Original article

doi: 10.1111/jcal.12110

Journal of Computer Assisted Learning

Computerized writing and reading instruction for students in grades 4–9 with specific learning disabilities affecting written language

S. Tanimoto,* R. Thompson,* V.W. Berninger,† W. Nagy‡ & R.D. Abbott§

*Department of Computer Science and Engineering, University of Washington, Seattle, USA
†Learning Sciences and Human Development, University of Washington, Seattle, USA
‡Education, Seattle Pacific University, Seattle, USA
§Statistics and Measurement, University of Washington, Seattle, USA

Abstract Computer scientists and educational researchers evaluated effectiveness of computerized instruction tailored to evidence-based impairments in specific learning disabilities (SLDs) in students in grades 4–9 with persisting SLDs despite prior extra help. Following comprehensive, evidence-based differential diagnosis for dysgraphia (impaired handwriting), dyslexia (impaired word reading and spelling), and oral and written language learning disability, students completed 18 sessions of computerized instruction over about 3 months. The 11 students taught letter formation with sequential, numbered, coloured arrow cues with full contours who wrote letters on lines added to iPAD screen showed more and stronger treatment effects than the 21 students taught using only visual motion cues for letter formation who wrote on an unlined computer monitor. Teaching to all levels of language in multiple functional language systems (by ear, eye, mouth and hand) close in time resulted in significant gains in reading and writing skills for the group and in diagnosed SLD hallmark impairments for individuals; also, performance on computerized learning activities correlated with treatment gains. Results are discussed in reference to need for both accommodations and explicit instruction for persisting SLDs and the potential for computers to teach handwriting, morphophonemic orthographies, comprehension and composition

Keywords computerized language lessons, dysgraphia, dyslexia, OWL LD, teaching to all levels of language

Epidemiological studies show that one in five school-age children and youth in the USA has a specific learning disability (SLD) impairing reading and/or writing (e.g., Katusic, Colligan, Barbaresi, Schaid, & Jacobsen, 2001; Katusic, Colligan, Weaver, & Barbaresi, 2009). Computerized differentiated instruction may provide a viable, cost-effective way to provide differentiated instruction tailored to the nature of an SLD in general education because pull-out special education services for 20% of students are not affordable. Neither are pull-out services viable because students with SLDs are expected to meet standards and pass annual high-stake tests and thus need access to the regular curriculum. Computerized differential

Accepted: 26 April 2015
Correspondence: Steven Tanimoto, Box 352350, Dept. CSE, University of Washington, Seattle, WA 98195, USA. Email: tanimoto@cs.washington.edu

instruction may also have applications in other countries that struggle with effective ways to meet the needs of students who have a variety of SLDs. Consensus has not been achieved regarding evidence-based definitions of different kinds of SLDs across countries or within countries. For example, in the USA, despite federal laws guaranteeing free appropriate public education, instead of treatment-relevant, differential diagnosis, as is used in medicine, states vary in criteria used to decide if students are eligible for special education services. Computer-supported differentiated instruction has promise for meeting more instructional needs in cost-effective and treatment-effective ways.

Considerable research exists now on using technology tools to teach reading, writing and math to school-age children and youth with and without SLDs (see Aleven, Beal, & Graesser, 2013), but research has shown that simply making laptops available is not sufficient; it is also necessary to consider how laptops are used for specific kinds of instruction and instructional goals (cf. Cristia, Ibarrarán, Cueto, Santiago, & Severin, 2012). Although middle school students in general education show more robust response to intervention (RTI) to technology-assisted reading comprehension instruction than do special needs students (Pearson, Ferdig, Blomeyer, & Moran, 2005), students with SLDs might show more robust RTI if intervention was tailored to the nature of their SLD. Despite much research on using computer tools with students with SLDs (for review, see MacArthur, 2009), little research has focused on computerized reading and writing lessons in which participants are first carefully diagnosed as to whether they have dysgraphia (impaired handwriting), dyslexia (impaired word reading and spelling), or oral and written language learning disability (OWL LD) and then given specialized computer instruction to evaluate their RTI on the impaired skills associated with their diagnosis. Also of interest is whether (a) computer instruction in writing might transfer to improved reading as has been found for human instruction in writing (Graham & Hebert, 2010), and (b) differentiated instruction for specific kinds of SLDs embedded in instruction aimed at all levels of language might benefit not only students with a particular SLD but also all students regardless of their diagnosis. One research aim was, therefore, to draw on over two decades of interdisciplinary research to design computerized differentiated instruction with seven unique features.

The *first unique feature* is that these computer lessons provide RTI during specific learning activities in the form of computer scored and displayed feedback, that is, immediate RTI, which the student records on an RTI form at the end of many of the learning activities. At the completion of a session, the human teacher reviews with the student RTI within the session and across sessions and notes if the student was paying attention and engaging in the learning activities (see Cheung & Slavin, 2012) and sets goals for next session.

The *second unique feature* is lessons organized by *levels of language* as introduced in psycholinguistic research in the 1970s and 1980s (e.g., Bloom & Lahey, 1978). Language is multi-leveled with different units of language that are related, but not in a simple one-to-one way: subword (e.g., sounds and single letters or letter groups), word (semantic meanings, pronunciations, spellings, morphology), syntax (ordered words with subject and predicate and sometimes embedded non-syntactic idioms or incomplete clauses), and discourse or text (multiple syntax or other multi-word units). Thus, in each session students completed a lesson set with varied learning activities focused on subword letters, a lesson set focused on subword and word level processes in word reading and spelling, and a lesson set focused on syntax and text comprehension and construction. Prior randomized controlled studies with human teachers have shown the benefits of teaching to all levels of language close in time to create functional language systems in which the various levels of language work in concert (for review, see Berninger, 2009).

