Motoric and Language Systems Associated with Note-taking:

Going Beyond Handwriting Speed

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Abstract

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In children with well-developed handwriting, handwriting speed is more strongly related to orthographic coding—the speed at which they can access verbal codes (SAVC) in memory—than fine motor speed. Only one study has investigated this relationship in an adult population (Peverly et al., 2014). This dissertation is a replication of that study, using archival data collected during two prior studies. Two separate groups of students from an undergraduate university (Study 1, N = 147; Study 2, N = *94)* completed measures of handwriting speed (Studies 1 and 2: a modified Alphabet Writing Task from Detailed Assessment of Speed of Handwriting 17+), fine motor speed (Study 1: Digit Symbol Copy task from the WAIS-III; Study 2: Diagonal Line task developed by Peverly et al., 2014), SAVC (Study 1: an adapted Verbal Fluency measure from the NEPSY; Study 2: RAN-A designed by Denckla & Cutting, 1999), language comprehension (Study 2: Nelson-Denny Reading Test), working memory (Study 1 and 2: Listening Span Test developed by Daneman & Carpenter, 1980), and executive attention (Study 2: group administered Stroop Color and Word Test). In the analysis, handwriting speed (DV) was regressed on all other variables (IVs) in each study. In Study 1, three variables significantly and positively predicted handwriting speed: fine motor speed, compositional fluency, and SAVC (semantic retrieval only). Because of the measure of SAVC used in this study, the construct was split between phonetic retrieval and semantic retrieval. In Study 2, only fine motor speed and SAVC were positively predictive. Despite the differences in measurement between Study 1 and Study 2, the relationship between handwriting speed, SAVC, and fine

motor speed remained consistent. Overall, these results lend further support to the conclusion of Peverly et al. (2014) that the relationship between fine-motor fluency and SAVC to handwriting speed is consistent beyond childhood and is evident in an adult population.

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Acknowledgments

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Chapter 1: Introduction

One of the most important skills in classrooms is lecture note-taking—creating a written record of visually or orally presented material from lecture. After elementary school, teachers and professors use lecture as the predominant means of conveying academic material for review (Mulcahy-Ert & Caverly, 2009; Snow, 2002; Stains et al., 2018), and expect students to take notes (Carrier & Titus, 1979; Landrum, 2010). Students in turn rely on note-taking (94% of undergraduate students often or always take notes) (Peverly & Wolf, 2019) and consider it an important skill (Dunkel & Davy, 1989). Teachers and students' beliefs about the efficacy of note-taking are well founded: taking and reviewing notes is predictive of better learning outcomes (Peverly et al., 2007; Peverly & Sumowski, 2012).

Note-taking as an academic strategy serves two primary functions: encoding information and external storage (Armbruster, 2009; Di Vesta & Gray, 1972). The encoding function, the act of recording information from lecture, promotes learning even without subsequent review of the notes (Kobayashi, 2005). This is due to the processing that note-taking requires beyond that of merely listening (Di Vesta & Gray, 1972; Kobayashi, 2005; Peverly et al., 2007; Piolat et al., 2005). The storage function—the physical permanent record of the lecture created by taking notes—enables the review of notes at some later point in time (Kiewra, 1989). Lecture note-taking is therefore both a process and a product (Carrier & Titus, 1979). Although both functions of note-taking are related to academic success, review is more strongly related to test outcomes than encoding, because review enables the consolidation and elaboration of information in notes, and its integration with background knowledge (Armbruster, 2009; Di Vesta & Gray, 1972; Kiewra, 1987; Piolat et al., 2005). Students who take and review their notes perform better on examinations than those who take notes but do not review them, and those who only listen to the lecture (Armbruster, 2009; Hartley, 1983; Kiewra, 1985a; Kobayashi, 2005, 2006; Peverly et al., 2007).

Although effective lecture note-taking plays an important role in academic success, the encoding process itself is complex and demanding. Effective note-takers must attend to and hold relevant information in working memory, contemporaneously identify the most important information, and then physically record that information (Peverly et al., 2007; Piolat et al., 2005). Since many lectures are presented at a rate far faster than the average writer is physically able to record or transcribe, the note-taker must constantly balance the process of recording information with the need to attend to and comprehend the lecture as it continues. Students must both record information they are holding in mind while also attending to new information to be recorded next, in a cyclical manner. Thus, it is not surprising that research has found that individual differences in the quality and quantity of notes are largely related both to physical/manual and cognitive factors, particularly handwriting fluency (Peverly et al., 2007, 2013, 2014), language comprehension (Peverly et al., 2007, 2013), and sustained attention (Gleason, 2012; Peverly et al., 2014; Vekaria, 2011).

Theories on cognitive capacity highlight that, despite the sophistication of the brain's ability to execute complex tasks, it is severely limited by the rate at which information can be attended to and processed; the amount of information that can be stored in short-term memory; and the cognitive burden of maintaining, monitoring, and appropriately selecting responses to stimuli (Marois & Ivanoff, 2005). Theories of academic skills such as reading (Vellutino et al., 2004), writing (Berninger et al., 2006; McCutchen, 2000), and mathematics (Geary, 1994) suggest those skills are subject to processing limitations. Taken together, they indicate the following: (1) competence requires simultaneous and parallel execution of basic and higher-level domain-specific skills within a limited capacity working memory, (2) basic domain-specific skills must be sufficiently automatized and/or fluent in order to allow limited working memory resources to be utilized for higher-level cognitive skills, and (3) once basic skills are sufficiently automatized and fluent, proficiency in an academic skill is principally determined by the quality of the higher-level skills (Peverly & Sumowski, 2012).

Research on children's essay writing has found that fluent handwriting lessens the burden on a limited capacity working memory. This in turn facilitates their access to the higher order skills needed to create a higher quality written product (Kellogg, 2008; McCutchen, 1996, 2000). Note-taking shares many of the same physical and cognitive mechanisms with essay writing. For both, requisite lower-level skills include transcription speed, which encompasses manual fine-motor speed and orthographic skill (the cognitive representation of the conventions of language: letters, sounds letter groups, and words) (Berninger & Swanson, 1994; Peverly, 2014). Similarly, for both note-taking and essay writing, requisite higher-level cognitive skills include language comprehension and sustained attention. If lower-level skills are not adequately developed or deployed, fewer cognitive resources can be accessed to create good notes or essays (Anderson, 1990; Baddeley, 1998, 2000; Ericsson & Kintsch, 1995; Perfetti, 1986). Conversely, when handwriting is fluent, cognitive resources are more available for higher-level processing (Pevelry et al., 2007, 2013, 2014; Peverly & Sumowski, 2012). The notetaking literature has consistently recognized the importance of handwriting speed as a significant predictor of quality of lecture notes (Peverly et al., 2007, 2013, 2014).

Although it seems intuitive that handwriting speed is related to fine motor speed, research with children has found that once letter writing is well developed, handwriting speed is more strongly related to orthographic coding, the cognitive representation of written language in memory (Abbot & Berninger, 1993; Berninger et al., 2006; Berninger & Rutberg, 1992; McCutchen et al., 1994; Phillips, 1999; Rodriguez-Aranda, 2003). Indeed, orthographic coding, hereafter referred to as the speeded access to verbal codes (SAVC), seems to mediate the relationship between handwriting speed and fine motor speed (Abbott & Berninger, 1993).

Only one study to date has used college students to investigate the cognitive components of handwriting speed as it relates to note-taking (Peverly et al., 2014). That study replicated the child literature: when handwriting speed was regressed on all the other independent variables included in the study (language comprehension, working memory, executive control of attention, sustained attention, fine motor fluency and SAVC), only fine motor fluency and SAVC were related to handwriting speed.

The aim of this dissertation is to replicate Peverly et al. (2014) by analyzing archival data collected during two other studies by Peverly and colleagues (2007, 2013). Both studies used college students, similar to Peverly et al. (2014), and measured the following variables: handwriting speed, fine motor speed, SAVC, language comprehension, working memory, executive attention, and sustained attention. The studies differ in the way fine motor speed and SAVC were measured. As such, any finding of a significant relationship should have increased robustness.

Chapter 2: Review of Literature

Notes are a transcribed record of information for later use. Peverly and Wolf (2019) defined taking notes as "the act of selecting and cryptically and idiosyncratically transcribing important information that can be used as a personal memory aid for later reference, review and/or memorization by the note-taker." Thus, note-taking requires transcribing information extracted from the internal or external world into a written format for subsequent access.

Note-taking is utilized in many facets of life, and, while some researchers have investigated its use by teachers, jurors, and others, most research has focused on the importance and efficacy of students' notes in the classroom. As students move through the grades, beyond elementary school and through high school and college, lecture becomes the most prevalent and predominant means of conveying academic information (Mulcahy-Ert & Caverly, 2009; Snow, 2002; Stains et al., 2018; Van Meter et al., 1994). Wirt et al. (2001) found that lecture made up about 83% of teaching methods used by college instructors, and Armbruster (2009) estimated that 80% of undergraduate class time is spent listening to lectures. Further, the vast majority of teachers and professors expect students to take notes during lectures (Carrier & Titus, 1979; Landrum, 2010), and some format course materials with this in mind, by providing PowerPoint visuals or providing notes on chalkboards or whiteboards (Landrum, 2010). Since lectures often represent the important themes of the course, and the content of the lecture may not be available elsewhere, students recognize the importance of note-taking and frequently take notes even when they are not instructed to do so (Dunkel & Davy, 1989; Williams & Eggert, 2002). In fact, the majority of students report taking notes as a classroom strategy (approximately 94%, Peverly & Wolf, 2019; approximately 98% Palmatier & Bennett, 1974). The activity is so pervasive in college that a survey of undergraduate students from 2012 to 2013 found that 99.8% take notes at least some of the time (Peverly & Wolf, 2019). In the latest large-scale survey of note-taking by Morehead et al. (2019b), the authors found that 96% of students reported taking notes in class.

