EXAMINING THE EFFECTS OF SUB-WORD PROCESSING UNITS ON THE TIME-COURSE OF TYPEWRITING

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Abstract

Contrary to models of speech production and handwriting, models of typewriting lack an account of processing of sub-word units (i.e. processing that occurs after the writer / speaker has started to output the word). This thesis examines factors that affect the time-course of production of sub-word letter strings.

The first series of experiments examined letter-chunking in typewriting. Participants repeatedly typed short letter-stings, manipulated for trigram and bigram frequency. Onset latency was shorter for high frequency bigrams and trigrams relative to low-frequency controls. Latencies were also shorter for the second keystroke in higher frequency bigrams. These findings can be interpreted as providing strong evidence that: (1) higher levels of processing are not limited to preparing individual letters when familiar words are not available; (2) stored motor plans are available for frequently used bigrams.

The second series of experiments addressed whether phonology affects within-word typewriting time-course. Participants typed letter strings designed to elicit resyllabification – the adjustment of syllable structure across a word boundary to aid speech articulation (see Levelt, Roelofs, & Meyer, 1999). For example, "bent inwards" is articulated with /tin/ as the second syllable. Participants typed word pairs in which consonant-vowel structure was manipulated across the word boundary such that if the words were articulated (including internally as inner speech) resyllabification would or would not occur. Latency of the consonant immediately before the word boundary in the resyllabification condition was shorter than in the control condition. Conversely, keystroke latencies after the word boundary were longer in the resyllabification condition. This is evidence of inner speech influencing the timing of motor production.

The time-course of typewriting is influenced by sub-word processing units – production is facilitated for high-frequency letter combinations – but that motor processing after word output is not, contrary to some current theory, informationally encapsulated, but instead affected by concurrent, non-motor processing.

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1. General Introduction

This section introduces and outlines the research related to this thesis. It begins with an initial overview of language production research, indicating the fundamental stages of processing required in language preparation and production. Then moving on to a more specialised area of language production, written language production. This provides a specific account of two processing routes available in written/orthographic production, lexical retrieval and sub-lexical conversion. The discussion of these two processing routes outlines how writing can be affected by the phonological processing that runs concurrently in the preparation of the spoken form, as well as being able to retrieve stored orthographic information for words. This then branches onto theoretical accounts of typewriting, providing an early indication of how sub-word processing units that are influential in written and spoken production, are somewhat overlooked in theoretical accounts of typewriting. This feeds onto discussions of four key questions that will be examined within this thesis: (1) Are sub-word graphemic representations larger than single letters passed to the motor level; (2) Are frequently used letter combinations stored as retrievable motor-chunks; (3) Does the inner loop run to completion without interference from other (e.g. phonemic) representations; (4) Is the time-course of typewriting affected by inner speech?

1.1. Language Production

In understanding how within-word representations affect the time-course of typewriting, it is essential first to understand the processes involved from the intention to type to the execution of keystrokes. Before moving onto written production, which includes both handwriting and typewriting, this section will outline vital information relating to how information is processed in both written modalities and in speech production. The reasoning for including evidence from speech production research is simple; speech production has been researched much more extensively. This is important as the evidence found in speech production research often provides a rationale for examining similar effects within writing research. This proves more relevant when considering that speech is usually learned at a much younger age than writing, resulting in writing being dependent on the phonological (speech) representations, particularly in the earlier years (Kandel & Valdois, 2006). Fundamentally, there are a number of mechanisms / processes that are common to speech and writing.

In a similar fashion to speech production, writing is argued to be composed of several processing stages between the intention, and the motor execution required, to write (Caramazza, 1997; Tainturier & Rapp, 2001; van Galen, 1991). Within spoken language, the production of a word involves the encoding of a concept, grammatical encoding, and phonological encoding before articulation (Levelt, 1999; Levelt et al., 1999). Writing is thought to involve similar mechanisms, albeit written production must retrieve orthographical codes prior to output (Damian, Dorjee, & Stadthagen-Gonzalez, 2011). This can involve assistance from phonological processes used within speech, or independent orthographic processing, as shall be later discussed.

Typically, investigations of the processes involved in language production have involved two different methods of inquiry. On the one hand, there are investigations of the type of errors made in language production. On the other hand, chronometric methodologies examine the response time of the process in typical language production. As stated by Levelt et al. (1999, p.2), "models of lexical access have always been conceived as process models of normal speech production. Their ultimate test, […], cannot lie in how they account for infrequent derailments of the process but rather must lie in how they deal with the normal process itself". This is an important consideration for this thesis which examines typical, not atypical, sub-word processing within typewriting. The research conducted within this thesis does not focus on typewriting accuracy or errors for this reason but instead focuses on the time-course of typewriting.

To examine the time-course of typewriting, we must first account for the processes involved during production. From the intention to speak, write, or type, language is processed at several independent levels of processing. Each stage is processed in a step-by-step fashion in which the output of one level is the input to the following level. Each level produces its own respective unit size/processing unit. This also means that each level must contain its own temporary storage buffer to hold the information. As argued by Christiansen and Chater (2016), the language system must compress/chunk and recode linguistic information as soon as possible. Information can decay rapidly as it very quickly is replaced or interfered with by new information. Each level of processing has limited memory constraints (i.e., Dell, Schwartz, Martin, Saffran, & Gagnon, 1997), meaning that chunks are passed down to the next level immediately after they are available. This 'chunk and pass' concept highlights the importance of separate memory buffers and distinct chunked representations across different levels of processing. Fundamentally, this means that each form of chunked representation represents individual levels of processing.

The flow of information processing may occur in a discrete or cascaded manner. The concept of cascaded processing is captured in the ‘chunk and pass’ processing described by Christian and Chater (2016). If information is passed across levels as soon as it is available, information from a single word may be spread across multiple processing levels. If a larger representation such as a word is being processed into smaller sub-word representations such as syllables (or phonemes, graphemes, etc.), once the initial syllable has been processed it may be passed to the following levels of processing while the remaining syllables of the word are being processing. For example, when considering the word ‘detention’, the initial syllable (‘de’) could arguably be being spoken, written or typed while the remaining syllables are still being processed (see Kandel, Peereman, Grosjacques, & Fayol, 2011). Cascaded processing allows later stages of processing to begin, or even complete, processing before processing at the earlier levels has been completed. This allows for spelling processing to cascade into the motor performance as the lower levels responsible for motor performance and execution can complete their task of the partial information given to them from the spelling levels.

In contrast, discrete processing requires the information to be fully processed at one level before it can be passed to the next. Using the example of the word ‘detention’ once again. The initial syllable of *de* is only given to the next stage once all the syllables within the word (*de* + *ten* + *tion*) are available to pass to the next level. This is an essential consideration within theoretical accounts of typewriting that shall be later discussed in greater detail: Do all sub-word representations within a word have to be passed to lower-level motor processing levels at once in a discrete fashion? Or can individual sub-word representations be given to the lower level motor processing levels in a sequeed manner?

There are various theoretical accounts of how words are encoded (i.e., Caramazza, 1997; Dell, 1986; Dell et al., 1997; Levelt et al., 1999). Across these models, there exists recognition of three main levels of processing. A conceptual level selects the appropriate concept to be later articulated, written, or typed. A lexical level then retrieves the appropriate word form. A sub-lexical level retrieves the segments of the corresponding word form. This involves phonological segments (i.e., phonemes) when processing words to be spoken, but includes orthographic segments (i.e., graphemes) when processing words to be written or typed.

However, phonological segments may also be used to assist in written production. These processes are explored in greater detail below.

1.1.1. Written Production

Written production involves the encoding of orthographic representations (i.e., graphemes) to be passed to the lower levels of processing responsible for motor production. However, this could occur with or without the assistance of phonological processing. Access to orthographical codes can be dependent on the prior retrieval of phonological codes (Luria, 1970). This can be referred to as obligatory phonological mediation (see Rapp, Benzing, & Caramazza, 1997) or Phonology to Orthography Conversion (POC; see Tainturier & Rapp, 2001). Irrespective of the terminology used, the principles are the same. In order to write a word, the phonological representations must first be retrieved, in which the phonological code would then be subsequently converted into an orthographic form. This can occur in multiple ways, as illustrated in Figure 1.

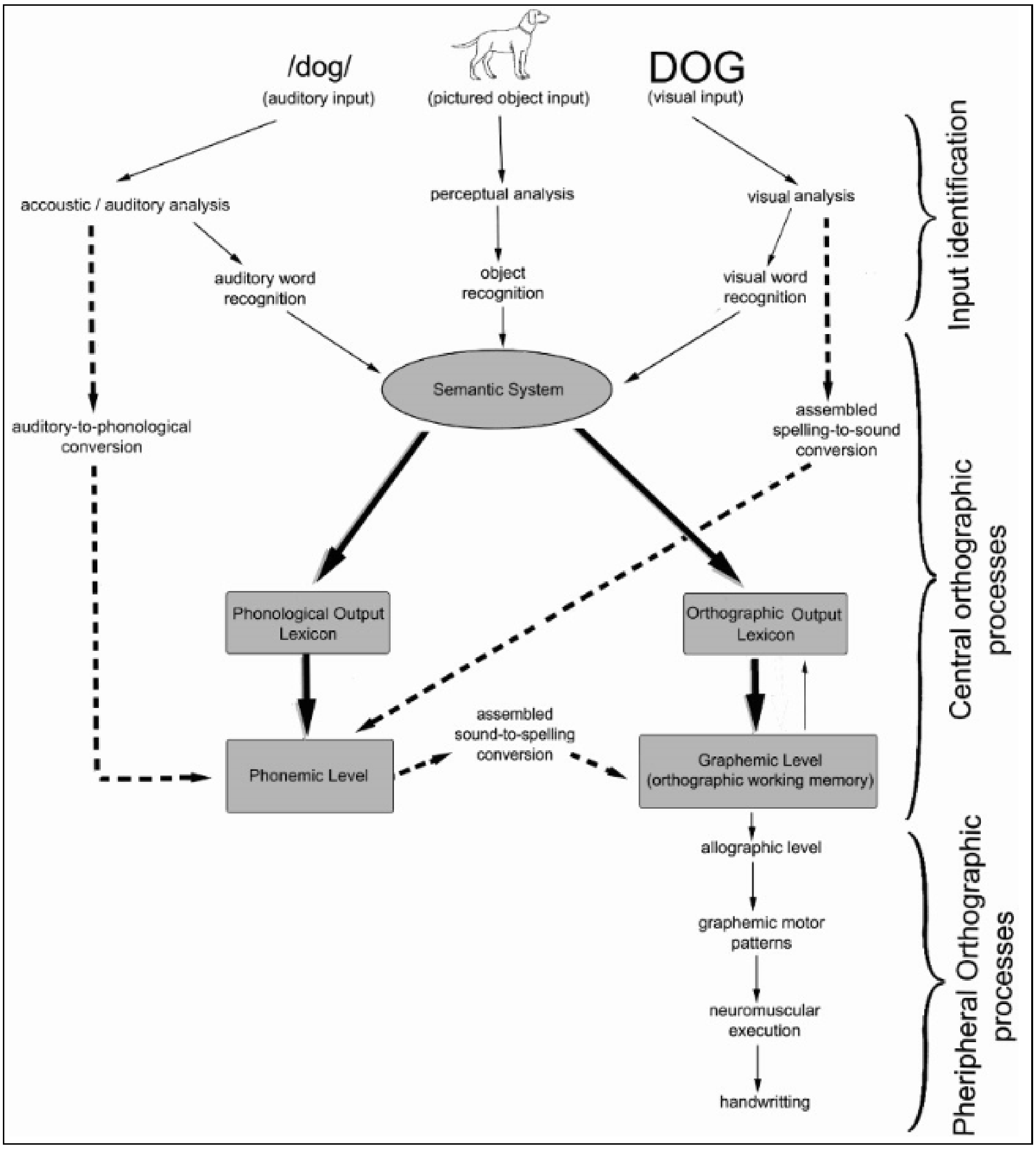

Figure 1: Architecture of written spelling (from Bonin et al., 2015).

The most widely recognised influence of phonological processing occurs at the sublexical level, which is depicted in Figure 1 by the phonemic level, passing information to the graphemic level. This involves phonological processing up to the point of the phonemic level. At this level, a phonological lexeme is split into multiple phonemes. Phonemes are the smallest phonetic unit available in a language that can affect the meaning of a word when swapped. For example, replacing the /sh/ phoneme in the word /ship/ would change the meaning of the word (i.e., /slip/, /trip/, /blip/).

These basic phonological units are then converted into an orthographic form via phoneme to grapheme conversion. A grapheme is the corresponding orthographic form for the smallest meaningful unit within the writing system. It forms a cluster of the letters required to form the spelling for a corresponding phoneme. However, if the sound-to-spelling conversion was always used, a large number of errors would be produced in languages with deep orthographies. The accuracy of converting the sound-based phoneme into the spelling-based grapheme varies from one language to another depending on the depth of the orthography within the language. Languages with deep orthographies, such as English, have multiple spellings for the same sound. For example, the /shun/ sound may be spelled as the word *shun*, or the syllable *tion* (i.e., within *station* or *ration*). Phonological representations such as phonemes can be mapped onto a range of possible spellings. Similarly, the *ough* spelling has multiple phonological representations (i.e., *dough*, *tough*, *through*, *thought*, etc.). If the orthographic representation occurs only via phoneme-to-grapheme conversion, then languages with deep orthographies would have many more errors occurring. For example, if the phoneme of /or/ (or /aw/) was to be converted into the corresponding grapheme for the word *bought*, this may produce the misspelling of *bort*. Knowledge of the spelling of the word must be stored and used during production to avoid frequently producing such errors.

For writers to regularly write words correctly that have different sounds and spellings, there must be knowledge available about how the word should be written at some level. Indeed the spelling of a word can be constructed by orthographic long-term memory (Purcell, Turkeltaub, Eden, & Rapp, 2011; Tainturier & Rapp, 2001), often termed the orthographic lexicon. This is independent of phonological processing, as demonstrated in Figure 1. In support of the orthographic lexicon being independent of phonological processes, Miceli, Benvegnù, Capasso, and Caramazza (1997) evidenced that an aphasic patient showed errors within the phonological form but not in the orthographic form, suggesting distinct processing occurs between the two modalities. Additional evidence has been found with respect to phonologically based spelling errors such as homophone substitutions (Aitchison & Todd, 1982). The production of similar/same sounding words that contain dissimilar spellings such as *there* and *their* suggest that phonological information alone is not enough to produce the correct spelling of the word. The orthographic output is not necessarily dependent upon the prior activation of phonological information (Miceli et al., 1997; Miceli, Capasso, & Caramazza, 1999).

As discussed above, the orthographic form of a word can be retrieved from the orthographic lexicon. This route of spelling retrieval is referred to as the lexical route. Familiar words can be retrieved via the retrieval of the orthographic form directly from semantic activation with no dependence upon phonological processing. An advantage of the lexical route is that in languages such as English, which have deep orthographies, there are many words that are not spelled in the same manner in which their phonological counterpart is pronounced. With such complex grapheme structures being employed in languages such as English, it is beneficial to store knowledge of individual word forms to prevent inconsistent spelling mistakes occurring when writing. In contrast, the sublexical route serves a greater purpose in languages with much simpler orthographical structures as the phonemes corresponding to the respective graphemes, meaning that phoneme-to-grapheme conversion is much more efficient. This is the case in Spanish for example, as "each letter of the alphabet has a unique pronunciation" (Álvarez, Carreiras, & Perea, 2004, *p*. 206; Alvarez, Cottrell, & Afonso, 2009) and only a few phonemes are mapped onto by more than one letter.

However, languages, even those with deep orthographies, must also involve phonological conversion in some instances. This is particularly the case for unfamiliar words, non-words or letter strings. If asked to spell an unfamiliar word, there would be no stored orthographic representation to retrieve. This is particularly the case with non-words as the word form has probably never been encoded. The retrieval of stored orthographic word forms is only as effective as the volume of stored orthographic representations. For unfamiliar words, sound-to-spelling conversion must be used to convert the phonemes into graphemes in order to compute the orthographic spelling.

The retrieval of the word's spelling via the orthographic lexicon may also be assisted by phonological processing via the phonological lexicon. While this is not shown in Figure 1, there is evidence to suggest that the spelling can be retrieved from the orthographic long-term memory via the recognition of a spoken word even when semantic activation is unavailable (Patterson, 1986). However, as this is demonstrated within an aphasic patient, this is atypical language production that has not been demonstrated within the general population and is not considered within this thesis for that reason. For this thesis, I surmise that the spelling of the word can be achieved either by the retrieved orthographic spellings from long-term memory or by the sublexical conversion of phonological information into orthographic information. In both instances, stored orthographic information is needed, and abstract forms of the spelling are produced.

Bonin et al.'s (2015) theoretical illustration demonstrate a dual-route account of how the spelling of the word can be generated by orthographic and phonological processes that run in parallel. Both routes, the lexical route, and sublexical route are processing information at the same time. Effectively, the parallel processing acts like a horse race in which the first route to finish will provide the spelling of the word. This process is sensitive to word frequency, the extent to which a word is used within the language. High-frequency words, words which are written frequently, will have stored orthographic representations within the orthographic lexicon. This allows the lexical route to operate faster than the sub-lexical route as the spelling can be retrieved rather than constructed. In contrast, the sub-lexical route is typically faster for low-frequency words as retrievable spellings of the word may not be available via the orthographic lexicon.

The routes of processing involved to generate the words to be written are believed to be no different in handwriting or typewriting. Stored orthographic forms of the word can be retrieved for familiar words to generate the language to be written (or typed), whereas phonological processing occurs concurrently that may assist in the generation of the abstract form of the word that is sent to the motor level. It is at the motor level where the key differences occur between handwriting and typewriting. The main principle here is that typewriting shares the processes involved in handwriting and speaking up to, but not including, the point of motor preparation.

To summarise, words can be constructed via either of the two processing routes running in parallel. For familiar words, the spelling can be constructed by orthographic long-term memory (Purcell et al., 2011; Tainturier & Rapp, 2001) via the lexical route. For unfamiliar words, sound-to-spelling conversion must be used to convert the phonemes into graphemes in order to compute the orthographic spelling (see Tainturier & Rapp, 2001). This occurs within the sub-lexical route. Both routes are processing information at the same time, whereby the first route to complete the orthographic preparation will provide the spelling of the word. The routes of processing involved to generate the words to be written are believed to be no different in handwriting or typewriting. It is at the motor level where the key differences occur between handwriting and typewriting as shall be discussed in greater detail later in the thesis.

1.1.2. Theoretical accounts of typewriting: Integrating motor skill performance with language production

The previous sections have outlined how abstract forms of language are formed before being passed to lower levels responsible for motor processing and production. As stated previously, domains of written language production, such as handwriting and typewriting, can generate the abstract spelling of a word via the retrieval of stored orthographic information. Additionally, concurrent phonological processing can assist in the assembly of the spelling via the conversion of phonological representations to orthographic representations (i.e., phonemes to graphemes). The motor processing that occurs after the retrieval of the abstract graphemic form (the word's spelling) is different in typing and handwriting.

While typewriting is now considered the dominant form of written output in many cultures, it was once a skill possessed by a minority of people. Before the increase of computer use at the end of the 20th century, skilled typewriting was an ability shared by the few who had, and regularly used, either a typewriter or early versions of the computers regularly used today. The rise of computer use in the workplace and the home in recent decades has dramatically inflated the number of people who are skilled typists. This has seen somewhat of a shift of how typewriting is used in the context of research. Much of the earlier studies examining typewriting performance investigated typewriting as a specialised motor skill (i.e., Gentner, 1983; Salthouse & Saults, 1987; Sternberg, Monsell, Knoll, & Wright, 1978). This makes sense given that typewriting was a skill only a small number of people had acquired. Typewriting allows for the investigation of how movements can be planned and executed in fast succession. The small number of people who acquired the skill was sufficient for research studies examining motor performance. Typewriting was not used frequently enough to be considered as one of the dominant forms of communication. This has since changed. Now typewriting is recognised as a highly practiced motor skill, as well as a dominant form of communication. This has seen a rise in typewriting research investigating how the skilled motor performance in typewriting is also affected by linguistic processing (i.e., Feldman, Dale, & van Rij, 2019; Pinet, Dubarry, & Alario, 2016; Pinet & Nozari, 2018; Pinet, Ziegler, &

Alario, 2016; Scaltritti, Arfé, Torrance, & Peressotti, 2016; Scaltritti, Pinet, Longcamp, & Alario, 2017; Torrance et al., 2018).

Theoretical accounts of typewriting typically propose a hierarchical structure with initial processing from lexeme to spelling and then motor programming of letters to generate keystrokes (Logan & Crump, 2009; Rumelhart & Norman, 1982; Salthouse, 1986; Wu & Liu, 2008). Arguably, the most influential of recent models of typewriting is Logan and Crump's Two-Loop Theory of Typewriting (Crump & Logan, 2010c, 2010b; Logan, 2018; Logan & Crump, 2009, 2010, 2011; Logan, Miller, & Strayer, 2011; Snyder, Logan, & Yamaguchi, 2015; Yamaguchi, n.d.; Yamaguchi & Logan, 2014a, 2014b; Yamaguchi, Logan, & Li, 2013). Logan and Crump (2011) propose that typewriting is controlled by two nested feedback loops, the inner and outer loop. They argue that the two loops are not only distinguished from each other, but also, the information processed at each loop is distinguished separately from one another. This occurs in a hierarchical manner in which the outer loop must process the comprehension and language generation necessary for words to be passed to the inner loop. These are passed as single words, one at a time, to the inner loop (Logan & Crump, 2011). The inner loop then translates the word to the individual letters, motor plans of the keys to their respective location on the keyboard, and then executes them as keystrokes. This staged hierarchy is similar, to an extent, of the structure of hierarchical models in speech and handwriting. The higher-level processes are responsible for the spelling of the word form; the lower-level processes are responsible for the motor processing and execution of the intended message.

The two loops are argued to function at different levels of processing, outputting different representations and relying on different types of feedback (Crump & Logan, 2010b; Logan, 2003; Logan & Crump, 2009; Logan & Zbrodoff, 1998). The inner loop, while executing the keystrokes, monitors the proprioceptive and haptic feedback of the movements when typewriting. When interfering with the 'feel of the keyboard,' typewriting slows dramatically. Crump and Logan (2010b) asked participants to type on deconstructed keyboards, which interfered with typical feedback (i.e., the resistance of the keys) when correctly typewriting the intended words. By interfering with the quality of the feedback, typewriting performance is slowed.

In contrast, the visual appearance of the words being typed on the screen is monitored by the outer loop (Logan & Crump, 2010). Logan and Crump (2010) demonstrated that when the visual appearance of the words being typed on the screen is manipulated; the typists take authorship for the visual content on the screen. When correcting the appearance of words that were mistyped, or inserting errors within words typed correctly, typists report the errors and take responsibility for the errors. Even when kinaesthetic and haptic feedback of the movements generated when typewriting does not indicate an error, the visual feedback of the screen is sufficient enough for the typist to take ownership of the observed errors. Typists have access to two different feedback mechanisms, one monitoring the visual representation on the screen (outer loop) and one tracking the feel of the movements when typewriting (inner loop).

It also argued that the inner loop is informationally encapsulated (Logan & Crump, 2011). The outer loop does not know how the keystrokes are implemented by the inner loop (Liu, Crump, & Logan, 2010; Logan & Crump, 2009; Tapp & Logan, 2011), suggesting that the two loops function autonomously. The only information shared between them is the words passed from the outer loop to the inner loop. Evidence for the informational encapsulation of the inner loop is provided by Logan and Crump (2009). Participants, all of which were experienced typists, typewriting only the left-hand letters, or only the right-hand letters, were found to increase from a 6% error rate to a 33% error rate. This was also met with a reduction in speed, as an average production time of eighty words per minute was reduced to fourteen words per minute when typewriting only the letters belonging to one hand. To type the letters from only one hand, the inner loop is slowed down dramatically, so the outer-loop has time to observe, and possibly inhibit unnecessary keystrokes, from the executed keystrokes from the inner loop. This study provided clear indications that the outer loop does not know what the inner loop is doing, as demonstrated by a lack of explicit knowledge of which hand types which keys.

Typists also have poor explicit knowledge of the location of keys on the keyboard (Liu et al., 2010). Expert typists were examined on their explicit knowledge of the keyboard. By examining their knowledge of the location of one key in reference to another, it was demonstrated that the error rates were significantly higher for subjects who were required to imagine a keyboard, compared to subjects who were able to look at a keyboard, or feel (but not see) the keys on a keyboard. Explicit knowledge of the key location is poor, and not available to the outer loop.

There are some important distinctions to be made when comparing theoretical accounts of typewriting to those of handwriting. Unlike in handwriting, there is little to no emphasis on sub-word processing units larger than a single letter. In typewriting an abstract word straddles the boundary of the outer loop and inner loop. This abstract word representation contains information regarding the letters and order of the letters to be typed. The words, including information of the letters and letter order only, are passed from the outer loop to the inner loop. The keystrokes within the word are then activated in parallel (Logan, 2003; Logan et al., 2011) before being executed in fast succession. This places a great emphasis on the importance of chunking letter information into words in the outer loop. There is no account for the chunking of sub-word representations, even when a familiar word is unavailable. “Non-words push skilled typists back on the learning curve by removing their ability to use a single chunk to type several letters” (Logan, 2018, *p.*454). Instead, individual letters are arguably passed from the outer loop to the inner loop when a familiar word is unavailable. If typewriting utilises similar pre-motor processing stages to handwriting, sub-word processing units may be used. This possibility could allow for abstract letters to be chunked as sub-word representations, bridging the outer and inner loops.

As has been outlined and discussed so far, there are some fundamental differences between theoretical accounts of typewriting and research findings from handwritten and spoken language production. Much of the earlier studies examining typewriting performance investigated typewriting as a specialised motor skill (i.e., Gentner, 1983; Salthouse & Saults, 1987; Sternberg, Monsell, Knoll, & Wright, 1978). In contrast, psycholinguistic research investigating handwriting and speech production have investigated language generation before the motor level in much greater detail. As a result, sub-word processing units are evidenced far more in handwriting and speech than typewriting. The following sections will explore potential influences of sub-word processing units upon the time-course of typewriting.

Additionally, influences of phonological processing are somewhat overlooked in theoretical interpretations of typewriting. For many years, typewriting has been considered as an alternative output from the spelling processes used for handwriting or speech production

(Margolin, 1984; van Galen, 1991), in which the development of the motor skills for typewriting are grafted onto pre-existing language processes (see Logan & Crump, 2011). Potential influences of concurrent phonological processing are not accounted for. This is despite the recognition that concurrent phonological processing can be used to assemble the spelling of a word in handwriting (see Bonin et al., 2015). This begs the question of what influence phonological processing may have upon the time-course of typewriting?

1.2. Unanswered question one: Are sub-word graphemic representations larger than single letters passed to the motor level?

The first consideration of this thesis is to examine whether graphemic representations greater than an individual letter but smaller than a word are passed to the motor level. The theoretical underpinnings of language production have been discussed so far. Writing modalities such as handwriting and typewriting dramatically differ in the motor processing required for writing, but not in the preparation of the spelling of the words to be communicated.

Let us first direct our attention to how sub-word processing units can affect the time-course of writing before motor preparation. There is evidence of the time-course of handwriting being modulated by sub-word processing units such as syllables (Alvarez et al., 2009; Kandel, Alvarez, & Vallée, 2006; Kandel, Hérault, Grosjacques, Lambert, & Fayol, 2009; Kandel et al., 2011; Kandel & Valdois, 2006; Lambert, Kandel, Fayol, & Espéret, 2008). Evidence in support of syllables as processing units in an orthographic form, mainly in the form of handwriting and reading, have been found within manipulations of syllable frequency (Carreiras, Alvarez, & Devega, 1993; Chetail & Mathey, 2009; Conrad, Grainger, & Jacobs, 2007; Conrad & Jacobs, 2004; Perea & Carreiras, 1998), syllabic or implicit priming studies (Álvarez et al., 2004; Chetail & Mathey, 2009), and chronometric examinations of phonological syllable boundaries (Ferrand & New, 2003; Kandel et al., 2006, 2009, 2011; Stenneken, Conrad, & Jacobs, 2007).

Evidence of syllabic processing is an indication of phonological influences upon orthographic processing. A syllable is a processing unit formed in speech production, both as an early abstract representation (Levelt et al., 1999) and as a motor chunk that can be retrieved or computed before articulation (Cholin, Levelt, & Schiller, 2006). This is clear from the earlier discussion within this thesis. What is unclear is how the time-course of production is affected by syllabic processing.

Handwriting slows at the boundary of syllables: Letter latencies at the syllable boundary are slower than letter latencies within a syllable (Alvarez et al., 2009; Kandel et al., 2006, 2009, 2011). Furthermore, the time-course of writing is affected by the number of syllables within a word (Bogaerts, Meulenbroek, & Thomassen, 1996; Lambert et al., 2008). One possible explanation is that writing commences once motor preparation for the initial syllable is available. This possibility has been supported in both the writing of children (Kandel & Valdois, 2006) and adults (Bogaerts et al., 1996). The duration of the first letter of the second syllable within a word increases, signifying the initiation of a new motor chunk for the second syllable. This possibility hinges on the availability of syllable-sized motor chunks. It also raises additional questions as to why motor chunks may be stored/retrieved as syllabic-sized chunks. Is the spelling of the word prepared in full before the onset of typewriting? Alternatively, is the abstract spelling of the word passed to motor level syllable by syllable as soon as the next syllable becomes available? These are some of the considerations that will be discussed and explored in the context of typewriting later in the thesis.

There are, however, alternative interpretations of syllabic effects in writing. The majority of people will be familiar with the internal monologue we may hear when writing, reading or thinking aloud. This is often termed inner speech. The influence of syllabic representations upon the time-course of writing may arise from the internal monologue of inner speech. Words may be produced one syllable at a time because the inner speech expresses the word in the same manner. As will be discussed in greater detail later in the thesis, feedback mechanisms are employed when writing to check for mistakes that need correcting. It is conceivable that the availability of inner speech could be used during feedback mechanisms. If so, the time-course of production may be influenced by the time-course of inner speech. The influence of inner-speech upon writing has received very little attention compared to research examining phonological conversion at the sub-lexical level. Despite the relative lack of research on the influences of inner speech in written production, it is still conceivable that the co-existence of inner speech when writing may influence the time-course or production. At this point, this possibility is only being discussed to highlight an additional way in which the time-course of writing may be influenced by sub-word processing units such as syllables.

