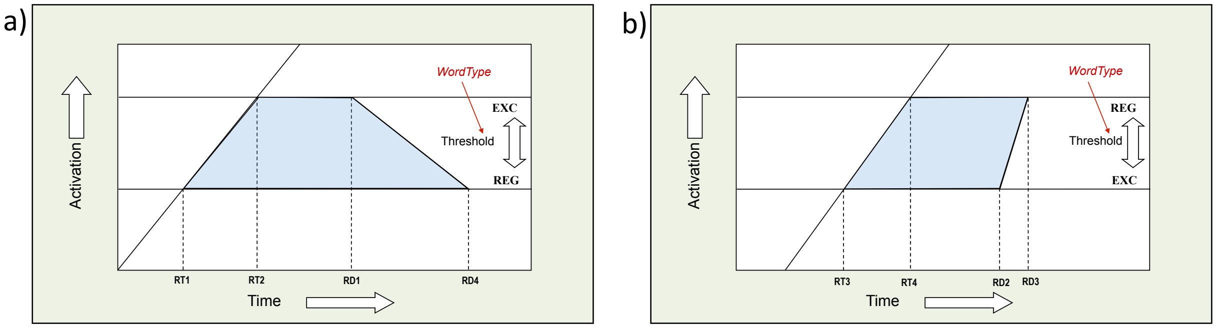
One of the major goals of the present study was to explore the interaction between word and picture identification processes, and to expand the dual-route model of basic reading to include picture identification processes. As described in Chapter 1, the dual-route model of reading assumes that processing operates on two routes: a sublexical GPC route, which allows less familiar letter strings (including nonwords and novel words) and REG words (e.g., coin) to be "sounded out", and a lexical route, which allows familiar words and EXC words (e.g., comb) to be read as "whole-words" (see Figure 27). These routes have been mapped onto the dorsal and ventral visual processing streams, respectively (e.g., Borowsky et al., 2012; Cummine et al., 2010, 2013). This model also assumes that processing due to a particular stimulus is cascaded among the subsystems, specifically that the onset of activation in systems down-stream (e.g., phonological output system) has at least some delay relative to the onset of activation of an earlier system (e.g., orthographic lexical system). This assumption is necessary to account for additive effects between variables, such as the Format + WT and POA + WT additive effects described above. Given that WF and POA have their effects in the lexical/semantic systems, including the orthographic lexical system, their influences are early enough to interact with the effects of Format, which is assumed to gate processing through the lexical route under the picture condition, especially for EXC pictures.

Based on Paivio's (1986, 2007) work, the model of picture identification that we are extending to the dual-route model of reading assumes four stages (see Figure 27): (1) A visual feature encoding stage, which allows basic visual features such as vertical and horizontal elements, lines, edges, angles, and depth to be analyzed and encoded; (2) A shape encoding stage, which integrates the elementary aspects into an object (geometric) representation, and allows for basic shape to be identified; (3) A picture memory stage, which links the picture representation to previous memory, associations, and to the semantic and orthographic lexical systems; and lastly (4) Nonverbal-to-verbal translation is handled through connections from the picture memory stage to the orthographic lexical, semantic, phonological-lexical, and phonological-output systems, which allows the appropriate name and meaning to become activated and the picture to be verbally identified.

A central focus of the present study was the *picture memory stage*, which we predicted would be connected to the word recognition system. In order to study this connection, EXC items (i.e., EXC words and EXC pictures), served as critical stimuli, as it is well-known that EXC words must be processed through the orthographic lexical route, and show larger WF effects compared to REG words (e.g., Cummine et al., 2010; 2013; and in the present study). As predicted, we found that EXC pictures showed larger WF effects compared to REG pictures, supporting the notion that pictures have a strong connection to the orthographic lexical system. There is also a direct connection from the picture memory stage to the phonological lexical system that previous picture naming research has referred to. However, we have provided converging evidence that suggests that the connection between the picture memory system and the orthographic lexical system is utilized when naming pictures: larger orthographic WF (HAL WF) effects for pictures than for words (i.e., Format x HAL WF rising overadditive interaction), larger POA effects for pictures than for words (i.e., Format x POA rising overadditive interaction), and there is a rising overadditive interaction between orthographic WF (HAL WF) and POA for EXC words.