College-age students have reported that taking notes aids their comprehension of the subject material (Van Meter et al., 1994), a belief that may in turn affect their study behavior both during and after class. Thus, it should not be surprising that those who take and review their notes perform better on examinations than those who do not (Armbruster, 2009; Hartley, 1983; Kiewra, 1985a; Kobayashi, 2005, 2006; Peverly et al., 2007). Multiple studies have found that notes were not only the best, but sometimes were the only predictor of test performance (Peverly et al., 2007, 2013, 2014; Peverly & Sumowski, 2012; Reddington et al., 2015; Vekaria & Peverly, 2018). Thus, academic success is reliant on students' ability to identify, record, and study important information.

Function of Notes

The efficacy of note-taking as a study strategy is derived from its two primary functions: encoding (the way the brain processes information during transcription) and external storage (the creation of a record for subsequent review) (Armbruster, 2009; Di Vesta & Gray, 1972). Both processes support learning (Carrier & Titus, 1979). Students must identify and record important information, which can help them understand and remember the information. The physical product is later used for reference, review, and further consolidation (Armbruster, 2009; Carrier & Titus, 1979; Di Vesta & Gray, 1972; Kobayashi, 206). The end result of both aspects of note-taking is the absorption and retention of information in long-term memory (Armbruster, 2009; Carrier & Titus, 1979; Di Vesta & Gray, 1972; Kobayashi, 2006).

Both encoding and external storage have been studied independently, beginning with Di Vesta and Gray (1972), who compared two groups: those who took notes while listening to information and those who listened to information without recording notes. These groups were then subdivided and either tested after being allowed to review their notes or to only contemplate the information without looking at their notes. They found that recall of the material was positively influenced by the note-taking process (encoding) and then further enhanced by review. Following Di Vesta and Gray, there has been great deal of research on the efficacy of encoding and review. Peverly and Wolf (2019) outlined the general research methods used to isolate their respective effects. Investigations of the encoding function have typically compared two groups: (1) students who listened to a lecture and did not take notes, and (2) students who took notes but did not review. Investigations of the review function have typically compared: (1) students who listened to a lecture, took notes, but did not review their notes; (2) students who took notes and reviewed them; (3) students who listened to the lecture, did not take notes, and reviewed a pre-prepared set of notes; and (4) students who did not listen to the lecture but reviewed a set of prepared notes.

Encoding

The encoding function, or the actual transcription of information, has been shown to produce more meaningful processing of information than is achieved by merely listening to a presentation of information (Di Vesta & Gray, 1972; Kiewra, 1985a; Piolat et al., 2005). One hypothesis for why note-taking improves test performance is that the act of taking notes positively impacts the encoding of information in students' long-term memory (Di Vesta & Gray, 1972; Kobayashi, 2005).

A few studies found that the encoding function—that is, simply taking notes, without subsequent review—did not significantly improve testing outcomes compared to simply listening to lecture (Fisher & Harris, 1973; Glover et al. 1980; Riley & Dyer, 1979). However, the majority of the research found that the act of recording information was itself useful to the student, even in the absence of later review/studying (Bligh, 2000; Einstein et al., 1985; Kiewra et al., 1991; Rickards & Friedman, 1978; Suritsky & Hughes, 1991). Large scale reviews of the literature (Armbruster, 2009; Hartley & Davies, 1978; Kiewra, 1985b, 1989; Kobayashi, 2005, 2006) showed that note-taking was found to be more favorable than not, supporting the overall assertion that note-taking is an effective and important study skill. Specifically, Kobayashi (2005) found an effect size of .26 in favor of note-takers. Kiewra (1985b) reviewed a set of 56 studies that compared students who took notes to those students who listened to a lecture and did not take notes; 33 of those studies found that students who took notes had better achievement, whereas 21 studies found no difference between the groups, and 2 studies found better outcomes for students who listened without taking notes.

The two most prevalent explanations for the efficacy of the encoding function are the translation hypothesis and the generative hypothesis. The translation hypothesis suggests that the process of writing leads to more distinctive encoding and therefore better memory (Conway & Gathercole, 1990; De Haan et al., 2000). The generative hypothesis (Peper & Mayer, 1978, 1986; Wittrock, 1974) suggests that the act of note-taking provides the note-taker with more opportunity to incorporate what they are learning with their own existing background knowledge. Relatedly, Craik and Lockhart (1972) posited a conceptual framework within memory research suggesting that information that is more thoroughly and conceptually analyzed at input is better remembered or retrieved. This suggests that the strategies used to process and record information are related to learning outcomes; taking notes more passively would lead to less information absorption.

Review

The second aspect of note-taking—external storage—is the product or permanent physical record of the lecture that students keep to further conceptualize, consolidate, and expand upon the recorded information, as well as transfer it into long-term memory (Kiewra, 1985a, 1985b, 1989; Kiewra et al., 1991; Kobayashi, 2006; Peverly & Wolf, 2019). In contrast to studies of the encoding function of note-taking (which have shown mixed results), the efficacy of external storage and subsequent review of notes on academic performance has been well-supported by the research. Multiple reviews and meta-analyses have reviewed the evidence (Hartley & Davies, 1978; Kiewra, 1985b; Kobayashi, 2006). Kiewra (1985b) qualitatively examined 22 studies comparing note-takers who reviewed their notes and those who did not. He found that the majority of studies, 17 of the 22, supported the assertion that students who review notes perform better than those who do not review notes, five did not find a significant difference, and zero found review to be detrimental.

A later meta-analysis by Kobayashi (2006) compared studies that included (1) note-taking plus review versus no note-taking with no review (21 independent samples), or (2) note-taking plus review versus only mental review (34 independent samples), and found a substantial benefit in favor of note-taking with review, resulting in mean weighted effect sizes of .75 and .77 respectively. According to Cohen's effect size criteria (1988), these fall in a medium to large range, demonstrating that review increases the value of note-taking alone.

Conclusion

The research presented above has indicated that taking and reviewing notes is related to positive academic outcomes, but it has not provided us with information on the processes related to individual differences in taking notes. That literature is presented next.

Variables Associated with Note-taking

The majority of the cognitively-oriented research on the development of academic skills has focused on those that develop in elementary school. Very little has focused on academic skills that develop later. As discussed previously, middle school is a time when students' academic load increases significantly (Thomas et al., 1987). Thus, students need to refine old strategies or learn new ones. Not surprisingly then, note-taking takes on a much larger role in predicting a student's success in middle school and beyond (Armbruster, 2009; Fisher & Harris, 1973; Kiewra & Benton, 1988; Kiewra et al., 1987, 1991; Peverly et al., 2007).

Note-taking is a complex and demanding task that requires the coordination of multiple acquired skills (Kobayashi, 2005; Peverly, 2006; Piolat et al., 2005). The note-taker must comprehend the presented information, attend to and hold relevant information in working memory, contemporaneously identify the most important information, and then physically record that information before it is forgotten, all while listening to and maintaining the continuity of the lecture (Peverly et al., 2007; Piolat et al., 2005). Thus, the skills required of an effective note-taker include basic handwriting speed and higher order cognitive skills, such as language comprehension, working memory, and sustained attention (Kiewra et al., 1987; Kobayashi, 2005; Peverly, 2006, 2013; Peverly et al., 2007; Piolat et al., 2005; Vekaria & Peverly, 2018). Further, lower-level skills must be fluent or at best automatized to facilitate access to higher order cognitive skills to enable effective note-taking.

Working Memory

In cognitive psychology, working memory can be thought of as a temporary processing and storage system, or cognitive workspace, wherein information from the environment and long-term memory can be held and manipulated for purposes of learning and reasoning

(Baddeley, 2000; Baddeley & Hitch, 1974; Peverly et al., 2013). Although working memory is hypothesized to be a critical component of complex human thought and thus academic performance, it has severe limitations. Working memory is limited both in the amount of information it can hold and the length of time that information can be held (Piolat et al., 2005). Thus, the brain is unable to process all of the information it receives from the senses and long-term memory, because of the limitations of working memory (Marois & Ivanoff, 2005). Research on limited capacity systems proposes a "bottle neck" effect in which there are multiple gateways through which information is processed, any of which can slow or halt incoming stimuli and behavioral responses (Marois & Ivanoff, 2005). The consequence is that, unless basic processes are highly automatized, people cannot perform multiple activities simultaneously and accurately (Just et. al, 2001; Neumann, 1984), which is necessary for time-limited skills such as lecture note-taking. Automaticity likely develops as a result of practice (Cohn et al., 1990; MacLeod & Dunbar, 1988), with ability moving from controlled processing to greater fluency or automaticity as expertise develops (Shiffrin & Schneider, 1984).