Alternatively, it can be argued that evidence of slowed writing at the boundary of a syllable is merely a product of bigram frequency. Low-frequency bigrams, which also demonstrate slowed movements, typically coincide with the syllable boundary. The start and end of a syllable are often consonants taking the role of the onset and coda surrounding the nucleus of the syllable. This often provides consonant-consonant bigrams at the syllable boundary (e.g. *yb* in the word *keyboard*) that have a much lower frequency to consonant-vowel, vowel-consonant, or vowel-vowel bigrams located within the syllable. Kandel et al. (2011) examined the syllable-bigram controversy within both a child and an adult sample to determine whether either representation is used when low-frequency bigrams and syllable boundaries do not coincide. By manipulating the location of the lowest frequency bigram within a word, either within a syllable or at the syllable boundary, they were able to examine how movement durations are affected by bigram frequency and syllable boundaries when they coincide, and independently from one another. They found that syllabic processing is more apparent in children. Production times were more influenced by syllable frequency, with a lesser extent of bigram frequency influencing production times. In adults, the time-course of writing was modulated more greatly by bigram frequency.

However, supplementary analyses found that in the condition where the lowest frequency bigram occurs before the syllable boundary, the manipulated bigram frequency affected the movement duration of the syllable boundary (Kandel et al., 2011). The movement durations at the syllable boundary were slower when the lowest bigram frequency was high. This effect was removed when the lowest bigram frequency was low. This suggests that higher frequency bigrams are processed faster than their low-frequency counterpart, and this faster retrieval allows the syllable boundary to be more exposed to the syllabic encoding that also occurs.

However, the two processes likely run in parallel if the syllabic effect is removed at the syllable boundary when more time is required to encode the proceeding low-frequency bigram. It was concluded that processing of both bigrams and syllables occur but at different stages of processing (Kandel et al., 2011). The generation of an abstract spelling of a word involves processing information related to the syllable structures within a word and the syllabic boundaries via the syllable module. It also involves retrieving information from the letter module related to letter combinations (bigrams) as well as graphemic information mapping the relationship between phonemes and orthographic letter representations. This information is then passed onto the motor level providing information relating to letter identity and order.

Kandel et al.'s (2011) findings highlight an important consideration for the research examined within this thesis. It demonstrates the level of experimental control that is required to adequately examine sub-word processing units. For example, if syllable boundaries typically coincide with low-frequency bigrams, any examination of bigram frequency must control for syllabic processing.

There are some key distinctions to be made when comparing theoretical accounts of typewriting to those of handwriting. Unlike in handwriting, research has not explored sub-word processing units greater than a single letter. In typewriting an abstract word straddles the boundary of the outer loop and inner loop (Logan & Crump, 2011). This abstract word representation contains information regarding the letters and order of the letters to be typed. The words, containing information of the letters and letter order only, are passed from the outer loop to the inner loop. The keystrokes within the word are then activated in parallel (Logan, Miller, & Strayer, 2011; Logan, 2003) before being executed in fast succession. This points towards the importance of chunking letter information into words in the outer loop. There is no account for chunking sub-word representations, even when a familiar word is unavailable. "Non-words push skilled typists back on the learning curve by removing their ability to use a single chunk to type several letters" (Logan, 2018, *p*.454). Instead, individual letters are arguably passed from the outer loop to the inner loop when a familiar word is unavailable. I argue that if typewriting utilises similar pre-motor processing stages to handwriting, sub-word processing units may be used. This possibility could allow for letters to be chunked as sub-word representations, bridging the outer and inner loops.

Words are likely to be essential processing unit in typewriting. When considering the text, we type, there is a hierarchical structure in which paragraphs contain sentences, which contain words, which contain letters. Previous research has demonstrated that manipulations to sentence structure do not affect the time-course of typewriting. Sentences with a jumbled order of words are produced as quickly as sentences with words that are not jumbled (Fendrick, 1937; Gentner, Larochelle, & Grudin, 1988; Shaffer & Hardwick, 1968). Jumbling the letters within words significantly slows the time-course of typewriting (Fendrick, 1937; Gentner, Larochelle, & Grudin, 1988; Shaffer & Hardwick, 1968).

Manipulating the content within words have a significant effect on the time-course of typewriting. However, the importance of words as a processing unit does not derogate the importance of sub-word processing units. This thesis shall investigate if the outer loop prepares letter chunks when familiar words are available.

1.3. Unanswered question two: Are frequently used letter combinations stored as retrievable motor-chunks?

Frequently executed motor chunks, high-frequency chunks, are argued to be stored as a result of being frequently loaded within the motor buffer (Sternberg et al., 1978; Verwey & Dronkert, 1996). These stored representations specify the movements and their order for output (Keele, Cohen, & Ivry, 1990). This is advantageous as the stored representation allows for the required information to be retrieved as a single response rather than being computed individually (Abrahamse, Ruitenberg, de Kleine, & Verwey, 2013; Pew, 1966; Verwey, 1996, 1999; Verwey, Abrahamse, & Jiménez, 2009) whereby multiple motor elements are mapped onto a single motor representation, the motor chunk (Klapp & Jagacinski, 2011). Primarily, if stored motor chunks are available for retrieval prior to typewriting, motor representations for multiple keystrokes could be retrieved in one transaction, rather than extracting them individually for each keystroke.

Within speech production, there is evidence of stored articulatory gestures for frequently used syllables (Carreiras & Perea, 2004; Cholin, Levelt, & Schiller, 2006; Laganaro & Alario, 2006; Levelt & Wheeldon, 1994) within a mental syllabary, allowing for the features of a frequently used syllable to be retrieved as a single response. The mental syllabary, a mental repository of pre-compiled motor chunks, enable the motor representation to be retrieved rather than computed for high-frequency syllables (Cholin et al., 2006; Crompton, 1981; Levelt et al., 1999). Cholin et al. (2006) demonstrated that the time-course of speech initiation is affected by syllable frequency. By manipulating the frequency of syllables to be spoken across three experiments, it was found that high-frequency syllables were initiated faster than low-frequency syllables. High-frequency syllables are stored as articulatory gestures within the mental syllabary (Cholin et al., 2006), whereas the articulatory gestures for the low-frequency syllables are assembled not retrieved. Cholin et al. (2006) observed that their findings are consistent with the assembly route running in parallel with the retrieval route, with the motor chunk being selected from the fastest route available. This would allow frequently used syllables to be retrieved from the mental syllabary, and therefore be produced faster than infrequently used syllables that would have to be constructed.

Motor chunks also exist for frequently used hand movements in handwriting. Motor chunks of individual letters (allographs) are stored which contain the individual hand-strokes needed to write the letter, as well as the directions of the movements (Teulings, Thomassen, & van Galen, 1983). Teulings et al. (1983) demonstrated that when handwriting letter pairs, those who require similar movements such as similar strokes and stroke direction (i.e., *eu*) showed similar response times and movement times as dissimilar letter pairs with opposite features such as different strokes and stroke durations (i.e., *en*). If hand strokes constituted the motor code activated before the initiation of the movement, the letter pairings sharing similar strokes would be expected to initiate faster. In contrast, letter pairs containing identical letters (i.e., *ee*) benefited from a faster response time than the condition of the similar letters. Despite similar strokes being used within both conditions, the fundamental difference between two is the number of allographs (letters) that need activating before writing. This provides the notion that a well-practiced letter is treated as a single motor chunk containing all hand movements required.

The supporting evidence for motor chunking in both speaking and handwriting demonstrate that motor chunking occurs in various domains of language production. However, this only supports the plausibility of motor chunking in typewriting. The findings cannot be extended to typewriting as the movements required are independent across the three forms of language production. When speaking, vocal muscles are used, whereas when typewriting, the main movements required are located at the fingers. Both involve independent movements from one another. The movement patterns are much more alike for handwriting and typewriting, but this similarity only extends to the use of hand and fingers movements to provide a form of written text. The actual movements required vary dramatically. A single keystroke involves fewer movements and fewer changes in direction to execute a single letter. In contrast, letters within handwriting constitute multiple movements that often involve changes in direction. Thus, if fewer movements are required to produce a letter when typewriting, a greater number of letters may be chunked in typewriting compared to handwriting. While support for motor chunking in speaking and handwriting cannot support motor chunking in typewriting, it still justifies the concept that motor chunking may occur in typewriting.

I will now discuss motor chunking in typewriting. One way of examining potential motor chunking effects is via chronometric analyses, in which the timing of keystroke latencies is examined. As demonstrated in speech production, high-frequency syllables are initiated faster than low-frequency syllables (Cholin et al., 2006), demonstrating the retrieval of motor chunks prior to speaking. If frequently used letter-strings are stored as motor chunks for typewriting, the frequency would be expected to affect the time-course of typewriting. Keystrokes may be faster for the high-frequency representations if motor representations for the letter-string can be retrieved as an individual motor chunk. Alternatively, a low-frequency letter-string would most likely not have a stored motor chunk for the full letter-string, resulting in smaller movements (i.e., individual keystroke) being retrieved one at a time.

Typically, chronometric analysis of the keystroke in typewriting can be separated into two distinct types of keystrokes, onset latencies, and Inter-Key Intervals (IKIs). The onset latency is a reflection of the encoding of the spelling, motor preparation, as well as the execution of the initial keystroke (Pinet, Ziegler, et al., 2016; Snyder & Logan, 2014). Examinations of onset latencies have already demonstrated that words consist of multiple motor chunks. As the length of a word increases, the time taken to initiate the initial keystroke increases (Verwey, 1999), suggesting that more time is required to select and initiate the movements required for the additional keystrokes. However, as sequences get longer, the sequence length effect appears to level off (Rosenbaum, Hindorff, & Munro, 1987; Sternberg, Knoll, Monsell, & Wright, 1988; Sternberg et al., 1978). It appears that only a limited amount of motor representations can be prepared within the motor buffer.

One of the limitations of drawing inferences from the onset latency is that it may be difficult to differentiate between the processes of the outer loop and the inner loop. Faster initiation of the onset latency may indicate faster generation of the spelling of the word (outer loop). However, it could also indicate faster inner loop performance such as faster retrieval/generation of the initial motor chunk, or faster execution of the first keystroke. The clearer, more reliable, method of examining motor chunking within the time-course of typewriting is via the examination of the IKIs. These are the time intervals between successive keystrokes. As a result of the encoding of the spelling of the word occurring in full prior to the initiation of the initial keystroke, the subsequent keystrokes are a reflection of motor execution processes only, demonstrating the time required to execute each step of the motor program (Crump & Logan, 2010a; Logan & Crump, 2011; Salthouse, 1986).

Slower IKIs , particularly when in words greater than four or five letters (Bo & Seidler, 2009; Brown & Carr, 1989; Kennerley, Sakai, & Rushworth, 2004; Verwey, Lammens, & Honk, 2002; Wymbs, Bassett, Mucha, Porter, & Grafton, 2012), are argued to reflect the transition from one motor-chunk to the next (Chapman, Healy, & Kole, 2016; Verwey, 1996). Many small motor chunks may exist as a result of the limited capacity of the short-term motor buffer (Bo & Seidler, 2009; Verwey & Eikelboom, 2003; Verwey et al., 2002). Abrahamse, Ruitenberg, De Kleine, and Verwey (2013) acknowledge the slowing within the IKIs as the concatenation point, a point in which the next motor chunk is prepared and initiated. The concatenation point marking the end of one motor and chunk, and the beginning of another allows us to examine the size of motor representations utilized in language production. If sub-word motor chunks are used within typewriting, we would expect to find at least one concatenation point within a word or letter-string.

If frequently executed motor chunks are stored as a result of being frequently loaded within the motor buffer (Sternberg et al., 1978; Verwey & Dronkert, 1996), the time-course of typewriting should be sensitive to the availability of stored motor chunks. Typewriting may be faster where frequently used motor chunks are available, but much slower where infrequent letter combinations may not have a stored representation. There is some evidence of the time-course of production being sensitive to letter-string frequency. The typewriting speed of novice typists is sensitive to monogram frequency (Behmer & Crump, 2015), whereas the typewriting speed from expert typists is sensitive to bigram and trigram frequencies (Behmer & Crump, 2015; Gentner et al., 1988; Pinet, Ziegler, et al., 2016). Additionally, faster keystroke latencies are produced for high-frequency letters and letter-strings (Behmer & Crump, 2015). It appears that the more frequent a letter sting is typed, the faster it can be produced. However, these effects occur within naturally occurring words that may be affected by higher-level sublexical constraints such as syllabic or morphemic constraints. These bigram frequency effects may arise due to the lowered bigram frequency that is often found at a syllable boundary, known as the bigram trough (Seidenberg, 1987;

Seidenberg & McClelland, 1989) as previously discussed in the context of handwriting (i.e., Kandel et al., 2011).

The research within this thesis aims to explore how the time-course of typewriting may be sensitive to the frequency of letter combinations such as bigrams and trigrams. If motor chunks can be developed over time with practice, the availability of motor chunks should be dependent upon how often they have been typed previously. High-frequency letter-strings such as *GHT* (from *might, sight, brought,* etc.) could potentially have a stored motor chunk containing all the movements required to execute the three letters in fast succession. In contrast, low-frequency letter-strings such as *QZP* that are not typed in the English language will not have a stored motor chunk. If *QZP* is not regularly loaded into the motor buffer before typewriting, there would be no reason to store the three letters as a singular chunked motor representation.

1.4. Unanswered question three: Does the inner loop run to completion without interference from other (e.g. phonemic) representations?

As discussed previously, Logan and Crump's (2011) theoretical account of typewriting divides the spelling and motor processes across two separate loops, an outer loop and an inner loop. The outer loop is responsible for the higher-level processes such as the comprehension and generation of the spelling of a word. The outer loop outputs the spelling of a word as singular word forms that act as an input to the inner loop. The inner loop, responsible for the motor processing and execution of the keypresses, converts the word to individual letters, which are then converted into keyboard specific motor plans before being executed as keystrokes. Such activation is argued to occur in parallel (Crump & Logan, 2010b). Within the hierarchical two-loop model, it is argued that the inner loop is informationally encapsulated (Logan & Crump, 2011).

Information encapsulation is essential to modularity theory (Fodor, 1983). The theory builds on the premise that the mind consists of innate mental structures that perform computational processes. Modules are biologically predisposed to perform such processes in an automatic and fast manner. As such, information inputted to the module is only influenced by processes within the module itself, ignoring information outside of the module to process in an automatic and fast manner. An informationally encapsulated module cannot access information from external processes that do not reside within the module. The informationally encapsulated module operates in isolation from central cognitive processes. The necessary information and processing are available within the module to perform the desired function. The lack of interaction with other modules enables quick processing that is not slowed by accessing information external to the module. In contrast, central processes are believed to be non-modular and not informationally encapsulated. They operate with fewer restrictions on the information given to them, allowing for a greater consideration of the information available within modular processing. Typewriting itself is not modular. We are not biologically predisposed to type on keyboards. However, the motor planning of fine finger movement could be modular, and therefore could also be encapsulated.

In the context of the two-loop theory of typewriting (Logan & Crump, 2011), it is argued that the outer loop has no purpose for knowing what the inner loop is doing. Such an argument has been supported by the outer loop not knowing which hand types which keys (Logan & Crump, 2009), as well as not knowing where the letters are located on a keyboard (Liu et al., 2010). Liu et al. (2010) examined typists' explicit spatial knowledge of the keyboard across two experiments. They examined if explicit spatial knowledge is as accurate as visual feedback or haptic and proprioceptive feedback. They found that subjects who were forced to imagine the keyboard provided slower responses and larger angular error between the target letter and response letter compared to subjects who were able to see the keyboard (visual feedback) or were able to physical touch (but not see) the keyboard (haptic and proprioceptive feedback). There was no difference in angular error between the touch and look conditions, indicating that judgements assisted by perceptual feedback do not differ across modalities. In Experiment 2, subjects were required to place a moveable key in relation to the keyboard location with respect to a presented letter on the screen. Similar findings were observed, as the imagine group contained larger errors for the distance between keys and angular error, along with the time taken to respond, when compared to the touch and look conditions. The overall findings suggest that typist's explicit knowledge of the spatial arrangement of the keyboard is poor. Liu et al. (2010) argue that as the arrangement of letters on the keyboard is different, and arguably incompatible, with the left-to-right ordering of letters within words, the two arrangements may be separated across the two loops. The outer loop responsible for word processing and the inner loop responsible for the spatial knowledge of the key locations.

Both Liu et al. (2010) and Logan and Crump (2009) suggest that the higher levels, in the form of the outer loop, does not know the details of how the lower levels (inner loop) are executed, with only knowledge of the prior commands and the observed execution of the keystrokes. While the findings of both studies suggest that the outer loop has very poor spatial awareness of the keyboard, this is not necessarily a strong enough indication that the inner loop is informationally encapsulated. Both studies examine if such information can be accessed via the outer loop, but do not examine influences upon the inner loop. Furthermore, other studies have demonstrated that the outer loop can access alternative sources of information contained within the inner loop (i.e., Cerni, Velay, Alario, Vaugoyeau, & Longcamp, 2016; Kalfaouğlu & Stafford, 2014; Pinet & Nozari, 2018; Pinet, Ziegler, et al., 2016).

In contrast to the supporting evidence for the encapsulation of information within the inner loop, there is growing contradictory evidence within typewriting. Despite lexical representations acting as an interface between the outer and inner loop, it is argued that the outer loop can access post lexical information that should be informationally encapsulated within the inner loop (Pinet & Nazari, 2018; Pinet et al., 2016; Cerni, Velay, Alario, Vaugoyeau, & Longcamp, 2016; Kalfaoğlu & Stafford, 2014). Pinet and Nozari (2018) demonstrated that a greater number of errors were observed, as well as slower production, when subjects were required to type words within a phrase that contained the same segment/vowel in the final two words (i.e., *fog top*), compared to phrases that do not contain the same vowel. This was taken to reflect feedback occurring from a post-lexical level to the lexical level. Interference caused on the fourth word via the third word could be interpreted as priming effects occurring within the outer loop only whereby the third word primes the fourth word. However, this explanation can be eradicated as the majority of such errors occurred in an anticipatory fashion in which the fourth word influenced the third word (i.e., *fog top becomes tog top*). Assuming the lexical word interfaces the outer and inner loop as stated as one of the fundamental arguments within the two-loop model (see Logan & Crump, 2011), the feedback occurring between lexical and post-lexical processes suggest that the inner loop is not informationally encapsulated.

As discussed previously, the two loops are argued to be constrained by the feedback that is independent of one another (see Logan & Crump, 2011). The outer loop relies on visual feedback, whilst the inner loop relies on haptic and proprioceptive feedback. Both methods of feedback detect errors during typewriting. As the outer loop generates the word to be typed, it observes accuracy via the visual appearance of the word on the screen. If the appearance on the screen does not match the word sent from the outer loop, the outer loop asks the inner loop to correct the error(s). In contrast, the inner loop is responsible for the generation of the keystrokes, so observes the accuracy of the executed keystrokes and their ordering, via haptic and proprioceptive feedback. Where movements do not match the intended output, typewriting is slowed.

The importance of this in the context of information encapsulation is concerning the outer loop detecting or correcting errors when visual information is not available. Kalfaoğlu and Stafford (2014) demonstrated that when errors were made, even mid-word, the typists pressed the backspace and continued typewriting the word from the correct position. This occurred despite visual information not being available to the typist. Typists did not see the typed output appear on the monitor, and their hands were covered. The lack of visual information suggests that the outer loop must have had access to the feedback within the inner loop. If the outer loop could only access feedback via visual information and does not know what the inner loop is doing, it would not be able to provide the information to correct the error and continue typewriting from the correct position within the word. Kalfaoğlu and Stafford (2014) argue that the outer loop relies on visual information when it is available but can access the feedback from the inner loop for instances such as when visual information is not available.

An understanding of the claim that the inner loop is informationally encapsulated is important as inferences made about the involvement of the two loops is anchored on the information encapsulation of the inner loop. Interpretations of typewriting research based on such claims may incorrectly discount potential influences from central-spelling processes upon motor execution. Furthermore, if the inner loop is not informationally encapsulated, fewer limits can be assumed regarding what information is fed back to the outer loop. While there is evidence to suggest that the outer loop does not contain information within the inner loop (Liu et al., 2010; Logan & Crump, 2009), this does not necessarily mean that the inner loop is only constrained by the word form passed from the outer loop. Furthermore, there is evidence to suggest that the outer loop can obtain information from the inner loop (Pinet & Nazari, 2018; Pinet et al., 2016; Cerni, Velay, Alario, Vaugoyeau, & Longcamp, 2016; Kalfaoğlu & Stafford, 2014).

While the extent of which the outer loop can access information from the inner loop is clearly debated. There is a weaker understanding of how motor processing and execution of the inner loop is influenced by external processes, a reflection of the inner loop being constrained to more information contained within the loop. If the inner loop is informationally encapsulated, inner loop processing should not be influenced by manipulations to outer loop processing beyond the initial keypress. Whilst the onset latency will reflect both outer loop and inner loop processes (Pinet, Ziegler, et al., 2016; Snyder & Logan, 2014), as all letters and keystrokes within a word, are argued to be activated in parallel (Crump & Logan, 2010b; Logan et al., 2011), the IKIs are a reflection of motor planning and execution only (see Logan & Crump, 2011). However, since the two-loop model argues that words are passed from the outer loop to the inner loop, which then activates the letters and keystrokes in parallel, IKI's reflect motor execution only. All motor planning/processing would occur before the onset latency. If manipulations to spelling processes of the outer loop influence the IKI's, it would suggest that the inner loop can access information external to the inner loop, and thus, is not informationally encapsulated. This thesis shall examine if the inner loop runs to completion without interference from other (e.g. phonemic) representations.

1.5. Unanswered question four: Is the time-course of typewriting affected by inner speech?

One of the critical considerations for this thesis is whether the time-course of typewriting is affected by inner speech. As discussed previously, the generation of the language to be written/typed can be assisted by phonological processing at the sub-lexical level (see Bonin et al., 2015). An orthographic lexical route and a phonological sub-lexical route run in parallel. Where the generation of language via the sub-lexical route is faster, such as for unfamiliar words with no stored spelling information, phonological representations (i.e., phonemes) can be converted into orthographic representations (i.e., graphemes) to provide an abstract spelling of a word to be passed to the motor level.

In addition to phonological processing aiding abstract spelling processes, there is evidence to suggest that the time-course of typewriting can be affected by the phonological processing of the word(s) that can be named via inner speech (Chenoweth & Hayes, 2003). Inner speech is an aspect of verbal working memory, required for grammatical, phonological, and orthographic encoding (Chenoweth & Hayes, 2003; Levy & Marek, 1999; Mueller, Seymour, Kieras, & Meyer, 2003). The inner voice may serve the purpose of rehearsing the articulatory form of the word(s) to be typed. Considering Baddeley and Hitch's (1974) model of working memory along with Baddeley's (1986) account of the phonological loop, short-term phonological information decays rapidly unless it is rehearsed. Inner speech may serve as a method of repeating phonological information so that it is not lost before being used during typewriting. This is only hypothetical at this point, as there is little research on the effect of inner speech on orthographic production.

One line of evidence to support the concept of inner speech affecting the time-course of typewriting is that of Chenoweth and Hayes (2003). They examined if the inhibition of articulatory rehearsal, which can be considered as an inner voice implicitly saying the word(s) to be typed, affected typewriting performance. Subjects were required to type sentences describing multi-panel cartoons presented to them. The inhibition of articulatory rehearsal was manipulated via an articulatory suppression task in which subjects were required to repeatedly speak aloud a syllable when typewriting. It was demonstrated that typewriting performance is affected by articulatory suppression, as the production was significantly slowed in comparison to control conditions. Interfering with the inner voice slows the time-course of typewriting.

When comparing the influence of phonological information upon orthographic production/processing, it is important to consider the differences between the phonological form available during sublexical processing and the phonological form available for the inner voice. For phonological influences upon typewriting via the inner voice, the phonological information of the word would have been fully processed up to and including the point of phonetic encoding and is also available for articulation. The phonological information available at this point is very different from what is available during sublexical processing. It is not an abstract word form with abstract syllables. It is a fully processed word with a finalised syllable structure across word boundaries that is already available for articulation. If the time-course of typewriting is influenced by the inner voice, this could arguably occur in two ways. One possibility is the phonological information of a fully processed phonological word is translated into the corresponding orthographic form. This is the interpretation taken by Chenoweth and Hayes (2003) in support of their model of written language production

(Chenoweth & Hayes, 2001). However, this possibility contradicts a widespread consensus that the conversion of phonological information to orthographic information occurs at the sublexical level (Bonin et al., 2015; Purcell et al., 2011; Tainturier & Rapp, 2001), though there is evidence of phonological assistance that is not necessarily a conversion of phonology to orthography at the sublexical level (Bonin et al., 2001; Damian, Dorjee, & Stadthagen-Gonzalez, 2011).

Alternatively, the phonological information available via the inner voice may be used during the self-monitoring process to ensure the output matches the intended outcome. The feedback/monitoring process is fundamental in ensuring that the intended goal has been executed correctly. Where this has not been achieved, detected errors are removed and corrected. The detection of an error is typically met with post-error slowing (Logan & Crump, 2010; Salthouse, 1986). The reasoning for the slowing is debated as it may occur from a state of confusion that may have caused the error (Gehring, Goss, Coles, Meyer, & Donchin, 1993), or a state of surprise because of the mismatch between the executed text and the intended message (Notebaert et al., 2009). Alternatively, the typist may slow down in an attempt to improve accuracy (Gentner, 1987; Yamaguchi, Crump, & Logan, 2013). Whatever the reason for the post-error slowing, the feedback/monitoring process influences the time-course of typewriting. Hypothetically, if inner speech plays a role in this process, the time-course of typewriting may be mediated by inner speech.

Within monitoring processes in speech, inner speech can be used before articulation (Levelt, 1983; see Levelt et al., 1999). It is possible that the same processes may run in parallel during typewriting. The monitoring system within typewriting may use this information as well as visual information on the screen (Logan & Crump, 2010) and proprioceptive and kinaesthetic information (Crump & Logan, 2010c). Similar to these feedback systems, the inner voice may be compared to the intended message during production. Alternatively, the inner voice may not provide an additional feedback system but instead play an essential role in the comparison of the visual information on the screen to the intended message. As the typed output on the screen must be read to compare to the intended message, the read information must be processed into a meaningful form to make direct comparisons to what was meant to be typed. This may involve converting to an orthographic form or a phonological form in which the inner voice may play a role. On a similar note, what is more probable is the intended message that is being compared to the typed output is not the abstract word form produced by the outer loop but instead a fully processed phonological form being read aloud by the inner voice. If you were to type a sentence, you would most likely implicitly hear (via the inner voice) the word you intend to type, rather than the outputted word that may feature errors.

In examining phonological influences upon typewriting, this thesis will examine the late phonological processes of resyllabification within typewriting. Based on current knowledge, there is no evidence of resyllabification effects within typewriting to date. Such justification for examining the potential impacts of resyllabification shall be discussed. “Resyllabification is a phonological process in which a consonant is attached to another syllable than that from which it originally came” (Vroomen & de Gelder, 1999, p. 414). In a typical instance within speech, this involves the vowel that starts a word (i.e., *i* in the word *it*) takes the form of an obligatory nucleus that attaches to the preceding consonant of the prior word, or/and the proceeding consonantal coda (Kahn, 1976). Take, for example, the phrase we defend it. The three lexical words have their respective syllable boundaries based upon their lexical identity (we.de.fend.it) but once resyllabified, the phonological word has a resyllabified syllable structure (we.de.fen.d-it). The syllable boundaries straddle across the lexical word boundaries, indicating different syllabification parameters to that of the lexical word(s). Instead, the syllabification parameters are based upon that of the phonological word (Nespor & Vogel, 1986), a larger phonological word frame, often a phrase, consisting of multiple lexical words. Once the phonological syllables have been constructed via the association of the segments with the metrical frame, it is argued that the phonological syllables are used to activate the phonetic syllables stored within the mental syllabary (Cholin et al., 2006; Levelt & Wheeldon, 1994).

Unlike the abstract form of the syllable representation produced during earlier phonological processing, the syllable representation provided during resyllabification is an articulatory (i.e., inner speech) phenomenon. The importance of this is that any influence of resyllabification upon typewriting is available via the articulated form and inner speech but not available for the sublexical conversion to an orthographic form as this occurs at much earlier stages of processing (see Levelt et al., 1999). Of equal importance, any influences upon resyllabification occur at the word boundary and are not subject to confounding influences such as n-gram frequencies or alternative sub-word processing units. This is essential for the research within this thesis as evidence for syllabic processing units within orthographic production can also be explained by bigram frequency effects. Syllable boundaries have been found to coincide with low-frequency bigram troughs (Seidenberg, 1987; Seidenberg & McClelland, 1989) whereby between-syllable letters typically have a lower frequency than within-syllable letters. While the nucleus of a syllable is usually a vowel to allow for peak sonority, less sonorous letters are assigned to the onset and coda positions found at the syllable boundary. For example, as discussed by (Rapp, 1992), the word *ANVIL* is separated into two syllables, *AN* and *VIL*. The initial syllable of *AN* has a much higher bigram frequency (289) to that of the *NV* (5) located at the bigram trough. While examinations of syllabic representations in handwriting or typewriting is support for phonological influences upon the orthographic processing, such apparent syllabic effects may simply be the co-occurrence of low-frequency bigrams. This is an important confounding factor that is typically not addressed within research examining syllabic effects. By manipulating the phonetic syllable across the word boundary via the resyllabification process, the problems of confounding n-gram frequency effects are accounted for and controlled.