New assumptions/tests of hypotheses

Although the majority of our hypotheses were confirmed through the present research, there were also two unexpected findings, specifically, the underadditive interactive pattern between Format x WT, and the positive frequency effects for REG items on RD. These findings have led us to propose that there is additional knowledge in the mental lexicon in addition to orthography, semantics, and phonology, as both findings can be explained if WT is considered to be represented in the mental lexicon. For example, in order to explain the Format x WT underadditive interaction, one must consider the time that it takes for words and pictures to reach a threshold for each WT (see Figure 28a & b). Figure 28a shows the rate of activation for words, whereby activation reaches the threshold for REG words (RT1), resulting in the fastest RT for REG words, and subsequently, the activation reaches the threshold for EXC words (RT2), resulting in a slower RT for EXC words. This is the typical pattern of results reported in the literature, whereby REG words and named faster than EXC words. Conversely, Figure 28b shows the rate of activation for pictures, whereby activation reaches the threshold for EXC pictures (RT3), resulting in a faster RT for EXC pictures, whereas the activation reaches the threshold for REG pictures afterwards (RT4), resulting in a slower RT for REG pictures. One explanation for why the threshold for REG pictures is higher than for EXC pictures, which is opposite to each WT threshold for words, is that REG pictures are more likely to invoke the sublexical reading system because of having “regular” word status in the orthographic lexical system, given that REG words typically benefit from both lexical and sublexical processing. In this case, invoking the sublexical reading stream takes additional processing time, and thus REG pictures have longer RTs than EXC pictures.



Words

Pictures

Figure 28: An Additive Factors Method (AFM) interpretation of the Format x WT underadditive interactive pattern: (a) For words, the activation reaches the threshold for REG words (RT1), resulting in the fastest RT for REG words, and subsequently, the activation reaches the threshold for EXC words (RT2), resulting in a slower RT for EXC words. The dissociation between WT effects for words on RT and on RD, whereby REG words have faster RTs but have the longer RDs (RD4), and EXC words have slower RTs but shorter RDs (RD1) is also illustrated. (b) For pictures, the activation reaches the threshold for EXC pictures (RT3), resulting in a faster RT for EXC pictures, whereas the activation reaches the threshold for REG pictures afterwards (RT4), resulting in a slower RT for REG pictures. The similar pattern of WT effects for pictures on RT and RD, whereby EXC pictures have faster RTs and shorter RDs (RD2), and REG pictures have slower RTs and longer RDs (RD3) is also illustrated.

The dissociation between WT effects for words on RT and on RD, whereby REG words have faster RTs but have the longer RDs (RD4), and EXC words have slower RTs but shorter RDs (RD1), is also illustrated in Figure 28a (see also Gould et al., 2012). The similar pattern of WT effects for pictures on RT and RD, whereby EXC pictures have faster RTs and shorter RDs (RD2), and REG pictures have slower RTs and longer RDs (RD3), is also illustrated in Figure 28b.

In order to explain the positive coefficients that relate REG word and picture RD to WF, the high frequency offset for REG items must be later than for low frequency REG items. The duration is lengthened for high frequency REG items because, although the naming onset is initiated as a negative function of WF, it is more likely that the phonological output system would be waiting for the output of the sublexical GPC system, whereas for low frequency REG items, it is more likely that the phonological output system would receive the output of the sublexical GPC system and the phonological lexical system at a similar time. It is important to note, however, that the positive coefficients for REG items only occurs in Experiment 3, but does not occur for REG words in Experiments 1 and 2. The fact that these effects only occur with a smaller set of items (126 words in Experiments 1 & 2 versus 60 words/pictures in Experiment 3) provides the author reason to be cautious about over-interpreting the results.

Limitations and Future Directions

There is a growing body of research that examines whether the neural and cognitive mechanisms of *picture* processing can apply to real-world 3D objects (e.g., Snow, Pettypiece, McAdam, McLean, Stroman, Goodale, & Culham, 2011). Snow et al. have found neurophysiological differences between pictures in 2D and 3D real objects, whereby 2D pictures produced robust functional magnetic resonance adaptation (fMR-adaptation) effects in object-selective cortical regions along the ventral and dorsal visual processing streams, but 3D objects did not, suggesting that the neural mechanisms involved in processing pictures may be distinct from those involved in processing objects, and that there may be fundamental differences between processing pictures and real objects. Therefore, the current findings provide implications for *picture* processing, rather than generalizing to real *object* processing. However, considering that many pictures appear alongside words in everyday life, such as in advertising, reading on the internet, playing video games, and textbooks/educational resources, it is important that we understand the nature of picture identification processes, as well as how they interact with basic reading processes. Given that Snow et al. showed that fMR-adaptation occurs with 2D pictures in a reliable way, but not with 3D objects, one of our future directions for research is to develop a fMR-adaptation paradigm that will allow us to investigate the overlap between word and picture processing by comparing 2D picture adaptation functions to word adaptation functions, as well as a hybrid of picture and word alternation adaptation functions in order to see whether neural adaptation occurs across modalities.