The role of working memory in note-taking is equivocal, as studies have been inconsistent in their findings. Some researchers argued that verbal working memory plays a significant role in quality note-taking (Kiewra et al., 1987; Kiewra & Benton, 1988; McIntyre, 1992), as it does in other academic skills and abilities, like reading, writing, and verbal abilities (Baddeley, 2001; Bayliss et al., 2003; Daneman & Carpenter, 1983; Just & Carpenter, 1992; Kellogg, 2001, 2004; Swanson & Siegel, 2001). Others have not found working memory to play a significant role in note-taking (Cohn et al, 1995; Gleason, 2012; Hadwin et al., 1999; Peverly et al., 2007, 2013, 2014; Vekaria & Peverly, 2018).

Peverly and Sumowski (2012) posited three possible reasons for the discrepancy. First, it might be a measurement issue. For example, those who found a positive and significant relationship between working memory and note-taking measured working memory using tasks that did not measure both the storage and processing components of working memory, as might be required in a task like note-taking. Thus, in their investigation, Peverly and Sumowski (2012) included a complex span task of the type typically used in working memory research, which measures both storage and processing. Second, other investigators may not have measured the right component of working memory. Baddeley (2000) and Engle (2001, 2002), for example, have both argued that executive attention is a key component of working memory. Thus, Peverly and Sumowski (2012) included a second task, the Stroop, a measure typically used to assess executive attention, selective attention, and cognitive flexibility (Engle, 2001; Spreen & Strauss, 1998). Peverly and Sumowski (2012) did not find a significant relationship between working memory and note-taking with either measure.

Another potential reason for discrepant findings in the literature may be the issue of collinearity. Working memory may share variance with other independent variables, all of which may be correlated with note-taking, the dependent variable. For example, in a sample of 85 college-age students, Peverly et al. (2007) found that verbal working memory was significantly correlated with most of the other independent variables (i.e., spelling, letter and compositional fluency, identification of main ideas), and note quality, but only letter fluency significantly predicted notes quality, perhaps indicating a shared underlying construct: speeded access of verbal codes from long-term memory. However, it was not found to be predictive of recall or note quality. Therefore, independently, verbal working memory was not related to note-taking skill, though may share underlying constructs with other variables.

Although it is not clear that working memory is related to note-taking, the notion that a limited capacity system constrains note-taking seems to align with our understanding of constrained functioning in other foundational academic skills, such as reading (Rayner et al., 2001; Vellutino et al., 2004), writing (Berninger, 2012; Berninger et al., 2006; McCutchen, 2000), and mathematics (Geary, 1994). In those skills, the literature has recognized the hierarchical nature of actions that must be executed simultaneously and in parallel. In short, to access and maximize use of higher-level abilities, one must execute basic prerequisite skills fluently or automatically to use the limited capacity of working memory efficiently. In other words, inadequately developed prerequisite skills can severely limit performance in academic domains (Perfetti, 1983).

Handwriting

Students often have options for writing, such as using a pencil and paper or a laptop. That said, almost all of the research on the relationship of fluent writing to writing outcomes (e.g., essays; notes) has been on handwriting. Among elementary school students, transcription fluency (a latent variable that is a combination of handwriting speed and spelling skill) is by far and away the best predictor of the number of words written and the quality of essays among elementary school children (Graham et al., 1997). More specifically, fluency results from the coordination of lower-level processes like motor output, lexical access, and syntactic frame construction, and higher-level cognitive resources (e.g., proposition integration; metacognition) including elaboration of ideas and maintenance of coherence (Fayol, 1999; Kellogg, 1996; McCutchen, 1996). Thus, the latter is enabled by the former. In other words, to create a final product, the writer must be able to generate an idea and record that idea before it is forgotten because of the temporal limitations of working memory (Berninger & Swanson, 1994; McCutchen, 2000). Fluency is paramount.

Lecture note-taking, from a temporal perspective, is more challenging than writing an essay. Most lectures are presented verbally and at a rapid pace, far faster than the average writer is physically able to record or transcribe. Spoken speed is roughly two to three words per second, while written speed is approximately 0.2 to 0.3 words per second (Foulin, 1995; Piolat et al., 2005). Therefore, it is not surprising that handwriting speed has consistently been found to be a significant predictor of the quantity and quality of lecture notes (Gleason, 2012; Peverly et al., 2007, 2013, 2014) as well as taking notes from texts (Peverly & Sumowski, 2012).

In a study of undergraduate students, Peverly et al. (2007) looked at the contributions of letter fluency, verbal working memory, and identification of main ideas, and found that handwriting speed was the only predictor of quality of notes, and further, that quality of notes was the only significant predictor of test performance. In a replication and expansion of that 2007 study, Peverly et al. (2013) found that handwriting speed as well as language comprehension and condition (whether or not students received an outline to aid note-taking) were significantly related to note quality. Peverly and colleagues (2013) remarked that the alphabet task used to measure handwriting speed involved not only fluent manual movements but also knowledge of the verbal codes associated with letters of the alphabet. Thus, individual differences in handwriting may be related to both variables, fine motor fluency and speeded access to verbal codes (SAVC).

Handwriting speed has consistently been found to be highly predictive of note quality (Peverly et al., 2007, 2013, 2014; Peverly & Sumowski, 2012), but little is known about the variables that facilitate handwriting speed, particularly in adults. There is some evidence that handwriting speed is comprised of the variables discussed briefly in the previous paragraph, fine motor fluency and SAVC (Peverly et al., 2007, 2014). As discussed previously, Peverly et al. (2014) examined the cognitive skills needed for skilled note-taking. They had two purposes: (1) to investigate the relationship of handwriting speed, fine motor fluency, SAVC, language comprehension, working memory, and attention (executive control and selective) to note-taking and written recall, and (2), to investigate whether handwriting speed was related to fine motor speed and/or SAVC. Participants (N = 70) listened to a 20-minute lecture on the psychology of problem solving and completed measures of handwriting speed (alphabet fluency task), language comprehension (the Nelson-Denny Reading Test), working memory (listening span task), SAVC (the Rapid Automatized Naming task), fine motor speed (Lafayette Finger Tapper Task), attention (the Stroop and the Lottery), and written recall. Notes and written recall responses were coded for quality. To address the first purpose, notes were regressed on all of the variables included in the investigation. Handwriting speed and sustained attention were the only predictors of notes, and notes were the only significant predictor of written recall. To address the second purpose of the study, handwriting speed was regressed on all of the other independent variables. Only fine motor fluency and SAVC were related to handwriting speed. Thus, it appears that handwriting fluency in lecture note-taking is related both to motor and language systems.

Motoric Systems in Handwriting. In children, the relationship between fine motor skills (the control of small muscle movements) and academic achievement in mathematics, writing, and even reading, has been well documented (Cameron et al., 2012; Carlson et al., 2013; Dinehart & Manfra, 2013; Grissmer et al., 2010; Son & Meisels, 2006). Children with poorer fine motor skills, dexterity in particular, perform more poorly on academic tasks and can experience difficulty in other areas of cognitive development, especially executive functioning (Roebers et al., 2014), lexical processing (Suggate & Stoeger, 2017), processing speed, nonverbal reasoning, and general knowledge (Martzog et al., 2019). Martzog et al. (2019) suggested that these findings may be due to the importance of motor skills to children's exploration of and interactions with their environments (Piaget, 1952) or to the similarity of the neural circuits that underlie dexterity and reasoning (Ullman & Pierpont, 2005). The latter idea has been supported by studies that have tied difficulties with verbal comprehension to difficulties with sequenced motor tasks (Johnston et al., 1981; Schwartz & Regan, 1996).

Adults require fine motor skills for taking lecture notes, by gripping a pencil/pen, coordinating control of eye and hand movements, and manipulating both small (hand) and large (posture) muscles to produce precise and legible symbols. The interplay between motor fluency and written output holds for typing (Penney & Blackwood, 1989) and handwriting (Bourdin & Fayol, 1994). Further, Bourdin and Fayol (1993, 1994, 1996) found that seven- and eight-year-old children experienced more difficulty with serial recall and sentence production tasks in written than oral modalities, and adults were only impaired when forced to use all capital letters. Thus, both children and adults experience decrements in higher-level tasks (i.e., maintenance and recall of an unrelated series of items) when basic skills are less fluent.

Investigations of adult writing skills (Brown et al., 1988; Connelly et al., 2006; Olive et al., 2009) have shown a significant relationship between handwriting speed and the quality and quantity of written work (e.g., essays). Connelly and colleagues (2005) compared undergraduate essays written under unpressurized (class essay) and pressurized (timed essay exam) conditions and found that the quality of writing was constrained by handwriting fluency: those in the timed condition produced writing of lower quality. Alves, Castro, and Olive (2008) investigated slower and more fluent typists and found that the former produced poor-quality narrative text (less informative, greater number of problems with language correctness, and less emotional detail). Further, higher-level writing processes (planning and revising) were primarily activated during pauses between the physical movements, while less demanding processes (translation) occurred concurrently with typing. The faster writers are able to record, the greater the amount of time they have for other processes.