The *third unique feature* is that the word level instructional activities were designed for learning to read and spell English, a morphophonemic orthography. Not only is the alphabet principle taught in both the reading direction (grapheme to phoneme) and the spelling direction (phoneme to grapheme), but also students are taught to integrate phonology, orthography and morphology. Although use of the alphabetic principle is necessary, it is not sufficient in English (Venezky, 1970, 1995, 1999); also see Bear, Ivernezzi, Templeton, and Johnston (2000), Fry (1996), and Nagy, Diakidoy, and Anderson (1993). Also both alphabetic principle and morphology should cover words of Anglo-Saxon, Romance (French and Latin) and Greek origin for students in grades 4 and above (see Henry, 2010).

The *fourth unique* feature is that alphabetic principle was not taught as declarative, rule-based language knowledge mediated only by cortex, but also as *procedural language knowledge*, which is mediated by basal ganglia as well as cortex (e.g., Bitan & Booth, 2012; Stocco, Yamasaki, Natalenko, & Prat, 2014), and more readily applied to the process of word reading and spelling. Students were taught that they were programming their own brain by listening to heard words (language by ear), looking at written words, mostly in black letters, but target letter or letter groups in red (language by eye), saying the name of the word, the letter or letter group, and the sound that goes with the named letter or letter group (language by mouth), and then spelling words composed of the letter/s, sounds and morphology (language by hand).

The *fifth unique feature* is that letter production is not taught just by copying, but rather involves viewing the motion of letters forming, holding the letter form in the mind's eye, producing the letter from memory, receiving feedback as to whether the produced letter matches the model letter, accessing, retrieving, and producing the letters before and after others named in the ordered alphabet from memory, and learning multiple formats of letter production (manuscript and cursive lower case and upper case).

The *sixth unique feature* is that reading and writing are taught both as separate and integrated skills. Integrated reading and writing and integrated listening and writing are required for many academic tasks across the curriculum in fourth grade and beyond.

The *seventh unique feature* is that all of the learning activities have been validated in randomized controlled studies with human teachers (e.g., Bear et al., 2000, Berninger, 2009; Berninger & Richards, 2010; Henry, 2012; MacArthur, Graham, & Fitzgerald, in press; Singson, Mahony, & Mann, 2000; Troia, 2009). Thus, the current study tackled the question of whether computer instruction using the same instructional strategies might also be effective. Answers to that question are relevant to the new federal mandate in the US that requires schools to show that students with disabilities make academic progress (Duncan, 2014).

Research design and hypotheses

Quasi-experimental design

A quasi-experimental design (Shadish, Cook, & Campbell, 2002) was employed in which two sequentially acquired cohorts in different project years were compared on the same computerized lessons, which differed only in two computer platform features: nature of the way letter formation was modeled and absence or presence of lines on iPad screen to guide placement of the letters. Except for these two contrasting features, both groups received the same set of HAWK™ lessons, which they completed in one or two sessions a week over a 3-month interval on average, depending on when their parents were able to bring them to the university.

First tested hypothesis

In the version Group A used, arrow cues for forming the letters were not numbered, indicated only where to start, and lacked full cues for curved as well as straight letter strokes. In the version used by Group B, the multiple ordered strokes for the same letters were numbered, each component stroke was in a different colour, and arrows provided full directional cues for both curved and straight lines. Also, for the version used by Group B, but not Group A, lines, spaced like lined paper used at school, were provided on the screen to guide letter formation. Other than that the versions were identical. First, we tested the hypothesis that Group B would outperform Group A on the handwriting, spelling and composition learning activities during the lessons.

Second tested hypothesis

Dual criteria were used to test the second hypothesis that not only the group but also individuals would show RTI. The first criterion was significant correlations between individual RTI during learning activities and significant treatment outcomes for the group showing that individual RTI mediates significant treatment outcomes. The second criterion was individual RTI evidenced by significant pretest-possttest gains by individuals on the hallmark deficits associated with their diagnosis. For the second criterion, normed measures were used so that any gains can be compared with age or grade peers. Evidence from both criteria would provide converging evidence for the potential of computerized lessons for differentiated instruction for individual students with persisting SLDs during middle childhood and early adolescence.

Method

Participants and assignment to diagnostic groups

Sample recruitment

Participants in grades 4–9 with writing or reading problems were recruited via flyers distributed to local schools. Interested parents referred by teachers contacted the third author and were interviewed over the phone to make an initial determination of whether the child would probably qualify for the study because of persistent struggle with some aspect of writing or reading (handwriting, spelling, sentence composition, word reading, and/or sentence reading comprehension) despite considerable extra help at school and often outside school. Also histories were obtained to rule out pervasive or specific developmental disabilities, other neurogenetic or brain-based disorders or injuries; however, Attention Deficit Hyperactivity Disorder (ADHD) was not an exclusion criterion.

Participants who met the initial screening criteria and whose parents gave informed consent and the child gave assent were invited to the university for comprehensive assessment (on average about 4 h) that used evidence-based normed measures of oral language, reading, and writing skills and of phenotypes shown in prior genetics and brain research to be associated with evidence-based differential diagnosis of dysgraphia, dyslexia and OWL LD. The parent completed questionnaires about developmental, medical, family and educational histories. At posttest following completion of the 18 computerized lessons, the entire pretest battery was readministered except for the cognitive measures. Students were assigned to diagnostic groups (dysgraphia, dyslexia, OWL LD or typical language learner control) using a differential diagnosis framework developed in a cross disciplinary collaboration between speech and language specialists and psychologists (Silliman & Berninger, 2011) and a two-decade interdisciplinary research program (Berninger & Richards, 2010). All those diagnosed with SLDs had had prior special help with their writing and/or reading problems either at school or outside school or both, but their reading and/or writing problems had persisted beyond the early elementary grades to the upper elementary and middle school grades in the hallmark impairment(s) for the diagnostic group to which they were assigned also based on test scores.