To summarise, phonological processing arguably plays a role in the time-course of typewriting. This is still not clear as the majority of evidence for phonological influences upon orthography occur in research into word recognition and handwriting. However, as discussed there is enough evidence to suggest that similar phonological processes may occur within typewriting, and furthermore, typewriting may also be influenced by such late stages of phonological processing that the phonological word is fully processed and can be named aloud and in inner speech. If there are within-word phonological effects within typewriting, there are two possible ways this could occur. One possibility is that the orthographic form of the words is assembled via a phonological route. An alternative option is that inner speech runs concurrently with typewriting and affects how it is produced. Both of these possibilities are met with additional unknown questions in terms of how, where, and when the influences of phonology cause an effect. If phonological information is converted into orthographic information to provide the spelling of word, this could arguably occur at the sublexical level (Bonin et al., 2015; Purcell et al., 2011; Tainturier & Rapp, 2001) or once a full articulatory form is available, along with inner speech (Chenoweth & Hayes, 2003). If inner speech provides phonological information to create the orthographic spelling of the word, this will occur when inner speech runs concurrently with typewriting.

However, there are additional ways in which inner speech may affect concurrent processing. Inner speech may serve as a new feedback system to ensure that the output matches the intended message. A similar possibility is that inner speech may be required in an already documented feedback system within typewriting. According to (Logan & Crump, 2011) the outer loop responsible for the spelling of the word uses the visual information from the screen to ensure there is not a mismatch between the outputted text and the intended message. This is also supported by Logan and Crump (2010). When comparing the text to the intended message, it may be the case that the intended message is not compared as the abstract orthographic form created within the outer loop but as the fully processed inner voice that you may hear when you are typewriting. All of these possibilities provide further reasoning for the rationale of examining the poorly understood influence of phonological effects within typewriting.

1.6. Thesis overview

The discussion within the introduction has provided the background research relevant for the research within this thesis, which are presented in the subsequent chapters. This has progressed from theoretical accounts of language production in section 1.1., before then outlining the literature and arguments related to each of the four questions examined within this thesis within sections 1.2. – 1.5. The four questions examined within this thesis are:

(1) Are sub-word graphemic representations larger than single letters passed to the motor level?[1]
(2) Are frequently used letter combinations stored as retrievable motor-chunks?
(3) Does the inner loop run to completion without interference from other (e.g. phonemic) representations?
(4) Is the time-course of typewriting affected by inner speech?

In relation to the concepts and literature discussed in sections 1.2. and 1.3., Chapter 2 aimed to determine whether (1) sub-word graphemic letter chunks are passed to the motor level; (2) high-frequency letter combinations are stored as retrievable motor-chunks; and if so, whether (3) motor-chunks scope over just two keystrokes or can also scope over three.

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[1] The terms motor level and inner loop are used interchangeably within this thesis. Particular aspects that are being investigated within this thesis, such as the information encapsulated of the inner loop, are specific to the two-loop theoretical account of typing (see Logan & Crump, 2011). Whereas, the term motor level is used instead in areas that are relevant but not specific to the two-loop theoretical account.

Across 5 experiments, participants typed frequency-manipulated letter-strings consisting of only consonants (no vowels) and were asked to do so as fast and as accuracy as possible. The frequencies of individual letters were controlled across conditions (high- and low-frequency letter combinations), and where bigram and trigram frequencies were not being directly manipulated, they were also controlled across conditions. Keystroke latencies were recorded and analysed across conditions as measures of the frequency manipulations. Across the five experiments, frequencies were carefully controlled, and a stringent experimental paradigm was employed to control for additional confounding influences. The content in Chapter 2 is presented as a paper that is prepared for publication but not yet submitted at the time of writing this thesis.

The second empirical chapter, Chapter 3, discussed the theoretical concepts and literature from sections 1.2., 1.4., and 1.5., in respect to a single experiment, Experiment 6. This experiment also aimed to determine whether (1) sub-word graphemic letter chunks are passed to the motor level; as well as examining whether: (2) the motor level (inner loop) runs to completion without interference from other (e.g. phonemic) representations; (3) the time-course of typewriting is affected by inner speech. Using a similar procedure to Experiment 1-5, in Experiment 6 participants typed letter-strings that were manipulated by the frequency of the letter combinations and were also manipulated by the CV-status of the second letter in the trigrams. This provided either pronounceable (CVC; i.e., *GAT*) or unpronounceable (CCC; i.e., *GHT*) letter strings, that could potentially aid pre-motor level graphemic preparation, and/or influence the time-course of typing via inner speech. Keystroke latencies were recorded and analysed across conditions (high-frequency CVC; high-frequency CCC; low-frequency CVC; low-frequency CCC) as measures of the frequency and CV-status manipulations.

In respect to the theoretical content discussed within sections 1.4. and 1.5., the third empirical chapter (Chapter 4) further examined whether: (1) the motor level (inner loop) runs to completion without interference from other (e.g. phonemic) representations; (3) the time-course of typewriting is affected by inner speech. In the two experiments (Experiment 7 and 8) presented in this chapter, participants typed letter strings designed to elicit resyllabification – the adjustment of syllable structure across a word boundary to aid speech articulation (see Levelt, Roelofs, & Meyer, 1999). For example, “bent inwards” is articulated with /tin/ as the second syllable. The consonant-vowel structure of the letters surrounding the word boundary of word pairs were manipulated. This provided word pairs that, if articulated, (including internally as inner speech) resyllabification would or would not occur. The keystroke latencies surrounding the word boundaries where the CV-status is manipulated were recorded and analysed across conditions. As in Chapter 2, Chapter 4 is presented as a paper that is prepared for publication but not yet submitted at the time of writing this thesis.

2. Frequency Effects in Typed Trigram Production: An Investigation of Sub-Word Letter Chunking[2]

Introduction

Typewriting is typically rapid. Experienced typists execute keystrokes fluently with very little explicit knowledge of how they are able to do so. The expertise that allows this to happen is a reflection of highly efficient motor processes that are practiced over time. This fluency is achieved through extended practice. The automaticity that results from this practice may be associated with single keypresses: Skilled typists may have very well learned motor programs for mapping specific letters onto specific finger movements. However, it is possible that expertise extends to frequent key combinations.

Research into skilled performance in both handwriting and speech suggests that fluent production results from combinations of movements becoming represented as single, chunked motor plans (handwriting: Teulings, Thomassen, & van Galen, 1983; speech production: Carreiras & Perea, 2004; Cholin, Levelt, & Schiller, 2006; Laganaro & Alario, 2006; Levelt & Wheeldon, 1994). This may also occur in typewriting. If motor chunks are stored for frequently executed movements, then the time-course of motor production should be sensitive to differences in n-gram frequencies. Five experiments examined pre-motor and motor chunking via the manipulation of bigram and trigram frequencies upon the time-course of typewriting.

The availability of stored motor representations and chunks is argued to be dependent on the frequency in which it is used. In speech production, there is evidence for stored motor chunks in the form of chunked articulatory gestures for frequently used syllables (Carreiras & Perea, 2004; Cholin et al., 2006; Laganaro & Alario, 2006; Levelt & Wheeldon, 1994). Abstract syllables are initially encoded during phonological processing, which then activate the selection of syllabic articulatory gestures within a repository of motor plans (Indefrey & Levelt, 2000). These motor plans encode the set of movements required to articulate the sound of the syllable, stored as retrievable chunked representations. Cholin et al. (2006) demonstrated that high-frequency syllables are produced significantly faster than low-

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[2] This chapter is presented as a paper that is prepared for publication but not yet submitted the time of writing this thesis.

frequency syllables. By employing a stringent experimental paradigm that controlled for phoneme and bigram frequencies, and that avoided potential confounds associated with reading the target syllable, they were able to conclude that the frequency effects were associated with retrieval of articulatory gestures (motor codes) for phonetic syllables.

There is also evidence for motor chunking within handwriting. Letter-sized motor chunks are stored containing the individual hand-strokes and the direction of such movements (Teulings et al., 1983). Teulings et al. (1983) demonstrated that there is no difference in response and movement durations when handwriting letter-pairs containing similar movements (similar strokes and stroke direction; e.g., *eu*), and letter-pairs with dissimilar movements (e.g., *en*). If hand strokes constituted the motor code activated before the initiation of the movement, the letter pairings sharing similar strokes would be expected to initiate faster. This was not the case. It is only when identical letters are prepared as a letter-pair (e.g., *ee*) that response durations are significantly faster compared to non-identical letter-pairs with similar movements (e.g., *eu*). Despite similar strokes being used within both conditions, the fundamental difference between two is the number of allographs (letters) that need activating before writing. In handwriting, individual movements are not prepared individually, but instead, a well-practiced letter is treated as a single motor chunk containing all hand movements required.

Syllables spoken, or letters written, more frequently are stored as retrievable motor chunks (Cholin et al., 2006; Teulings, 1983). This allows for faster production than the online construction of a motor-plan. This may also occur within typewriting. Motor representations may be stored, retrieved, and encoded as motor chunks for multiple keystrokes. The movements required to execute a single keystroke may not have to be prepared individually. Considering that the time-course of typing is sensitive to bigram and trigram frequencies (Behmer & Crump, 2015; Gentner et al., 1988; Pinet, Ziegler, et al., 2016), it is possible that frequently typed bigrams and trigrams have stored motor chunks that can be retrieved as a single unit. Behmer and Crump (2015) demonstrated that changes to single letter (monogram) frequency affects typewriting speed for novice typists, whereas changes to bigram and trigram frequencies affect the typewriting speed of expert typists. These frequency effects may reflect motor processing, whereby novice typists are forced to prepare keystrokes individually, but expert typists are able to retrieve stored motor chunks for frequent bigrams and trigrams.

However, although previous research has found bigram frequency effects, it is not clear whether this represents chunking within the motor level. It could represent something else entirely. The findings from Behmer and Crump's (2015) research are based upon the production of lexical words that are susceptible to concurrent processes. Without controlling for processes before the motor level, it is unclear whether the bigram effects occur within the motor level or beforehand. It is also possible that the observed bigram frequency effects do not represent faster performance for frequent letter-combinations, but something else entirely. These bigram frequency effects may arise due to the lowered bigram frequency that is often found at a syllable boundary, known as the bigram trough (Seidenberg, 1987; Seidenberg & McClelland, 1989). Consider that typewriting is sensitive to syllable boundaries and frequency (Gentner et al., 1988; Nottbusch, Grimm, Weingarten, & Will, 2005; Pinet, Ziegler, et al., 2016; Weingarten, Nottbusch, & Will, 2002). The observed bigram frequency effect may represent higher-level syllabic processing.

Chunking can also occur before the motor level. Language generation involves multiple levels of processing, each outputting information chunks from one level to the next. In speech, clusters of sounds are chunked as syllables before motor processing (see Levelt et al., 1999). Similarly, in handwriting, letters and letter combinations are chunked at the graphemic level before motor processing (see Bonin et al., 2015). In typewriting, it is argued that letters are chunked as words before being passed to the motor level (Logan & Crump, 2011; Logan, 2018). When familiar words are not available, such as when typing a string of consonants, non-chunked letters are passed to the motor level individually (Logan & Crump, 2011). This places a large emphasis on processing at the word level without the possibility of sub-word chunking before the motor level. The present series of experiments shall examine this possibility while also examining motor chunking in typewriting.

The present research examined the effect of letter-string frequencies upon typewriting latencies for high- and low-frequency letter-combinations, via the manipulation of bigram and trigram frequencies. The implementation of consonant only letter-strings controls for potential linguistic confounders such as influences from morphemic or syllabic representations or boundaries. This control is crucial as such boundaries frequently coincide with low-frequency bigrams (Seidenberg, 1987; Seidenberg & McClelland, 1989; Kandel et al., 2011). Furthermore, the unpronounceable nature of the consonant only letter-strings that are employed within this study control for potential phonological confounders.

Additional experimental controls were employed to reduce any influences of reading/perception of the letter-strings affecting the recorded keystroke latencies. This is important as frequency effects have been observed with word perception studies (e.g., Solomon & Postman, 1952). A symbol-position association learning task (see Cholin et al., 2006; Levelt & Wheeldon, 1994) was employed in which letter-strings were associated with a location on the screen (left or right) to allow for the associated location to act as a cue to type the letter-string. The task involves three stages (see Figure 2) involving (1) association learning; (2) association confirmation; and (3) production. In the association learning stage, two-letter strings were presented on the screen in either the left or right position. Participants had to associate the letter strings with the presented location. In the association confirmation stage, the letter-strings were presented in the center of the screen, and participants were required to specify the location of the association via keypress (left or right). This confirmed that the association was learned correctly. These two stages allow for the associations to be learned without typewriting the letter-strings. Only an abstract representation of the letter-strings was activated at this point as no activation of the letter-strings is required at the motor level. This ensures that typewriting performance at the production stage is not affected by practice effects. In the production stage, a box was presented in the left or right position of the screen. At this point, participants typed the letter-string associated with the location of the box presented on the screen (left or right).

If chunked keystrokes clusters are stored as retrievable motor representations, they are likely stored for frequent representations only, as evidenced in speech production (Cholin et al., 2006). The comparison of the keystroke latencies for high- and low-frequency letter combinations allowed us to examine if stored motor representations are available for chunked units greater than individual keystrokes. Analogous to the faster speech initiation when high-frequency syllables are available as stored motor chunks (Cholin et al., 2006), the onset of typing may be initiated faster if motor chunks are available for high-frequency letter-combinations, and motor chunks must be constructed for low-frequency letter-combinations. The onset latency, the time taken to execute the initial keypress, has been demonstrated to reflect the time to encode and retrieve the spelling, prepare the initial motor chunk and execute the initial keypress (Pinet, Ziegler, et al., 2016; Snyder & Logan, 2014). Consequently, the onset latency is argued to mainly reflect higher level processes responsible for preparing the spelling of the word (Logan & Crump, 2011). However, higher level processes are well controlled by the experimental paradigm and controls utilized across the five studies, arguably to the point where the onset latency may reflect mainly motor preparation and execution processes.

However, it is also possible that motor chunks are not constructed for low-frequency letter combinations. Instead, motor representations for individual keystrokes may be prepared and executed separately. In this instance, the keystroke latencies after the onset latency can indicate motor chunking. The subsequent keystrokes after the onset latency, the Inter-Key Intervals (IKIs), represent the time interval between successive keystrokes. They are a measurement of motor preparation and motor execution (Logan & Crump, 2011). If a frequent letter combination such as *GHT* is retrieved as a motor chunk, the motor representations for the second and third letters are retrieved at the same time as the first letter. This would allow the IKIs for the second and third letters to be produced much faster for frequent letter combinations, as motor preparation is not required, only the motor execution of the already retrieved motor representations.

If motor chunks are available in typewriting, the analysis of the IKIs can also determine whether motor chunks scope over two keystrokes, or if they can also scope over three. If motor chunks scope over two keystrokes, the motor representation for the second keystroke of the bigram is retrieved in advance and the second keystroke can benefit from faster production. Whereas, if motor chunks scope over three keystrokes, the motor representations for both the second and third keystroke of the typed trigram are retrieved in advance, allowing both the second and third keystrokes to benefit from faster production. The aims of the present five experiments were to determine whether (1) high-frequency letter combinations are stored as retrievable motor-chunks; and if so, whether (2) motor-chunks scope over just two keystrokes or can also scope over three.

The present series of five experiments examined potential chunking effects within typewriting. This includes sub-word chunking at the boundary of the outer loop; as well as motor chunking in the inner loop. If letters cannot be chunked as sub-word representations, only words, in the outer loop we should observe no influence of the frequency of letter combinations upon keystroke latencies when individual letter frequencies are controlled.

Similarly, the manipulation of bigram and trigram frequencies may demonstrate support for motor chunking in typewriting. If chunked keystrokes clusters are stored as retrievable motor representations, they are likely stored for frequently typed representations only, as evidenced in speech production (Cholin et al., 2006). The comparison of high- and low-frequency letter combinations will allow us to examine if stored motor representations are available for chunked units greater than individual keystrokes. The aims of the present research were to determine whether (1) sub-word graphemic letter chunks are passed to the motor level; (2) high-frequency letter combinations are stored as retrievable motor-chunks; and if so, whether (3) motor-chunks scope over just two keystrokes or can also scope over three.

Experiment 1

Both the trigram frequency, and the frequencies of both bigram locations, were manipulated to examine how the time-course of typing may benefit from the retrieval of motor chunks. This experiment made no attempt to differentiate between the possible size of motor chunks. Instead, the frequencies of all letter combinations were manipulated as a proof of concept that that stored motor chunks are available for frequently typed letter combinations.

Experiment 1 also explored how motor chunking may affect the time-course of typewriting. If motor chunks are retrieved for high-frequency letter combinations, it may be demonstrated by the keystroke latencies in one of two ways:

(1) The retrieval of high-frequency motor chunks may allow for faster typing initiation at the onset latency for high-frequency letter combinations. If motor chunks are retrieved for frequent letter combinations, typing may be initiated faster than low-frequency combinations. This would especially be the case if the onset of typing for low-frequency letter combinations is delayed by the construction of motor chunks. Thus, the onset latency may be faster for the high-frequency letter combinations if (1) motor chunks are retrieved for high-frequency letter combinations only; and (2) motor chunks are constructed prior to typing for low-frequency letter combinations.

(2) The retrieval of high-frequency motor chunks may allow for faster IKIs for high-frequency letter combinations. Low-frequency letter combinations may not require the construction of

motor chunks. Motor representations for the keystrokes may be prepared and executed individually instead. This would mean that the second and third letters in the low-frequency trigram require the motor representations to be retrieved on the fly, whereas, the second and third letters in a high-frequency trigram may benefit from the motor representations being retrieved earlier as a part of a motor chunk (i.e., in *GHT*, the motor representations for *HT* are retrieved in advance). Thus, the IKIs may be faster in the high-frequency condition if (1) motor chunks are retrieved for high-frequency letter combinations only; and (2) keystrokes are prepared individually within the motor level for low-frequency letter combinations.

Methods

Design

The study employed a two condition (high trigram frequency, and low trigram frequency) repeated measures design. Trigrams were assigned in same-condition pairs to the location of a square that appeared on either the right or the left of the screen. The association between letter-strings and location were trained in the association learning stage and then checked in an association confirmation stage. Participants then completed a block of trails in which the square was presented to the left or right of the screen and they were asked to quickly and accurately type the associated trigram.

Stimuli comprised of 16 high frequency and 16 low frequency trigrams, which were presented in 16 blocks with one same-frequency pair of trigrams associated with each block. Each block comprised 8 experimental trials – 4 for each trigram in random order. This gave a total of 128 experimental trials.

Onset latencies and IKIs were recorded. The onset latencies reflected the time from appearance of the square to first keystroke. The IKIs reflected the time between pressing the first and second key in the trigram, and time between pressing the second and third key.

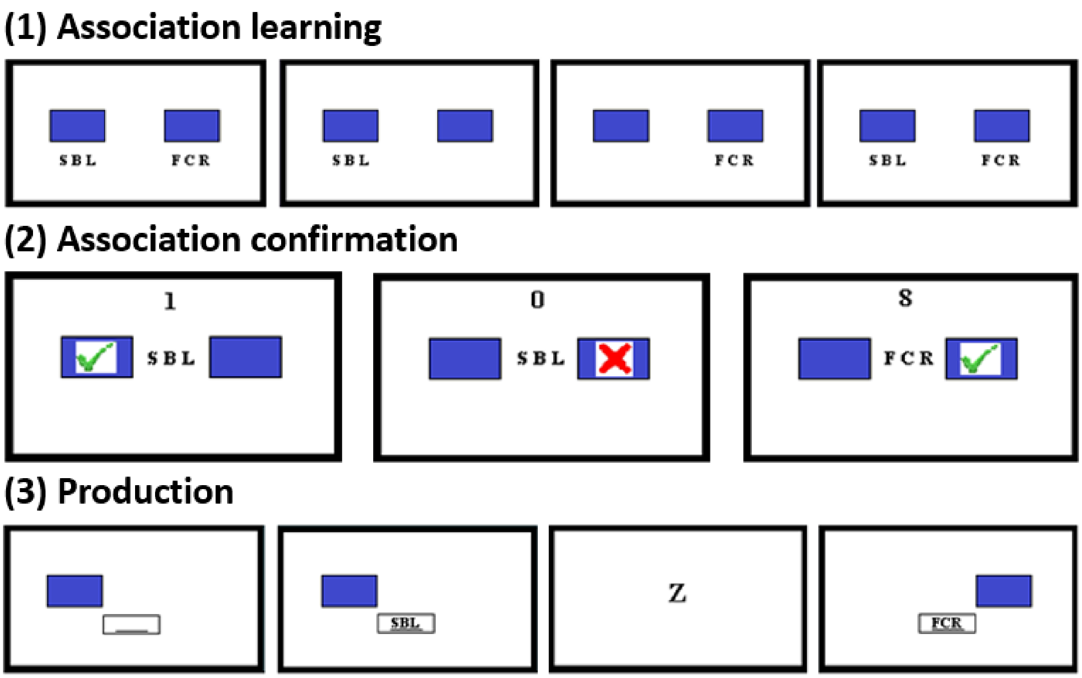

Figure 2: The Symbol-Position Association Learning Task. (1) Letter-strings are associated with one of two locations on the screen (left or right); (2) participants must correctly confirm the location of the associated letter strings on eight successive trials; (3) presentation of a rectangle cues participants to type the letter string associated with the location. Letters not used within the letter strings (i.e., z) are presented between trials to prevent priming effects across trials.

Participants

Twenty-four native English speakers took part in the experiment. All participants were undergraduate students with normal or corrected-to-normal vision, no history of language difficulties, and of self-reported adequate typewriting ability. Participants received research credits for their participation as part of Nottingham Trent University's SONA Research Participation Scheme.

Materials

N-gram frequencies were calculated from occurrences within the WebCELEX site's word frequency lists (Max Planck Institute for Psycholinguistics, 2001). The reported frequencies per word (on the CELEX database) was based on per 17.2 million words. The n-gram frequencies were based on the number of occurrences of words within the lexicon, which were then multiplied by their corresponding frequency of the words in which they appeared.

The letter-strings were selected for each condition on the basis that: (1) the high-frequency condition contains high-frequency trigrams, consisting of high-frequency bigrams in both locations; (2) the low-frequency condition contains low-frequency trigrams, consisting of low-frequency bigrams in both locations; (3) mean letter frequencies must be lower, or the same, in the high-frequency trigrams compared to low-frequency trigrams. This ensures that high-frequency letter-strings do not benefit from higher letter frequencies. A summary of the frequency breakdown across conditions is provided below, in Table 1.

Table 1: Mean Letter, bigram and trigram frequencies for stimuli used in Experiment 1

Condition	Trigram	Bigram one	Bigram two	Letter one	Letter two	Letter three
High-Frequency	21,517.00	186,546.73	101,650.27	3,183,236.00	3,254,879.20	3,590,317.33
Low-Frequency	1.47	56,323.00	50,425.20	3,366,952.00	3,254,879.20	3,659,632.47

Letter-strings were then paired for the purpose of the symbol-position association-learning task. Stimulus pairs were constructed of letter-strings from the same experimental condition (high- or low-frequency), in which the letters were independent of the other trigram within the pair. For example, the high-frequency letter-string *GHT* was paired with the letter-string *RLD*, as it was not allowed to be paired with other high-frequency letter strings containing the letters *G, H,* or *T*. A breakdown of the stimuli pairings is provided below, in Table 2.

Table 2: Stimuli pairings used in Experiment 1

BLOCK NUMBER	LEFT_STRING	RIGHT_STRING	CONDITION
1	S T R	M P L	HIGH
2	R L D	G H T	HIGH
3	R N M	S T L	HIGH
4	X T R	N S P	HIGH
5	R D S	M B L	HIGH
6	M P R	L D N	HIGH
7	R M S	N D S	HIGH
8	C K L	N S W	HIGH
9	F P L	S T N	LOW
10	G H R	R L B	LOW
11	M T L	R N H	LOW
12	N S R	X T C	LOW
13	N B L	R D T	LOW
14	K D N	H P R	LOW
15	T D S	N M S	LOW
16	N S D	F K L	LOW

Apparatus

The experiment was set up using the SR Research Experiment Builder program to perform the experiment, with custom Python code to record the response latencies for all key presses. Standard ASUS keyboards were used with ASUS 27inch widescreen monitors (1920*1080p resolution; 144hz screen frequency).

Procedure

Participants were tested individually. All participants first completed a questionnaire to identify any concerns regarding their vision, typewriting abilities, and any language difficulties or impairments they may suffer with. The experimental procedure used alternating stages comprising an association learning stage, an association confirmation stage, and a production stage.

The association learning stage involved the participant associating a visually presented letter string with one of two positions on a computer screen (left or right). Two small (5cm x 3cm) icons of a blue rectangular shape were presented to the two respective locations (left or right of the screen) on a white computer display screen at the same time as the three-letter CCC strings were presented below their respective icon. Two-letter strings were used per sequence of alternating phases, with each letter string being presented four times in its designated location. Participants were instructed to learn each letter string and the associated location.

In the association confirmation stage, both icons were presented at the same time while one of the two-letter strings were presented in the centre of the screen. Participants were required to identify which location corresponded to the identified word. For subjects to identify the left location, they would press the left arrow on the keyboard, and if they wish to identify the location as being on the right, they will press the right arrow key. The association confirmation stage contained a minimum of four trials for each of the two-letter strings. The association confirmation stage ended once eight successive correct responses were made. Participants were instructed to not articulate, write, or type any of the letter strings until the final (production) stage in which they must be typed. Before beginning the production stage, participants were prompted on the screen that they must respond as quickly and accurately as possible.

In the production stage, one of the two-screen positions were cued using a (5cm x 3cm) blue rectangle. An empty text box was also present in the centre of the screen. Participants were instructed to type the letter string that corresponds to the presented icon as quickly and accurately as possible. A series of letter prompts was interleaved between experimental trials within the final phase. This involved presenting a letter in the middle of the screen for participants to type. The letter prompts used letters that did not appear in any of the stimuli sets. This prevented participants from anticipating the next trial and was intended to eliminate any potential priming effects. Each of the two-letter strings was presented eight times in each test phase, with eight of each of the distractor numbers presented also. As a result, each production stage involved eight experimental stimuli and eight filler trials. Thus, 16 items were used in total per stimulus pair. The first set of the experiment was used as practice, with the same (non-manipulated) stimuli used for each participant.

Results

Starting with the initial 2,856 recorded trials, incorrect responses were excluded from the analyses. A response was treated as correct if the participant typed the three keys associated with the correct trigram. Otherwise, responses were treated as incorrect. This removed 493 trials (17.3%; 230 High-frequency; 263 low-frequency). Responses were excluded if the first letter response time was less than 200ms or greater than 3000ms. This removed 49 responses (1.7%, 21 High-frequency; 28 low-frequency). Keystroke latencies were then excluded if they exceeded the two standard deviations of the participants mean latencies for the respective keystroke location (i.e. onset latency, first IKI, second IKI). This was performed on a by-analysis basis. This removed 106 responses for the onset latencies (3.7%, 53 High-frequency; 53 low-frequency), 109 responses for the first IKIs (3.8%, 57 High-frequency; 52 low-frequency), and 106 responses for the second IKIs (3.8%, 53 High-frequency; 55 low-frequency).

Statistical analyses were performed by linear mixed-effects modelling using the R lme4 package (Bates, Maechler, Bolker, & Walker, 2015). This approach allows for both participants and items to be treated as random effects in the same model (Baguley, 2012). If the stimuli are treated as fixed effects, the conclusions can only be made in reference to the stimuli used (Clark, 1973; Judd, Westfall, & Kenny, 2012). This started with a baseline (zero) model with random by-subject and by-item-pair intercepts and random by-subject slopes for the effect of frequency. We then added effect of frequency (high, low). Models fitted were based on restricted maximum likelihood (REML) and models fits are reported in terms of AIC (e.g., Akaike, 1974). Models were compared using chi-square change tests.

Table 3: Observed mean keystroke latencies (milliseconds) with 95% confidence intervals for Experiment 1

	Onset latency	First IKI	Second IKI
High-Frequency	930 [923, 937]	210 [205, 215]	166 [161, 171]
Low-Frequency	995 [989, 1002]	212 [207, 217]	186 [181, 191]
Difference	65	2	20

Mean keystroke latencies and confidence intervals are summarised in Table 3. A significant main effect of frequency was detected when comparing the model containing the onset latencies (AIC = 1783.2) and the null model containing random effects but no fixed effects (AIC = 1785.9, χ^2 (1) = 4.744, p = .029). When comparing the null model (AIC = 2407.8) and the model with frequency, no main effect of frequency was detected for the first IKI (AIC = 2414.0), χ^2 (1) = 0.036, p = .850. The second IKI had no main effects for frequency (AIC=2173.0), χ^2 (1) = 2.087, p = .149 when compared to the null model (AIC= 2173.1).

Discussion

Experiment 1 demonstrated that the time to initiate typing was significantly faster in the high-frequency condition. The results suggest that the onset of typing is speeded by the high-frequency bigrams or trigram. Motor chunks may be retrieved as a single unit in the high-frequency condition. In the low-frequency condition, additional motor preparation may be required. Where stored motor chunks are not available, such as in the low-frequency condition, motor chunks may be constructed instead before typing onset. These findings are consistent with an account in which motor plans are prepared for all letters prior to execution, but motor plans for familiar trigrams are stored as a chunk.

In contrast, these findings are not consistent with an account in which typing execution starts as soon as a key is planned. If motor representations for individual keys are prepared and executed separately for low-frequency letter combinations, the onset of typing for low frequency letter combinations would be as quick, or quicker, than high frequency letter combinations. Retrieving a motor representation for a single keystroke in the low-frequency condition should be no slower, if not quicker, than retrieving a motor chunk in the high-frequency condition. These results imply that the initial bigram or trigram is prepared in full within the motor level, before the onset of typing.