In a study of college students with and without dyslexia, Connelly and colleagues (2006) found that handwriting speed was one of two variables that accounted for the highest proportion of variance in essay quality (20.8%) for all students. In a similar study investigating learning disabilities and notetaking, Oefinger and Peverly (2020) found learning disability status was correlated with handwriting speed, among other variables, and that students with a learning disability performed more poorly on measures of note-taking and test performance. In order to gain a better picture of handwriting speed in the dyslexic population, Sumner et al. (2013) used a digital writing tablet for a precise measurement of speed of execution. They found that when they measured the time and distance of pen movements, excluding pauses, children with dyslexia had a similar handwriting speed as their same-age peers. However, the two populations differed in spelling ability and proportion of spelling errors, both of which were greater in children with dyslexia. These results were supported by Sumner and Barett (2014), who further examined the relationship between spelling and handwriting in sentence-copying tasks that removed all compositional demands. A final study by Sumner et al. (2016) found that oral language skill and fine motor components of writing were not what constrained quantity of words written and quality of text in this population, but rather frequent within word pauses during composition and poor spelling ability.

Generally, as stated previously, researchers posit that faster handwriting speed lessens the burden on the limited capacity working memory system, allowing the writer to access higher level skills, including verbal ability and metacognition, which leads to a higher quality written product. Interestingly, Kalsbeek (1965) found evidence that not only do lower-level skills constrain higher-level processes, but that the relationship between higher- and lower-level skills could in fact be inverted: after increasing the difficulty of managing higher-level processes, the quality of graphic transcription in adults was diminished (Fayol, 1996).

Language Systems in Handwriting. Language is intrinsically related to handwriting (or typing) since writing systems are culturally constructed symbol systems that represent oral languages. Perfetti (1983) defined language processes as any cognitive activity involving recognition, retrieval, or understanding of linguistic forms. Simple verbal processes are those related to letter and word recognition and generation, which include phonetic and orthographic coding (spelling) rules. More elaborate processing incudes proposition encoding and integration via complex language rules (e.g., cohesion, coherence) and organized knowledge systems. Perfetti (1983) argued that skilled verbal processing underlies both reading and writing. Similarly, Peverly et al. (2013) argued that the skills that underlie the ability to write are largely similar to those needed for skilled note-taking.

Orthographic coding, the ability to represent language, including letters, letter groupings (spelling rules) and words in the mind (Berninger et al., 1991; Berninger & Swanson,1994; Peverly et al., 2014) is absolutely essential to understanding and generating words in reading and writing (Berninger et al., 1991, 2008; Berninger & Swanson, 1994; Richards et al., 2009). The vast majority of the writing literature has investigated orthographic coding in elementary and early middle school children, who were still developing basic academic skills (Berninger et al., 1997; Christensen, 2004; Graham et al., 1997, 2000; Olive et al., 2008). Studies have found that orthographic coding was predictive of both handwriting and compositional fluency in children (Berninger et al., 1991), and orthographic-motor integration—the integration of fine motor production demands and orthographic knowledge—was a major predictor of quality and quantity of written products (Berninger et al., 1992; Christensen & Jones, 2000; Graham, 1990). For example, students with dysgraphia, a neurodevelopmental disorder with impairment in written expression, showed impairment in orthographic word storage and processing, and benefited from specialized instruction in orthographic coding, in addition to planning and fine motor skills (Berninger & Swanson, 1994). Researchers have also found a relationship between handwriting speed and the ability to quickly access individual words or verbal codes in children (McCutchen et al., 1994; Phillips, 1999; Rodriguez-Aranda, 2003). When measuring different subtypes of orthographic coding, Berninger et al. (1994) found that, among other contributing factors (working memory span and Verbal IQ), speeded receptive orthographic coding and speeded orthographic-motor integration contributed to predicting the quality of written composition. In combination, research on written language supports the hypothesis that handwriting speed is in fact related to both fine-motor speed and speed of access to these verbal codes (speeded access to orthographic codes and lexical access will be referred to as speeded access to verbal codes or SAVC throughout the rest of this document).

Intervention studies are also supportive: performance on writing tasks improved for early elementary school children who were taught handwriting skills (Berninger et al., 1997), letter formation and activities promoting letter writing speed and accuracy (Jones & Christensen, 1999), and/or were given explicit spelling instruction (Berninger et al., 1998). As students age, however, spelling skills may be less important than handwriting. Graham et al. (1997) found that in earlier grades, both handwriting and spelling were related to compositional fluency and quality, whereas in intermediate grades only handwriting was significant, which suggests that mechanical skills may constrain quality and quantity of written compositions.

Most of the aforementioned research was with children. Thus far, only one known study investigated the relationships of these variables using an adult population (Peverly et al., 2014). As discussed earlier, the authors were interested in the cognitive variables associated with note-taking skill and evaluated the relationship of handwriting speed, fine motor speed, speeded access to verbal codes, language comprehension, working memory, and attention to note-taking and recall performance (a final test of learning as measured by free recall of lecture content in the absence of notes). Notes, as an outcome measure, were coded by independent raters for quality (i.e., record of a topic, elaboration and explanation) and quantity. The major findings were: (1) handwriting speed and attention were the only independent variables significantly related to notes, (2) quality of notes was the only variable significantly related to recall performance, and (3) fine motor fluency and SAVC were the only variables related to handwriting speed. Overall, this offers strong support for the supposition that the relationship between handwriting speed, fine motor speed, and speeded access to verbal codes that has been observed in children continues into adulthood.

Purpose and Hypotheses

The purpose of this dissertation is to extend the findings of Peverly et al. (2014) using data from two different studies on the cognitive processes related to note-taking (Peverly et al., 2007, 2013), specifically to investigate the relationship of fine-motor fluency and SAVC to handwriting speed in an adult population. The data sets include different measures of handwriting speed, fine motor speed, and SAVC, among other variables. Unlike the Peverly et al. (2014) study, this dissertation will not focus on the quality/quantity of notes, nor the measure of learning; variables of interest are process-based in nature.

Question 1: When handwriting speed is regressed on all the independent variables included in each study (e.g., compositional fluency, fine motor speed, verbal working memory, attention, and SAVC), will fine motor speed and SAVC be the only variables significantly related to handwriting speed?

Hypothesis 1: Both fine motor speed and SAVC will be the only variables that predict handwriting speed.

Question 2: Will differences in the manner in which the primary constructs were measured between data sets impact the results?

Hypothesis 2: Despite differences in the manner in which handwriting speed, fine motor speed, and SAVC were measured, results will remain consistent across data sets.

Chapter 3: Method and Results

Study 1

Data collected by Peverly et al., 2007

Overview 1

The first data set to be used in the current analysis was gathered during a study by Peverly and colleagues in 2007, investigating the underlying cognitive processes necessary for quality note-taking in an adult population. Their primary purpose was twofold: first, to evaluate the relationship of transcription fluency, verbal working memory, and identification of main ideas to quality of notes; second, to confirm that quality notes were positively and significantly related to test performance. The variables of interest were transcription fluency (graphomotor and compositional fluency), verbal fluency (phonetic and semantic retrieval), verbal working memory, notes quality, and test performance. They hypothesized that, (1) notes and verbal working memory would be predictive of test performance, (2) transcription fluency would be positively related to quality of notes, (3) verbal working memory would account for a significant amount of variance in quality of notes, and (4) verbal fluency would be positively related to note quality.

Their findings indicated that, (1) quality of notes was the only variable that significantly predicted test performance, (2) transcription fluency was the only significant predictor of quality notes, (3) verbal working memory alone had not contributed significantly to that variance in quality of notes, and (4) verbal fluency alone had not contributed a significant amount of variation. They posited that the latter two variables—verbal working memory and verbal fluency—may share an underlying construct (i.e., speeded access of verbal codes from long-term memory) which itself may relate to quality and quantity of notes.

Method 1

Participants

Participants (*N* = 151) were undergraduates from a large, public university in the northeastern United States. The mean age of participants was 20.07 (*SD* = 2.22) with a range of 18 to 42 years of age. In this ethnically homogenous population, 91.4% of participants identified as White, 4% as Asian, 3.3% as Latino/a, and 1.3% as Black. English was the first language spoken for 96% of participants. A total of 86.1% of participants identified as female, 13.9% as male. The majority of students were in their second year of study (*M* = 2.2, *SD* = 0.48): 0% were in their first year, 82.1% were in their second year of study, 12.6% in their third, 3.3% in their fourth, and 2% did not report.

Materials

The following variables were collected during this study: handwriting speed, compositional fluency, fine motor speed, verbal working memory, and SAVC.

Handwriting speed. In the notetaking and essay-writing literature, handwriting speed is customarily measured by the number of letters or words written within a speeded time frame (Berninger et al., 1991; Oefinger & Peverly, 2020; Peverly, 2007). A frequently used measure in both adult and child populations is an alphabet speed task, two variations of which were used for the two studies of interest. In Study 1, participants were provided a lined sheet of paper, and asked to write the letters of the alphabet horizontally and consecutively (starting at "a" and ending at "z"). Participants were instructed to alternate between capital- and lower-case letters, first writing the entire alphabet in all capital letters followed by the entire alphabet in lower-case letters as many times as they could within a 45-second time limit. The total score was the number of legible letters the participant was able to produce. This is a modified version of a measure used by Berninger et al. (1991). Though this specific task does not have any known reliability data associated with it, it is similar in nature to a standardized measure used to evaluate handwriting difficulties in individuals aged 17 to 25 years: the Alphabet Writing Task from the Detailed Assessment of Speed of Handwriting 17+ (DASH 17+; Barnett et al., 2010). The test-retest reliability from the DASH 17+ is .9, with good predictive validity.