Another future direction for research is to further explore the connections between picture and word processing using stimuli that control for overall visual complexity. Although picture and word stimuli can be matched for visual angle, there are other differences between pictures and words that cannot be as easily controlled. For example, there is greater visual complexity in picture identification, such as visual detail, spatial frequency, and colour that could affect processing. As such, it is important to develop a paradigm in which the visual stimuli are equated for complexity. For example, using stimuli in which the words are superimposed on the picture, and instructing the participant to name either the word or the picture will allow us to control the stimuli for visual complexity, as the same stimulus is used for both the picture and word naming conditions. As such, the paradigm would be like a Stroop task, in that the pictures and words could be either congruent (e.g., picture of a bear with the word 'bear') or incongruent (e.g., picture of a bear with the word 'foot'). If pictures are easier to ignore than words (i.e., there is name ambiguity with pictures but not with words), the size of the Stroop congruency effect should be smaller for word naming than picture naming. Such an experiment could inform us about the relative strength of the influence of one modality onto the other, in that the influence of the word processing system on the picture processing system may be stronger than vise versa.

Conclusions

Pursuing an understanding of the meanings of things in our world is a central feature of the human condition. We have an insatiable curiosity to understand how to interact with objects in our environment, how to interpret symbols and actions, as well as the meanings of words. In our word identification experiments (Experiments 1 & 2), the joint effects of INST, WF, SND, and WT on naming RT support a cascaded, dual-route, ventral-lexical/dorsal-sublexical model. The naming RD results from these experiments provide evidence that basic reading processes, and their joint effects, are occurring even after the initiation of a vocal response, and support the notion that the more lexically a word is read, the shorter the RD. Given the joint effects on RT, the dissociating effects of INST and WT on RT versus RD, models of basic reading processes now have new challenges to accommodate these effects. An important question for future research is the degree to which RD effects are due to phonological-lexical versus orthographic-lexical processing, which our lab is beginning to explore.

In order to further explore the interaction between word and picture identification processes, and to expand the dual-route model of basic reading, Experiment 3 examined the effects of Format, Picture-Orthography Agreement, Word Frequency, and Word Type in order to reveal the loci of their effects among the processing systems, and how picture and word processing systems interact in the cognitive chronometric architecture. The pattern of joint effects on RT supported a multistage triple-route model of reading and picture processing. The results suggest the orthographic lexical system is accessed for both picture and word naming, and replicated a dissociation between regular and exception words on RT versus RD, whereas pictures consistently yielded an exception item advantage for both measures. Similarly, Arabic digits (like pictures) produced shorter RDs than their corresponding number words. In general, these results suggest that the picture and word identification systems are strongly coupled between the picture memory system and the orthographic lexical system, particularly for items that rely on "whole-word" lexical representations. Extending RD measures to pictures, while used in conjunction with traditional onset RT measures, provides a wider window for exploring cognition, and a converging measure of lexical processing (i.e., shorter RDs corresponding to greater lexical involvement), which is informative when studying basic identification processes of any stimulus type.

Given the extent to which reading is such a fundamental skill for functioning in today's society, it is imperative that we understand the underlying nature of basic reading processes. The Canadian Council on Learning reported that by 2031 more than 15 million Canadian adults are predicted to have low literacy levels, a worrisome trend. Given that a broad definition of 'literacy' should also include picture processing, the development of a model that includes word and picture processing will serve to advance research on how reading and picture processing interact with each other, which is critical to understanding both normal processing and individuals with low literacy skills. The present thesis focused on developing such a model, and identified some of the behavioural markers of normal reading and picture processing, which may help by providing a roadmap for reversing this trend.

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Appendix A

Exception Items


bear


blood


bowl


bread


brooch


bull


comb


door


dough


foot


glove

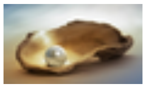

geese


heart


hook


mould


pear


pearl


pint


shoe


soup


sponge


steak


sword


thread


vase


wasp


wolf


wood

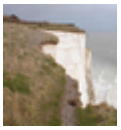

wool


world

Regular Items


brain


bridge


cliff


coin


couch


crib


cube


flame


flea


girl


hand


harp


hoop


leaf


match


mouth

mug

plum

pope

pork

reef

saw

shed

shelf

slug

stump

thorn

toad

toast

tooth