However, it cannot be ruled out at this point that the significant difference at the onset latency occurs as a result of preparation before the motor level. The stringent experimental paradigm, along with the experimental controls, reduces many higher-level confounds. Yet, the mean duration of the onset latencies is still much larger than the IKIs that represent motor performance. The additional time represents some level of pre-motor level preparation. If so, it would appear that chunking occurs before the motor level. If non-chunked individual letters were passed to the motor level instead, there should be no effect of the frequency of letter combinations when controlling for individual letter frequencies. Thus, non-word letter chunks may be passed to the motor level. However, further investigations are required to establish if the observed frequency effect at the onset latency reflects preparation before the motor level, within the motor level, or a combination of the two.

As reported, this experiment observed relatively high error-rates across the two conditions. The observed number of errors recorded highlight a limitation of the methods used in this experiment. Participants may slow their typing performance to prevent making additional errors being made. Considering that a greater number of errors were observed in the low-frequency condition. Typing in the low-frequency condition may be slowed more often, and/or more rigorously, than the high-frequency condition, potentially confounding the observed frequency effect at the onset latency. To address this possibility, and the weakness of the current methods, the remaining experiments employ a modified experimental paradigm in which incorrect trials are later repeated/recycled to ensure that the analyses are a reflection of equal distribution of subjects and stimuli items. Experiment 2 is a replication of Experiment 1 using the modified experimental paradigm to validate the observed findings within Experiment 1.

Experiment 2

Based on the findings from Experiment 1, it looks as though high-frequency letter combinations are prepared much faster than low-frequency letter combinations. This could occur within the motor level, whereby motor chunks can be retrieved as a single unit in the high-frequency condition, but motor chunks must be constructed before typing onset for the low-frequency condition. Alternatively, faster preparation for the high-frequency condition could also occur before the motor level.

However, the relatively high error-rates observed in Experiment 1 highlighted a limitation of the methods used. In Experiment 1, the participants making a large number of errors may have slowed down their typing performance in an attempt to reduce error frequency. As a greater number of errors were observed in the low-frequency condition, this possibility could have had a greater influence in the low-frequency condition, which, in turn confounds the observed frequency effect at the onset latency.

Employing a modified experimental paradigm, Experiment 2 replicated the first experiment while controlling for the high error-rates observed in the first experiment. The same trigram frequency manipulation was used whereby individual letter frequencies are controlled across conditions, with the high-frequency condition consisting of high-frequency trigrams made of high-frequency bigrams. The low-frequency condition consists of low-frequency trigram made of low-frequency bigrams. If high-frequency letter combinations are prepared faster than low-frequency letter combinations, as demonstrated in Experiment 1, Experiment 2 should replicate the same effects.

Methods

Design

The same two condition (high trigram frequency, and low trigram frequency) repeated measures design was employed as in Experiment 1. Experimental trials were increased to 256 per participant, with each participant accurately producing the trigrams eight times each. Where the trigrams were mistyped, the experimental trial was recycled until the 8 correct trials criterion was reached. All other aspects of the design were the same as Experiment 1.

Participants

Twenty-four additional participants were recruited based on the same eligibility requirements as Experiment 1.

Materials

The same materials were used as in Experiment 1.

Apparatus

The same apparatus were used as in Experiment 1.

Procedure

The same procedure was adopted as in Experiment 1, with the following modifications. Where experimental trials were typed incorrectly, the trial was recycled to be performed at a later point (determined randomly) within the same block of trials. A response was only treated as correct if the participant typed the three keys associated with the correct trigram. Upon typing a trial incorrectly, participants received visual feedback on the screen in the form of a red cross. The trial is then inserted randomly within the same block of trials for the participant to attempt later in the block. All participants were instructed on this procedure and given practice trials (containing letters not used within the stimuli) to familiarize themselves with the procedure before beginning the experiment.

Results

The raw data was treated the same as in Experiment 1. A total of 6,144 accurate trials were recorded, with an additional 608 error trials recycled within the experiment (9.55%; 250 High-frequency; 358 low-frequency). An additional 39 responses were removed as outliers of the 200-3000ms latency limits (0.61%; 16 High-frequency; 23 low-frequency). As in Experiment one, Keystroke latencies were then excluded if they exceeded the two standard deviations of the participants mean latencies for the respective keystroke location (i.e. onset latency, first IKI, second IKI). This was performed on a by-analysis basis. This removed 265 responses for the onset latencies (4.16%, 128 High-frequency; 137 low-frequency), 243 responses for the first IKI (3.82%, 120 High-frequency; 123 low-frequency), and 231 responses for the second IKI (3.63%, 117 High-frequency; 114 low-frequency). Statistical analyses were performed in the same manner as Experiment 1.

Table 4: Mean keystroke latencies (milliseconds) with 95% confidence intervals for Experiment 2

	Onset latency	First IKI	Second IKI
High-Frequency	855 [746,865]	201 [157,208]	172 [137,178]
Low-Frequency	933 [809,943]	200 [155,209]	180 [142,186]
Difference	78	2	8

Findings replicate those of Experiment 1. There was a significant effect of frequency at the onset latency when comparing the model containing frequency (AIC = 3582.2) and the null model containing random effects but no fixed effects (AIC = 3588.9, χ^2 (1) = 8.692, *p* = .003). When comparing the null model (AIC = 4206.4) and the model with frequency, no effect of frequency was detected for the first IKI (AIC = 4208.4), χ^2 (1) = 0.004, *p* = .95). Similarly, the second IKI had no effect for frequency (AIC= 3844.9), χ^2 (1) = 0.939 *p* = .333 when compared to the null model (AIC= 3843.8).

Discussion

Experiment 2 was a replication of Experiment 1 with the high error rates being controlled for by a modified experimental paradigm. The same effects were found as in Experiment 1. The onset latency was produced significantly faster for high-frequency trigrams than low-frequency trigrams. As in Experiment 1, letter frequencies were controlled across conditions, ruling out the possibility that the effect is as a result of letter frequencies. Instead, the bigram and trigram frequencies were manipulated across conditions. These results, along with the same pattern of results demonstrated in Experiment 1, demonstrate clear bigram or trigram frequency effects when typewriting letter-strings.

As mentioned previously in Experiment 1, the findings at the onset latency may not represent performance within the motor level, but instead, faster preparation before the motor level.

The mean onset latency durations are much larger than the IKIs, signifying pre-motor level preparation. This again suggests that chunking occurs before the motor level. The frequency of letter-combinations should have no effect at the onset latency if single graphemic letters are passed to the motor level individually. The effect at the onset latency may denote that the spelling of chunked abstract graphemic representations may be faster is to prepare for high-frequency trigrams.

These results could either reflect preparation before the motor level, preparation/execution within the motor level, or a combination of the two. At the motor level, as in Experiment 1, these findings are not consistent with an account in which typing execution starts as soon as a key is planned. If the high-frequency condition can retrieve motor chunks for high-frequency letter combinations, it would still likely be no faster than retrieving a motor representation for a single keystroke in the low-frequency condition. It would appear that motor plans for full bigrams or trigrams may be prepared in advance of typing onset. This would involve constructing the motor representations for the full (initial) bigram or trigram in the low-frequency condition but retrieving a motor chunk in the high-frequency condition.

However, if motor chunks are retrieved for the high-frequency letter combinations, they may be retrieved for only the initial bigram or the full trigram. As both bigram frequency and trigram frequency were manipulated across conditions, we cannot differentiate between the two possibilities at this point. Experiment 3 therefore aimed to separate out / differentiate between trigram and bigram effects. This was performed by controlling/matching the initial bigram frequencies within high- and low-frequency trigrams (i.e., high: *GHT*, low: *GHF*). If (1) motor chunks are retrieved for high-frequency trigrams, and (2) motor chunks are constructed for full trigram before typing onset for low-frequency trigrams, we should observe significantly faster onset latencies for the high-frequency condition, as demonstrated so far in Experiments 1 and 2.

Experiment 3

Experiments 1 and 2 both demonstrated significantly faster onset latencies for high-frequency letter combinations. These findings are open to several interpretations at this point. They may reflect faster preparation before the motor level, or faster performance within the motor level. If the frequency effect reflects performance at the motor level, the findings are consistent with an account in which motor chunks are retrieved for high-frequency letter combinations, but motor chunks are constructed in full before typing onset for low-frequency letter combinations. As both bigram frequencies and trigram frequency were manipulated across conditions, it is unclear whether the initial bigram or the full bigram is retrieved/constructed before typing onset. This was explored in the present experiment.

Experiment 3 examined if the initial bigram or the full trigram is retrieved/constructed before typing onset by manipulating only the final letter of the trigram across conditions. Manipulating only the final letter allows for the same initial bigrams to be used across conditions while manipulating the final bigram and trigram frequencies (i.e., high-frequency: GHT, low-frequency: GHR). If the effect observed at the onset latency in Experiments 1 and 2 are as a result of trigram frequency manipulation, the same effect should be observed in the present experiment when high- and low-frequency trigrams share the same initial bigram frequencies. However, there is also the possibility that the effect observed in Experiments 1 and 2 may have been as a result of differences in the initial bigram frequency, or a combination of bigram and trigram frequencies. If high-frequency bigrams benefit from speeded production, the present experiment should find significant differences in the keystroke latencies at the final bigram where bigram frequency is manipulated once again.

Methods

Design

As in previous experiments, Experiment 3 compared effects of high trigram frequency, and low trigram frequency. All participants produced the 16 experimental trigrams eight times each resulting in 128 experimental trials each. All other aspects of the design were the same as Experiment 1.

Participants

Twenty-four participants were recruited based on the same eligibility requirements as Experiment 1.

Materials

Letter string frequencies were calculated in the same manner as in Experiment 1. The letter-strings were selected for each condition on the basis that: (1) the high-frequency condition contains high-frequency trigrams, whilst the low-frequency condition consists of low-frequency trigrams; (2) the same initial bigrams are used across conditions; (3) it is only the final letter that differs across conditions, which will also manipulate the trigram frequency and the frequency of the final bigram; (4) the high-frequency condition contains a high-frequency bigram in the second bigram position; (5) the low-frequency condition contains a low-frequency bigram in the second bigram position; (6) mean letter frequencies must be lower, or the same, in the high-frequency trigrams compared to low-frequency trigrams. This ensures that high-frequency letter-strings do not benefit from higher letter frequencies. For example, the high-frequency trigram of *GHT* shares the same initial bigram as the low-frequency trigram of *GHF*, but changing the final letter manipulated the trigram frequency. The frequency of the final letter was controlled across conditions by ensuring that the same letters that feature as the third letters in the high-frequency condition, must also feature as the third letters in the low-frequency condition. A summary of the frequency breakdown across conditions is provided below, in Table 5.

Table 5: Mean Letter, bigram and trigram frequencies for stimuli used in Experiment 3

Condition	Trigram	Bigram one	Bigram two	Letter one	Letter two	Letter three
High-Frequency	27,141.63	228,743.88	124,995.25	3,362,920.00	3,776,938.63	3,710,466.13
Low-Frequency	28.50	228,743.88	1,723.25	3,362,920.00	3,776,938.63	3,710,466.13

Letter-strings were then paired for the purpose of the symbol-position association-learning task in the same manner as in Experiment 1. A breakdown of the stimuli pairings is provided in Table 6.

Table 6: Stimuli pairings used in Experiment 3

BLOCK NUMBER	LEFT_STRING	RIGHT_STRING	CONDITION
1	R L D	G H T	HIGH
2	S T R	M P S*	HIGH
3	R C H	L D N*	HIGH
4	N D R	C K S	HIGH
5	H T F	W S P	HIGH
6	M P N*	R L H	LOW
7	G H F	S T D	LOW
8	L D C*	R C S	LOW
9	C K R	N D T	LOW
10	W S R	H T P	LOW

*Stimuli not used within the analyses. Frequency matched stimuli could not be paired with each other fully because of matching letters in pairs of letter-strings. Additional letter strings were paired with the experimental stimuli where necessary.

Apparatus & Procedure

The same apparatus and procedure were used as in Experiment 2.

Results

The raw data was treated the same as in Experiment 2. A total of 3,072 accurate trials were recorded, with an additional 276 error trials recycled within the experiment (8.24%; 127 High-frequency; 149 low-frequency). An additional 22 responses were then removed as outliers of the 200-3000ms latency limits (0.66%, 8 High-frequency; 14 low-frequency). Keystroke latencies were then excluded if they exceeded the two standard deviations of the participants mean latencies for the respective keystroke location (i.e. onset latency, first IKI, second IKI). This was performed on a by-analysis basis. This removed 148 responses for the onset latencies (4.42%, 76 High-frequency; 72 low-frequency), 129 responses for the first IKIs (3.85%, 63 High-frequency; 66 low-frequency), and 110 responses for the second IKIs (3.29%, 55 High-frequency; 55 low-frequency). Statistical analyses were performed in the same manner as Experiment 1.

Table 7: Mean keystroke latencies (milliseconds) with 95% confidence intervals for Experiment 3

	Onset latency	First IKI	Second IKI
High-Frequency	852 [692,866]	174 [140,198]	153 [120,156]
Low-Frequency	890 [751,934]	190 [149,212]	187 [149,195]
Difference	38	16	34

There was no evidence of an effect of frequency on the onset latency when comparing the null model (AIC = 2134.7) to the model containing frequency (AIC = 2134.7, χ^2 (1) = 2.045, *p* = .153). For the first IKI, the comparison of the model containing frequency (AIC = 2627.1) with the null model (AIC = 2625.4) found no effect of frequency (χ^2 (1) = 0.316, *p* = .574). A significant effect of frequency was found for the second IKI when comparing the null model (AIC= 2704.0) to the model containing frequency (AIC= 2700.8), χ^2 (1) = 5.261, *p* = .022).

Discussion

Experiment 3 manipulated trigram frequencies across conditions via the manipulation of the frequency of the second bigram. The first bigram was matched across conditions. Controlling the initial bigram frequency in this way resulted in a substantial reduction in the effect of frequency on onset latency, and this effect failed to reach significance. This suggests that effects in the previous two experiments were at least in part due to initial bigram frequency rather than the frequency of the trigram as a whole. When initial bigram frequency is controlled across conditions, trigram frequency does not result in significant differences in the onset latencies.

If the frequency effect at the onset latency in Experiments 1 and 2 is not a trigram frequency effect, as indicated by the findings of the present experiment, it may be a bigram frequency effect instead. As discussed previously, both bigram and trigram frequencies were manipulated in Experiments 1 and 2. One possible explanation for the effect is that motor chunks are retrieved for high-frequency letter combinations, and motor chunks are constructed for low-frequency letter combinations before typing onset. The failure to replicate significant frequency effect at the onset latency in this experiment suggests that (1) motor chunks are retrieved for high-frequency bigrams, and (2) motor chunks are constructed for low-frequency letter combinations.

However, the present experiment demonstrated a significant frequency effect at the second IKI, whereby the second IKI was produced significantly faster for high-frequency trigrams. This contradicts an account where typing onset does not commence for low-frequency letter combinations until chunked motor representations are prepared. For there to be a significant frequency effect within the IKIs, motor preparation could not be complete for at least the (slower) low-frequency condition. The significant findings at the second IKI suggest that motor preparation is not completed for the low-frequency condition at the second IKI. Consistent with an account where motor representations are executed as soon as they are available, these findings suggest that a motor chunk was retrieved in full for the high-frequency trigrams. Whereas, the initial (high-frequency) bigram is retrieved as a motor chunk in the low-frequency condition, but the motor representation for the final letter (the second IKI) must be prepared separately afterwards.

Comparing the findings across the three experiments, there are currently two key questions that need to be addressed: (1) Is the observed frequency effect at the onset latency in Experiment 1 and 2 a reflection of motor chunks being retrieved for high-frequency bigrams, and motor chunks being constructed for low-frequency letter combinations before typing onset? Alternatively, (2) is the significant frequency effect at the second IKI in the present experiment a reflection of motor chunks being retrieved for the high-frequency trigram, but only a motor chunk being retrieved for the initial (high-frequency) bigram for the low-frequency trigrams? The key distinction between these two questions is whether motor representations are executed as soon as they are available for low-frequency letter combinations or does the onset of typing wait for a motor chunk to be constructed.

To differentiate between the two contradictory accounts of motor chunking, Experiment 4 examines frequency effects when typing only single bigrams. If motor chunks are retrieved for high frequency bigrams, keystroke latencies should be slower for low-frequency bigrams in one of two locations: (1) the onset latency should be slower for low-frequency bigrams if typing onset does not commence until a motor chunk is constructed; alternatively, (2) the first IKI should be slower for low-frequency bigrams if motor representations for individual letters and executed as soon as they are available.

Experiment 4

The findings of the previous experiments suggest that motor chunks are retrieved for high-frequency letter combinations. Experiments 1 and 2 found significant frequency effects at the onset latency. This was interpreted as a reflection of either faster pre-motor preparation, or faster motor preparation for high-frequency letter combinations. If it is the latter, it would suggest that the motor chunks are constructed for low-frequency letter combinations.

However, the findings in Experiment 3 contradict an account in which motor chunks are constructed for low-frequency letter combinations. When typing high- and low-frequency trigrams containing the same initial high-frequency bigram (i.e., high: *GHT*, low: *GHF*), the second IKI (third letter) was produced significantly faster in the high-frequency condition. This indicates that motor preparation is not complete in the low-frequency condition. Thus, contradicting the alternative account that typing onset does not commence in the low-frequency condition until motor chunks are constructed. Instead, the findings in Experiment 3 suggest that motor chunks are retrieved in full for the high-frequency trigrams, but only the initial high-frequency bigram is retrieved for low-frequency trigrams. The motor representation for the final letter (second IKI) in the low-frequency trigrams is prepared separately afterwards. This would suggest that if motor chunks are not available, motor representations for individual letters are retrieved and then executed as soon as they are available.

Experiment 4 examines if unfamiliar bigrams are prepared and produced letter-by-letter, or constructed as a motor chunk. Typists were required to type high- and low-frequency bigrams. If motor representations for unfamiliar (low-frequency) bigrams are prepared separately and executed as soon as they are available, and motor chunks are retrieved for high-frequency bigrams, the first IKI (second letter) should be significantly faster in for high-frequency bigrams. Conversely, if motor chunks are constructed before typing commences for infrequent (low-frequency) bigrams, and motor chunks are retrieved for high-frequency bigrams, the onset latency should be significantly faster for high-frequency bigrams.

Methods

Design

A two condition (high bigram frequency, and low bigram frequency) repeated measures design was employed following the same design as Experiments 2 and 3.

Participants

Twenty-four additional participants were recruited based on the same eligibility requirements as Experiment 1.

Materials

Letter string frequencies were calculated in the same manner as in Experiment 1. In total, 24 low frequency and 24 high frequency consonant-consonant bigrams were selected, with mean first letter and second letter frequencies held constant across conditions. To control for letter frequencies across conditions, bigrams were duplicated in some instances. Any influence of additional familiarity for the duplicated bigrams was controlled across condition by ensuring fewer duplications occurred within the high-frequency condition. The letter-strings were selected for each condition on the basis that: (1) the high-frequency condition consists of high-frequency bigrams; (2) the low-frequency condition consists of low-frequency bigrams; (3) mean letter frequencies must be lower, or the same, in the high-frequency trigrams compared to low-frequency trigrams. This ensures that high-frequency letter-strings do not benefit from higher letter frequencies. A summary of the frequency breakdown across conditions is provided below, in Table 8.

Table 8: Mean Letter, bigram and trigram frequencies for stimuli used in Experiment 4

Condition	Bigram one	Letter one	Letter two
High-Frequency	54,178	2,620,426	3,235,597
Low-Frequency	3,260.5	2,620,426	3,539,501

Letter-strings were then paired for the purpose of the symbol-position association-learning task in the same manner as in Experiment 1. A breakdown of the stimuli pairings is provided below, in Table 9.

Table 9: Stimuli pairings used in Experiment 4

BLOCK NUMBER	LEFT_STRING	RIGHT_STRING	CONDITION
1	B L	S W	HIGH
2	C R	F L	HIGH
3	S W	F R	HIGH
4	T C	G H	HIGH
5	N F	B S	HIGH
6	T C	D G	HIGH
7	W N	F L	HIGH
8	W R	G N	HIGH
9	C T	L W	HIGH
10	W R	R L	HIGH
11	W N	S P	HIGH
12	D G	B S	HIGH
13	S B	W L	LOW
14	F C	L R	LOW
15	F S	R W	LOW
16	G T	H C	LOW
17	B N	S F	LOW
18	D T	G C	LOW
19	F W	L N	LOW
20	G W	N R	LOW
21	L C	W T	LOW
22	B W	L N	LOW
23	R W	P G	LOW
24	S D	S R	LOW

Apparatus & Procedure

The same apparatus & procedure were used as in Experiment 2.

Results

The raw data was treated the same as in Experiment 2. A total of 9,216 accurate trials were recorded, with an additional 465 error trials recycled within the experiment (4.8%; 234 High-frequency; 231 low-frequency). An additional 30 responses were then removed as outliers of the 200-3000ms latency limits (0.31%; 15 High-frequency; 15 low-frequency). Keystroke latencies were then excluded if they exceeded the two standard deviations of the participants mean latencies for the respective keystroke location (i.e. onset latency, first IKI). This was performed on a by-analysis basis. This removed 381 responses for the onset latencies (3.94%, 200 High-frequency; 181 low-frequency), and 353 responses for the first IKIs (3.65%, 183 High-frequency; 170 low-frequency). Statistical analyses were performed in the same manner as Experiment 1.

Table 10: Mean keystroke latencies (milliseconds) with 95% confidence intervals for Experiment 4

	Onset latency	First IKI
High-Frequency	751 [656, 754]	139 [110, 140]
Low-Frequency	768 [666, 773]	151 [117, 152]
Difference	17	12

For the onset latency, a non-significant effect of frequency was detected when comparing the model containing frequency (AIC = 6215.8 and the null model (AIC = 6217.2, χ^2 (1) = 0.550, *p* = .458). When comparing the null model (AIC = 8977.5) and the model with frequency, a significant effect of frequency was detected for the first IKI (AIC = 8975.6), χ^2 (1) = 3.915, *p* = .048.

Discussion

Experiment 4 examined the bigram frequency manipulation in standalone bigrams. The results replicated the bigram frequency effect demonstrated in Experiment 3. The second keystroke of the high-frequency bigram was prepared significantly faster compared to the low-frequency condition. The observed bigram frequency effect is further support for the findings observed in Experiment 3.

The observed bigram frequency effect supports an account in which motor representations for keystrokes are executed as soon as they are available. Motor chunks are retrieved for high-frequency bigrams, but not for low-frequency bigrams. Instead, it appears that for low-frequency bigrams, the motor representations for each keystroke are retrieved separately and executed as soon as they are retrieved, rather than waiting for a motor chunk to be constructed before the onset of typing. For example, comparing *GH* (high-frequency bigram) and *GT* (low-frequency bigram), there is no difference at the onset latency as single motor representations are retrieved before typing in both instances (*GH* in the high-frequency condition, and *G* in the low-frequency condition). The significant difference occurs at the second letter (the first IKI) because additional motor processing is required in the low-frequency condition in order to prepare the motor representation for the second keystroke. In contrast, the motor representation for the second keystroke of the high-frequency bigram is already available as it was retrieved in advance as part of a motor chunk.

As is Experiment 3, but not Experiments 1 and 2, no significant difference across conditions was observed at the onset latency. It appears that the onset latency is not significantly influenced by bigram frequency (Experiment 4) or trigram frequency (Experiment 3) alone. It is only when both the trigram and initial bigram frequency are manipulated that a significant effect is demonstrated at the onset latency (Experiments 1 and 2).

However, the present experiment compared bigrams only. The smaller unit size of the bigram may reduce potential frequency effects upon preparation that could potentially have extended to frequency effects in Experiments 1 and 2. As discussed previously, the significant effect at the onset latency in Experiments 1 and 2 could represent trigram frequency manipulation, initial bigram frequency manipulation, or a combination of the two. Experiment 3's failure to replicate the effect when manipulating trigram frequency while controlling for initial bigram frequency suggests the effect may represent either the initial bigram frequency or a combination of the two.

The observed frequency effects within the IKIs, observed in the present experiment and Experiment 3, support an account in which motor representations are executed as soon as they have been retrieved. However, the observed frequency effects at the onset latency in Experiments 1 and 2 may represent motor performance at the motor level, not performance before the motor level. If so, the findings support an alternative account in which typing initiation does not commence until motor chunks have been constructed. The frequency effect at the onset latency in Experiments 1 and 2 may represent motor chunks being retrieved for high-frequency letter combinations, but motor chunks being constructed for low-frequency letter combinations before typing the first keystroke.

The present experiment suggests that unfamiliar bigrams are prepared letter-by-letter, to the point where motor representations for individual letters are executed as soon as they are available. As discussed, this contradicts earlier suggestions, based on the findings of Experiments 1 and 2, that typing does not commence until motor chunks are retrieved or constructed. Experiment 5 aimed to discriminate between these two possibilities by embedding high-and low-frequency bigrams into low-frequency trigrams and manipulating the order of the bigrams (either high- then low-frequency: high-low; or low- then high-frequency: low-high). If motor chunks are constructed in full for the low-frequency trigrams there should be no difference in any of the keystroke locations. All motor preparation would occur before the onset latency and both conditions consist of low-frequency trigrams containing a high- and a low-frequency bigram. However, if motor representations are executed as soon as they are available, and motor chunks are retrieved for high-frequency letter combinations, the second keystroke of high-frequency bigrams should be significant faster as they would benefit from advanced preparation of the second keystroke.

Experiment 5

Experiment 5 aimed to discriminate between two possible interpretations of the results observed in Experiments 1-4. Either typing may commence as soon as a motor representation is available or typing only commences once a motor chunk is constructed/retrieved.

Experiments 1 and 2 demonstrated significant frequency effects at the onset latency where high-frequency letter combinations were initiated significantly faster than low-frequency letter combinations. This could reflect faster preparation before the motor level, or faster preparation and/or execution within the motor level. If the frequency effect is a reflection of performance within the motor level, it would suggest that (1) motor chunks are retrieved as a single unit for high-frequency letter combinations, and (2) motor chunks are constructed before typing onset for low-frequency letter combinations.

The manipulations to the frequency of letter combinations occurred for both bigram frequencies and the full trigram frequencies. This makes it difficult to interpret whether the frequency effect at the onset latency reflect manipulation to the initial bigram, the full trigram, or a combination of the two. If these findings reflect performance at the motor level, it would suggest one of two possible explanations: (1) motor chunks were retrieved (high-frequency trigrams) or constructed (low-frequency trigrams) in full before the onset of typing; or (2) motor chunks were retrieved (high-frequency trigrams) or constructed (low-frequency trigrams for the initial bigram before the onset of typing.

In contrast, the frequency effects observed within the IKIs in Experiments 3 & 4 support an alternative account whereby keystrokes are executed as soon as motor representations are available. Typing commences as soon as a motor chunk is retrieved, if a motor chunk cannot be retrieved, a motor representation for a single keystroke is retrieved and then executed. For example, in Experiment 3, high- and low-frequency trigrams contained the same initial high-frequency bigram (i.e., *GH*). The significant difference found at the second IKI (third letter) appears to reflect the additional motor preparation required in the low-frequency trigrams. While a motor chunk may be retrieved in full for a high-frequency trigram (i.e., *GHT*), only the initial high-frequency bigram can be retrieved within the low-frequency trigrams (i.e., *GH* in *GHF*), resulting in the third letter (i.e., *F*) not benefitting from advanced preparation/retrieval as in the high-frequency condition. In contrast to the two explanations offered above, these findings, which offer the same interpretation in Experiment 4, suggest that (3) keystroke are executed as soon as motor representations are available, and motor chunks can be retrieved for high-frequency letter combinations.

To discriminate between the three possible interpretations of the results so far, Experiment 5 examined if motor chunks are constructed for low-frequency letter combinations before the onset of typing. This was examined by manipulating bigram frequencies within low-frequency trigrams. Using low-frequency trigrams only, bigram-frequency was manipulated across conditions to create high- and low-frequency initial and final bigrams (high-low condition), and low- and high-frequency initial and final bigrams (low-high condition). This differentiates between three possible outcomes: (1) If motor chunks are constructed for the full trigram in both conditions, there should be no difference across any keystroke latencies as both conditions consist of low-frequency trigrams containing a high- and low-frequency bigram that would be constructed before typing onset; (2) if typing does not commence until the initial bigram is constructed (for low-frequency bigrams) or retrieved (for high-frequency bigrams), the onset of typing would be faster in the high-low condition as a motor chunk can be retrieved for the full bigram, whereas additional motor preparation would be required in the low-high condition as the motor chunk for the initial low-frequency bigram would need constructing before the onset of typing; (3) if keystroke are executed as soon as motor representations are available, and motor chunks can be retrieved for high-frequency letter combinations, no significant difference should occur at the onset latency as similar motor preparation is required at the first letter in both conditions. A motor chunk can be retrieved in the high-low condition, and a single motor representation for the first letter is retrieved for the low-high condition. However, significant differences should be found within the IKIs. Using an example of the initial bigram, the motor representation for the second keystroke of a high-frequency bigram (high-low condition; i.e., *FL*) benefits form advanced preparation as a result of being retrieved as a motor chunk. In contrast, when comparing to a low-frequency bigram (low-high condition; i.e., *FW*), the second letter of the low-frequency bigram (i.e., *W*) is not retrieved/prepared in advance, resulting in a slower keystroke latency.

Methods

Design

A two condition repeated measures design was employed. In the high-low condition participants typed trigrams in which letters 1 and 2 formed a high frequency trigram and letters 2 and 3 formed a low frequency trigram. In the low-high condition this was reversed, with trigrams starting with a low frequency bigram. The experimental design followed that of Experiments 2 to 4 with all participants producing the 24 experimental trigrams accurately, eight times each resulting in 192 experimental trials each. All other aspects of the design were the same as for all previous experiments.

Participants

Twenty-four participants were recruited based on the same eligibility requirements as Experiment 1.

Materials

Letter string frequencies were calculated in the same manner as in Experiment 1. The letter-strings were selected for each condition on the basis that: (1) both conditions consisted of low frequency trigrams with the same trigram frequencies; (2) the high-low condition consisted of high-frequency bigrams for the initial bigram, and low-frequency bigrams for the second bigram; (2) the low-high condition consisted of low-frequency bigrams for the initial bigram, and high-frequency bigrams for the second bigram; (3) mean letter frequencies were matched closely across conditions to prevent confounding letter frequency effects. A summary of the frequency breakdown across conditions is provided below, in Table 11.