Compositional Fluency. Compositional fluency was measured using the Writing Fluency subtest from the Woodcock Johnson Psycho-Educational Battery - III (WJ-III, Form A; Woodcock et al., 2001). This task measured the speed and accuracy of combining words into phrases. Participants were given a set of three prompt words for each item and were required to construct as many sentences as they could within a seven-minute time limit. The WJ-III is a well validated and reliable measure, normed for ages 5 to 95 or grades from Kindergarten to 18. It is frequently used in psychoeducational evaluations and informs academic intervention and services. Internal consistency and reliability are .86, with a standard error of measurement of 5.63. Interrater agreement is between .98 and .99 (Woodcock et al., 2001).

Fine Motor Speed. Fine motor speed was measured using the Digit Symbol Copy task, a subtest from the Wechsler Adult Intelligence Scale, Third Edition (WAIS-III; Wechsler, 1997), one of the most widely used standardized measures of intelligence and cognitive functioning in adults aged 16 to 89 years. In this task, participants were required to copy rows of simple symbols into rows of blank boxes directly below. The total score was derived from the number of identifiable symbols copied out of 133 within a 90 second time limit. The test-retest reliability coefficient is .90 and the interrater agreement is .99 (Wechsler, 1997). The Symbol Copy task was used as a measure of fine motor speed without a memory component, and has been shown to have a strong correlation ($r = .67$, $p < .05$) with another measure of graphomotor speed, Name Printing, in which participants printed their first and last names as rapidly as they can one letter at a time in provided boxes (Joy et al., 2003).

Verbal Working Memory. Working memory was measured using the Listening Span task which was adapted from the Reading Span Task (Daneman & Carpenter, 1980). Daneman and Carpenter (1980) found that the two tasks were strongly correlated ($r = .80$, $p < .01$). Typical measures of working memory, such as digit or word span tasks, have shown no or low correlation with higher level language-based skills like reading (Perfetti & Lesgold, 1977). Thus, studies of note-taking have incorporated this broader measure (Oefinger & Peverly, 2020), which better mimics the demands of a typical student listening to a lecture. The test included 60 unrelated sentences varying from 9 to 16 words in length. Participants listened to three sets of two, three, four, five, and six sentences, presented as increasingly longer sets until they failed all three sets in the level. As each sentence was presented, the participant had to determine whether the sentence made sense, and circle "yes" or "no" in a test packet. Then, following the completion of a set, a prompt was provided and the participant had to recall the last word from each sentence in that set. The true-false component was included to ensure participants were processing the entirety of the sentence and not focusing only on the final word of the sentence. Scores were based on the highest level (2-6) at which the participant remembered all of the final words for at least one set. Scores could range from 1.5 to 6 in increments of 0.5. The interrater agreement was 1.00.

Speeded Access to Verbal Codes (SAVC). SAVC was measured using an adaptation of the Verbal Fluency subtest from the Developmental Neuropsychological Assessment (NEPSY; Korkman et al., 1998), a developmental neuropsychological assessment for children. The Verbal Fluency subtest measures an individual's ability to quickly access words from their memory using phonetic or semantic cues. Usually, this subtest is administered to a single individual at a time and requires the participant to provide their answers verbally. For the purposes of this study, the subtest was modified for group administration, with participants writing their responses on a sheet of paper. On the phonetic retrieval portion of the test, participants were asked to write down as many words as they could that began with the letters *S* and *F* within one minute. On the semantic retrieval portion of the test, participants were asked to write down as many words as they could that belonged to the categories *animals* and *food/drink* within one minute. The correct number of responses were based on the number of correct words fitting the criteria, without repetition, proper names, or different forms of the same word. The scores from the two phonetic tasks were combined, as were the two scores from the semantic tasks. Interrater agreement was .99 for both phonetic and semantic retrieval.

Procedure

This study used a within-subjects design. All participants received the same measures administered in a group within a single session. The protocol ran over the course of two days. On the first day, after completing demographics and consent forms, participants watched a 20-minute video lecture on the psychology of problem solving and were told to take notes using two pieces of paper. They were further told they would have time to review their notes, and to make the notes as complete as possible. Following the note-taking task, they reviewed their notes for 10 minutes in preparation for a test on the material. Next, they completed the handwriting speed task (one minute), fine motor fluency speed task (90 seconds), SAVC measure (five minutes), and finally the lecture test (an organized summary of the content). Two days later, participants returned and completed the verbal working memory (20 minutes) and the compositional fluency measure (seven minutes). The entirety of the study took roughly 90 minutes.

In the analysis, handwriting speed was regressed on all other variables: compositional fluency, fine motor speed, verbal working memory, and SAVC.

Results 1

Data was coded and analyzed using SPSS (IBM, 2020). Visual inspection of independent variables of interest and the dependent variable, handwriting speed, revealed no significant violations to the assumption of normality. Of the total number of participants ($N = 151$), full data was available for a total of 147 individuals; measures of verbal working memory and semantic retrieval contained missing data. See Table 1 for a summary of descriptive statistics, including means, standard deviations, and total number of participants for each.

Table 1.

Study 1: Means and Standard Deviations of Variables

	M	*SD*	*N*
Handwriting Speed	57.52	10.36	147
Fine Motor Speed	127.82	11.54	147
Compositional Fluency	27.54	3.51	147
Verbal Working Memory	4.69	.87	147
SAVC: Phonetic Retrieval	28.20	5.73	147
SAVC: Semantic Retrieval	33.09	5.93	147

Using a multiple linear regression model, handwriting speed was regressed on all independent variables of interest (fine motor speed, compositional fluency, verbal working memory, and phonetic and semantic SAVC measures).

The full regression model was significant, with tolerance and variance inflation factors (VIF) within acceptable limits; $R = .63$, Adjusted $R^2 = .37$, $F(5, 141) = 18.41$, $p < 0.001$ (see

Tables 2, 3, and 4). Overall, 37.4% of the variance in handwriting speed is explained by the independent variables in this model, with a large effect size of $f^2 = 0.65$ (Cohen, 1992). These findings lend support for the first hypothesis, that only fine motor speed and SAVC would predict handwriting. Holding constant all other variables, fine motor speed ($B = .17$, $p < .01$) and SAVC (semantic retrieval only; $B = .53$, $p < .001$) predicted handwriting speed. Compositional fluency was also a significant predictor of handwriting speed ($B = 1.05$, $p < .001$). As expected, verbal working memory ($B = .09$, $p = .917$) was not significantly associated with handwriting fluency, nor was the other of the measure of SAVC, phonetic retrieval ($B = -.01$, $p = .950$).

Significant correlations were found between all variables with the exception of fine motor speed and compositional fluency, and SAVC (phonetic retrieval only) and verbal working memory. See Table 5.

Table 2.

Study 1: Model Summary

R	*R Square*	*Adjusted R Square*	*Std. Error of the Estimate*
.62	.4	.37	8.17

Table 3.

Study 1: ANOVA Results

	Sum of Squares	*df*	*Mean Square*	*F*	*Sig.*
Regression	6183.59	5	1236.72	18.41	.000
Residual	9471.08	141	67.17		
Total	15654.67	146			

Table 4.

Study 1: Coefficients

	Unstandardized Coefficients			
	B	Std. Error	t	Sign.
(Constant)	-11.15	8.93	-1.25	.21
Fine Motor Speed	.17	.06	2.82	.01
Compositional Fluency	1.05	.22	4.72	.00
Verbal Working Memory	.09	.82	.10	.92
SAVC: Phonetic Retrieval	-.01	.14	-.0.63	.95
SAVC: Semantic Retrieval	.53	.14	3.79	.00

Table 5.

Study 1: Pearson Correlations

Variable	1	2	3	4	5	6
1. Handwriting Speed	--					
2. Fine Motor Speed	.32***	--				
3. Compositional Fluency	.51***	.12	--			
4. VWM	.19**	.19*	.21**	--		
5. SAVC: Phonetic Retrieval	.29***	.15*	.37***	.10	--	
6. SAVC: Semantic Retrieval	.51***	.21***	.43***	.26**	.43***	--

*$p < .05$. **$p < .01$. ***$p < .001$

Study 2

Data collected by Peverly et al., 2013

Overview 2

The second data set to be used in the current analysis was gathered during a study by Peverly and colleagues in 2013. This 2013 study had two primary purposes: first, to determine if other cognitive processes beyond handwriting speed were related to notes' quality, with specific interest in language comprehension and working memory, and to additionally determine if a lecture outline would reduce/eliminate the relationship of handwriting speed to notes. Second, to replicate the findings of Peverly et al. (2007) that notes mediated the relationship between other cognitive processes and test performance. The variables in Peverly et al. 2013 included an outline for taking notes, note quality, test outcome (i.e., written summary of the content of the lecture), handwriting speed, language comprehension, verbal working memory, and executive attention. Participants were randomly assigned to one of two outline conditions: those who took notes using a skeletal outline and those who took notes on blank sheets of paper.

Their findings indicated that, (1) handwriting speed, language comprehension and group membership (outline) were significantly and positively related to notes; (2) handwriting speed was significantly correlated with attention and language comprehension for the outline group but not the no-outline group; (3) the relationship between the independent variables (handwriting speed, language comprehension, working memory (span and attention)) and test outcome was not completely mediated by notes, inconsistent with the 2007 study; and (4) using a path analysis, group, language comprehension, and handwriting speed predicted notes, and notes, group, and language comprehension predicted test performance. The use of outline did not moderate the relationship between handwriting speed and notes.