Of the 21 students with SLDs [14 males (66.7%) and 7 females (33.3%)] in Group A, mean age was 139.43 months ($SD = 18.57$), with range of 108–180 months. Of the 11 students with SLDs [4 males (36.4%) and 7 females (63.6%)], mean age was 140.18 months ($SD = 21.64$ in Group B), with range of 117–178 months. Of the six without SLDs in Group A ($n = 3$) or Group B ($n = 3$) [1 male (16.7%) and 5 females (83.3%)], mean age was 143.5 months ($SD = 23.30$), with range of 111–171 months.

Comprehensive assessment battery

The following measures were given for differential diagnosis prior to participation in the computerized reading and writing instruction and were readministered after completion of the computer lessons. Test–retest reliabilities are from the respective test manuals and based on national standardization samples.

Alphabet letter writing from memory (first 15 s)

Students were asked to produce the alphabet from memory by (a) writing manuscript letters, (b) writing cursive letters and (c) selecting letters on keyboard. The raw score is accuracy of number of correct letter productions in the first 15 s, which is an index of automatic, correct letter production (Berninger, 2009). Only z-scores for grade based on research norms, available only for manuscript, were used for the dysgraphia diagnosis because neither norms nor z-scores were available for cursive and keyboard in the grade range studied, but RTI was evaluated for raw scores in all letter production formats.

Detailed assessment of speed of handwriting (DASH) best and fast (Barnett, Henderson, Scheib, & Schulz, 2007)

The task is to copy a sentence with all the letters of the alphabet under contrasting instructions: one's best handwriting or one's fast handwriting. Students can choose to use manuscript or cursive or a combination. The score is a scaled score ($M = 10$, $SD = 3$). Intraclass correlation coefficient for interrater agreement for *DASH Best* and for *DASH Fast* is 0.99.

Test of orthographic competence (TOC) (Mather, Roberts, Hammill, & Allen, 2008)

For the *TOC Letter Choice* subtest (test–retest reliability .84), the task is to choose a letter in a set of four provided letters to fill in the blank in a letter series to create a correctly spelled real word (word-specific spelling). For the *TOC Sight Spelling Subtest* (test–retest reliability .91), the task is to listen to dictated words and then write missing letters in partially spelled words to create correctly spelled real words (word-specific spelling).TOC subtest scores are scaled scores ($M = 10$, $SD = 3$).

Wechsler individual achievement test, 3rd edition (WIAT 3) spelling (Pearson, 2009)

The task is to spell in writing dictated real words, pronounced alone, then in a sentence, and then alone. Raw scores were converted to standard scores for age ($M = 100$, $SD = 15$). Test–retest is .92.

Test of word reading efficiency (TOWRE) (Torgesen, Wagner, & Rashotte, 1999)

The TOWRE Sight Word Efficiency task measures the child's accuracy in pronouncing printed real words in a list within a time limit of 45 s. Raw scores were converted to standard scores for age ($M = 100$, $SD = 10$). Test–retest reliability is .91. The *TOWRE Pseudoword Efficiency Test* requires a child to read a list of printed pronounceable non-words accurately within a 45 s time limit. Raw scores were converted to standard scores for age ($M = 100$, $SD = 15$). Test–retest reliability is .90.

Test of silent word reading fluency (TOSWRF) (Mather, Hammill, Allen, & Roberts, 2004)

The timed task, which assesses silent orthographic coding rate without context, is to mark the word boundaries in a series of letters arranged in rows. The score is the number of correctly detected and marked word boundaries in 3 min. Raw scores were converted to standard scores for age ($M = 100$, $SD = 15$). Test–retest reliability is .92.

WJ3 oral comprehension (Woodcock, McGrew, & Mather, 2001a)

This aural cloze subtest is an analogue of the written passage comprehension test in the reading measures, which also uses a cloze procedure. The task is to listen to spoken text and when there is a pause supply a word orally that would make sense in the accumulating context of the current sentence and prior text. The raw score is converted to a standard score with $M = 100$ and $SD = 15$. Test–retest reliability is .88.

Clinical evaluation of language function, 4th edition CELF4 (Semel, Wiig, & Secord, 2003)

The child is given three words and asked to construct an oral sentence. Results are reported in scaled scores with a *mean* of 10 and *SD* of 3. According to the test manual, test–retest reliabilities for the ages assessed range from .62 to .71.

WJ3 passage comprehension (Woodcock et al., 2001b)

The task is to read text in which there is a blank and supply orally a word that could go in the blank that fits the accumulating context of the current sentence and preceding text. The raw score is converted to a standard score with $M = 100$ and $SD = 15$. Test–retest reliability is .85.

PAL II sentence sense accuracy (Berninger, 2007)

This task, which assesses silent sentence reading comprehension, was given only to Group B and scaled scores are only available through grade 6 ($M = 10$, $SD = 3$), after which raw scores are reported. The student is given three sentences each containing only real words and asked to choose the one that could be a real, meaningful sentence. The two that could not be meaningful each contained one real word that did not make sense in the context of other words in the sentence syntax. Test–retest reliability is .82.

WIAT III sentence combining (Pearson, 2009)

The task is to combine two provided sentences into one well-written sentence that contains all the ideas in the two separate sentences. The score is a standard score ($M = 100$, $SD = 15$). Test–retest reliability is .81.

For WJ3 writing fluency (Woodcock et al., 2001b)

The task is to compose a written sentence for each set of three provided words, which are to be used without changing them in any way. There is a 7-min time limit. The raw score is converted to a standard score with $M = 100$ and $SD = 15$. Test–retest reliability is .88.

Differential diagnosis
To qualify for the dysgraphia diagnosis, students had to be impaired on two or more of the handwriting measures below and have a history of handwriting difficulties and no signs of dyslexia or OWL LD. To qualify for the diagnosis of dyslexia, students had to be impaired on two or more word reading/spelling measures below and have a history of word reading and spelling problems and no signs of OWL LD. To qualify for the OWL LD diagnosis, students had to be impaired on two or more of the syntax measures below and have a history of listening comprehension, oral expression, reading comprehension, and/or written composition problems. Impairment was defined as below −2/3 *SD* on relevant measures. For brain evidence that SLD groups differ from each other and from controls, see Richards et al. (2015) and Berninger et al. (2015).