Table 11: Mean Letter, bigram and trigram frequencies for stimuli used in Experiment 5

Condition	Trigram	Bigram one	Bigram two	Letter one	Letter two	Letter three
High-Low	0.08	51,423.67	3,474.67	2,428,808.83	3,056,416.17	3,399,602.75
Low-High	0.08	2,082.58	53,432.50	2,428,808.83	3,068,347.25	3,399,602.75

Letter-strings were then paired for the purpose of the symbol-position association-learning task in the same manner as in Experiment 1. A breakdown of the stimuli pairings is provided below, in Table 12.

Table 12: Stimuli pairings used in Experiment 5

BLOCK NUMBER	LEFT_STRING	RIGHT_STRING	CONDITION
1	F L R	S W L	HIGH-LOW
2	D G C	F R W	HIGH-LOW
3	F L N	S P G	HIGH-LOW
4	B S F	R L N	HIGH-LOW
5	G N R	L W T	HIGH-LOW
6	B S R	G H C	HIGH-LOW
7	S B L	F C R	LOW-HIGH
8	F S W	D T C	LOW-HIGH
9	S D G	F W N	LOW-HIGH
10	R W N	L C T	LOW-HIGH
11	B N F	G W R	LOW-HIGH
12	G T C	B W R	LOW-HIGH

Apparatus & Procedure

The same apparatus & procedure were used as in Experiment 2.

Results

The raw data was treated the same as in Experiment 2. A total of 4,608 accurate trials were recorded, with an additional 420 error trials recycled within the experiment (8.35%; 204 high-low condition; 216 low-high condition). An additional 18 responses were then removed as outliers of the 200-3000ms latency limits (0.36%; 9 high-low condition; 9 low-high condition). The exclusion of keystroke latencies exceeding the 2 standard deviations of the mean resulted in 216 responses for the onset latencies (4.3%, 112 high-low condition; 104

low-high condition), 195 responses for the first IKIs (3.88%, 100 high-low condition; 95 low-high condition), and 167 responses for the second IKIs (3.32%, 90 high-low condition; 77 low-high condition). Statistical analyses were performed in the same manner as Experiment 1.

Table 13: Mean keystroke latencies (milliseconds) with 95% confidence intervals for Experiment 5

	Onset latency	First IKI	Second IKI
High-Low Frequency	861 [731, 868]	172 [139, 177]	184 [146, 190]
Low-High Frequency	869 [745, 877]	189 [153, 193]	182 [146, 190]
Difference	8	17	2

For the first letter latencies, a comparison of the null model containing random effects but no fixed effects (AIC = 3301.8) found no effect of frequency when compared to the model containing frequency effects (AIC = 3303.3, χ^2 (1) = 0.502, *p* = .479). In contrast, an effect of frequency was found for the first IKI when comparing the null model (AIC = 3537.6) and the model with frequency (AIC = 3534.9, χ^2 (1) = 4.632, *p* = .031). The second IKI had no effect of frequency (AIC= 3914) χ^2 (1) < 0.005, *p* = .996 when compared to the null model (AIC= 3912).

Discussion

Experiment 5 examined if motor chunks are constructed for low-frequency letter combinations before the onset of typing. The order of high- and low-frequency bigrams were manipulated within low-frequency trigrams. This created a high-low condition where the initial bigram was high-frequency and the second bigram was low-frequency; as well as a low-high condition where the initial bigram was low-frequency and the second bigram was high-frequency.

The findings of the previous experiments support accounts in which stored motor chunks can be retrieved for frequent letter combinations, but cannot distinguish between three possible accounts: (1) typing onset does not commence until motor chunks for the full trigram are either retrieved, where available (high-frequency letter combinations), or constructed, where motor chunks are not available (low-frequency letter combinations); (2) typing onset does not commence until motor chunks are constructed or retrieved for the initial bigram; (3) keystroke are executed as soon as motor representations are available, and motor chunks can be retrieved for high-frequency letter combinations, but do not need constructing for low-frequency letter combinations.

The results of Experiment 5 revealed no significant difference at the onset latency. This goes against an account in which motor chunks are either constructed or retrieved for the initial bigram before the onset of typing. We were able to compare high- (high-low condition) and low-frequency (low-high condition) bigrams directly in the initial bigram position, whilst also controlling for trigram and individual letter frequencies. Yet, the lack of a significant effect at the onset latency demonstrates that the onset latency is not a reflection of constructing (low-frequency bigram; low-high condition) or retrieving (high-frequency bigram; high-low condition) the initial bigram in full before typing onset, as retrieving a stored motor chunk should be much faster than constructing a motor chunk.

While there was no significant effect of bigram frequency at the onset latency, there was a significant bigram frequency effect within the IKIs. The results found a significant effect of bigram frequency when the bigram was in the first position in the trigram. This occurred at the second keystroke of the bigram (first IKI) as in Experiment 4. The likely explanation for this effect is that the second letter is executed significantly faster in the high-low condition because a motor chunk for the initial high-frequency bigram has already been retrieved by that point (i.e., *SW* in *SWL*). When typing the second letter, the motor representation of the second letter has already been retrieved in advance. In comparison, the initial low-frequency bigram (i.e., *SB* in *SBL*) cannot be retrieved as a motor chunk, meaning that the motor representations for the first two keystrokes must be prepared and executed separately. This is consistent with an account of motor chunking whereby motor chunks are retrieved for frequent letter combinations, but motor representations are retrieved and executed individually for letters/keystrokes that are not part of a frequent letter combination.

The significant bigram frequency effect observed within the first IKI also refute an account in which motor chunks are constructed in full before the onset of typing. Both condition consisted of low-frequency trigrams containing a high- and a low-frequency bigram. If the motor chunk for the trigram is prepared in full before typing onset, there should have been no difference in any of the keystroke latencies as motor preparation would have occurred in full before the onset latency. Yet, this was not the case.

However, unlike the findings for Experiment 3, we found no evidence of bigram frequency in the second bigram position. Although the effects of frequency were generally weaker in this experiment, this does not account for the failure to find this effect. The difference between high- and low-frequency bigrams in the third keystroke latency was just 2ms.

This pattern of effects is, arguably, consistent with an account in which high-frequency letter combinations (bigrams in this instance) are retrieved/chunked as single motor plans. In the high-low condition, this would permit preparation of the initial bigram in advance of execution (i.e., before the first keypress). This would (a) leave just a final keypress to plan and (b) allow this to be planned earlier – perhaps before the second key press. This would have the effect of speeding the production of the final keystroke. Conversely, the low frequency of the preceding bigram in the low-high condition may have reduced the possibility of advanced preparation, having the opposite knock-on effect on the third keystroke latency.

The obvious conclusion from these findings is that high-frequency letter combinations benefit from faster motor performance within the IKIs, most likely as a result of advanced preparation via the retrieval of stored motor chunks that can be prepared as a single unit. Whereas, letters/keystrokes that are not part of a frequent letter combination must be retrieved and executed as separate motor representations.

General Discussion

The aims of the present research were to determine whether (1) sub-word graphemic letter chunks are passed to the motor level; (2) high-frequency letter combinations are stored as retrievable motor-chunks; and if so, whether (3) motor-chunks scope over just two keystrokes, or can also scope over three. The five experiments reported examined keystroke durations as an effect of bigram and trigram frequencies within short consonant-only letter-strings. The frequencies of the letters, bigrams, and trigrams were controlled or matched across conditions within the experiments where the frequency was not directly being manipulated. In all experiments, consonant-only letter strings were used that do not provide any word form in the English language, and are not pronounceable (i.e., GHT, MPR, DGC). The importance of this is the letter-strings do not have any obvious phonological referent.

In Experiments 1 and 2, the time taken to execute the initial keystroke was significantly faster in the high-frequency condition compared to the low-frequency condition. Letter-strings consisting of frequently used letter combinations were initiated faster than letter-strings consisting of less frequent letter combination. In both experiments, letter frequencies were controlled across conditions. The time taken to initiate the initial keystroke is significantly affected by the frequency of the letter combinations – either the trigram as a whole or the initial bigram - and not the frequency of the initial letter. This effect at the onset latency can be considered as a reflection of faster pre-motor level preparation (Logan & Crump, 2011).

However, the frequency effects observed at the onset latency in Experiments 1 and 2 could also be interpreted as faster preparation and/or execution within the motor level (see Pinet, Ziegler, et al., 2016; Snyder & Logan, 2014). If so, it can be interpreted that motor chunks are retrieved for high-frequency letter combinations before typing onset, and where motor chunks are not available for retrieval (low-frequency letter combinations) they are constructed in full before typing onset. The additional time taken to initiate typing in the low-frequency condition reflects additional preparation of the letter combinations. This could involve additional pre-motor level preparation, preparation within the motor level, or a combination of the two. This is discussed in greater detail below.

The frequency of letter combinations also affects the keystroke latencies beyond the onset latency. The IKIs, a reflection of motor performance (Logan & Crump, 2011), are speeded by the frequency of both bigram and trigram frequencies. When typing along bigrams with controlled letter frequencies, production of the second letter (first IKI) of the bigram is significantly faster in the high-frequency bigrams (Experiment 4). A similar pattern of results is also observed when typing trigrams. The second letter of high-frequency bigrams are produced significantly faster for high-frequency bigrams in the first bigram position within the trigram (Experiment 5). Additionally, Experiment 3 found a significant frequency effect at the second IKI (third letter) when typing high- and low-frequency trigrams that contain the same initial high-frequency bigram (i.e., high-frequency: GHT, low-frequency: GHR). This provides a clear indication that the low-frequency condition requires additional preparation at the final letter in the trigram compared to the high-frequency trigram that is arguably prepared as a chunked trigram. The interpretations of these frequency effects are discussed below.

Are sub-word graphemic letter chunks passed to the motor level?

It is argued that typewriting scrambled letter strings or non-words disrupts the association between words and letters (Yamaguchi & Logan, 2014b), forcing the typist to pass individual graphemic letters to the motor level instead (see Logan, 2018). When typewriting strings of consonants, the two-loop theory argues that the consonants are represented as several units in the outer loop (pre-motor level preparation) and it is "assumed that only the first unit would be passed to the inner loop" (Logan & Crump, 2011, p.10).

However, the time-course of typewriting is mediated by the frequency of letter combinations. The performance of expert typists is significantly correlated with bigram and trigram frequencies when typewriting large volumes of text (Behmer & Crump, 2015). Sub-word graphemic letter-chunks may be passed to the motor level as well as full words.

Experiments 1 and 2 supported this possibility. Significantly faster onset latencies were produced in the high-frequency condition despite letter frequencies being controlled across conditions. Letter-strings containing high-frequency letter combinations benefitted from a significantly faster onset latency compared to letter-strings with less frequent letter combinations. If letters were passed individually to the motor level, the onset latency would not be affected by bigram or trigram frequencies. Instead, the significant effect from the bigram and trigram frequency manipulations demonstrate that chunked graphemic letters (either the initial bigram or the full trigram) were passed to the motor level as a single representation.

The frequency effects demonstrated within the IKIs in Experiments 3, 4, and 5 also indicate that graphemic letter chunks are passed to the motor level as a single chunked representation. The second keystroke of high-frequency bigrams is produced faster than the second keystroke of low-frequency bigrams. This occurred within the IKIs at the initial bigrams (Experiment 5) of a trigram and within individual bigrams (Experiment 4). Similar findings were also observed in Experiment 3 where trigram frequency manipulation allowed for significantly faster keystrokes at the second IKI (third letter) when comparing high- and low-frequency trigrams containing the same initial bigrams.

While the IKIs are considered a reflection of motor level performance, chunking within the motor level may only occur if graphemic letter chunks are prepared as a single representation beforehand. The motor level will not wait for additional graphemic letters to be prepared one at a time. Information decays rapidly in the language system (Christian & Chater, 2016) forcing the motor level to execute motor representations rapidly, rather than waiting for a threshold of motor representations to arrive and then chunking them. This is clear from the findings within Experiment 1-5, as has been discussed. Any evidence of letter chunking within the motor level is also evidence of chunking during pre-motor level preparation. Sub-word graphemic letter chunks must be passed to the motor level when familiar words are unavailable.

Are high-frequency letter combinations stored as retrievable motor-chunks?

Research into skilled performance in handwriting and speaking suggests that fluent production results from movement combinations becoming represented as single, chunked motor plans (handwriting: Teulings, Thomassen, & van Galen, 1983; speaking: Carreiras & Perea, 2004; Cholin et al., 2006; Laganaro & Alario, 2006; Levelt & Wheeldon, 1994). The present research explores this possibility in typewriting. If motor chunks are stored representations for frequently typed keystrokes, it is likely that the availability of stored motor representations is dependent upon the frequency of the letter string.

The present research has found mixed results for preparation at the onset latency. The onset latency is significantly faster when the initial bigram and trigram frequencies are manipulated (Experiments 1 and 2) but not when the initial bigram frequencies (Experiment 5) or trigram frequencies (Experiment 3) are manipulated separately. These findings offer little support for high-frequency letter combinations being stored as retrievable motor chunks. While the motor level must prepare the initial motor chunk/representation before beginning to type (Pinet, Ziegler, et al., 2016; Snyder & Logan, 2014), the onset latency also reflects pre-motor level preparation (Logan & Crump, 2011).

Initially, it was explored whether the observed frequency effects at the onset latency in Experiments 1 and 2 reflect solely performance at the motor level. It was argued that if this was the case, the effect at the onset latency can be interpreted as motor chunks being retrieved (high-frequency condition) or constructed (low-frequency condition) in full before the onset of typing. This possibility was later dismissed based on the findings of Experiments

3-5, as will be discussed shortly. Instead, the frequency effect observed at the onset latency in Experiments 1 and 2 appear to represent mainly pre-motor level preparation.

In research investigating speech production, faster initiation of syllables supports the storage of frequently prepared motor chunks (Cholin et al., 2006). High-frequency syllables can be retrieved, whereas low-frequency syllables have to be constructed on the fly before articulation (Cholin et al., 2006). This does not appear to be the case in the present research. The significant effects at the onset latency may represent differences in pre-motor level preparation (Logan & Crump, 2011) rather than the motor level loop retrieving stored motor chunks for high-frequency letter combinations, and compiling motor chunks in full before typing onset for low-frequency letter combinations.

The linguistic units used in speaking and typewriting differ dramatically. In speech, words are split into pronounceable syllables (see Levelt et al., 1999). Where stored syllables are not available in the motor store (mental syllabary: see Cholin et al., 2006; Crompton, 1981), smaller units cannot be articulated. Instead, the syllable must be constructed. For example, imagine reading aloud an unfamiliar word such as *abscond*, featuring a familiar initial syllable (i.e., *ab*) and a less familiar and low-frequency second syllable (i.e., *scond*). Even though the second syllable may be unfamiliar and will most likely not have a stored motor representation, it must still be prepared as an intact syllable. We would not expect to hear it broken down and pronounced as multiple smaller sounds (i.e., individual phones corresponding to each letter).

This is dramatically different in typewriting. The smallest linguistic unit that can be used in typewriting is an individual keystroke. If motor chunks containing multiple keystrokes are not stored, and thus retrievable, the motor level can execute individual keystrokes one at a time. For example, let us compare the high-frequency bigram of *GH* to the low-frequency bigram of *GW*. Stored motor chunks may be available for frequent bigrams such as *GH*, allowing for motor representations of both letters to be retrieved in one instance. In comparison, infrequent bigrams such as *GW* would not have a stored motor chunk for both letters, forcing them to be retrieved independently from one another. When retrieving the motor chunk for the high-frequency bigram of *GH*, the motor level can retrieve the initial letter (i.e., *G*) from the low-frequency bigram. Stored motor representations are also available for independent letters, so there is likely very little difference in the latencies at the onset of high- and low-frequency letter combinations.

Instead, retrieved motor chunks may benefit from speeded production for the remainder of the motor chunk. Using the above example once again, if the high-frequency bigram of *GH* is retrieved as a motor chunk¸ production of the second letter (i.e., *H*) can be executed faster as the motor representation for that letter is retrieved in advance. In contrast, the motor representation of the second letter in low-frequency bigrams (i.e., W from GW) is not retrieved in advance and must be retrieved independently on the fly. This was observed in the present experiments. The second keystroke in high-frequency bigrams is produced significantly faster than low-frequency bigrams. This was demonstrated when typewriting alone bigrams (Experiment 4), and within the first bigram (Experiment 5) when typewriting trigrams.

A similar pattern of results was also observed for high-frequency trigrams in Experiment 3. When typing high- and low-frequency trigrams that contain the same initial bigrams, the second IKI (third letter) was significantly faster in the high-frequency condition. Thus, indicating that additional motor preparation is required for the final letter in the low-frequency trigram compared to the high-frequency trigram. It appears that when typing high-frequency trigrams (i.e., *GHT*), the motor representations for the full trigram can be retrieved as a single unit before typing the initial keystroke. In comparison, the low-frequency trigram (i.e., *GHR*) contained the same initial high-frequency bigram, which allowed for the motor representations of the first two letters/keystrokes to be retrieved as a single unit before typing the first keystroke. At the point in which the third keystroke is being typed, the low-frequency trigram still must prepare the motor representation, whereas the final keystroke is faster in the high-frequency condition as it has been retrieved in advance.

The observed bigram and trigram frequency effects in Experiments 3-5 support the possibility of frequently typed letter combinations being stored as retrievable motor chunks. However, there are alternative explanations for motor performance being speeded by the frequency of the letter combinations. As discussed by Logan (2018), bigram frequency effects may represent faster activation when identifying the next motor representation for a single keystroke to activate/prepare/retrieve. Letter combinations that occur in more words will be represented more in a set of stored contexts that could arguably be typed. The increased representation could arguably speed the retrieval of the next motor representation. For example, in a high-frequency bigram such as *GH* (appearing in many words such as *bright, thigh, thought, plough,* etc.), orthographic knowledge of letter combinations may allow for typing the initial letter (i.e., *G*) to activate/prepare/retrieve the motor representation for the second letter (i.e., *H*) faster as there are more possible outcomes/contexts that can be typed.

However, the pattern of results in Experiment 5 provide a clear indication that motor representations were prepared/retrieved incrementally. Experiment 5 manipulated the location of high-frequency bigrams within low-frequency trigrams. Comparisons were made between letter-strings that contain an initial high-frequency bigram followed by a secondary low-frequency bigram (high-low), and letter-strings with a reversed order, low-frequency bigrams followed by high-frequency bigrams (low-high). Analyses of the initial bigrams demonstrated the same pattern as Experiments 3 and 4, the second keystroke of high-frequency bigrams is produced significantly faster than low-frequency bigrams. Though, there was no difference when comparing the high- and low-frequency bigrams in the second location. It appears that the retrieval of an available motor chunk allows for the retrieval or computation of the next motor representation to commence sooner. For example, in letter-strings with a high-low bigram frequency structure such as *FLR*, the high-frequency bigram of *FL* is a retrieved before typewriting the initial letter, allowing the motor level to prepare the motor representation of *R* whilst typewriting the initial bigram.

The pattern of results in Experiment 5 suggest that motor representations were retrieved incrementally. This is not consistent with an account in which typing one letter allows for faster selection of the motor representation for the next letter when part of a frequent bigram. This account should not benefit from advanced planning, or demonstrate incremental production, as the bigram frequency effects occur on the fly when typing the initial letter of the bigram. Instead, the findings in Experiment 5 provide further support for an account in which motor chunks can be retrieved as a single representation for frequent letter combinations.

Conclusion

In conclusion, clear frequency effects were observed for frequently typed bigrams and trigrams. High-frequency letter combinations benefit from speeded production within the

IKIs compared to low-frequency letter combinations. These findings were interpreted as indications that frequently typed letter combinations are stored and retrieved as motor chunks for bigrams and trigrams in typewriting.

3. Examining Phonological Influences on Motor Performance

Experiment 6

Introduction

In Experiments 1-5, the frequency of letter combinations (bigram and trigrams) were manipulated in consonant-only trigrams to determine whether (1) sub-word graphemic letter chunks are passed to the motor level; (2) high-frequency letter combinations are stored as retrievable motor-chunks; and if so, whether (3) motor-chunks scope over just two keystrokes or can also scope over three. The five experiments provided supporting evidence that sub-word graphemic letter chunks are passed to the motor level; and that high-frequency letter combinations (bigrams and trigrams) are stored as retrievable motor-chunks.

The pattern of results in Experiments 1 and 2 suggest that graphemic letter combinations, not individual letter graphemes (see Logan & Crump, 2011; Logan, 2018) may be prepared in advance of typewriting when familiar words are unavailable. High-frequency letter combinations were initiated significantly faster than low-frequency letter combinations. The time taken to initiate typing (onset latency) was significantly affected by manipulations to the frequencies of the bigrams and trigram when controlling for letter frequencies. These significant frequency effects at the onset latency can arguably be interpreted as either a reflection of pre-motor level preparation, and/or preparation of the initial motor chunk and execution of the initial keystroke (see Pinet, Ziegler, et al., 2016; Snyder & Logan, 2014). The onset latency is argued to reflect mainly pre-motor level preparation in typewriting (Logan & Crump, 2011). This is indicated by much larger keystroke durations compared to the proceeding keystrokes, which represents the additional preparation required before keystrokes can be prepared/retrieved within the motor level.

In Experiments 3-5, the significant frequency effects within the IKIs support an account in which motor representations are executed as soon as they have been prepared/retrieved. After all, any difference in the keystroke latencies after the onset latency signifies that additional preparation/processing has occurred. These findings contradict an account in which the observed frequency effects at the onset latency in Experiments 1 and 2 reflect motor level performance, whereby motor chunks may be prepared in full before the onset of typing. To further explore the validity of the interpretations to the findings in Experiments 1-5, Experiment 6 manipulated the pronounceability of the letter-strings. By typing letter-string such as *GAT* instead of *GHT*, the pronounceable letter-strings may be assisted by phonological processing and may benefit from faster pre-motor level preparation. Considering the interpretations of the findings from Experiments 1-5, if (a) the duration of the onset latency reflects pre-motor level preparation; and (b) sub-word graphemic letter chunks are passed to the motor level; then typing onset should be significantly faster for pronounceable letter-strings. This was examined in the present experiment.

The stimuli in the previous experiments were constructed of consonants, ensuring that the letter-strings were unpronounceable (i.e., RNH). As a result, it was possible to prevent the pre-motor level preparation being speeded by the phonological preparation of letter chunks running in parallel to orthographic preparation. Phonological processing, a fundamental stage within speech production (Levelt et al., 1999), has been demonstrated to assist in the processing of handwriting (Bonin et al., 2015; Bonin, Peereman, & Fayol, 2001; Damian et al., 2011; Damian & Qu, 2013), via the sublexical conversion of phonemes to graphemes (see Bonin et al., 2015).

By manipulating the CV-status of the letter-strings, unpronounceable consonant-only letter-strings (CCC) and pronounceable letter-strings containing vowels (CVC) can both be prepared via the lexical route involving the retrieval of stored orthographic graphemic information. However, the graphemes within the pronounceable CVC letter-strings may also be prepared, and possibly prepared faster, by phonological processing, via the sub-lexical route that runs in parallel to the lexical route (see Bonin et al., 2015). If single graphemic letters are prepared and passed to the motor level independently when familiar words are unavailable, there should be no difference in the time to initiate the first keystroke when the initial letters are the same across conditions. However, if graphemic letter-chunks can be passed as a single chunked unit to the motor level, the time to initiate typewriting may be influenced by the pronounceability (CV-status) of letter combinations.

The present experiment further examined whether graphemic letters are prepared and passed to the motor level individually when familiar words are unavailable. The frequency of letter combinations was manipulated once again, while also matching the initial letters across conditions. The same initial letters were used in all experimental conditions to eliminate confounding influences of initial letter frequencies and the distance between fingers and the initial key to be typed. Any difference in keystroke latencies across conditions are as a result of either the frequency of letter combinations or the CV-status of the letter-strings. Both of which indicate that graphemic letter chunks are prepared and passed as a single unit to the motor level. By employing the same symbol-position association-learning paradigm used within the previous experiments, the present experiment examined if sub-word letter chunks are passed to the motor level. The prediction is that if graphemic letters are prepared as a single chunk before being passed to the motor level, the onset of typing may be significantly influenced by the frequency of letter combinations, or the pronounceability of the letter-string (via the CV-status of the second letter).

Methods

Design

The study employed a 2 x 2 repeated measures design for the variables of trigram frequency (high and low) and CV-status (CVC and CCC). As in Experiments 1 to 5, letter-strings were assigned to a location on the screen (left or right). The association between letter-strings and location were enforced in the association learning stage, before being checked in the association confirmation stage. Letter-strings were then typed in the production stage upon presentation of a rectangular block on the left or right position, acting as the cue for the letter-string associated with the presented location.

Trigrams were assigned in same-condition pairs to the location of a square that appeared on either the right or the left of the screen. All participants produced the 32 trigrams eight times, resulting in 256 experimental trials each. This resulted in 16 sets of alternating association learning, association confirmation, and production stages. Letter-strings were then typed in the production stage upon presentation of a rectangular block on the left or right position, acting as the cue for the letter-string associated with that location. The pairs of letter-strings contained no matching letters across the letter-strings, and both letter-strings were paired from the same experimental condition. All stimuli pairings are available in the appendices.

Participants

Twenty-four native English speakers took part in the experiment. All participants were undergraduate students with normal or corrected-to-normal vision, no history of language difficulties, and self-reported adequate typewriting ability.

Materials

Letter string frequencies were calculated in the same manner as in Experiment 1. The letter-strings were selected for each condition on the basis that: (1) CCC trigrams consisted of only consonants; (2) trigrams in the CVC condition consisted of a consonant-vowel-consonant order; (3) the high-frequency conditions contained high-frequency trigrams, consisting of high-frequency bigrams in both locations; (4) the low-frequency conditions contained low-frequency trigrams consisting of low-frequency bigrams in the second bigram location[3]; (5) the same initial letters were used across all four conditions, resulting in the same mean letter frequencies[1]. The breakdown of frequencies is provided below, in Table 14.

Table 14: Mean letter and letter-combination frequencies for stimuli used in Experiment 6

CV-status	Frequency	Trigram	Bigram 1	Bigram 2	Letter 1	Letter 2	Letter 3
CVC	High	34,727	301,709	724,091	4,165,306	6,379,079	4,744,798
CVC	Low	6	295,400	24,571	4,165,306	6,379,079	1,810,174
CCC	High	34,926	573,435	155,482	4,165,306	3,367,388	4,744,798
CCC	Low	6	118,034	1,456	4,165,306	3,031,521	1,810,174

Letter-strings were then paired from the same experimental condition for the purpose of the symbol-position association-learning task. A breakdown of the stimuli pairings is provided below, in Table 15.

Table 15: Stimuli pairings used in Experiment 6

BLOCK NUMBER	LEFT_STRING	RIGHT_STRING	CONDITION
1	M O R	G A T	CVC-HIGH
2	N E S	R I T	CVC-HIGH
3	N I S	T O R	CVC-HIGH
4	S E R	N A L	CVC-HIGH
5	M P R	N T S	CCC-HIGH
6	T H R	N D S	CCC-HIGH

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[3] The frequencies of the initial bigrams, and second and third letters, were unable to be matched or evenly controlled across conditions without hindering the frequency control of the initial letter frequencies, which were given priority.

7	R S T	N G L	CCC-HIGH
8	G H T	S C R	CCC-HIGH
9	N A H	G O P	CVC-LOW
10	N E J	R I W	CVC-LOW
11	T E Q	N O H	CVC-LOW
12	S I W	M A F	CVC-LOW
13	R M W	N D H	CCC-LOW
14	N R J	T D Q	CCC-LOW
15	N K H	S R W	CCC-LOW
16	G T P	M B F	CCC-LOW

Apparatus

The same apparatus was used as in the previous experiments.

Procedure

The same procedure was employed as in previous experiments.

Results

Within the initial 6,606 recorded observations, incorrect responses were excluded from the analyses. A response was treated as correct if the participant typed just the three keys associated with the correct trigram, in the correct order. Otherwise, responses were treated as incorrect. Responses were also excluded if the initial response time was less than 200ms or greater than 3000ms. Of the initial excluded responses, 462 responses (6.99%) were excluded as incorrect responses, and 17 responses (0.26%) were excluded as outliers from the latency limits (<200ms; >3000ms). Keystroke latencies were then excluded if they exceeded the two standard deviations of the participants mean latencies for the respective keystroke location (i.e. onset latency, first IKI, second IKI). This was performed on a by-analysis basis. This removed 338 responses for the onset latencies (5.52%), 307 responses for the first IKIs (5.01%), and 305 responses for the second IKIs (4.98%).

Statistical analyses were performed by linear mixed-effects modelling. This started with a baseline (zero) model with random by-subject and by-item-pair intercepts and random by-subject slopes for the frequency (high vs. low) by stimulus type (CCC vs. CVC) main effects and interaction. We then added to this model the main effect of frequency (Model 1), the main effect of CV-status (Model 2), and finally tested a full-factorial model that included the frequency by CV-status interaction (Model 3). Table 16 summarises the mean keystroke latencies with 95% confidence intervals. Models fits are reported in terms of AIC (i.e., Akaike, 1974) with the models compared using chi-square change tests (Table 17).

Table 16: Mean keystroke latencies (milliseconds) with 95% confidence intervals for Experiment 6

	Onset latency	First IKI	Second IKI
CVC - High Frequency	804 [788, 820]	163 [160, 167]	170 [166, 174]
CVC - Low Frequency	828 [812, 844]	176 [172, 180]	215 [209, 221]
CCC - High Frequency	851 [835, 867]	204 [199, 210]	195 [190, 200]
CCC - Low Frequency	972 [953, 991]	276 [268, 284]	261 [253, 269]

At the onset latency, main effects for Frequency were found, with main effects also being found for CV-status. Finally, a non-significant interaction was also recorded for the full model featuring an interaction of CV-status and Frequency (see Table 17). For the first IKI, significant main effects for CV-status were found. However, there was no significant main effect for Frequency and no significant effect for the interaction of CV-status and Frequency. For the second IKI, the effect of frequency was non-significant, with significant main effects for CV-status. The interaction between CV-status and Frequency was also non-significant.