This study included measures of fine motor speed and SAVC that were not included in the analyses presented in Peverly et al. (2013). Thus, the purpose of this study was to replicate Peverly et al. (2014) with different variables measuring fine motor speed and SAVC than were contained in Peverly et al. (2014) or Peverly et al. (2007).

Method 2

Participants

Over two hundred undergraduate students (*N* = 204) were initially recruited from an introductory educational psychology course at a large university in the northeastern United States. This sample size was reduced to 94, as some students did not follow procedures for completing the fine motor speed measure and/or the SAVC measure, and an additional four students indicated that they were color-blind, which would have implications for color-dependent measure of attention. Of the final population, the mean age of participants was 20.53 years (*SD* = .77) and 86.2% identified as female. The racial/ethnic distribution was 93.8% White, 4.6% Asian American/Pacific Islander, and 1.5% Latino/a. English was the primary language spoken by 96.9% of participants. The majority of students were in their second year of study (*M* = 2.11, *SD* = .53): 7.7% were in their first year, 75.4% in their second year of study, 15.4% in their third, and 1.5% in their fourth.

Materials

The following variables were collected during this study: handwriting speed, fine motor speed, SAVC, language comprehension, verbal working memory, and executive attention. Participants were also randomly assigned to an outline or no outline group; however, group assignment was not included in this paper's analysis, as it is not relevant to the hypotheses.

Handwriting Speed. As in Study 1, as a measure of handwriting speed, participants were provided a lined sheet of paper, and asked to write the letters of the alphabet horizontally and consecutively (starting at "a" and ending at "z") as many times as they could in 45 seconds. For this study, participants did not alternate between lower and upper case.

Fine-Motor Speed. As a measure of fine-motor speed, participants were given one sheet of paper printed with 20 rows of 20 small boxes. Participants were instructed to draw a diagonal line in each empty box, based on the example provided at the start of each row. The direction of the diagonal in the first box of the first row ran from the upper left corner to the lower right corner. The direction of the diagonal in the first box of the second row ran from the upper right-hand corner to the lower left-hand corner. The following rows alternated in the direction of the diagonal line. Participants were instructed to complete as many lines as they could in 45 seconds. The final score was the number of identifiable diagonal markings out of a total of 380. This diagonal line task was newly developed by Peverly in order to remove the language component of most typically utilized fine-motor tasks.

SAVC. SAVC was measured using an alternate version of the Rapid Automatized Naming task (RAN-A), designed by Denckla and Cutting (1999). This version was highly correlated with the original RAN (r = .85; Compton et al., 2002) and has been frequently used for diagnosing reading ability in children as well as adults (Catts et al., 2002; Felton et al., 1990). The RAN-A measures the fluency of ability to recognize and name verbal symbols, specifically a visual-verbal domain under time constraints. On this task, participants were provided a list of six letters (a, b, d, o, p, s) presented in random order, in 13 rows of five items each for a total of 75 items. Participants were asked to name each letter from left to right as quickly as possible in 15 seconds. The total score was the number of correctly named letters within the time limit.

Language Comprehension. Language comprehension was measured by the comprehension component of a timed reading task, the Nelson-Denny Reading Test, Form G (Brown et al., 1993). The Nelson-Denny is a commonly used standardized reading test for late adolescent and college-age students, with reported correlations from the manual ranging from .81 to .88 for undergraduate students. Among undergraduate adults, reading comprehension ability is often used as a proxy for language comprehension. Once word recognition is sufficiently automatized (as it is for the adult college population), language comprehension accounts for most or all the variance in reading comprehension (Adolf et al., 2006, 2011; Gernsbacher et al., 1990; Peverly et al., 2013). The Nelson-Denny comprehension test consists of seven short reading passages followed by 38 factual and inferential comprehension questions in multiple-choice format with five possible answers each. Participants were instructed to read as many passages and answer as many comprehension questions as they could. Standard administration time is 20 minutes. However, in order to increase the variance in performance distinguishing between those with good and poor comprehension, time was reduced to 15 minutes, which had been done before in other studies (Brown, 2005; Sumowski & Peverly, 2012). Total score was the number of correct answers.

Verbal Working Memory. Verbal working memory was measured in the same manner as described in Study 1 (Daneman & Carpenter, 1980). The inter-rater agreement out of 25 randomly chosen protocols was .96.

Executive Attention. As a measure of executive attention, participants were administered a modified group version of the Stroop Color and Word Test (SCWT), a neuropsychological test commonly used for clinical and experimental purposes to assess the inhibition component of executive attention that occurs when processing one feature of a stimulus effects the processing of another feature of that same stimulus (Stroop, 1935). The most widely used SCWT, developed by Golden (1978), is designed for individual administration. Golden's SCWT asks the test-taker to view a page in which words are printed in either a congruous or incongruous color and to read aloud the color a word is printed in instead of the word itself (e.g., say "red" when the word green is printed in red ink), within a time-limit. A score based on color-word interference is used to determine the individual's level of cognitive flexibility and selective attention.

The Group Stroop, developed by Peverly and Sumowski (2012), is a paper-and-pencil adaptation of Golden's SCWT wherein participants circle their answer on the page instead of saying it aloud. Like the original test, the Group Stroop includes three conditions: word reading, color naming, and incongruent color-word naming. Pilot testing found a high correlation between the Group Stroop and the individually administered Golden's Stroop ($r = .89$, $p = <.001$). Participants were first provided directions, sample items, and practice items prior to each condition. The following two pages included 45 total items arranged in nine rows with five stimulus items each. For each item, the participant was required to scan a stimulus on the left side of a box, make a judgement based on condition-instructions, and circle one of three possible response choices in the right side of the box (e.g., red, blue, green). For the word reading condition, participants were presented a black, boldface color name on the left and were told to circle the word on the right that matched that word. For the color naming condition, they were presented with a red, blue, or green boldface 'XXX' on the left and were told to circle the name of the color on the right that matched the color on the left. For the incongruent color-word trial, participants were presented with a boldface color name printed in red, blue, or green ink, and were told to circle the name of the color matching the color of the ink on the right. Each condition had a 45-second time limit. The total score for each is the number of correct responses, with possible scores from 0 to 90. Inter-rater agreement across 25 randomly chosen protocols was 1.00.

Procedure

This study used a within-subjects design. All participants received the same measures administered in a group format, with the exception of the RAN, which was administered individually. Participants were initially randomly assigned to group (outline or no outline); however, group was not included in the current analysis, as it fell outside the scope of the question, and removing it saved power. The protocol ran over the course of two days. On the first day, after completing demographics and consent forms, participants watched a 23-minute video lecture on the psychology of problem solving while taking notes, reviewed their notes for 10 minutes, completed the handwriting speed task (one minute), the fine motor speed task (one minute), and wrote a summary for 15 minutes (not included in the present analysis). On the second day, participants returned and completed the verbal working memory task (20 minutes), the executive attention task (10 minutes), the language comprehension measure (15 minutes), and finally the SAVC measure (two minutes).

As in Study 1, for this analysis, handwriting speed was regressed on all other variables: fine motor speed, SAVC, language comprehension, verbal working memory, and executive attention.

Results 2

As in Study 1, data in Study 2 was coded and analyzed using SPSS (IBM, 2020). A visual inspection of independent variables of interest and the dependent variable, handwriting speed, revealed no significant violations to the assumption of normality. Data analysis was performed on $N = 94$, a significantly reduced number from the original $N = 204$. Four participants were initially removed from the analysis as they reported a diagnosis of color blindness, which would have significantly impacted their performance on the Group Stroop. Additional subjects had missing or incorrectly completed measures of find motor speed, SAVC, compositional fluency, and/or language comprehension. The two variables missing from more than 10 percent of subjects were measures of fine motor speed (missing $N = 59$, 29.5%) and SAVC (missing $N = 106$, 53.0%). See Table 6 for a summary of missing data. Missing data was analyzed with Little's Missing Completely at Random Test (MCAR), which indicated no statistically significant systematic pattern, X^2 (17, $N = 200$) = 27.34, $p > .05$. Multiple imputation was performed with the target variable of fine motor speed in order to preserve a greater number of data points in the set and increase the power of the results. Handwriting speed, fine motor speed, language comprehension, working memory, attention, and SAVC were all used as predictor variables. The final N in this analysis, using the pooled imputation set, is 94. See Table 7 for the means and standard deviations of original variables and Table 8 for means and standard deviations of variables with imputed fine motor speed variable.

Table 6.

Study 2: Summary of Missing Data

	Missing				
	N	*Percent*	*Valid N*	*M*	*SD*
Fine Motor Speed	59	29.5%	141	101.58	15.25
SAVC	106	53.0%	94	50.98	6.04

Table 7.

Study 2: Means and Standard Deviations of Original Variables

	M	*SD*	*N*
Handwriting Speed	89.89	17.49	65
Fine Motor Speed	100.18	13.15	65
Language Comprehension	26.37	5.76	65
Verbal Working Memory	3.86	1.37	65
Executive Attention	45.75	8.69	65
SAVC	50.65	5.98	65

Table 8.

Study 2: Means and Standard Deviations of Imputed Variables

	M	*SD*	*N*
Handwriting Speed	90.59	18.73	94
Fine Motor Speed	100.46	14.27	94
Language Comprehension	26.52	6.07	94
Verbal Working Memory	3.85	1.47	94
Executive Attention	46.48	8.96	94
SAVC	50.98	6.04	94

Using a multiple linear regression model, handwriting speed was regressed on all independent variables of interest (fine motor speed, language comprehension, verbal working memory, executive attention, and SAVC).