Platform development

Each student progresses at his or her own pace through three sets of lessons in HAWK™ (Letters in Motion, Words in Motion and Minds in Motion) that take advantage of modern electronic learning material and its affordances for colour, graphics, animation, sound and interaction. Five considerations informed design of the platform: (1) the type of devices the lessons are delivered on, and the accessories for those devices, (2) the client–server architecture for the delivery system, (3) the nature of the client software, (4) the nature of the server software, and (5) the provisions for experimental data gathering and retrieval.

The software is designed to run on a variety of different client devices: tablets, netbooks, laptops and desktop, but the tablet (iPad) platform was given priority because technical obstacles were not expected, portability facilitates taking them into schools and low cost. Multiple modalities were incorporated into responding to the various specific learning activities: finger touch for drumming, selecting choices and dragging letters or words; stylus for letter or word formation; or composition and keyboard for sentence and text composing. The iPad is designed with a *capacitive touch sensing system* in the display screen, which can sense the positions of one or more fingers touching the screen at the same time. We used styluses, which feel more like writing on paper with pen or pencil, that cost under $10 each and external, physical keyboards made by Apple for the iPads (about $60 each). So that students were not distracted by other students producing oral responses, we purchased for each iPAD earbuds (for less than $10/pair). .

We adopted client–server architecture for the software because of (a) simplicity of setup procedure for users – no installation of software required; (b) ease in releasing corrections and feature updates; (c) ability to monitor and control current activity; and (d) ability to easily collect extensive usage data in a central database. We exploit the Internet for the connection between clients and server in using the architecture for instructional research. Our servers are located in the Computer Science and Engineering building at the university where staff habitually maintains several dozens of servers in a secure and climate-controlled environment.

In addition to the relative costs, risks of the alternatives and their technical affordances, we conducted some early trials of HTML5-based animations on the iPad to assess the feasibility of developing the instructional software with HTML5 and the results were encouraging so we chose HTML5. The particular JavaScript libraries we use include JQuery and Raphael. We take advantage of HTML5's SVG graphics facilities, especially for representing the shapes of letters of the alphabet, in both printed and cursive styles. We used Raphael to simplify the implementation of graphical animations primarily in the learning activities for letters and words.

Because many lessons repeat the use of activity formats, our software is structured to separate the activity formats (called the 'Platter' because it serves as a platform for the contents) from the particulars (e.g., vocabulary, sentence examples) called the 'Silver' portion of the lessons using a two-level structure called 'Silver/Platter' with the 'Silver' supported by the 'Platter'. This enables encapsulating functionality at a higher level of abstraction than if everything were implemented directly. We used the standard Safari browser on the iPad, and left it up to the proctoring teachers to make sure that students were not browsing to unapproved websites. Our client software also works on the Google Chrome browser, but not with Firefox, which does not directly support the required MP3 audio playing. On the server side, the primary technologies are Linux, Apache, PHP, CodeIgniter and

MySQL. We modified a web framework (Community Auth) so it maintains user accounts and keeps detailed data on the activity of each user within the lessons. The client–server architecture as a whole makes use of an AJAX style of service (Asynchronous JavaScript and XML) so that transitions within lessons occur relatively seamlessly. The custom PHP code on the server handles logging of lesson events and lesson score data in response to AJAX requests.

Our data-gathering infrastructure permits acquiring detailed performance profiles of each user, while not overstepping the bounds of our Institutional Review Board (IRB) approval. For example, we capture precise timing information about each lesson event such as a handwriting stroke or a multiple-choice answer selection, but not video or audio of the students as they work. The data gathering keeps in mind a few specific hypotheses about the language skills we aimed to teach and assess. Student performance data of two kinds are collected and stored. First are 'lesson-event' records. A lesson event is a short action taken by a student in the course of doing a lesson. Examples include drawing a stroke, clicking a button or pressing a key on a physical or virtual keyboard. The logged data include a timestamp, duration, user identification code, lesson locus and event-specific data such as which button was pressed, which key was pressed or what the geometry and timing of the drawn stroke were. Lesson events provide us with a 'replay-complete' representation of the user's activity. The second kind of performance data is the 'lesson-score' record, which represents a computed performance characteristic for an activity within a lesson. The score is always a number, but its meaning depends upon the activity for which it is computed. Lesson scores offer a prima facie form of performance assessment. They are, in principle, redundant with the lesson events, but they simplify the process of data analysis and open up the possibility of giving performance feedback to students upon activity completion. To facilitate data analysis, we developed specialized tools for reconstructing certain lesson events in the database on the server. We also developed Python scripts and SQL queries for extracting relevant records for statistical analysis.

Nature of computerized learning activities

The first session typically takes 1.5–2 h because of special introductions to each lesson set and learning activities so students understand both what the tasks are and why they are asked to perform them. Thereafter, the sessions typically took less time and midway as the students became more familiar with the procedures lasted about 1 h to complete all three lesson sets described next.

Handwriting learning activities

Participants used a stylus for the handwriting learning activities in *Letters in Motion*™. For both of the compared versions, the first six lessons focus on all lower case manuscript letters in each lesson. The second six lessons focus on all lower case cursive letters in each lesson. The last six lessons focus on (a) reviewing both manuscript and cursive lower case letters by writing letters that came before or after named letters, and (b) forming capital manuscript and cursive letters and applying them to beginning of sentences in the same letter font format. For all lessons, students engage their sensory and motor systems for listening (through the earphones to the computer teacher's instructional talk for directions and naming letters), reading (through eyes what appeared on the screen and viewing their own letter formations on the screen) and writing letters on the screen (through hand). In addition, they may have engaged subvocal talking (through mind's mouth for covert naming of letters) in learning legible and automatic letter formation and automatic access and written letter production. See screen shots in the Appendix for steps in LIM learning activities in lessons 7–12 when handwriting required cursive, but the steps for learning letters remain otherwise the same as for manuscript letters in lessons 1–6.