Table 17: Inferential statistics across keystroke latencies in Experiment 6

	Onset latency			**First IKI**			**Second IKI**		
Source	**AIC**	***χ2 Difference***	***p***	**AIC**	***χ2 Difference***	***p***	**AIC**	***χ2 Difference***	***p***
Intercept only (0)	2118.8	-	-	6570.5	-	-	3853.1	-	-
Frequency (1)	2116.7	4.08	.04*	6569.9	2.63	.11	3852.7	2.38	.12
Frequency + CV-status (2)	2107.6	11.11	<.001***	6560.6	11.3	<.001***	3843.8	10.95	<.001***
Frequency x CV-status (3)	2106.5	3.14	.08	6559.9	2.74	.10	3842.9	2.86	.09

Value in brackets indicate model number; df=1 in all cases; *Below a significance threshold of .05 ** Below a significance threshold of .01 *** Below a significance threshold of .001

Discussion

The aim of the present experiment was to examine if sub-word graphemic letter chunks can be prepared and passed as a chunked unit to the motor level when familiar words are unavailable. The CV-status and frequency of letters and letter combinations were manipulated within short letter-strings. The letter-strings were employed in this experiment as a method of examining the time-course of typewriting when familiar words are unavailable. All letter-string were effectively non-words, which should arguably force single letter graphemes to be passed to the motor level individually.

Previous research has demonstrated that when familiar words are unavailable, typewriting is dramatically slowed (Salthouse, 1986; Yamaguchi & Logan, 2014b, 2016). It is argued that "nonwords push skilled typists back on the learning curve by removing their ability to use a single chunk to type several letters" (Logan, 2018, *p*.454). Without the availability of a familiar word, the outer loop is argued to pass individual letters to the inner loop (see Logan & Crump, 2011).

Experiments 1 and 2 previously demonstrated significant frequency effects at the onset latency, which arguably reflect faster pre-motor level preparation for high-frequency letter combinations. Typing onset was significantly affected by the frequency of letter combinations when individual letter frequencies were controlled across conditions. The present experiment improved on the level of control at the first letter by matching the same letter across all four experimental conditions. As in Experiments 1 and 2, the frequency of the initial letter is controlled across conditions, but additionally, there was no variation in the location of the keys across conditions. Regardless of the typists typing style/preference, the same initial movements are required to execute the initial keystroke across conditions.

Analyses of the onset latency, the time taken to execute the initial keystroke, demonstrated significant main effects from the frequency of the letter combinations. As was the case in Experiments 1 and 2, the onset latency is significantly faster for letter strings consisting of higher frequency letter combinations. Despite typewriting the same initial letters across experimental conditions, manipulations to the frequency of letter combinations within the letter-strings significantly affect the time required to initiate typewriting. Consider that the onset latency is mainly a reflection of pre-motor level preparation (Logan & Crump, 2011).

Letter graphemes must have been prepared and passed to the motor level as a chunked representation.

Significant main effects were also observed at the onset latency for the CV-status of the letter-strings. The CV-structure of the second letter within the letter-strings were manipulated across conditions. Consonant only (CCC) letter-strings were used, as well as Consonant-Vowel-Consonant (CVC) letter-strings. The CCC conditions do not allow for the pronunciation of the letter-strings (i.e., *RMW*), preventing phonological assistance during pre-motor level preparation. In contrast, the pronounceability of the CVC letter-strings (i.e., *GOP*) allows for the potential of phonological assistance, which may speed preparation of the letter graphemes if they are prepared as a chunked graphemic representation. The analysis of the keystroke latencies demonstrated that the time taken to initiate typewriting is also influenced by the CV-status of the letter-strings. The onset latency is significantly faster within CVC letter-strings compared to CCC letter-strings.

The IKIs also appear to be influenced by the CV-status of the letter-strings. Both the second and third keystrokes within the trigrams were typed significantly faster in the CVC letter-strings compared to the CCC letter-strings. It would appear as though motor level performance is influenced by the phonological representation of the letter-strings. This does not appear to reflect faster pre-motor level preparation via sub-lexical processing , as the findings at the onset latency indicate that at least the initial 2, possibly 3, letters graphemes were already prepared before the onset of typing. Instead, these findings indicate that the pronounceability of the letter-strings affects motor performance. It is possible that when typing the pronounceable letter-strings (CVC's), typists were overtly naming the letter-strings via inner speech. If so, this appears to speed the timing of motor execution. This is potentially an interesting insight into whether (1) the motor level runs to completion without interference from other (e.g. phonemic) representations; and (2) the time-course of typewriting is affected by inner speech.

However, it is difficult to draw meaningful conclusions from these findings because of the variability in letter frequency controls across conditions in the second and third letters. One limitation of the present study is that unlike the previous experiments, the second and third keypress may be subject to confounding letter frequency effects. The inclusion of CVC trigrams has restricted the level of control for letter and n-gram frequencies for the final two keystrokes when controlling for the letter, bigram and trigram frequency at the initial keystroke. While the results suggest that there may be phonological influences upon typewriting, which also influence motor level performance, such examinations are confounded by letter frequencies using the current experimental paradigm. To examine the influence of phonology within typewriting, controls upon potential confounding letter and n-gram frequencies need to be made. This shall be re-visited within a new experimental paradigm within the next chapter.

In conclusion, this experiment provides supporting evidence that the graphemic letter chunks can be prepared and passed to the motor level when familiar words are unavailable. The time taken to execute the initial keystroke is influenced by the frequency of the letter combinations within a letter-string. The CV-status of the letter-string also influences the time taken to initiate typewriting. Pronounceable letter-strings are initiated faster, suggesting that pre-motor level preparation is speeded by the phonological form of letter chunks.

4. Resyllabification Effects in Typewriting: Inner Speech Affects Motor Execution[4]

Introduction

Typewriting is a growing method of communication. Children are learning to type at a younger age and can be considered as expert typists by the age of starting college. By the time students reach college, they can have ten years of typewriting experience and can type over 60 words per minute (Logan & Crump, 2011). This can extend to 50-100 words per minute for experienced typists (Rayner & Clifton, 2009). This is a slower rate than observed in speaking (120-200 words per minute; Rayner & Clifton, 2009), which can allow for fluent typewriting to occur concurrently with an internal monologue that can be heard when typewriting. It is possible that the internal monologue of inner speech may affect the time-course of typewriting.

The concept of inner speech influencing the time-course of typewriting is not inconceivable as typewriting is considered an alternative output of linguistic processes such as speaking or handwriting (Margolin, 1984; van Galen, 1991), in which learned motor processes are grafted onto pre-existing spelling processes (Logan & Crump, 2011). As phonological processing influences handwriting (Bonin et al., 2015, 2001a; Damian et al., 2011; Purcell et al., 2011; Tainturier & Rapp, 2001), it may also influence typewriting.

There are two ways in which phonology may influence the time-course of typewriting. Abstract phonological information may be converted into a corresponding orthographic form at the sublexical stage, as can occur within handwriting (Bonin et al., 2015; Purcell et al., 2011; Tainturier & Rapp, 2001). Alternatively, motor-planning processes may be affected by inner speech the internal monologue that can be heard when reading, writing, or typewriting. Chenoweth and Hayes (2003) demonstrated that the typewriting of sentences was slowed when inner speech was inhibited via an articulatory suppression task, the verbal repetition of a syllable when typewriting. The verbal repetition of the syllable consumes the phonological processing capacity that is needed for inner speech to concurrently occur when typewriting, which makes inner speech unavailable. The slowed typewriting performance

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[4] This chapter is presented as a paper that is prepared for publication but not yet submitted.

observed suggests that time-course of typewriting is slowed by interference to the inner voice.

An effect of inner speech upon the time-course of typewriting could be interpreted in several ways. Chenoweth and Hayes (2003) interpret their findings as support for their theoretical account of written language production (Chenoweth & Hayes, 2001), suggesting that inner speech is used to assist in orthographic spelling processes. Alternatively, an effect of inner speech upon the time-course of typewriting may arise as a result of the role inner speech plays within self-monitoring processes/feedback mechanisms. Within typewriting, monitoring and feedback play an essential role in successful motor performance to ensure that errors are detected and corrected (Lashley, 1951; Miller, Galanter, & Pribram, 1960). The rate of production is typically slowed after an error (Logan & Crump, 2010; Salthouse, 1986). Within speech production, inner speech is used within monitoring processes to ensure the spoken message matches that of the intended message in speaking (Levelt, 1983; see Levelt, Roelofs, & Meyer, 1999), this could also occur within typewriting.

Similar feedback mechanisms to that of the self-monitoring processing in speaking (Levelt, 1983; see Levelt, Roelofs, & Meyer, 1999) are proposed within typewriting, albeit with no account of phonological influences. Logan and Crump's (2011) theoretical account of typewriting proposes that visual information is monitored on the screen (Logan & Crump, 2010), along with proprioceptive and kinaesthetic information from the finger movements (Crump & Logan, 2010c). This information is monitored in order to check for potential mismatches between the outputted message and the intended message. Considering the typed output on the screen is silently read as it is being typed, this may activate acoustic representations in the form of inner speech (Abramson & Goldinger, 1997). Another possibility is that the intended message used within the feedback mechanism, rather than the monitored information, manifests as inner speech. It is possible that the abstract word form produced by spelling processes in the outer loop is used to compare to visual information on the screen (see Logan & Crump, 2011). However, I argue it is more likely, and more efficient for inner speech to be used instead of an abstract form of spelling. As I type these words, the internal monologue of inner speech cannot be ignored. When I observe an error of a mistyped word, my inner speech does not pronounce the error but instead recites the word I intended to type correctly. However, whether my account of inner speech is agreed with or not, this is not evidence of inner speech being utilised within a feedback mechanism, nor is it evidence for inner speech affecting the time-course of typewriting in any capacity.

To examine the influence of inner speech upon the time-course of typewriting, manipulations must be made to influence the late phonological/phonetic stages of processing. This ensures that abstract phonological representations formed at the sub-lexical stage are not affected. One of the late processes of phonological/phonetic encoding is that of resyllabification, in which the previously formed abstract syllable representations may be adjusted. To aid pronunciation of the words within a phrase, the syllable structure can be adjusted across word boundaries so that a word does not start with a highly sonorous vowel sound. Instead, the word with a vowel onset borrows the final consonant of the preceding word to make it easier to pronounce. For example, in English, the word *defend* (*de-fend*) would be resyllabified when followed by a word (i.e., *it*) with a vowel onset (*de-fen-dit*). The process occurs across a word-boundary where a word-ending consonant straddles across a word boundary to a word containing a vowel onset in the initial syllable. This allows for the consonant to act as the onset of the next word; and thus, the vowel moves from the onset position to the obligatory nucleus position (Kahn, 1976).

In typewriting, the division of labour is distributed across two independent processing loops, the outer loop and the inner loop (Logan & Crump, 2011; Logan, 2018). The outer loop has responsibility for higher-level processes such as the generation of the spelling of a word. The individual words prepared by the outer loop are inputted to the inner loop one at a time. The inner loop is then required to prepare and execute the movements required to type the keystrokes associated with the word. Within this hierarchical two-loop model, it is argued that the inner loop is informationally encapsulated (Logan & Crump, 2011). The processing of information within the inner loop is contained within the inner loop. The outer loop does not know what the inner loop is doing. The outer loop does not know the location of the letters on the keyboard (Liu et al., 2010). Typists are poorer at identifying the location of letters on the keyboard when visualising the keyboard compared to being able to see or physically touch the keyboard. Furthermore, the outer loop does not know which hands type which letters (Logan & Crump, 2009). Typewriting performance is dramatically slowed and more error-prone when typists are instructed to type using only the letters associated with one hand. Logan and Crump (2011) argue that the outer loop is forced to instruct the inner loop to slow down in order to observe which hand is selected for the next keystroke and inhibit the execution of the keystroke if necessary. Fundamentally, the outer loop has poor spatial knowledge of the keyboard and is forced to instruct the inner loop to slow down in order to observe the output of the inner loop. The outer loop is unable to observe the information within the inner loop, so must instead observe the inner loop's output.

However, the outer loop's poor spatial awareness of the keyboard is not necessarily sufficient evidence for the information encapsulation of the inner loop. Previous research has also established that information from within the inner loop is accessible to the outer loop (i.e., Pinet & Nazari, 2018; (i.e., Cerni, Velay, Alario, Vaugoyeau, & Longcamp, 2016; Kalfaouğlu & Stafford, 2014; Pinet & Nozari, 2018; Pinet, Ziegler, et al., 2016; Cerni et al., 2016; Kalfaoğlu & Stafford, 2014). For example, the outer loop may be able to access the kinaesthetic and proprioceptive feedback of the inner loop (Kalfaoğlu & Stafford, 2014). In Kalfaoğlu and Stafford's (2014) research, typists were prevented from receiving feedback from the outer loop, as they were unable to see the visual feedback of what is being typed. They did not see the typed output appear on the monitor, and their hands were covered. It was found that when errors were made by the typist, they were still able to correct the error in a typical manner. Typists were still able to detect an error was made, and then press the backspace and continue typing the word from the correct position. If the outer loop could only access feedback via visual information and does not know what the inner loop is doing, it would not be able to provide the information to correct the error and continue typewriting from the correct position within the word. Kalfaouglu and Stafford (2014) argue that the outer loop can access the proprioceptive and kinaesthetic feedback within the inner loop. If the inner loop was informationally encapsulated, the outer loop should not be able to access the feedback within the inner loop before instructing the inner loop to correct the error.

An informationally encapsulated inner loop should also not be influenced by information external to the two loops. The inner loop should only be able to receive a singular word from the outer loop, and proprioceptive and kinaesthetic feedback of the keys when typewriting as information inputted to the inner loop. The outer and inner loops prepare one word at a time, and the word is prepared in full before the onset of typewriting. Any influence from the outer loop should only occur at the onset latency before the initiation of typewriting. The keystrokes beyond the onset latency are a reflection of inner loop performance (Logan & Crump, 2011). The present research examines how inner loop performance is influenced by information external to both the outer and inner loops, the phonetic relationship of two adjacent words.

In the present two experiments, investigating potential phonetic influences across the word boundary of word pairs allows for a novel and innovative method of investigating (1) if the time-course of typewriting is influenced by inner speech, and (2) if lower-motor levels of processing are informationally encapsulated in typewriting. To my knowledge, this is the first study to examine how the time-course of typewriting a word is influenced by the phonetic relationship with an adjacent word. If the time-course of typewriting is not affected by the word form(s) in inner speech, keystroke latencies should not be influenced by manipulations to the phonetic word form. Similarly, If the inner loop is informationally encapsulated, the preparation and/or execution of the motor code for a word should not be influenced by manipulations to the phonetic syllable structure across the word boundary of two words.

By manipulating the CV-status of the letters surrounding a conjoining word boundary, it was examined if the timing of keystrokes is influenced by the late phonological/phonetic stage of resyllabification. Typists were required to type short phrases in which one word in a two-word phrase is changed to manipulate the cv-status across the word boundary. For example, the first word remains constant across conditions in Experiment 1 when comparing phrases that can (i.e., *product onion*) and cannot be resyllabified (i.e., *product depot*). Thus, as the first word is identical across conditions, any difference in the timing of keystrokes can only be an effect of inner speech via the resyllabification process. In Experiment 2, the second word is constant across conditions instead.

The time-course of typewriting was measured via the keystroke latencies surrounding the conjoining word boundary, including the initial keypress of the second word, the onset latency, as well as the surrounding IKIs. The onset latency was considered to represent the time to encode the relevant spelling then prepare and execute the initial keystroke (Pinet, Ziegler, et al., 2016; Snyder & Logan, 2014). The IKIs were considered as indications of motor/response execution processes (see Logan & Crump, 2011; Yamaguchi, Logan, & Li, 2013). The influence of the present experimental paradigm upon the keystroke latencies provides valuable insight into the examination of inner speech influences and the information encapsulation of the inner loop in typewriting.

Experiment 7

Experiment 7 manipulates the phonetic form via the phonetic process of resyllabification. Two conditions are employed. Word pairs in the first condition (e.g., *product onion*), which we shall name as RESYLL, are susceptible to resyllabification across the word boundary. Words in the second condition (e.g., *product depot*), which we shall refer to as the control condition, are not susceptible to resyllabification across the word boundary (pro-duc-tun-yun). Across both conditions, the first word of the two-word phrase was matched to examine influences of the phonetic form within the first word. The first word ends in a consonant cluster. The manipulations of the two conditions occur at the initial letter of the second word. Within the RESYLL condition, a vowel onset would comply with resyllabification constraints as the vowel onset would use the final coda/consonant of the first word as an obligatory nucleus (Kahn, 1976). A consonant onset in the second word would not be compliant with resyllabification constraints. This is used for the control condition. Within the RESYLL condition, the final letter of the first word shall (phonetically) act as both the final coda of the first word and the onset of the second word. For example, the phrase *product onion* would see the final letter of the first word (i.e. *t*) straddle across both word boundaries. We shall refer to this as the straddle point, as this letter straddles both word boundaries. If the phonetic form affects spelling processes, we would expect to find significantly different onset latencies across conditions. If the phonetic form affects motor execution, we would expect to see significantly different IKI's across conditions

Methods

Participants

Twenty-four undergraduate students from Nottingham Trent University participated. All had normal or corrected-to-normal vision and were native speakers of English. All participants reported being experienced and competent typists. Those that did not complete the task within the allotted hour were excluded from the analyses. This was in addition to the twenty-four participants who were able to complete the task within an hour. Participants received research credits for their participation as part of Nottingham Trent University's SONA Research Participation Scheme.

Design

We used a counterbalanced repeated measures design to examine the effect of manipulations on the phonetic form across two conditions, an experimental condition that we shall refer to as RESYLL, and a control condition, on keystroke latencies. Keystroke latencies were recorded for all keystroke locations for the purpose of the analyses (see Figure 3).

The condition that was assigned as RESYLL contained word pairs that can be phonetically resyllabified across the word boundary. The word pairs in the control condition cannot be phonetically resyllabified across the word boundary. For each trial, a four-word phrase consisted of a word pair from the RESYLL phrases and a word pair from the control phrases (see Figure 3). Responses were elicited by the presentation of the four-word phrase and were initiated at the participants discretion via a keystroke. The order was counterbalanced across participants.

Materials

Sixteen four-word stimuli phrases were used. Each four-word phrase consisted of a word pair that could be phonetically resyllabified (RESYLL) and a word pair that cannot (control). RESYLL word pairs differed to the control word pairs on the second word only. Within the RESYLL word pairs, the second word began with a vowel (i.e., product Onion). Within the control word pairs, the second word began with a consonant (i.e., product Depot).

RESYLL	**P**	**R**	**O**	**D**	**U**	**C**	**T**	**_**	**O**	**N**	**I**	**O**	**N**
Letter location					***Word End -2***	***Word End -1***	***Word End***	***SPACE***	***Word Initial***	***Word Initial +1***	***Word Initial +2***	***Word Initial +3***	
Control	**P**	**R**	**O**	**D**	**U**	**C**	**T**	**_**	**D**	**E**	**P**	**O**	**T**

Figure 3: Word-End and Word-Initial keystroke locations with example stimuli across conditions in Experiment 7.

In all instances, the final letters of the first word were always consonant clusters (i.e., product). The first word was matched across conditions. Counterbalancing of the words used in the four-word phrases were performed by rotating both the word pairs and the first (non-manipulated) word of each word pair. This counterbalancing created 4 counterbalanced versions of each four-word stimulus. Nouns were used in all instances. Examples are provided below in Table 18 (see Appendix 1 for all stimuli for Experiment 7).

Table 18: Example of the counterbalanced order of presentation for experimental stimuli in Experiment 7

Counterbalanced order of presentation	
Order 1	PRODUCT ONION TITLE EXAM
Order 2	TITLE ONION PRODUCT EXAM
Order 3	PRODUCT EXAM TITLE ONION
Order 4	TITLE EXAM PRODUCT ONION

Procedure

Participants were tested individually in a quiet secluded room in front of a computer with an ASUS 27inch widescreen monitor (1920*1080p resolution; 144hz screen frequency). Each of the trials consisted of a 50ms presentation of a blank screen, followed by a 250-500ms fixation of a fixation point (+) presented on the screen. Finally, the target four-word phrase was presented on the screen until the participant pressed a key on the keyboard to begin the trial. At the point of the initial key press, the prompt is removed, and a text box appears presenting the keys executed in the current trial. Presented stimuli prompts were presented in Arial with a font size of 22. The text box had the same font and font size. All items were presented in black in the centre of a plain white background. Participants were instructed to type the phrase as quickly and accurately as possible. Responses that were incorrect or were slower than mean response rate of 300ms per keypress were deemed incorrect and were restarted. Participants received instant feedback of incorrect responses in the form of a red flash on the screen, followed by a reminder of the instructions and the stimulus prompt. Participants repeated this process until they successfully completed 8 trials of the stimulus that were both accurate and under the pre-specified 300ms/keystroke time specification. Upon completion of the 8 trials, they move onto the next four-word stimulus. Participants were required to complete the 16 stimulus-phrases within an allotted hour. Those not completed within the hour were not used for the analyses. All subjects were debriefed in full and thanked for their time.

Results

Timed keystroke data were recorded across all trials. Statistical analyses were performed on accuracy rates of trials, as well as chronometric analyses of correct trials. A response was interpreted as incorrect if it was misspelled, corrected, or the phrase was produced slower than the mean speed of 300ms per letter within the trial. Analyses of chronometric data were performed on the final keystrokes of the first word, and the first four keystrokes of the second word. Trials were categorized as incorrect within the experiment, not post-hoc. For 3 out of 24 subjects, one trial block was incomplete resulting in a loss of 0.8% of the overall trials. To reach the overall accuracy threshold of the 3,048 correct trials, 5,535 trials were completed. Or the extra (recycled) trials, 2,158 were excluded within the experiment due to being typed incorrectly, and 329 trials were excluded due to being typed slower than 300ms/keystroke. Of the correct trials, trials that were outside 2 standard deviations from the mean of the keystroke location were treated as outliers and removed. This process occurred for each individual keystroke location. The analysis of location-specific response latencies was performed for Word End (WE, first word) and Word Initial (WI, second word) keystroke latencies. Prior to analyses, responses outside two standard deviations of the mean for each keystroke location were treated as outliers and removed. This resulted in 225 responses being removed for WE-2, 202 for WE-1, 223 for WE, 309 for WI, 244 for WI+1, 274 for WI+2 and 263 for WI+3.

Analyses were performed using linear regression mixed-effect models for all our analyses (lme4 package in R statistical computing software, Bates, Mächler, Bolker, & Walker, 2015). We tested separate models on keystroke latencies associated with 7 different letter locations – WE-2 to W1+2, as detailed in Figure 3. Keystroke locations were analysed separately and were log-transformed. A baseline (null) model was used containing random by-subject & by-item intercepts, and random by-subject slopes for the effect of RESYLL. This was compared to a model that included RESYLL. Models were compared with chi-square change tests.

As presented in Table 19, the analysis of the keystroke latencies demonstrated significant effects across the keystroke latencies in both words. Strong effects were found for the initial IKIs in the second word (Word Initial +1, Word Initial +2, Word Initial +3). WI +3 were significantly faster the in the RESYLL condition, whereas the opposite effect was found at WI +1 and WI +2 where responses were significantly slower in the RESYLL condition. No significant main effects were found at WI.

A weaker, albeit still significant, effect was found at the end of the first word. Keystroke latencies at WE were significantly faster in the RESYLL condition compared to the control condition. No significant main effects were found at WE-1 or WE-2.

Table 19: Analysis summary for Experiment 7

	M [95% CIs]				
Keystroke Latency	*RESYLL*	*Control*	*Difference*	χ^2	*p*
Word End -2	146 [132, 155]	150 [134, 159]	-4	.695	.405
Word End -1	157 [139, 167]	154 [138, 165]	3	.105	.746
Word End	140 [124, 149]	148 [133, 156]	-8	5.063	.024*
Word Initial	285 [244, 292]	290 [241, 292]	-5	.058	.809
Word Initial +1	177 [155, 190]	150 [134, 161]	27	26.285	<.001***
Word Initial +2	210 [187, 223]	175 [156, 187]	35	25.194	<.001***
Word Initial +3	164 [147, 176]	186 [169, 201]	-22	22.69	<.001***

Below a significance threshold of .05 ** Below a significance threshold of .01 * Below a significance threshold of .001*

χ2 values are for chi-square change relative to a null model in which the RESYLL condition is missing.

Discussion

In Experiment 7, it was found that keystrokes were slightly faster within RESYLL word pairs at the final keystroke of the first word, WE, the letter straddling the word boundary. Within resyllabification, this letter phonetically straddles the word boundary of both words to act as both the final coda of the first word and the onset of the first syllable in the second word. Words used in the first word of the word pairs were identical across conditions, ruling out the letter or letter-string frequency effects. Resyllabification occurs in the later stages of phonological/phonetic encoding, ruling out the effects being attributed as sub-lexical conversion effects. These findings suggest that the phonetic word influences the timing of motor execution.

Within the second word, the mean IKI's were significantly slower within the RESYLL condition, as supported by the majority of individual IKI comparisons across conditions. This suggests that motor execution is slowed following the word boundary where the resyllabification occurs. However, great caution must be taken in this instance, as the words used in the second word of the word pairs were not identical across conditions. Such variability in the IKI's may simply arise from the variability in the letters within the second word. The results demonstrated in the second word may be from letter-string frequency effects, previously demonstrated to affect IKI's (Pinet, Ziegler, et al., 2016). To accurately examine if resyllabification affects the motor execution of the second word in a pair, the second word should be as similar as possible across conditions.

Experiment 8

The effects found in Experiment 7 suggest that the timing of motor execution is modulated by the phonetic form. In the first word, the words were identical across conditions. Latencies were produced significantly faster within the RESYLL condition at the final keystroke. This is the location where the letter phonetically straddles across both word boundaries. To further strengthen the claim that the effects demonstrated in the first word are from the phonetic form, Experiment 8 shall investigate this claim by moving the location of the straddle point in the first word. The final consonant in the first word shall be followed by a silent-e. Effectively, the last two letters within the word straddle across the word boundary to act as the onset of the second word in the pair. For example, the *se* in *response ulcer*, would (phonetically) straddle across the word boundary due to the non-pronunciation of the silent-e.

Analysis of the second word demonstrated that keystroke latencies were produced significantly slower in the RESYLL condition. However, non-identical words across conditions. This allows for the possibility that the keystroke latency differences may arise due to differences in the letter or letter-string frequencies. Keystrokes may have been produced faster for higher frequency bigrams for example, as demonstrated in Experiments 3-5. To control for such letter-string frequency effects and further examine the pattern of results found in Experiment 7, Experiment 8 will match the second word of the word pair across conditions. RESYLL shall be manipulated via changes in the first word only. This will be the only variability across conditions.

The RESYLL condition will use two-word phrases such as *response ulcer* where the penultimate letter of the first word (WE-1, i.e., *s*) is resyllabified to straddle across the word boundary due to the non-pronunciation of the final letter of the first word (WE, *e*) in its phonetic form. In contrast, the control condition shall use words ending in pronounceable vowels (i.e. *cargo ulcer*) to control for resyllabification compatibility. The bigram frequency at the straddle point is controlled across conditions. Bigram frequencies are higher in the control condition (M=3677701 occurrences per 100 million words) compared to the RESYLL condition (M=1169814 occurrences per 100 million words).

Methods

Participants

Twenty-four undergraduate students from Nottingham Trent University participated in this study, none of which had previously participated in Experiment 7. All participants had normal or corrected-to-normal vision were native speakers of English and reported being experienced and competent typists. The same payment strategy and exclusion criteria were used as in Experiment 7. Participants received research credits for their participation as part of Nottingham Trent University's SONA Research Participation Scheme.

Materials

Sixteen four-word stimuli phrases were used. These were different to those used in Experiment 7. As in Experiment 7, each phrase consisted of a RESYLL word pair and a control word pair. RESYLL word pairs differed to the control word pairs on the first word only. The second word in each pair was matched across conditions, all beginning with a vowel onset. The first word in all word pairs ended with a consonant followed by a vowel. In the RESYLL word pairs, the final vowel/letter was always the letter *e* (i.e., *expense*). In the control word pairs, an alternative vowel (i.e., *a, i, o, u*) was used as the final vowel/letter (i.e., drama). Examples are provided below in Table 20 (see Appendix 2 for all stimuli for Experiment 8).

Table 20: Example of the counterbalanced order of presentation for experimental stimuli in Experiment 8

Counterbalanced order of presentation	
Order 1	RESPONSE ULCER CARGO ANGER
Order 2	RESPONSE ANGER CARGO ULCER
Order 3	CARGO ULCER RESPONSE ANGER
Order 4	CARGO ANGER RESPONSE ULCER

Additional controls were taken to control for potentially confounding influences such as the frequency of the bigram (2-letter combination) at the straddle point in the first word. Bigram frequencies were higher in the control condition (M=3,677,701 occurrences per 17.2 million words) compared to the RESYLL condition (M=1,169,814 occurrences per 17.2 million words). The same counterbalancing strategy of the stimuli was employed as in Experiment 7.

RESYLL	***E***	***X***	***P***	***E***	***N***	***S***	***E***		***O***	***N***	***I***	***O***	***N***
Keystroke Location					***Word End -2***	***Word End -1***	***Word End***	***SPACE***	***Word Initial***	***Word Initial +1***	***Word Initial +2***	***Word Initial +3***	
Control			***D***	***R***	***A***	***M***	***A***		***O***	***N***	***I***	***O***	***N***

Figure 4: Word-End and Word-Initial keystroke locations with example stimuli across conditions in Experiment 8.

Design & Procedure

The same design and procedure were employed as in Experiment 7.