The full regression model was significant, with tolerance and variance inflation factors (VIF) within acceptable limits for all imputation models; $R = .56$, Adjusted $R^2 = .28$, $F(5, 88) = 8.06$, $p < 0.001$ (see Tables 9 and 10). Overall, 27.5% of the variance in handwriting speed was explained by the independent variables in this model with an effect size of $f^2 = 0.46$, which is considered to be a large effect (Cohen, 1992).

Only fine motor speed ($B = .52$, $p < .001$) and SAVC ($B = .71$, $p < .05$) predicted handwriting speed. As expected, language comprehension ($B = .45$, $p = .14$), verbal working memory ($B = -.73$, $p = .55$), and executive functioning ($B = .12$, $p = .62$) were not significant predicters of handwriting speed. See Table 11. These findings again lend support for the first hypothesis, that only fine motor speed and SAVC would predict handwriting.

The correlation between fine motor speed and SAVC was not significant ($r(92) = .11$, $p = .2$). The only significant correlations in the model were between fine motor speed and handwriting speed, fine motor speed and executive functioning, language comprehension and executive functioning, verbal working memory and executive functioning, and SAVC and executive functioning. For full correlations, see Table 12.

Table 9.

Study 2: Model Summary

R	*R Square*	*Adjusted R Square*	*Std. Error of the Estimate*
.56	.31	.28	15.94

Table 10.

Study 2: ANOVA Results

	Sum of Squares	*df*	*Mean Square*	*F*	*Sig.*
Regression	10243.12	5	2048.62	8.07	.000
Residual	22367.70	88	254.18		
Total	19584.25	93			

Table 11.

Study 2: Coefficients

	Unstandardized Coefficients			
	B	*Std. Error*	*t*	*Sig.*
(Constant)	-12.78	19.94	-.64	.52
Fine Motor Speed	.52	.16	3.34	.00
Language Comprehension	.45	.31	1.47	.14
Verbal Working Memory	-.73	1.24	-.59	.55
Executive Functioning	.12	.24	.50	.62
SAVC	.71	.31	2.31	.02

Table 12.

Study 2: Pearson Correlations

Variable	1	2	3	4	5	6
1. Handwriting Speed	--					
2. Fine Motor Speed	.45***	--				
3. Language Comprehension	.22*	.23	--			
4. Verbal Working Memory	.09	.12	.30**	--		
5. Executive Functioning	.29**	.32*	.28**	.21*	--	
6. SAVC	.29**	.12	.10	.18*	.32**	--

*$p < .05$. **$p < .01$. ***$p < .001$

Chapter 4: Discussion

Almost all college students take notes. Despite the ubiquity of computers in college classrooms, many students prefer to use the traditional pen-and-paper method for transcribing their notes (Luo et al., 2018; Morehead et al., 2019b; Peverly & Wolf, 2019). However, writing is a difficult and cognitively demanding task that requires the integration of multiple systems of cognitive and physical resources. The notetaker must attend to the lecture content, hold and manipulate that information in their working memory, determine the most salient parts of the information, tie it to their own background knowledge, and finally record it. This entire system is cyclical and simultaneous as new information continues to be presented. Thus, it is not surprising that the variables which most consistently have been found to impact the quality and quantity of notes are handwriting fluency (Peverly et al., 2007, 2013, 2014), language comprehension (Peverly et al., 2007, 2013), and sustained attention (Gleason, 2012; Peverly et al., 2013; Vekaria, 2011). Handwriting speed is especially important. Unless it is sufficiently fluent, higher level cognitive resources will not be as available as they otherwise might be for the production of a quality written product (McCutchen, 1996, 2000; Kellogg, 2008).

We know very little about the variables that contribute to handwriting fluency in adult populations, with only one study examining the question (Peverly et al., 2014), despite the ubiquity and importance of note-taking to academic achievement (Armbruster, 2009; Di Vesta & Gray, 1972; Dunkel & Davy, 1989; Peverly et al., 2007; Peverly & Sumowski, 2012; Peverly & Wolf, 2019). The literature on children's essay writing, which is similar to note-taking in terms of physical and cognitive functions, has shown handwriting speed to be highly related to not only fine motor speed, but even more strongly to cognitive representation of written language (i.e., orthographic codes) (Abbott & Berninger, 1993; Berninger et al., 2006; Berninger & Rutberg, 1992; McCutchen et al., 1994; Phillips, 1999; Rodriguez-Aranda, 2003). The speed at which one can access orthographic codes in memory, SAVC, seems to mediate the relationship between handwriting speed and fine motor speed (Abbott & Berninger, 1993). The findings of Peverly and colleagues (2014) replicated the child literature: when handwriting speed in adults was regressed on measures of language comprehension, working memory, executive attention, sustained attention, fine motor speed, and SAVC, only fine motor fluency and SAVC were significantly and positively related to handwriting speed.

The research questions presented here were as follows: (1) When handwriting speed was regressed on all the independent variables included in each study (e.g., compositional fluency, fine motor speed, verbal working memory, attention, and SAVC), would fine motor speed and SAVC be the only variables significantly related to handwriting speed? (2) Would the manner in which the primary constructs are measured between data sets impact the results? It was hypothesized that: (1) Both fine motor speed and SAVC would be the only variables that significantly and positively predict handwriting speed, and (2) Despite differences in the manner handwriting speed, fine motor speed, and SAVC were measured, results would remain consistent across data sets.

The data analyzed in this dissertation are from two prior studies, both investigating the cognitive and motoric processes underlying notetaking using an adult college-aged population. As noted earlier, both studies were comparable in many ways: participants (primarily White female undergraduates), general administration procedures, and both included measures of handwriting speed, fine motor speed, verbal working memory, and SAVC. The measures used for the constructs of fine motor speed and SAVC differed.

Results indicate that the first research question and hypothesis were partially supported. In Study 1, three variables significantly and positively predicted handwriting speed: fine motor speed, compositional fluency, and SAVC (semantic retrieval only). What was not hypothesized but nonetheless revealed in the analysis is that compositional fluency was a significant predictor in the model. Due to the largely language-based and motoric nature of compositional fluency—which in this case was measured by a speeded task requiring the combination of sets of three words into sentences—it is an understandable outcome. Because of the measure of SAVC used in this study, the construct was split between phonetic retrieval and semantic retrieval. Only semantic retrieval was a significant predictor of handwriting speed. In Study 2, the results fully support the first research question and hypothesis in that only fine motor speed and SAVC were positively significant.

The second research question was whether the differing manners in which the constructs of handwriting speed, fine motor speed, and SAVC were measured across both data sets produce consistent results. Comparisons between the outcomes partially supports the hypothesis that the outcomes would be similar. SAVC and fine motor speed were both found to be primary predictors of handwriting speed in each study, despite the differences in measurement. Interestingly, in Study 1, semantic but not phonetic measures of SAVC predicted handwriting speed.

Overall, these results lend further support to the conclusion of Peverly et al. (2014) that the relationship between fine-motor fluency and SAVC to handwriting speed is consistent beyond childhood and is evident in an adult population.

Continuity of Predictors Across Age

The literature on these variables has suggested that once a person becomes fluent in writing in elementary school, handwriting speed is no longer a matter of motor speed, but instead a skill fundamentally based in language and how fast one can access basic language code in their mind and translate it to the page (Abbott & Berninger, 1993; Berninger et al., 2006; Berninger & Rutberg, 1992). Abbott and Berninger (1993) demonstrated that in grades one through six, language skill (orthographic coding) was the most direct path to handwriting, above that of fine motor speed. Thus, language competence is a fundamental factor not only to reading (Vellutino et al., 2004), but also to handwriting and the quality of the written product.

Neurocognitive and brain imagining research has demonstrated support for the neural basis of a combined motor and language system within the brain (Longcamp et al., 2016, 2019; Planton et al., 2013). This amalgamation of motor and language systems is present prior to the instruction, use, and mastery of writing. In fact, it has an evolutionary basis through the necessary integration between recognizing and discriminating between speech sounds and the production of sounds through verbal-motor speech production (Longcamp et al., 2019). Language has even been hypothesized to be an innate ability, needing no formal instruction to acquire (Chomsky, 1965). Further neural research has described a developmental process during which the maturation of written language induces plasticity of systems that would have otherwise been used for other functions, creating a functional specificity directly tied to the basic levels of written language (Planton et al., 2013). A meta-analysis of neuroimaging studies of motor and orthographic processes by Planton and colleagues (2013) found that in the 18 reviewed studies, there was substantial variation; however, they agreed that the left-hemispheric network, most crucially the left frontal and superior parietal regions, is used for writing tasks across the languages they studied (English, Japanese, German, Japanese, Czech, French) and methodologies. In their conceptual model, the writing process is composed of three primary levels of input to output: (1) Input processing, wherein verbal auditory or visual input leads to phonologic or orthographic input, leading to a semantic system; (2) Writing/spelling, wherein independently the orthographic system and the phoneme-to-grapheme conversion lead to a graphemic buffer, then an allographic system, and to the graphic motor patterns, which leads finally to (3) Motor output, which is the neuromuscular execution.