The versions used by Groups A and B differ as to the whether the learning activity during modeling (a) provides only a brief visual cue (straight arrows) where to begin forming the letter (Group A) or numbered arrow cues to model the specific curved and straight component strokes and their order in letter formation (Group B); and (b) letter is formed component by component in motion (both groups), each sequential component was in black (Group A) or in a different colour (Group B). The versions also differ as to whether lines are (Group B) or are not (Group A) displayed on the iPad screen to help students with the positioning of the letters or words in visual spatial dimensions as they write letters on the screen for learning activities in the handwriting and spelling lessons. For both groups, the computer generates a time score at the end of the handwriting lesson. Students record time score on the RTI form for each lesson. Each student and the human teacher review these forms at the end of each lesson and across lessons to determine if the student's time is improving and set goals to do even better next time.

Word spelling and reading learning activities

Learning activities in *Words in Motion*™ were kept constant across Groups A and B so effects of different kinds of prior handwriting instruction on subsequent written word learning can be evaluated. Learning activities for subword alphabetic principle (in both the reading and spelling directions) alternated in every other lesson with learning activities for phonological, orthographic and morphological linguistic awareness and application to word reading and spelling.

Learning activities for alphabetic principle are the cross-code matrices, which require pressing red letters in written words in otherwise black print, naming the red letter or letter group, pronouncing word in which letter or letter group occurred, and orally producing associated phoneme for the letter or letter group. For teaching alphabetic principle in the reading direction (letter/s to sound), the example words are arranged in columns by categories of letter/letter group–sound relationships (e.g., single consonant, consonant group or syllable type for vowels). For teaching the alphabetic principle in the spelling direction (sound to letter or letter group), items are arranged in rows with same sound and alternative spellings for that sound (alternations, Venezky, 1970, 1995, 1999). For both directions, the teacher first models the steps of the process for each item, and then the student takes a turn executing each step in the process as quickly as possible to create automatic associations (procedural knowledge for applying correspondences rather than declarative knowledge for verbalizing a rule). For reading direction, see the first screen shot for WIM in the Appendix. For the spelling direction, see the second screen shot for WIM in the Appendix. The spelling–sound and sound–spelling correspondences taught include the frequent ones in English words of Anglo-Saxon, Latinate (Latin and French) and Greek origin (Fry, 1996; Henry, 2010). For the alphabetic principle learning activities, the computer does not provide feedback to record on RTI form, but the human teacher monitors whether students are pressing the red letter/s, looking at them, listening through ear phones, and taking a turn to say the words and sounds orally and record this for the student on the RTI form.

Most of the learning activities for phonological, orthographic and morphological awareness require finger drumming, pressing or dragging, but for only one dictated word spelling, writing by stylus; only for Group B were lines provided on the screen for this learning activity as for Group B in prior the handwriting lessons. Examples for phonological awareness include counting sounds in words at the syllable and phoneme level by drumming them on screen and pressing key to show which syllable in a pronounced word is accented (musical rhythm of words). See the third screen shot for WIM in the Appendix. Examples of orthographic awareness learning activities include identifying letters in designated positions in written words held in the 'mind's eye' and paying attention to letter order and position in word anagrams. See the fourth screen shot for WIM in the Appendix. Examples for morphological awareness (based on Nagy et al., 1993; Singson et al., 2000; Tyler & Nagy, 1989, 1990) include observing spoken and written words transform by adding suffixes and prefixes, but do not require a written response; others required pressing a yes key if a word has a true fix or no key if word does not (see screen shots for WIM in the Appendix).

Syntax learning activities

Some *Minds in Motion*™ learning activities bridge word and syntax levels of language. Examples include pressing key for base word with a suffix that fits a sentence context, choosing a glue word (e.g., preposition or pronoun) or conjunction (all function words) to combine words in a syntax unit or combine syntax units, respectively, or sentence anagrams (dragging words to change order to create a real sentence – see screen shot for MIM in the Appendix). The computer generated feedback for correct responses (number of correct on top and number of total items at the bottom) for the first five MIM learning activities. The student recorded this accuracy feedback on the RTI form for each lesson to review within and across lessons with the human teacher and discuss progress being made and set goals to work on.

However, in the sixth learning activity students used their fingers to press links for each strategy for writing the next sentence and they used the external keyboard to compose written texts in the seventh learning activity. Keyboarding was used for composing based on student feedback in preliminary studies that indicated students preferred typing because the text that appeared on the monitor was smaller and looked more like adult writing than what they could produce with a stylus. The student composed for 15 min (with prompts to continue if writing ceased before time limit): six self-generated autobiographical narratives (one in each of the first six lessons) and 12 written summaries about read or heard source material in content areas of the curriculum (six on history of math and role of writing in math; and six on world cultures and geography). In each of the last 12 lessons, one task was based on reading source material and one task on listening to source material, but both had a common writing task – summarization. The source material was equated on length based on number of words for the source material that was read and that was heard. The compositions were stored on the server for researcher to analyse at a later time. For current study, only RTI results for the first five MIM learning activities (not the self-generated text composing or integrated reading–writing or integrated listening–writing) are included because they are scored by the computer and are most relevant to word learning in syntactic context.

Results

Data analyses

For testing the first hypothesis, we used analysis of variance to evaluate change from pretest to posttest within each group separately and this formula to compute Cohen's effect sizes: $eta^2/(1 - eta^2)$ = Cohen's f^2. An $f^2 = .02$ is small effect, an $f^2 = .15$ is medium effect and an $f^2 = .35$ is large effect. To estimate effect sizes, we used Cohen's f^2, the ratio of partial $eta^2/(1 -$ partial $eta^2)$ and descriptive language (small, medium or large effect) as recommended by Murphy, Myors, and Wolach (2009). For the second tested hypothesis, we then analysed (a) correlations between scored and stored learning activities in the server supported data base and those outcomes from tested first hypothesis that showed significant treatment effects change from pretest to posttest, and (b) individual RTI for individuals with dysgraphia, dyslexia or OWL LD on the hallmark deficits associated with their diagnosed SLD.