Results

Statistical analyses were performed in the same manner as Experiment 7. For 2 of the 24 participants, 1 trial block was incomplete, resulting in a loss of 0.5% of the overall trials. To reach the overall accuracy threshold of the 3,056 correct trials, 7,496 trials were completed. Overall, 3,743 trials were excluded within the experiment due to being typed incorrectly, and 697 trials were excluded within the experiment due to being typed slower than the mean keystroke rate of 300ms/keystroke.

The analysis of location-specific response latencies was performed for Word End (WE, first word) and Word Initial (WI, second word) keystroke latencies. Prior to analyses, responses outside two standard deviations of the mean for each keystroke location were treated as outliers and removed. This resulted in 225 responses being removed for WE-2, 202 for WE-1, 223 for WE, 309 for WI, 244 for WI+1, 274 for WI+2 and 263 for WI+3.

As presented in Table 21, the analysis of the keystroke latencies demonstrated significant effects across the keystroke latencies, similar to those observed in Experiment 7. Despite identical words being typed across conditions, while also controlling for participant effects, the IKI's are significantly slower in the RESYLL condition. Motor execution appears to be slowed in word pairs in the RESYLL condition, strong significant effects were observed within the IKIs of the second word. WI +1, WI +2, and WI +3 were all significantly faster in the control condition compared to the RESYLL condition. As was the case in Experiment 7, no significant effects were found at the onset latency of the second word (WI).

Within the IKIs of the first word, a smaller, but still significant, effect was found at WE -1, whereby latencies were significantly faster in the RESYLL condition. The analysis at WE and WE-2 found no significant effects.

Table 21: Analysis summary for Experiment 8

	M [95% CIs]				
Keystroke Latency	*RESYLL*	*Control*	*Difference*	χ^2	*p*
Word End -2	182 [163, 200]	179 [159, 190]	3	1.964	.161
Word End -1	157 [141, 169]	169 [152, 177]	-12	4.703	.03*
Word End	161 [139, 169]	160 [143, 167]	1	.093	.76
Word Initial	322 [265, 336]	314 [261, 328]	8	.992	.319
Word Initial +1	187 [168, 200]	177 [157, 189]	10	5.189	.023*
Word Initial +2	208 [189, 223]	200 [180, 212]	8	7.011	.008**
Word Initial +3	168 [151, 177]	159 [143, 169]	9	6.982	.008**

*Below a significance threshold of .05 ** Below a significance threshold of .01 *** Below a significance threshold of .001

χ2 values are for chi-square change relative to a null model in which the RESYLL condition is missing.

Discussion

Analysis of the first word found a replication of the pattern of keystrokes demonstrated in Experiment 7. The straddle point, the letter that straddles the two word boundaries, was produced significantly faster in the RESYLL condition. More importantly, the use of stimuli ending with a silent-e meant that the straddle point was moved forward by a letter. Despite the adjustment in location, we replicated the same effect as in Experiment 7. When the location of the straddle point was moved to the penultimate letter in the first word (WE-1), the latencies in the RESYLL condition were significantly faster at that location compared to the control condition. This further supports the claim that the motor execution of the keystroke is influenced by the phonetic form.

It appears as though the motor execution of the keystrokes is influenced by the phonetic form of the word pair. As discussed above, move the phonetic location of the straddle point moved the location where the straddle point influences the keystroke latencies in the first word. Furthermore, we must also consider how the form of the silent-e varies phonetically to the orthographic form typed on the keyboard. The silent-e is still overtly typed, so is still prepared and executed at the motor level. Yet, the silent-e is not available in a phonetic form. Essentially, if the observed results were not as a result of the phonetic form we would not expect to see the location of significance move (compared to Experiment 7) as an influence of silent-e manipulation as the silent-e is not silent orthographically.

The second word analyses also supported the pattern demonstrated in Experiment 7. Following the straddle point where resyllabification occurs, the IKI's of the second word in a pair demonstrates significantly slower keystrokes. Importantly, this experiment matched the second word across conditions. Despite identical words being typed across conditions, while also controlling for participant effects, the IKI's are significantly slower in the RESYLL condition. Motor execution appears to be slowed in word pairs in the RESYLL condition.

General Discussion

There were two aims for the present study, the first of which is to examine if the time-course of typewriting is influenced by inner speech. When writing or typewriting, the preparation of the spoken form of the words run in parallel. Early stages of processing can even assist in preparing the spelling of a word to be written or typed (see Bonin et al., 2015). There is scarce evidence to suggest that the fully prepared spoken form may affect the time-course of typewriting. It is plausible for there to be some influence as the majority of us will be familiar with the internal monologue we may hear when typewriting. It is conceivable that the internal monologue may have some influence. The problem faced in examining inner speech is that it is difficult to determine if earlier stages of processing are affecting performance or the late phonetic form of inner speech. By manipulating the CV-status of the letters surrounding the word boundary of adjacent words in a word pair, it was possible to manipulate the phonetic structure of a word pair while maintaining the normal orthographic structure to be typed. Manipulating the phonetic structure allowed for the examination of inner speech influences. The phonetic manipulation only occurs at the late stage of phonetic encoding where inner speech would be influenced. Importantly, this phonetic manipulation occurs after the sub-lexical stage of processing where phonological information can assist in preparing the spelling of a word (see Bonin et al., 2015).

The second aim of the present study was to examine if lower motor levels of processing are informationally encapsulated in typewriting. It has previously been argued that the motor level, responsible for motor preparation and execution, is informationally encapsulated. The motor level should not be influenced by processes external to the motor level. In particular, the execution of keystrokes should not be influenced by the phonetic structure of the previous word. The manipulation of the CV-status of the letters surrounding the word boundary allowed for examining if the motor level is informationally encapsulated. Words are prepared one at a time in typewriting (see Logan & Crump, 2011). Yet, manipulating the phonetic relationship between two words allows for an examination of how information from an alternative word may affect the time-course in which the motor level executes the prepared keystrokes.

In two experiments, the CV-status of the letters surrounding the conjoining word boundary of a word pair was manipulated to affect the word pair's phonetic form. This was based on the principles of resyllabification where the syllable structure can be re-adjusted across a word boundary. Within speech production processes, the syllable structure of words may be adjusted (resyllabified) to aid the pronunciation of word combinations. A vowel onset of a word is highly sonorous, and as such, is not as easily pronounceable as when a consonant proceeds it within the syllable. Resyllabification would see, where possible, a consonant at the end of the proceeding word straddle across the word boundary and act as both the final coda of the first word and obligatory onset of the second word (Khan, 1976). For example, *'product onion'* would see the *t* straddle across both word boundaries in this manner. This principle was employed in both experiments.

For resyllabification to occur across the word boundary, the first word ended in a consonant that is able to straddle across the word boundary. In both experiments, the final consonant in the first word was typed significantly faster compared to the control conditions. Within Experiment 7 this occurred at *WE* where the *T* in *concepT oscar* straddles the word boundary and acts as both the coda to the first word and onset to the second word. Within Experiment 8, we employed a silent-e paradigm. The effect occurred at *WE-1* whereby the *C* in *violenCe angel* straddles the word boundary and acts as both the coda to the first word and onset to the second word. It should be noted that within Experiment 7, the first word was matched across conditions with the phrase being manipulated by the second word only. As a result, this appears to be a robust effect as participants are typewriting identical words across conditions, yet there is still a significantly faster IKI at the straddle point compared to the control condition. Furthermore, the effect was replicated within Experiment 8 despite the location of the final consonant being moved within the word as a result of utilising words ending in a silent-e. This also further suggests such an effect is from inner speech as the e is silent within a phonetic form, whereas the e takes a typical form within its orthographic form, as evidence by being overtly typed.

The second word follows the straddling of the final consonant in the first word. Experiment 7 demonstrated that the initial keystroke latencies after the onset latency were significantly slower compared to the control condition. These findings were initially met with caution, as different words were used across conditions. However, when matching the second word across conditions in Experiment 8, the same pattern of results was found. This is another robust effect of manipulating the phonetic form. Typists were typewriting identical words across conditions, with the only variation being the CV-status of the final letter in the previous word. The time-course of typewriting is influenced by the phonetic form of the words being typed.

Does inner speech influence the time-course of typewriting?

The pattern of results from Experiments 7 and 8 demonstrate that the time-course of typewriting is influenced by manipulation to the CV-structure across the word boundary of word pairs. This appears to be an influence of inner speech. To authenticate this claim we must first consider if the findings are a reflection of phonological processes. Also, if this is the case, we must also consider if the results occur as a result of the phonological form providing the spelling of the words to be typed. For inner speech to be influencing the time-course of typewriting, there must be a clear late phonological/phonetic effect.

First, let us consider the experimental manipulation utilised in Experiments 7 and 8 in their simplest form. The CV-status of the letters surrounding the word boundaries of a word pair were manipulated. If phonology did not influence the time-course of typewriting in the present experiments, manipulations to the CV-status across the word boundary should not affect the time-course of typewriting. In typewriting, words are prepared one at a time (see Logan & Crump, 2011), where spelling processes pass one word to the motor level. The letters/keystrokes with a singular word are then prepared at the motor level. As within typical typewriting, Experiment 7 and 8 demonstrated that the onset latencies of each word are dramatically larger than the following keystrokes within a word. The dramatically larger latency at the first keystroke within a word reflects the preparation of the full word and execution of the initial keystroke (Pinet, Ziegler, et al., 2016; Snyder & Logan, 2014). If word pairs were planned together, the onset latency of the first word in a pair would be slower but the onset latency of the second word in the paid should not be if the second word is already prepared. It appears as though we can rule out the possibility of the results occurring as a result of the orthographic preparation of the word.

Considering what the manipulation to the CV-status across the word boundary is deemed to reflect, the observed findings must be as a result of phonetic influences that do not affect the generation of the spelling. The manipulation of the CV-status in the present experiments allowed for resyllabification in the RESYLL condition but not in the control condition. Resyllabification, the late phonetic stage of processing (see Levelt et al., 1999), is not required in typewriting. In speech, it occurs to aid pronunciation of adjacent words in connected speech by re-adjusting the syllable boundaries of the words within a phrase to be articulated. There is no benefit or requirement for the re-adjusting of syllable structures in typewriting. Instead, the earlier abstract phonological form can be used to assist in the generation of the spelling of a word (see Bonin et al., 2015).

Importantly, the pattern of results observed in Experiments 7 and 8 provide overwhelming support that the findings are as a result of phonological/phonetic influences. These phonological/phonetic influences are not a reflection of the preparation of the spelling of the word. Instead, they affect the time-course of production after the spelling has already been made available to the motor level. But how is this clear from the observed pattern of results? As discussed previously, the results support the concept that the manipulation of the CV-status across the word boundary allowed for the phonetic form of the word pair to be adjusted via resyllabification. The final consonant within the first word straddles across the word boundary to act as the onset of the initial syllable within the second word. By moving the location of the final consonant in the first word of the pair, it was possible to examine if the observed results are a reflection of phonetic effects. In Experiment 8, the final consonant in the first word was followed by a silent-e (in the RESYLL condition). Despite moving the location of the final consonant from WE in Experiment 7 to WE-1 in Experiment 8, the final consonant was typed significantly faster in the RESYLL condition, as done previously in Experiment 7. The silent-e paradigm allowed for the silent-e to not require processing in a phonetic form, as it is not pronounced phonetically. Yet, the silent-e is effectively not silent in an orthographic form or as a motor representation. The e still needed to be prepared and typed. This tells us two things, firstly, the significant effect observed at the final consonant in both experiments is a reflection of phonetic processes. Secondly, the phonetic processes do not provide the spelling of the words to be typed otherwise the silent-e would not have been typed. Instead, the spelling must have been generated from stored orthographic knowledge of the words (see Bonin et al., 2015). Clearly, the observed pattern of results is a clear reflection of phonetic processes running in parallel during typewriting.

Does the inner loop run to completion without interference from other (e.g. phonemic) representations?

As discussed in the previous section, the findings reflect the manipulation of the phonetic form of the word pair. The findings have so far been explained in relation to inner speech affecting the time-course of typewriting. There are also clear ramifications concerning the information encapsulation of the inner loop. Analyses of the first word in the word pairs demonstrated that final consonant was produced significantly faster compared to the control condition. At the point in which the final consonant straddles across the word boundary of the adjacent word, the final consonant is executed significantly faster. At this point within the word, the keystroke latency is a reflection of motor execution. The outer loop prepares the word to be typed before the initial keystroke (Logan & Crump, 2011). Assuming the phonetic form does not reside within the outer or inner loop, the execution of the final consonant in the first word was speeded by the phonetic information that is external to the inner loop.

There is further support that the inner loop is not informationally encapsulated from the analyses from the second word in the pair. In both experiments, the initial keystrokes after the onset latency were produced significantly slower compared to the control condition. As stressed previously, this occurred even when the second word was always identical across conditions (Experiment 8). The only difference across conditions is that the RESYLL condition is borrowing the final consonant from the first word as its onset, whereas the control condition is not. It is argued that "if the movements match intentions, typewriting should remain fast and fluent. If there is a mismatch, typewriting should slow down or stop" (Logan & Crump, 2011, *p*. 17). The likely explanation for the slowing of the keystrokes in the second word is that the inner loop is forced to slow down performance in response to the mismatch between the available phonetic form of the word and the prepared word to be typed. For example, when typewriting the word pair *response ulcer*, the orthographic representation of *ulcer* is prepared to be typed, but this differs to the phonetic form of *s[e]-ulcer* (pronounced *sulcer*) that is also available.

If the slowing of the keystrokes in the second word occurs as a result of the mismatch between the phonetic form and the prepared orthographic form, one of the loops must have intervened and slowed down the speed of typewriting. One possibility is that once an error is observed, or in this case, a mismatch in the information available is observed, the outer loop takes control and instructs the inner loop what to do next. Before instructing the inner loop what action must be taken, the outer loop may slow down the typewriting speed to monitor the keys being executed. If an error is made, this would involve instructing the inner loop to stop typewriting, press the backspace key and then resume typewriting.

There is support for the concept that the outer loop intervenes and instructs the inner loop what to do next. Kalfaouglu and Stafford (2014) found that typewriting errors were corrected even when the outer loop does not receive visual feedback from the screen. They interpreted their findings as evidence that the outer loop can access feedback from the inner loop (kinaesthetic and proprioceptive feedback) in order to create a new plan of action to correct errors. This support for the inner loop not being informationally encapsulated varies dramatically to the present experiments. Kalfaouglu and Stafford's (2014) study shows that outer loop is able to access the proprioceptive and kinaesthetic feedback mechanisms contained within the inner loop. In contrast, in the present experiments, participants were able to view the words being typed, so the visual feedback associated with the outer loop was accessible.

However, it is possible that the inner loop slowed down the time-course of typewriting. According to Glover's (2004) model of movement organisation, during the execution of the movements, an online control system monitors and adjusts (where necessary) the motor program on the fly. It is possible that phonetic information, most likely via inner speech, is accessible to an online control system within the inner loop. Figure 5 provides a schematic illustration of how an online control system mediates the time-course of typewriting based on information made available to the inner loop. The outer loop prepares an abstract spelling of a word to be typed, one by one. This is then utilised by the inner loop to create a motor plan to be typed. After typewriting the initial keystroke within a word, the online control system monitors the keys being typed.

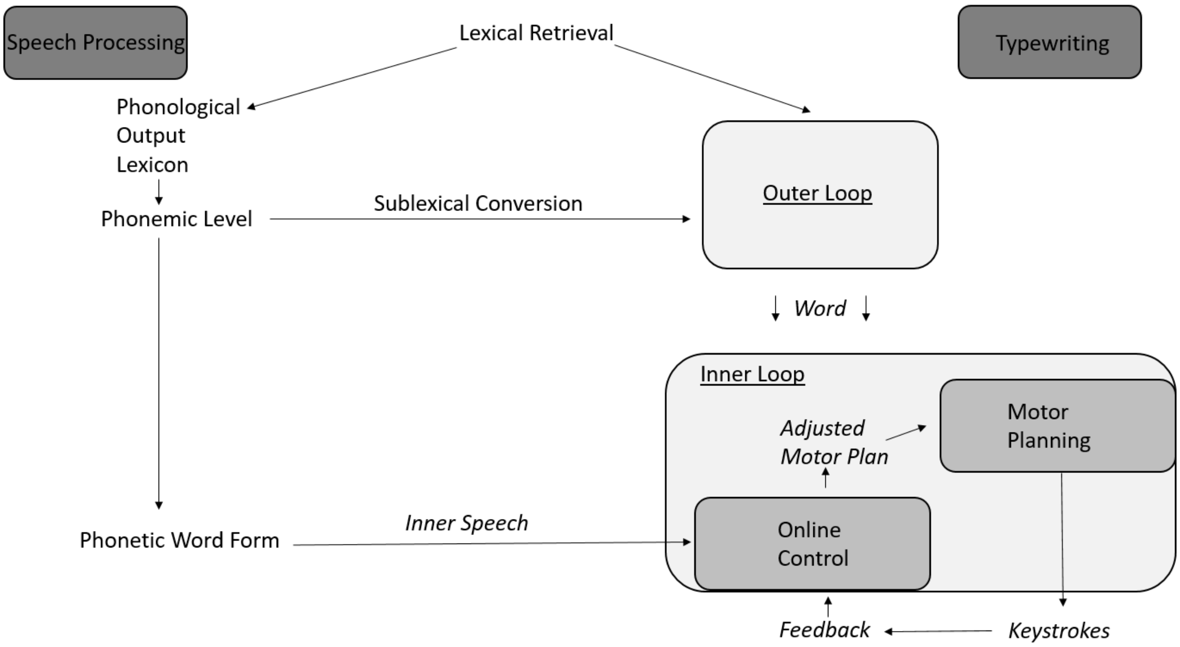

Figure 5: A visual representation of the two-loop model being mediated by phonetic interference via online control.

These results offer two distinct possibilities for how motor production is influenced by the phonetic information of the word-pairs. Either a non-informationally encapsulated inner loop can access the phonetic information and adjust the speed of typewriting where necessary in response to the information. Alternatively, this information may instead be accessed by the outer loop, which then instructs the inner loop to adjust the speed of typewriting. Without being able to differentiate between these two possibilities, these results can only imply that the inner loop may be informationally encapsulated. At the point of writing this thesis, research examining resyllabification, particularly how it impacts upon orthographic modalities such as typewriting, is in its infancy. Keystroke execution via the inner loop is significantly affected by the phonetic information of word-pairs. However, it is not yet known whether the phonetic relationship of the word pairs influence the outer loop, the inner loop, or both.

Conclusion

In both experiments, there was a clear demonstration of the time-course of typewriting being influenced by resyllabification. Manipulating the consonant-vowel structure of the letters at the word boundary of two adjacent words affects if the phonetic syllable structure is adjusted to span across two adjacent words. This was clearly demonstrated in both experiments with an almost identical pattern of results. When resyllabification occurs, the keystrokes following the word boundary are significantly slowed compared to the control condition. Furthermore, the final consonant in the first word, which effectively acts as part of the first syllable in the following word, is significantly faster compared to the control condition. Even when moving the location of the final consonant when following it with a silent-e, the consonant was significantly faster compared to the control condition despite moving the location of the effect. Both patterns of results occurred even when identical words were used across conditions.

5. General Discussion

The aim of the research was to examine if the time-course of typewriting is influenced by sub-word processing units. Across eight experiments, four different questions were examined: (1) if sub-word graphemic representations larger than single letters are passed to the motor level; (2) if frequently used letter combinations are stored as retrievable motor-chunks; (3) if the inner loop runs to completion without interference from other (e.g. phonemic) representations; and (4) if the time-course of typewriting is affected by inner speech.

5.1. Are sub-word graphemic representations larger than single letters passed to the motor level?

This thesis examined if sub-word graphemic representations larger than single letters are passed to the motor level. Theoretical accounts of typewriting argue that only words or individual letters are passed to the motor level/inner loop (Logan & Crump, 2011). It is not disputed that words and letters are important processing units in typewriting. However, sub-word representations (i.e. syllables) play important roles in the generation of handwriting (Kandel et al., 2011; Kandel et al., 2006; Lambert et al., 2008; Kandel et al., 2009; Alvarez et al., 2009; Kandel & Valdois, 2006). Considering the similarities between typewriting and handwriting, sub-word graphemic representations (i.e., letter chunks) may be available to be passed to the motor level when familiar words are unavailable.

A tightly controlled experimental paradigm was employed across six experiments in which participants learned the associations between the location on the screen (left or right) and stimuli pairs. When the association was correctly learned, any confounding influences from reading the stimuli, which may be influenced by letter-string frequency (e.g., Solomon & Postman, 1952), were removed. Instead, the presentation of a rectangular prompt in one of the two locations cued the initiation to type the learned letter-strings.

Experiments 1 and 2 demonstrated that the time taken to initiate the first letter is significantly affected by the frequency of the letter combination, not the frequency of the initial letter. When controlling for the frequency of the initial letter, typists were faster to initiate typewriting for letter combinations with higher trigram and initial bigram frequencies. The onset latency is a reflection of the time taken to retrieve the spelling, prepare the initial motor representation and execute the initial keypress (Pinet, Ziegler, et al., 2016; Snyder & Logan, 2014). This involves very little processing at the motor level and is mainly considered a reflection of pre-motor level preparation (Logan & Crump, 2011).

If individual letters were passed to the motor level as letter-sized graphemes, the onset latencies would signify the preparation and execution of the initial keystroke only. As letter frequencies were matched across conditions, there should be no difference to execute the initial letter whether it is part of a high-frequency letter-string or a low-frequency letter-string. These two experiments provide clear evidence that the outer loop passed a graphemic letter-chunk to the motor level.

The findings in Experiments 3 & 4 failed to replicate the frequency effect at the onset latency observed in Experiments 1 and 2. Manipulation to trigram frequency (and the final bigram) does not provide significant frequency effects at the onset latency. Similarly, the frequency of a bigram when typing alone bigrams does not provide significant frequency effects at the onset latency either. In both experiments, the direction of the effect supported the findings in Experiments 1 and 2 as the onset latencies were faster in the high-frequency conditions. Though, these are weaker effects, so failed to reach significance. Importantly, the non-significant frequency effects at the onset latency in Experiments 3 and 4 do not contradict the findings in Experiment 1 and 2. Neither do they support an account in which only single letter graphemes are passed to the motor level.

It is also worth considering that if single letter graphemes are prepared and passed to the motor level separately, there should be no effect of bigram or trigram frequency anywhere within the trigram. Experiments 3, 4, and 5 provided further indications that sub-word graphemic representations larger than single letters are passed to the motor level. When individual letter frequencies are controlled across conditions, there are clear bigram frequency effects where the second keystroke of the bigram was significantly faster for higher-frequency bigrams. In Experiment 4, typists were required to type individual bigrams. Even when the initial letter frequency was the same across conditions, and the second letter frequency was marginally higher in the low-frequency bigrams, high-frequency bigrams were produced significantly faster. The same pattern of results was observed in Experiments 5 where the second keystroke of high-frequency bigrams was significantly faster than low-frequency bigrams in the initial bigram of low-frequency trigrams.

These bigram frequency effects are most likely reflections the performance of the motor level, such as preparing/retrieving the motor representations and executing the keystrokes (see Logan & Crump, 2011). If individual letter graphemes were passed to the motor level, they should also be processed end executed by the motor level individually. The execution of the keystrokes should not be influenced by bigram frequency unless the bigrams (or greater) are passed as chunked graphemic letter combinations to the motor level.

Experiment 6 demonstrated similar evidence to Experiments 1 and 2. When controlling letter frequencies across conditions, both the frequency of the letter combinations within the letter-strings and the CV-status of the letter-strings affected the time taken to initiate the initial keystroke. Interestingly, and importantly, the initial letters were identical across experimental conditions. Not only is there no difference across conditions for the frequency of the letter, but there is no potential influence of key location affecting the distance between fingers and keys across conditions. The significant difference in onset latencies across conditions is from manipulation to the CV-status and letter combinations within the letter-strings only. The influence of letter-string frequency replicates the findings in Experiments 1 and 2. More than the initial letter was prepared before the onset of typewriting. Otherwise, the onset latency would not be influenced by manipulations to the frequency of the letter combinations.

Furthermore, this is supported more by the significant influence of the CV-status of the letter strings. If only the initial letter was prepared (pre-motor level preparation) before the onset of typewriting, the CV-status should not affect the onset latencies as the initial letters are always consonants in both conditions. It is only at the second letter where the CV-status of the letter-string is manipulated. This allows for a similar interpretation as the manipulation of the frequency of letter combinations. More than the initial letter was prepared. Otherwise, the onset latency would not be influenced by manipulations to the CV-status of the second letter. Interestingly, this also indicates that the phonological form of the letter-string, via the CV-status of the second letter, affects the time to initiate the initial keystroke. The main distinction between the CVC and CCC letter-strings is the pronounceability of the letter-strings. Those containing a vowel are pronounceable and allow for phonological processing to assist in the generation of the spelling. This could explain the faster keystroke latencies for CVC letter-strings compared to CCC letter-strings. During pre-motor level preparation, the graphemic representations can be prepared from both direct orthographic processing via the lexical route, but also, the CVC letter-strings may also be prepared from phonological conversion via the sub-lexical route, which may be faster. An influence of the phonological form of the letter-string at the first letter provides further validation that sub-word graphemic representations greater than individual letters can be passed to the motor level.

Overall, Experiments 1-6 provide clear indications that when an unfamiliar word is unavailable, sub-word preparation is not restricted to passing individual letter graphemes to the motor level one at a time. It appears that sub-word letter chunks can be prepared as a single chunked graphemic representation. Pre-motor level preparation, as indicated by the onset latency durations, is influenced by the frequency of letter-combinations within the letter-strings (Experiments 1, 2, and 6), as well as the CV-status of the second letter of the letter-strings (Experiment 6). Beyond the onset latency, motor level performance, as indicated by the IKIs, is significantly affected by bigram and trigram frequency (Experiments 3-5). Chronometric indicators of the pre-motor level preparation and motor level performance show supporting evidence that sub-word graphemic representations larger than a single letter are passed to the motor level when familiar words are unavailable.

5.2. Are frequently used letter combinations stored as retrievable motor-chunks?

The implementation of the symbol-position association learning task allowed for a stringent experimental paradigm. Stimuli were presented as associated locations on the screen, preventing confounding influences from reading the letter-strings. Furthermore, the stimuli were only associated with a location by visual instructions and memory. Participants were prevented from typewriting the letter-strings when learning the associations. Only during experimental trials were the letter-strings typed. This ensured that the experimental paradigm did not influence the availability of potentially stored motor chunks. These measures, along with well-controlled stimuli allowed for direct comparisons high- and low-frequency letter-strings. By comparing the keystroke latencies across conditions across six experiments, subtle manipulations to the frequency of letter combinations were examined.

Experiments 3, 4, and 5 demonstrated that IKIs were affected by the frequency of letter combinations when individual letter frequencies are controlled across conditions. The second letter of high-frequency bigrams was produced significantly faster than their low-frequency counterparts. This was demonstrated when typewriting alone bigrams (Experiment 4), and within the first bigram position (Experiment 5) when typewriting trigrams. A faster keystroke for the second letter within high-frequency bigrams supports an account in which motor chunks are retrieved for familiar (high-frequency) bigrams, but motor representations are retrieved/prepared and then executed individually for single letters/keystrokes when stored motor chunks cannot be retrieved (infrequent/low-frequency letter combinations). The second keystroke is faster in high-frequency bigrams because the motor representation has already been retrieved in advance, so additional motor preparation is required at the second letter of the low-frequency bigrams. For example, when comparing *GH* (high-frequency bigram) and *GT* (low-frequency bigram), *GH* can be retrieved as a single motor chunk containing the motor representations for both letters, meaning that once the initial letter *G* has been typed, the second letter *H* already has a motor representation prepared. In contrast, the low-frequency bigram of *GT* does not have a stored motor chunk that can be retrieved, meaning that once the initial letter/keystroke has been typed, the motor representation of the second letter (i.e., *T*) still requires some additional preparation time.

Additionally, the findings from Experiment 3 suggest that motor chunks can be retrieved for both frequent bigrams and frequent trigrams. Experiment 3 manipulated trigram frequencies across conditions via the manipulation of the frequency of the second bigram. The first bigram was matched across conditions. When typing high- (i.e., *GHT*) and low-frequency (i.e., *GHF*) trigrams that contain the same initial high-frequency bigram, the keystroke latencies for the final letter (second IKI) was produced significantly faster in the high-frequency condition. The significant findings at the second IKI suggest that motor preparation is not completed for the final letter in the low-frequency condition. One possible explanation is that the motor representations for the letters within the high-frequency trigram can retrieved as a single trigram-sized motor chunk, whereas only the initial high-frequency bigram can be retrieved as a motor chunk in the low-frequency trigrams. This results in additional motor preparation being required in the low-frequency condition for the final keystroke. These findings are consistent with an account in motor representations are executed as soon as they are available, and motor chunks can be retrieved for frequent letter combinations.

The findings in Experiment 5 indicate that the bigram frequency effects consistently observed in this research represent evidence of motor chunking rather than speeded finger selection. Experiment 5 contained trigrams with high-initial and low-final bigram frequencies, or trigrams containing the opposite, low-initial and high-final bigram frequencies. Analyses of keystroke latencies within the initial bigrams across conditions replicated the same bigram frequency effect observed in Experiments 3 and 4. The second letter of the high-frequency bigrams were produced significantly faster than the low-frequency bigrams. However, this pattern did not emerge when comparing the final bigrams. There was no difference across conditions for the second letter within the final bigrams.

Interestingly, any alternative explanation for bigram frequency effects (i.e., faster finger selection) where motor representations for all keystrokes are prepared in advance does not accommodate for incremental motor retrieval. This pattern of results is compliant with the concept that motor chunks are retrieved one at a time incrementally. For example, in trigrams with a high-low bigram frequency structure such as *FLR*, the *FL* is a retrieved before typewriting the initial letter, allowing for the motor representation of *R* to be retrieved in advance before or during the second letter (i.e., *L*) is being executed. The low-frequency bigram within the high-low condition may benefit from incremental motor retrieval. The second keystroke within the final bigram is no different across conditions as it has already been retrieved in advance as part of a motor chunk in the low-high condition. Similarly, it has already been retrieved in advance as a result of incremental motor retrieval in the high-low condition.