The research presented in this dissertation, as well as the work of Peverly et al. (2014), lends evidence for this connection between language and motor systems into the manual movements of the hands in a young adult population of college students, indicating that the early development of language and the connection between language in academic acquisition is long-lasting. As a neurological function, it is likely that this relationship, starting after the development of fluent motor production, would continue into and through adulthood, with the exception of injury to the brain.

Educational Implications

Understanding that handwriting speed includes both language and fine motor systems, the treatment of writing disorders and impairments should be approached as such, particularly as we now have data to suggest that the relationship seems to hold into later adulthood. This important connection should not be neglected as students move beyond elementary school. Interventions targeting fine motor ability should move beyond manual movements and would benefit from the integration of alphabetic knowledge, phonemic awareness and integration, and rapid fluency trials. Abbott and Berninger (1993) suggested that this may have implications for assessment of learning disabilities, in that orthographic coding measures ought to be used in comprehensive assessments of handwriting and spelling. This would also imply the need for a more holistic approach to the identification and referral of students to special education evaluation and support, including an understanding of the relationship of language to handwriting and vice versa.

In terms of intervention approach, this research lends further support to a phonic-based curriculum over a whole language learning approach, not only for students who struggle with early reading, but as a tier one universal approach to instruction. The focus and practice of small orthographic codes across all levels could help support even typically performing students in handwriting tasks. Berninger et al. (2006) found that handwriting is best supported by explicit letter formation instruction, including the use of directional arrows, and that neither fine motor training alone, nor motor-free orthographic training alone is best, but that a combinatory effect improved handwriting significantly for children. They found that handwriting instruction itself was the most effective intervention at improving handwriting speed and automaticity.

Certain pedagogical practices that limit the importance of speed may be supported by this research, including the use of guided notes. There is support for the use of guided notes, which are a skeletal outline of notes provided by the lecturer to which students add more notes. Students who are given guided notes record a greater quantity and, for some, a greater quality of notes (Austin et al., 2004; Bui & McDaniel, 2015; Kiewra et al., 1995). An additional teaching method would be planned pauses in lectures with added instruction for students to review and add to their notes as needed during that time. Luo and colleagues (2016) performed an intervention study of just that practice and found that students who took notes during a lecture that interspersed pauses throughout were able to record more complete notes. It is likely that students whose handwriting speed is limited by fine-motor skills and/or SAVC would benefit from reduced temporal pressures and the opportunity to gather information from other students.

Limitations and Future Research

The availability of information regarding the relationship between handwriting speed, SAVC, and fine motor fluency in adulthood is limited. Further, all papers that included an adult population have been consistently homogeneous in research populations (mostly female and White). To bolster our understanding of the contribution of language and motor systems across the developmental lifespan, cross-sectional and longitudinal research should be utilized to further explore how their relationship varies over time. We also do not know if these findings would vary with a more equitable distribution of gender, ethnicity, and education level in research samples. It is possible that a greater, more equitable distribution would actually provide greater variability in outcome measures with a less restricted range and thus more robust effects. For example, we know that there are gender differences in handwriting (Cohn et al., 1995; Reddington, 2011; Reddington et al., 2015), with females both recording and recalling more information, with faster handwriting speed. A more equitable distribution of gender could provide some insight into gender differences relating to measures of SAVC and fine motor speed as they relate to handwriting speed. A more heterogeneous population would certainly provide more information regarding the effects of language exposure, early educational experiences, socioeconomic status, and access to writing interventions. The demographics collected did not include many of these variables, which would be of interest in the note-taking literature; it currently suffers from a dearth of such information, despite it being well-established that these factors influence academic achievement (Cedeño et al., 2016; Hodgkinson & Goldberg, 2000; Krein, 1988; Okpala, 2002; Reardon & Portilla, 2016).

One interesting finding of this study was that the measure of SAVC differed in significance between Study 1 and Study 2. In Study 1, the measure of SAVC consisted of two subtests, which were each regressed onto handwriting speed. While SAVC generally was hypothesized to be a significant predictor of the handwriting speed variable, only the SAVC subtest measuring semantic retrieval showed significance. The measure of SAVC that measured phonetic retrieval did not approach significance. As a reminder, the phonetic subtest required a participant to write as many words as they could within a 60-second limit when first provided with the letter *S* and then again with the letter *F*. The semantic subtest had the same requirements; however, instead of being provided with a letter, they were asked to name as many items as they could in a given category, first *animals* and then *food*. In many ways, the semantic measure provides more structure and approaches a more true-to-life skill that might be used when creating shopping lists, or even in the case of listening to a lecture where context is built into the nature of the material. The phonemic measure is purely phonemic and requires the participant to potentially suppress their semantic activation, as categorically related words might not fit the task demand (Belke et al., 2017; Katzev et al., 2013). In this light, the phonemic test adds a layer of cognitive load, particularly as this task directly follows that of the semantic task, which could prime the participant for a semantically based strategy of retrieval.

This suggests that SAVC could in fact be parsed further into how language is stored within the brain to further understand its relationship to handwriting speed. Neuroimaging studies have demonstrated similar though not overlapping brain circuits, which has led some researchers to suggest that semantic fluency is more related to verbal ability, while phonetic fluency is more related to executive ability (Belke et al., 2017; Shao et al., 2014). This lends some support to the overall supposition of this dissertation, that handwriting speed is highly related to verbal ability and access. It is also possible that the manner in which the test was altered for group administration could have impacted these results. Typically, the SAVC measures used for Study 1 would be administered individually and the participant would verbally provide their answer, whereas for this study, the measure was provided to groups of participants who provided their answer in written form.

Another consideration in this dissertation is that, however significant these findings are, the amount of variance accounted for in handwriting speed was only 37.4% ($f^2 = .65$, $p<.000$) in Study 1 and 19.7% ($f^2 = .35$, $p = .003$) in Study 2. As we know, handwriting is a complex process and includes multiple cognitive, physical, sensory, and biological systems working in tandem. It is thus unsurprising that these constructs, many of which are being measured under time pressure in intervals as short as 45- and 60-seconds, do not fully capture the complexity of the handwriting process. There are further a variety of individual factors that are unaccounted for in these models, including learning, language, or attention-deficit disabilities or potentially even environmental factors within each study group.

Finally, the modality of writing and note-taking in classrooms has been in a state of transition, with laptop computers increasing in popularity. Aguilar-Roca et al. (2012) reported that nearly one-third of all college students use laptops to take notes, and Fried (2008) found that 64.3 percent of his college students reported using laptops for note-taking in at least one of their courses. A 2012 and 2013 survey of 435 students found that 96.5% of students take notes on paper at least sometimes and 53.4% take notes on computer at least sometimes (Peverly & Wolf, 2019). Luo et al. (2018) reported that 75% of their participants reported typically taking notes longhand, while 25% typically used a computer. Most recently Morehead et al. (2019b) found that 86% of students reported taking notes longhand in a notebook and 46% reported taking notes on a laptop. Of those Morehead et al. (2019b) surveyed, 32% of students reported taking notes using both mediums. When asked to explain their choice to use more than one method, 20% reported using a laptop when the instructor spoke quickly, 20% reported using a laptop when PowerPoint slides were available, and others reported that their choice was dependent on the class. Further, the use of technology, particularly computers, in the classroom has likely shifted drastically over the past year. The impact of the COVID-19 pandemic and resultant shift to computer-based education has not yet been documented in the note-taking literature, but it will likely have an impact on how students take and use their notes. Not only are students more frequently on their computers, potentially increasing the likelihood of choosing laptops to take notes, but teachers have been forced to adapt their teaching style and use of technology. It is possible that many of the alterations in education will continue post-pandemic, particularly for adult students. Future studies should include and compare measures of note-taking and fine-motor speed between hand writing and key-boarding in order to determine if these results remain consistent. Many studies have shown that transcription speed is faster when using a computer as compared to traditional handwriting (Brown, 1988; Rogers & Case-Smith, 2002). However, the product created is not necessarily of higher quality, as students are more likely to take verbatim notes in lieu of organized or generative notes (Bui et al., 2013; Luo et al., 2018; Morehead et al., 2019a; Mueller & Oppenheimer, 2014). Further, we do not yet know if the relationship between accessing verbal codes for traditional writing is the same as that for computer writing, which on its face is a mechanically disparate action.

Conclusion

The purpose of this dissertation was to investigate the relationship of fine-motor fluency and SAVC to handwriting speed in an adult population. The majority of the research on this subject thus far has been on children, with the exception of one study by Peverly et al. (2014). Research has consistently shown that handwriting speed is not only related to fine motor speed, but to the speed at which a person can access the cognitive representation of language stored in memory. This dissertation analyzed data from two distinct studies which used different measures of handwriting speed, fine motor speed, and SAVC, among other variables. The questions posed were: would SAVC and fine motor speed be the only significant predictors of handwriting speed; and, would the results across studies be comparable despite methodological differences? Both studies had similar results. SAVC and fine motor speed were the primary predictors of handwriting speed. Study 1 additionally found that compositional fluency was a significant predictor. The outcome of this research could provide some support for targeting aspects of language and speed further. Students who have difficulty in writing and handwriting speed should be provided with handwriting instruction that goes beyond fine motor interventions or orthographic interventions. Future research should also continue to expand upon the question of whether the relationship between these variables holds constant across the lifespan and perhaps includes the impact of early speech and language interventions on handwriting speed and note-taking skill.

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