First tested hypothesis: comparison of platform versions on pretest-posttest change

Results are reported by level of language (subword handwriting, word reading and spelling, and written language syntax) for Group A first and then Group B.

Group A – handwriting

For manuscript, pretest $M = 7.20$ ($SD = 3.87$) to posttest $M = 9.20$ ($SD = 4.31$) showed significant change, $F(1, 19) = 4.34$, $p = .05$, $f^2 = .23$. For cursive, pretest $M = 0.89$ ($SD = 1.53$) to posttest $M = 2.89$ ($SD = 2.00$) showed significant change, $F(1, 17) = 38.25$, $p = .001$, $f^2 = 2.2$. For manuscript, effect size was medium, but for cursive effect size was very strong.

Group B – handwriting

Significant change occurred for manuscript alphabet 15, pretest $M = 10.00$ ($SD = 5.62$) to posttest $M = 13.36$ ($SD = 6.22$), $F(1,10) = 5.74$, $p = .027$, $f^2 = .67$, cursive alphabet 15, pretest $M = 1.82$ ($SD = 2.44$) to posttest $M = 4.18$ ($SD = 2.67$), $F(1,10) = 6.37$, $p = .03$, $f^2 = .94$, alphabet 15 z-score based on grade norms, $M = - 0.97z$ (SD 0.77) to posttest $M = -0.39$ (SD -0.82), $F(1,10) = 6.78$, $p = .026$, $f^2 = 0.67$, and *DASH Copy Fast*, pretest $M = 6.82$ ($SD = 2.44$) to posttest $M = 8.45$ ($SD = 3.64$), $F(1,10) = 12.00$, $p = .006$, f^2 1.17. All effect sizes in Group B for handwriting were strong or very strong, and with one exception, yielded more and stronger effects sizes than for Group A.

Group A – word reading and spelling

Significant change was observed on *TOC Letter Choice*, pretest $M = 7.80$ ($SD = 3.09$) to posttest $M = 8.90$ ($SD = 2.40$), $F(1,19) = 6.99$, $p = .016$, $f^2 = .31$, and *TOWRE Phonemic Efficiency*, pretest $M = 91.65$ ($SD = 14.46$) to posttest $M = 94.60$ ($SD = 15.99$), $F(1,19) = 12.87$, $p = .002$, $f^2 = .68$. Thus, there was one medium effect size for spelling and one strong effect for oral decoding rate.

Group B – word reading and spelling

Significant change was observed on *WIAT III Spelling*, pretest $M = 76.22$ ($SD = 14.19$) to posttest $M = 80.55$ ($SD = 10.82$), $F(1,10) = 5.39$, $p = .043$, $f^2 = .54$, *TOC Letter Choice*, pretest $M = 8.03$ ($SD = 7.00$) to posttest $M = 8.55$ ($SD = 3.21$), $F(1,10) = 8.03$, $p = .018$,

$f^2 = .82$, *TOWRE Sight Word Efficiency*, pretest $M = 85.91$ ($SD = 16.54$) to posttest $M = 92.54$ ($SD = 20.04$), $F(1,10) = 5.10$, $p = .048$, $f^2 = .52$, and *TOSWRF Test of Silent Word Reading Fluency*, pretest $M = 89.55$ ($SD = 12.96$) to posttest $M = 92.55$ ($SD = 12.32$), $F(1,10) = 6.78$, $p = .026$, $f^2 = .67$. All effect sizes were strong.

Group B – syntax

Significant change was observed for *Sentence Sense* silent reading sentence comprehension accuracy pretest $M = 8.82$ ($SD = 7.81$) to posttest $M = 13.18$ ($SD = 6.74$), $F(1,10) = 10.77$, $p = .008$, $f^2 = 1.08$, and *WJ3 Writing Fluency Sentence Composition*, pretest $M = 81.64$ ($SD = 29.06$) to posttest $M = 88.27$ ($SD = 31.40$), $F(1,10) = 12.16$, $p = .001$, $f^2 = 1.22$. Both effect sizes were very strong.

Summary

As shown in Table 1, although Group A showed treatment effects for letter writing and word reading and spelling, clearly Group B showed more treatment effects than Group A for handwriting (4 compared with 2), word spelling (2 compared with 1), word reading (2 compared with 1), and syntax reading comprehension (1 compared with none), and written composition (1 compared with none). Except for cursive alphabet 15, all the effect sizes were stronger in Group B (consistently strong to very strong) than Group A (range from medium to very strong effect sizes). Thus, the addition of numbered, sequenced, colour strokes for full letter contour to the motion of letters forming and of lines to the iPAD screen had beneficial treatment effects.

Second tested hypothesis: correlation of learning activities with treatment effects (group results)

For each group, correlations were computed between the computer-generated mean time scores for handwriting lessons (LIM) or mean accuracy scores for the word spelling and reading (WIM) and syntax composing (MIM) learning activities across the 18 lessons and posttest scores for measures showing treatment effects in testing the first hypothesis. However, because building bridges by choosing a word that fits is scored for number of errors rather than correct responses, significant correlations for this learning activity were negative: the more errors made, the lower the posttest score. The sentence syntax silent reading comprehension measure was not included in these analyses because it had not been given to students in Group A. Results are reported by each posttest score, organized by levels of language and Group A and Group B. Posttest scores are bolded followed by the learning activities with which they were significantly correlated.