Overall, the present research demonstrated clear frequency effects associated with inner loop processing. In particular, the second keystroke within high-frequency bigrams was frequently found to be significantly faster than comparative low-frequency bigrams. There are arguments made that these results indicate the available retrieval of stored motor chunks for frequently typed bigrams.

5.3. Does the inner loop run to completion without interference from other (e.g. phonemic) representations?

The third experimental question of this thesis examined whether the inner loop runs to completion without interference from other (e.g. phonemic) representations. In the context of the two-loop theory of typewriting (Logan & Crump, 2011), it is argued that the inner loop is informationally encapsulated. The outer loop passes information to the inner loop as input, and movements are executed by the inner loop as output. With the exception of the input and output of the inner loop, the inner loop does not need to access any additional information that it is not related to the movements being executed. No additional sharing of information external to the inner loop is required. This seems logical as any additional processing will likely slow the speed of production, and as we know, keystrokes are executed rapidly for expert typists.

One of the key explanations for the information encapsulation of the inner loop is that the outer loop does not know what is happening in the inner loop. The outer loop does not know which hands type which letters on a keyboard (Logan & Crump, 2009), and also does not know the location of the letters on the keyboard (Liu et al., 2010). However, if the inner loop is informationally encapsulated, it will not be limited to the outer loop accessing information within the inner loop. An informationally encapsulated inner loop should arguably only have external access to information regarding the word representations sent from the outer loop, as well as the kinaesthetic and proprioceptive feedback of the movements during execution. Fundamentally, the performance of the inner loop should not be affected by information external to the two loops.

However, as discussed previously, previous research has provided mixed interpretations. There is evidence to suggest that the outer loop is unable to access information within the inner loop (Liu et al., 2010; Logan & Crump, 2009). Yet, there is also evidence to suggest that the outer loop is able to access alternative sources of information contained within the inner loop (i.e. Pinet & Nazari, 2018; Pinet, Ziegler, et al., 2016; Cerni et al., 2016; Kalfaoğlu & Stafford, 2014). The debate regarding whether the outer loop can access information contained within the inner loop is ongoing. There is a poorer understanding of how motor preparation and execution from the inner loop is influenced by information external to the two loops. It is within this context that this thesis examined the extent to which the inner loop is informationally encapsulated.

Experiments 7 and 8 examined how manipulations to the CV-status across the word boundaries of adjacent words affects the time-course of typewriting. One reason for this manipulation was to examine if the time-course of typewriting is affected by manipulations that only manifest during inner speech, as discussed above. This also allowed for a new and novel method of examination concerning the information encapsulation of the inner loop. As singular words are argued to be passed from the outer loop to the inner loop (Logan & Crump, 2011), typewriting research typically has not examined how motor processing and production is affected by manipulations to adjacent word boundaries. Outer loop processing sends independent word representations to the inner loop one at time. Experiments 7 and 8 demonstrated that the manipulation to the CV-status across the word boundaries of two adjacent words significantly affects the time-course of typewriting.

By manipulating the CV-status at the word boundaries of word pairs, it was possible to manipulate the phonetic susceptibility to the late phonetic stage of resyllabification. In speech production, the syllable structure of two adjacent words can be adjusted to avoid the initial syllable of a word commencing with a vowel. Using an example from Experiment 7, *product onion* can be resyllabified to allow for the *t* in *product* to phonetically straddle the word boundary and act as the onset to the word *onion*. The experimental conditions were based upon the principle that the final consonant in the first word may straddle across the word boundary when the second word commences with a vowel onset. In both experiments, this principle was employed in an experimental condition termed Resyll. In contrast, a control condition was used for comparison that prevented resyllabification from occurring. This was done by adding a pronounceable vowel at the end of the first word (Experiment 8) or by adding a consonant at the beginning of the second word (Experiment 7).

Experiments 7 and 8 both demonstrated that the keystroke latencies within a word are affected by the phonetic relationship of the word pair. The final consonant of the first word in the pair is significantly faster in the Resyll condition compared to the control condition. As discussed above regarding influences of inner speech, rigorous experimental controls allow us to be confident that this is from influences of the phonetic manipulations. The first words used in the stimuli were identical across conditions. As words are prepared one at a time (Logan & Crump, 2011), there is no difference across conditions except for the phonetic relationship across the word boundary.

Furthermore, the use of a silent-e at the end of the words in the Resyll condition in Experiment 8 demonstrated that even when the final consonant moves location, the effect still occurs. The final consonant is significantly faster compared to the control condition. This demonstrates that the significant effect is related to the final consonant that is argued to phonetically straddle across the word boundary. Furthermore, it also provides clear support that it must be a phonetic effect as the silent e is only ignored phonetically; it is still prepared and typed orthographically and at the motor level.

The analyses in Experiments 7 and 8 provide further considerations regarding the information encapsulation of the inner loop via the analyses of the second word in the word pairs. The initial keystrokes after the onset latency were significantly slower in the Resyll condition compared to the control condition. These findings were originally met with caution in Experiment 7 as the manipulation of the word pair stimuli occurred at the second word in each pair, meaning that the second word differed across experimental conditions. However, Experiment 8 resolved this concern as the manipulation of the word pair stimuli occurred in the first word instead, allowing for the same words to be used in the second-word location across conditions. Even when typists were typewriting the same words across conditions, Experiment 8 demonstrated the same pattern of results as Experiment 7. The initial few keystrokes after the onset latency were significantly slower than the control condition.

Upon initial inspection, the pattern of results appears to demonstrate that the inner loop must not be informationally encapsulated. The keystroke latencies affected occur after the onset latency where the spelling is prepared. The IKIs affected reflect motor execution processes of the inner loop (Logan & Crump, 2011). It appears that the motor execution process of the inner loop is affected by the available phonetic information of the word pair. Consider that the phonetic information of the word pair is not associated with either the inner or outer loops. It appears as though the performance of the inner loop is affected by the availability of information external to the two loops. Thus, suggesting that the inner loop must not be informationally encapsulated.

However, the claim that the inner loop is not informationally encapsulated hinges on the argument that the phonetic information is not known to be empirically associated with either the inner or outer loops. The problem with this is that the lack of an association may arise because of the lack of similar research. With no known previous research examining the effect of the phonetic relationships of words affecting the time-course of typewriting, it is not known how phonetic information is involved with either the outer loop or inner loop. It is possible that the phonetic information is made available to the outer loop, which in turns instructs the inner loop to slow down or speed up the rate of typewriting. While the phonetic information may also be directly accessed by the inner loop.

Looking ahead, future research is required to examine how the availability of phonetic information affects the inner loop. The findings in Experiments 7 and 8 are some of the first to demonstrate that the time-course of typewriting is influenced by the availability of phonetic information. The lack of similar research makes it difficult to interpret whether the phonetic information is accessed directly by the inner loop or not. It is possible that the outer loop accesses the phonetic information and the time-course of typewriting being influenced by the phonetic word forms is a by-product of the outer loop instructing the inner loop to slow down or speed up. The next step is to attempt to differentiate between the possibility that the phonetic information is available to the inner loop or the outer loop. If the information is accessible to the outer loop, it may be utilised during the visual monitoring of the letters being typed on the screen. It is possible that the phonetic form of the words could be used as a comparison to the visual information being read on the screen. This could be explored in future research. These results could lead to further research on how inner speech affect the time-course of typewriting. It may influence the outer loop, or it may influence the inner loop.

Further investigations would be required to investigate this distinction. It seems likely that inner speech is incorporated into monitoring/feedback mechanisms, as would explain the slowing of keystrokes in the second word in each pair. Inhibiting the feedback mechanisms will likely provide a greater understanding of how inner speech is utilised. For example, if it is used by the outer loop as a phonological/phonetic comparison of the words being read on the screen, removing the ability to read the words on the screen would remove the influence of inner speech.

To summarise, manipulation to the phonetic relationship across word pairs significantly affects the time-course of typewriting. The affected keystrokes are located within the word where the word is argued to have already been prepared in advance, and the keystrokes are instead a reflection of motor execution (Logan & Crump, 2011). This warrants speculation that the inner loop may not be informationally encapsulated simply because the motor performance of the inner loop is being influenced by information that is not associated with either the outer loop or the inner loop. However, this research is one of the first to demonstrate that the phonetic relationship across a word boundary affects the time-course of typewriting. As such, it is not known how the phonetic form influences typewriting or the extent to which the phonetic information is accessed by the inner loop. One possibility is that the inner loop can access the phonetic information directly. In contrast, it is also possible that the phonetic information is accessed by the outer loop instead and the instructions of the outer loop to the inner loop modulate the time-course of typewriting.

5.4. Is the time-course of typewriting affected by inner speech?

The fourth experimental question examined if the time-course of typewriting affected by the phonological representation present in inner speech. The majority of us are familiar with hearing an internal monologue when writing or typewriting. This internal monologue may serve some purpose, and if so, will likely affect the time-course of typewriting. There is very little research demonstrating an influence of inner speech in typewriting or even handwriting for that matter. The lack of supporting evidence suggests there may be no influence of inner speech in typewriting. However, there may also be a lack of supporting evidence because of the difficulty in manipulating inner speech without influencing the earlier stages of phonological processing, or even the orthographic structure of the words.

Inner speech is a fully prepared articulatory gesture that is heard internally instead of being outwardly spoken. It is only available at the end of phonetic encoding at the point where the words are available for articulation. As a result, it is difficult to differentiate between influences of inner speech and the phonological representations that are available earlier in the phonological processing of the words. These earlier phonological representations can assist in generating the spelling of words (see Bonin et al., 2015). If inner speech is manipulated in experimental conditions, it is difficult to not also manipulate the earlier stages of phonological processing.

There is also the additional challenge of ensuring that any influence of inner speech cannot be explained by changes to the orthographic content within the words. If the structure of the words is manipulated to examine inner speech, there will likely be a knock-on effect as the orthographic structure of the word will likely be affected too. The manipulation of letter co-occurrences such as bigrams and trigrams in the earlier experiments (Experiments 1-6) have already highlighted that the time-course of typewriting is sensitive to the frequency of letter co-occurrences. High-frequency letter co-occurrences such as bigrams benefit from faster production. Even a minor change, such as changing an individual letter within a word may influence the time-course of typewriting. To investigate the influences of inner speech, these phonological and orthographic confounding issues must be considered and addressed.

Experiment 6 provided an initial indication that the time-course of typing is influenced by inner speech. Participants were required to type pronounceable (consonant-vowel-consonant trigrams; i.e., *GAT*) and unpronounceable (consonant- consonant -consonant trigrams; i.e., *GHT*) letter-strings that were also frequency-manipulated. It was found that the IKIs (second and third letters) were both significantly faster in the pronounceable CVC trigrams. These findings were not interpreted as speeded sub- motor level preparation, as significant frequency and CV-status effects were found at the onset latency, demonstrating that graphemic letters were prepared as a full chunk and passed to the motor level before the onset of typing. Instead, it could be argued that the motor level may be assisted by the phonological referent of the trigram via inner speech (overtly naming the trigram). However, the inclusion of vowels, and thus, CV and VC bigrams, led to weaker controls of the letter and bigram frequencies within the IKIs in Experiment 6. Unlike the well-controlled frequency manipulations in Experiments 1-5, the significant CV-status effects within the IKIs may be confounded by the weaker frequency controls.

Experiments 7 and 8 provided much clearer examinations of whether inner speech affected the time-course of typewriting. Stringent considerations were made for the experimental methods in regard to how inner speech can be examined while also controlling for any influences from the earlier stages of phonological processing. To examine influences of inner speech, any manipulations to the stimuli in both experiments must only affect the late stages of phonetic encoding. Both experiments manipulated the CV-status of the letters surrounding the word boundary of a word pair to manipulate the late phonetic stage of resyllabification.

Resyllabification occurs within the late stages of phonological/phonetic processing in which the syllable structures of words can be re-adjusted to aid the pronunciation of the words. A word beginning with a vowel onset (i.e., oscar) starts highly sonorous making it more difficult to pronounce than a word beginning with a consonant. As a result, the process of resyllabification sees the syllable structure of words adjusted so the word with a vowel onset may borrow the final consonant of the proceeding word. For example, in the word pair *concept oscar*, the ***t*** straddles the word boundary to act as the onset of the second word (i.e., ***t****oscar*). Importantly, this process occurs much later than the sub-lexical level of phonological processing that may assist in generating the spelling of the words. This allows us to ensure that this type of manipulation targets inner speech only as it is only available at the point before articulation.

Importantly, this type of manipulation does not influence the orthographic representation of the words. Resyllabification only occurs during phonological processing to aid pronunciation of the words before articulation, or in this instance, inner speech. Resyllabification is not required in writing/typewriting as words are processed one at a time (Logan & Crump, 2011) with no concerns or requirements of the pronunciation. Fundamentally, manipulating the phonetic relationship across the word boundary of two words does not influence the orthographic content within the word. Words are still prepared orthographically one word at a time.

Furthermore, the stringent experimental paradigm employed in both Experiment 7 and Experiment 8 allowed for one word in the word pairs to be matched across conditions. As participants were typewriting the same words across conditions, it allowed for direct comparisons for how the manipulation affects the time-course of typewriting. In Experiment 7, the first word was constant across conditions. For example, in the experimental condition named Resyll, a word pair such as *produc****t*** *onion* was used where the ***t*** phonetically straddles the word boundary. In comparison, the control condition contained a comparative word pair of *produc****t*** *depot*, where the ***t*** is not required to straddle the word boundary as the second word begins with a consonant already. The first word, in this instance *product*, was the same across both conditions. Participants were typewriting the same words with no difference in what letters need to be typed. Experiment 8 employed similar principles as in Experiment 7 but instead matched the second word in the word pairs instead of the first word. Across the two experiments, alternating the matching of the words to be typed across conditions allowed for the stimuli to be meticulously controlled.

Experiment 7 demonstrated that the final consonant in the first word, which phonetically straddles the word boundary, benefited from speeded production in the experimental condition compared to the control condition. Considering the example word pairs of *produc**t** onion* (experimental condition) and *produc**t** depot* (control condition), the final consonant (i.e., ***t*** in this example) was produced significantly faster in the experimental condition. This occurred even though participants were typewriting the same first word (i.e., *product*) across conditions. In contrast, the analyses of the second word keystroke latencies demonstrated an opposing pattern of results. After the onset latency of the second word, the initial keystrokes of the word were significantly slower compared to the control condition. However, these findings were initially met with caution as the second words were not matched across conditions in Experiment 7. With different letters and letter co-occurrences featuring across conditions in the second word, direct comparisons cannot be easily made.

Experiment 8 employed a slightly modified paradigm for the arrangement of experimental stimuli used across conditions. In Experiment 8, the second word was matched across conditions. The first word in the experimental condition ended in a silent-e following the final consonant, whereas the first word in the control condition ended in a pronounceable vowel following the final consonant instead. For example, in the experimental condition, a word pair such as *respon**se** ulcer* was used where the final **e** was phonetically unpronounced and ignored allowing the final consonant of **s** to straddle across the word boundary to the onset of the second word. In comparison, the control condition contained a comparative word pair of *car**go** ulcer* whereby the final letter of **o** in the first word is phonetically pronounceable, preventing the final consonant of ***g*** from straddling the word boundary.

To further examine the pattern of results demonstrated in the second word of the word-pairs in Experiment 7, Experiment 8 matched the second word in the pairs across conditions. If the slower keystrokes in the second word (Experiment 7) were as a result of the phonetic manipulation, the same pattern of result should occur when the same words are being typed across conditions. Furthermore, Experiment 8 also further examined the pattern of results demonstrated in the first word of the pair in Experiment 7. If the speeded keystroke at the final consonant of the first word (Experiment 7) is from the phonetic manipulation, the same pattern of results should occur if the final consonant is followed by a phonetically silent-e. As the e would still have to be prepared and typed, it can only be silent/ignored phonetically. Thus, the final consonant of the first word should still be able to straddle the word boundary despite moving location within the first word. The pattern of results in Experiment 8 supported those observed in Experiment 7. When controlling for the content being typed in the second word of the pair by matching across conditions, the initial few keystrokes after the onset latency was significantly slower in the experimental condition. While, in the first word, despite moving the location of the final consonant that may straddle the word boundary, the final consonant was again significantly faster in the experimental condition compared to the control condition.

The pattern of results demonstrated in Experiments 7 and 8 are robust and clear. When the phonetic relationship of the word-pair is manipulated to allow for phonetic resyllabification, the timing of typewriting is adjusted even when the same words and letters are being typed. The final consonant at the word boundary between the two words is speeded. This occurs even when the same first word is being typed across conditions (Experiment 7), and also occurs even when the location of the final consonant is moved and is followed by a (phonetically unpronounced) silent-e (Experiment 8). Manipulation to the phonetic relationship between the word pair speeds the final consonant of the first word that can straddle across the word boundary. Consider that the phonetic representation of the word pair has the final consonant appearing in two locations, the end of the first word and the beginning of the second word. One likely explanation for this pattern of results is that there is an increase in activation of the final consonant, encouraging the inner loop to execute the keystroke to initiate that keystroke faster.

There are also clear and robust findings within the second word of the pair. After the onset latency of the first letter of the second word, the initial few following keystrokes are slowed. This was demonstrated in both experiments, even when the second word was matched across conditions (Experiment 8). Considering the phonetic representation of the second word, the slowing of the keystrokes may arise due to a mismatch between the words being typed (i.e., *ulcer*) and the phonetic representation of the word from inner speech (i.e., ***s[e]****ulcer*, pronounced ***s****ulcer*, from the word pair *respon****se*** *ulcer*). After typewriting the initial letter of the second word (i.e., *u*), production may be slowed to monitor the typewriting in more detail when the output of the first letter (i.e., *u*) does not match the first letter of the phonetic form (i.e., ***s***). However, these explanations are only speculative at this point. It is not yet known how typewriting is influenced by inner speech. What is clear from both experiments is that manipulations to the phonetic relationship of the word pairs affected the time-course of typewriting. There are strong and clear indications that the time-course of typewriting was influenced by the late phonetic process of resyllabification. The pattern of results demonstrated across both experiments provide clear support for the concept that the time-course of typewriting is influenced by the phonetic representation in inner speech.

One potential future direction of this type of research could implement the use of articulatory suppression. If the time-course of typewriting is influenced by inner speech, we would expect to see these patterns of results observed in Experiment 7 and 8 removed if participants were unable to access the phonetic form of the word pairs. By verbally repeating a particular sound/syllable at the same time as typewriting, phonological/phonetic processing is already being utilised to articulate the given sound. Thus, it is not possible to prepare the phonetic form of the word pairs, so should see no influence upon the time-course of typewriting. By utilising the same stimuli used in Experiments 7 and 8, direct comparisons can be made. Particularly where the words are the same across the Resyll and control conditions, the keystroke latencies should be no different across conditions.

However, we can say with relative certainty that the manipulation of the CV-status at the word boundary did induce the intended manipulation of resyllabification. This is clear from the same words being typed across conditions in the first word (Experiment 7) and the second word (Experiment 8) in the word pairs. This ensured that there were no influences in the orthographic structure of the word such a letter or bigram frequencies. The structure of the words being typed was only different across conditions in how the related to the adjacent word in a phonetic manner. Furthermore, the implementation of the silent-e stimuli in Experiment 8 provided further indications that the phonetic relationship of the word pairs was manipulated. As the phonetic information is only made available before articulation, and typists did not overtly articulate the word pairs, this information must influence the time-course of typewriting via inner speech.

To summarise, across two experiments, there is clear evidence for the influence of inner speech upon the time-course of typewriting. The implementation of stringent experimental controls rules out possible alternative explanations. Comparing the same words across experimental conditions eliminates the possibility of orthographic confounded such as the frequency of letter or letter co-occurrences. The implementation of the principles of resyllabification eliminates influences from earlier stages of phonological processing. Resyllabification occurs very late in phonological/phonetic processing. The processed form is only available before articulation or in this case via inner speech initial interpretations of the pattern of results across the two heavily controlled experiments suggest that inner speech may be used.

5.5. Conclusion

The principal aim of this thesis was to examine if the time-course of typewriting is influenced by adjustments to sub-word representations within a word. Theoretical accounts of typewriting hinge on the processing of words, letters, and keystrokes. The importance of sub-word representations smaller than a word and greater than a letter is overlooked.

Innovative research employing a well-controlled experimental paradigm provided convincing results that the time-course of typewriting is influenced by inner speech. The level of controls used within the experimental paradigm, where either the first (Experiment 7) or second words (Experiment 8) in a word-pair were identical across conditions allowed for clear-drawn conclusions to be made as there are no obvious confounding influences. This is also, to my knowledge, the first series of experiments to demonstrate that manipulation to the phonetic relationship of word pairs affects the time-course of typewriting. This provides an initial foundation for the research in this area, with the most likely future direction of this research investigating if the observed effects can be removed when typists are concurrently participating in an articulatory suppression task.

Additionally, controlled manipulations to the frequency of letter combinations provided multiple clear indications that sub-word graphemic letter chunks can be prepared and passed to the motor level/inner loop when familiar words are unavailable. The same series of experiments also provided supporting evidence for motor performance being significantly affected by the frequency of letter combinations. This was taken as an indication of motor chunking. However, I recognise that there are restrictions in how the findings contribute to the current theoretical understandings. The research cannot provide a clear concept of what the motor planning mechanisms are for motor chunking and cannot fully dismiss alternative interpretations to motor chunking in respect to the observed frequency effects.

Further discussions were also provided concerning the investigation of whether the inner loop is informationally encapsulated. On the basis of the discussed findings, I conclude:

(1) When familiar words are unavailable, sub-word representations can be prepared as a graphemic chunk before being passed to the motor level.

(2) Frequent letter combinations (i.e., bigrams and trigrams) benefit from faster preparation within the motor level compared to infrequent letter combinations. This is arguably a reflection of motor-chunks being retrieved as a single representation for frequent letter combinations.

(3) The inner loop/motor level in typing does not run to completion without interference from other (e.g. phonemic) representations. It is not clear whether phonemic representations interfere with inner loop performance directly, or via the instruction of the outer loop. It is clear, however, that the manipulation to the phonetic relationship of word pairs does interfere with the time-course of motor execution via the inner loop.

(4) The time-course of typewriting is affected by the phonetic relationship of word pairs. This can only infer influences of inner speech at this point. However, inner speech is the most likely explanation for the observed findings.

Overall, the present research demonstrates robust evidence that the time-course of typewriting is influenced by sub-word representations. The findings in this thesis highlight the importance of linguistic controls in typewriting research. Typewriting speed is significantly affected by subtle changes to one or two letters. These changes may affect the speed of processing for the generation of the spelling, and the motor preparation and execution processes. They may also affect the phonetic relationship from one word to the next via inner speech, which also affects the time-course of typewriting. Minor changes within a word can affect the timing of keystroke latencies. The use of typewriting performance in future psychological research should consider the discussed principles when controlling for influences upon typewriting performance.

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Appendices

Appendix 1: Experimental phrases and orderings for counterbalancing used in Experiment 7

Counterbalanced order of presentation			
Order 1	Order 2	Order 3	Order 4
PRODUCT ONION TITLE EXAM	TITLE ONION PRODUCT EXAM	PRODUCT EXAM TITLE ONION	TITLE EXAM PRODUCT ONION
HUSBAND AMINO VOLUME ALMOND	VOLUME AMINO HUSBAND ALMOND	HUSBAND ALMOND VOLUME AMINO	VOLUME ALMOND HUSBAND AMINO
CONTACT INSULIN PURPOSE ELASTIC	PURPOSE INSULIN CONTACT ELASTIC	CONTACT ELASTIC PURPOSE INSULIN	PURPOSE ELASTIC CONTACT INSULIN
STATEMENT ANGUS SOFTWARE INTRUDER	SOFTWARE ANGUS STATEMENT INTRUDER	STATEMENT INTRUDER SOFTWARE ANGUS	SOFTWARE INTRUDER STATEMENT ANGUS
PATTERN OBSTACLE SENTENCE ATTIC	SENTENCE OBSTACLE PATTERN ATTIC	PATTERN ATTIC SENTENCE OBSTACLE	SENTENCE ATTIC PATTERN OBSTACLE
CONCEPT OSCAR SURFACE ASTRONOMY	SURFACE OSCAR CONCEPT ASTRONOMY	CONCEPT ASTRONOMY SURFACE OSCAR	SURFACE ASTRONOMY CONCEPT OSCAR
CONTEXT OVAL ATTITUDE ASPIRIN	ATTITUDE OVAL CONTEXT ASPIRIN	CONTEXT ASPIRIN ATTITUDE OVAL	ATTITUDE ASPIRIN CONTEXT OVAL
PLANT INGREDIENT ABSENCE ARCADE	ABSENCE INGREDIENT PLANT ARCADE	PLANT ARCADE ABSENCE INGREDIENT	ABSENCE ARCADE PLANT INGREDIENT
STUDENT UMBRELLA RELATIVE ADVERT	RELATIVE UMBRELLA STUDENT ADVERT	STUDENT ADVERT RELATIVE UMBRELLA	RELATIVE ADVERT STUDENT UMBRELLA
NETWORK ENZYME MACHINE ARENA	MACHINE ENZYME NETWORK ARENA	NETWORK ARENA MACHINE ENZYME	MACHINE ARENA NETWORK ENZYME
DISTRICT INSECT FINANCE ARROW	FINANCE INSECT DISTRICT ARROW	DISTRICT ARROW FINANCE INSECT	FINANCE ARROW DISTRICT INSECT
BAND ALLEY EXAMPLE OVEN	EXAMPLE ALLEY BAND OVEN	BAND OVEN EXAMPLE ALLEY	EXAMPLE OVEN BAND ALLEY
CONTENT ORACLE CASTLE INVESTOR	CASTLE ORACLE CONTENT INVESTOR	CONTENT INVESTOR CASTLE ORACLE	CASTLE INVESTOR CONTENT ORACLE
CLIENT ALTON ARTICLE OFFSPRING	ARTICLE ALTON CLIENT OFFSPRING	CLIENT OFFSPRING ARTICLE ALTON	ARTICLE OFFSPRING CLIENT ALTON
RESPECT ANTIQUE INCOME ANCESTOR	INCOME ANTIQUE RESPECT ANCESTOR	RESPECT ANCESTOR INCOME ANTIQUE	INCOME ANCESTOR RESPECT ANTIQUE
PAYMENT ADVENT ESTATE OLIVE	ESTATE ADVENT PAYMENT OLIVE	PAYMENT OLIVE ESTATE ADVENT	ESTATE OLIVE PAYMENT ADVENT

Appendix 2: Experimental phrases and orderings for counterbalancing used in Experiment 8

Counterbalanced order of presentation			
Order 1	Order 2	Order 3	Order 4
RESPONSE ULCER CARGO ANGER	RESPONSE ANGER CARGO ULCER	CARGO ULCER RESPONSE ANGER	CARGO ANGER RESPONSE ULCER
IMPULSE AMBITION POTATO UPSIDE	IMPULSE UPSIDE POTATO AMBITION	POTATO AMBITION IMPULSE UPSIDE	POTATO UPSIDE IMPULSE AMBITION
ENTRANCE ONSET PLASMA INSTANT	ENTRANCE INSTANT PLASMA ONSET	PLASMA ONSET ENTRANCE INSTANT	PLASMA INSTANT ENTRANCE ONSET
EXPENSE ONION DRAMA INSULIN	EXPENSE INSULIN DRAMA ONION	DRAMA ONION EXPENSE INSULIN	DRAMA INSULIN EXPENSE ONION
MUSCLE UMPIRE ZERO ANSWER	MUSCLE ANSWER ZERO UMPIRE	ZERO UMPIRE MUSCLE ANSWER	ZERO ANSWER MUSCLE UMPIRE
DISCOURSE IMPACT CHINA OSCAR	DISCOURSE OSCAR CHINA IMPACT	CHINA IMPACT DISCOURSE OSCAR	CHINA OSCAR DISCOURSE IMPACT
DISTANCE ORGAN FORMULA UMBRELLA	DISTANCE UMBRELLA FORMULA ORGAN	FORMULA ORGAN DISTANCE UMBRELLA	FORMULA UMBRELLA DISTANCE ORGAN
KNOWLEDGE OPTION CAMERA OXFAM	KNOWLEDGE OXFAM CAMERA OPTION	CAMERA OPTION KNOWLEDGE OXFAM	CAMERA OXFAM KNOWLEDGE OPTION
SILENCE INCOME TOMATO ULTRASOUND	SILENCE ULTRASOUND TOMATO INCOME	TOMATO INCOME SILENCE ULTRASOUND	TOMATO ULTRASOUND SILENCE INCOME
CENTRE INCIDENT MENU ADVERT	CENTRE ADVERT MENU INCIDENT	MENU INCIDENT CENTRE ADVERT	MENU ADVERT CENTRE INCIDENT
VIOLENCE ANGEL PHOTO INPUT	VIOLENCE INPUT PHOTO ANGEL	PHOTO ANGEL VIOLENCE INPUT	PHOTO INPUT VIOLENCE ANGEL
SEQUENCE URCHIN CINEMA OBSTACLE	SEQUENCE OBSTACLE CINEMA URCHIN	CINEMA URCHIN SEQUENCE OBSTACLE	CINEMA OBSTACLE SEQUENCE URCHIN
LICENCE ANKLE PIANO INSECT	LICENCE INSECT PIANO ANKLE	PIANO ANKLE LICENCE INSECT	PIANO INSECT LICENCE ANKLE
OFFENCE INQUEST VOLCANO ADVICE	OFFENCE ADVICE VOLCANO INQUEST	VOLCANO INQUEST OFFENCE ADVICE	VOLCANO ADVICE OFFENCE INQUEST
CAMBRIDGE ANCESTOR CHICAGO UPROAR	CAMBRIDGE UPROAR CHICAGO ANCESTOR	CHICAGO ANCESTOR CAMBRIDGE UPROAR	CHICAGO UPROAR CAMBRIDGE ANCESTOR
CHALLENGE UNCLE HERO ORDEAL	CHALLENGE ORDEAL HERO UNCLE	HERO UNCLE CHALLENGE ORDEAL	HERO ORDEAL CHALLENGE UNCLE