Table 1. Comparison of Groups A and B on Treatment Effects, Effect Sizes, and Correlations of Accuracy or Total Time or Number of Errors with Learning Activities with Posttest Gains)

Group	Significant treatment effect for	Effect size	Correlated learning activity
A	Alphabet 15 manuscript	.23 medium	b
	Alphabet 15 cursive	2.2 very strong	none
	TOC Letter Choice	.31 medium	b
	TOWRE Phonemic	.68 strong	c, e, f
B	Alphabet 15 manuscript	.67 strong	b, c, d, e, f, g, i, j, l
	Alphabet 15 cursive	.94 strong	a, b
	Alphabet 15z manuscript	.67 strong	b, c, d, f, g, k
	DASH Copy Fast	1.17 very strong	b, d, e, f, k
	WIAT III Spelling	.54 strong	b, d, f, g, h, i, j, k, l
	TOC Letter Choice	.82 strong	b
	TOWRE Sight Word	.52 strong	b, d, e, f, g, h, i, j, k, l, m
	TOSWRF	.67 strong	b, f, j, m
	PAL Sentence Sense accuracy	1.08 very strong	n.a. only given to B
	WJ 3 Writing Fluency	1.22 very strong	e, i, j, l, m

Note. a = total time for handwriting lessons; b = paying attention to letter order and position; c = number of phonemes; d = stress pattern in word (musical rhythm); e = real fix or not?; f = choosing correctly spelled word; g = fake or real word?; h = deciding if phrase matches sentence description; i = constructing sentence from bases; j = constructing sentences from changing word order; k = building bridges by choosing word that fits sentence; l = using conjunctions to build sentences; m = Choosing homonym that makes sense in sentence.

Group A

For alphabet 15 manuscript posttest, scribes paying attention to letter order and position were correlated, $r = .653$, $p = .029$. **For alphabet 15 cursive posttest**, no learning activities were correlated. **For *TOC letter choice* posttest**, scribes paying attention to letter order and position were correlated, $r = .527$, $p = .017$. **For *TOWRE phonemic* posttest**, number of phonemes, $r = .513$, $p = .021$, fixes or not, $r = .43$, $p = .055$, and choosing correctly spelled words, $r = .618$, $p = .004$, were correlated.

Group B

For alphabet 15 manuscript raw score at posttest, identifying number of phonemes, $r = .599$, $p = .05$, fake or real words, $r = .605$, $p = .048$, scribes paying attention to letter order and position, $r = .786$, $p = .004$, musical rhythm words (stress patterns), $r = .906$, $p < .001$, real fixes or not, $r = .684$, $p = .02$, choosing correctly spelled word, $r = .763$, p = .007, constructing sentence word order from bases, $r = .775$, $p = .005$, changing sentence word order, $r = .641$, $p = .033$, and using conjunctions to build sentences, $r = .738$, $p = .010$, were correlated. **For alphabet 15 cursive raw score at posttest**, total time LIM, $r = .721$, $p = .012$, and scribes paying attention to letter order and position, $r = .635$, $p = .036$, were correlated. **For alphabet 15*z* posttest**, identifying number of phonemes, $r = .611$, $p = .046$, deciding if fake words could be real English words, $r = .674$, $p = .023$, paying attention to order and letters, $r = .796$, $p = .003$, musical stress patterns, $r = .869$, $p = .001$, deciding if real fixes or not, $r = .671$, $p = .023$, choosing correctly spelled words, $r = .768$, $p = .006$, and building bridges by choosing word that fits sentence, $r = -.655$, $p = .029$, were correlated. **For *DASH Copy Fast* posttest**, scribes paying attention to letter order and position, $r = .851$, $p = .001$, choosing correctly spelled word, $r = .714$, $p = .014$, constructing sentence word order from base, $r = .602$, $p < .001$, and building bridges by choosing word that fits the sentence, $r = -.675$, $r = .023$, were correlated.

For *WIAT III Spelling* posttest, deciding whether fake English word, $r = .791$, $p = .004$, paying attention to word order and letter position, $r = .941$, $p < .001$, musical rhythm, $r = .620$, $p = .042$, choosing correctly spelled word, $r = .864$, $p = .001$, deciding if phrase matches sentence description, $r = -.611$, $p = .046$, constructing sentence word order from base, $r = .735$, $p = .01$, constructing sentence by changing word order, $r = .744$, $p = .009$, building bridges by choosing word that fits the sentence, $r = -653$, $p = .03$, and constructing sentences with conjunctions, $r = .648$, $p = .031$, were correlated. **For *TOC Letter Choice* posttest**, paying attention to word order and letter position, $r = .653$, $p = .029$, was correlated. **For *TOWRE Sight Word Efficienc*y posttest**, deciding if words are fake, $r = .662$, $p = .062$, paying attention to letter order and position, $r = .811$, $p = .002$, musical rhythm, $r = .684$, $p = 020$, deciding if real fixes or not, $r = .706$, $p = .003$, choosing correctly spelled words, $r = .801$, $p = .003$, deciding if phrase matches description, $r = .777$, $p = .006$, constructing sentence word order from base, $r = .884$, $p = .001$, constructing sentence by changing word order, $r = .809$, $p = .003$, building bridges by choosing word that fits sentence, $r = -841$, $p = .003$, picking sentence with homonym that makes sense, $r = .710$, $p = .014$, and constructing sentences with conjunctions, $r = .750$, $p = .006$, were correlated. **For *TOSWRF Test of Silent Word Reading Fluency* posttest**, mean time LIM, $r = .782$, $p = .007$, paying attention to letter order and position, $r = .830$, $p = .003$, choosing correctly spelled word, $r = .727$, $p = .017$, constructing sentences from word order, $r = .749$, $p = .013$, and choosing sentence with correct homophone, $r = .681$, $p = .03$, were correlated.

For *WJ3 Writing Fluency* (Sentence Composition) posttest, real fixes or not, $r = .706$, $p = .015$, constructing sentence word order from base, $r = .723$, $p = .012$, constructing sentence by changing word order, $r = .860$, $p = 001$, picking sentence with homonym that makes sense, $r = .730$, $p = .011$, and constructing sentences with conjunctions, $r = .774$, $p = .005$, were correlated.

Summary

Collectively, the results summarized in Table 1 showing which learning activities during the computer lessons correlated with specific posttest scores provide evidence that individual's responses during instruction mediated students' learning outcomes.

Second tested hypothesis: individual's RTI in specific SLDs and controls (results for individuals)

See Appendix S1 for the posted text and Table S1 for Individual Response to Instruction (RTI). The material in Appendix S1 summarizes for each individual which measures of hallmark impairments for their diagnosed SLD showed a trend towards improvement from pretest to posttest of at least one-third standard deviation after 18 lessons over 2–3 months. The results, organized by Group A and Group B, showed that in general most individuals exhibited RTI in reference to these hallmark impairments. Thus, the treatment effects were found not just for groups but also for individuals. Because Group B had no dysgraphia cases, no conclusions about Group A versus Group B could be drawn for dysgraphia. For dyslexia, treatment response varied along a continuum from robust RTI to moderate RTI to minimal RTI. Mode RTI for OWL LD was three significant learning outcomes in Group B and two significant learning outcomes in Group A. Examination of individual treatment responding for controls provided preliminary evidence that students without SLDs can also benefit from the lessons.

Discussion

First tested hypothesis

The computerized reading and writing instruction, organized by levels of language, resulted in significant improvement for the whole sample of SLDs in subword handwriting level skills, word level reading and spelling skills, and syntax level reading and writing skills. However, specific significant treatment effects and effect sizes depended on the version of the computer platform for the handwriting lessons, with more treatment effects and stronger effect sizes for Group B, which provided multiple visual cues for modeling letter formation and lines on the screen for writing (see Table 1).

Second tested hypothesis

Whether learning outcomes were correlated with treatment outcomes depended on group. For Group A, there was modest evidence that learning activities were correlated with significant learning outcomes: an orthographic awareness learning activity was related to the cursive handwriting outcome; one orthographic awareness learning activity was related to a spelling outcome; morphological, phonological and orthographic awareness learning activities were correlated with one word reading outcome. For Group B, in contrast there was robust evidence that learning activities were correlated with significant learning outcomes and probably mediated RTI. The total time for learning activities in the handwriting lessons was significantly correlated with the cursive alphabet writing outcome. At least one morphology, phonology and orthography awareness learning activity was significantly correlated with each alphabet manuscript writing task (raw scores and *z*-scores), one measure of dictated spelling (*WIAT III Spelling)* and one measure of oral reading (*TOWRE Sight Word*). Overall, more significant correlations between phonological, orthographic and morphological awareness activities and handwriting, spelling and reading outcomes, for which there were treatment effects, occurred in Group B than Group A. Yet, individuals in both Groups A and B showed RTI related to the hallmark deficits associated with their diagnosis.

Benefits of using computers to teach handwriting

Of interest, the normed measures used to assess learning outcomes were all administered with pen and paper (except for keyboard letter selection). Thus, the computer lessons for writing showed transfer to writing with pen and paper! Of note, no RTI for keyboard was observed, probably because the way this test was given allowed hunting and pecking and students scored much higher on keyboard alphabet 15 than manuscript or cursive at pretest. Future research should focus on potential benefits of teaching touch typing, especially since annual tests are increasingly computer administered.

Relationship of handwriting to reading and other writing skills

Overall, more treatment effects with greater effect size and more correlations of learning activities with treatment outcomes occurred in Group B, which was taught letter formation with numbered, colour cued, arrows providing full curves and practiced letter writing on a screen with lines spaced like regular lined paper used at school, than Group A (see Table 1). Not only might the learning activities have mediated RTI, but also the prior version of the handwriting lessons given to Group B may have facilitated reading (see Graham & Hebert, 2010); and practice in letter production may have enhanced letter perception in word context thus facilitating word reading (see James, Jao,

& Berninger, in press). Of interest, an orthographic awareness learning activity correlated the most often with learning outcomes showing treatment effects (see Table 1).

Potential of computers for differentiated instruction in general education

The results of the current study provide converging evidence for proof of the concept that server-based computer reading and writing lessons might be used in general education classrooms to provide differentiated instruction tailored to the hallmark impairments in various kinds of carefully diagnosed SLDs. All too often the question is *what works* without sufficient attention to *what works for whom* as was addressed in the current study. At the same time, lessons aimed at multiple levels of language – subword, word, syntax/text – close in time with frequent feedback from the computer teacher and engaging language by ear, by eye, by mouth and by hand, which is monitored by a human teacher on a student's RTI form, might be used for students without SLDs. In this way, general education classroom teachers may be able to meet the instructional needs of both students with and without SLDs in an era of high stakes testing for state standards.

Persisting SLDs beyond the primary grades are treatable

Despite early intervention, special education and often private tutoring, some students face persisting writing and reading disabilities in upper elementary and middle schools, but these are treatable in general education with instruction delivered by computers with human teacher monitoring. Even though 18 lessons of approximately 1–2 h duration across 2 or 3 months do not necessarily improve all the hallmark impairments to a level that renders the students fully compensated forever, the gains show students with persisting SLDs who were not making progress until they entered the study can benefit from not only accommodations but also explicit instruction with computers. The current instructional research was conducted at the university and future evaluations of computerized lessons are needed in classrooms. Future research might also investigate the potential of comparable computer learning activities for other orthographies. In conclusion, instead of leaving handwriting behind in the information age, computers can be used to teach handwriting and provide differentiated written and oral language instructions in general education classrooms.

Dedication

This research is dedicated to the memory of Steve Jobs, an accomplished calligrapher before becoming a computer programmer, who left a legacy of multiple letter fonts in word processing.

Acknowledgements

The current study, supported by grant P50HD071764 from the Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD) at the National Institutes of Health (NIH) to the University of Washington Learning Disabilities Research Center, has been an interdisciplinary team effort: The first two authors designed, created and supported during implementation the computer platform for delivery of the lessons; the third and fourth authors wrote the lessons; and the fifth author conducted the analyses of the data collected under the supervision of the third author with assistance from the second author. The authors thank the graduate students who assisted with administration of the assessments and supervising the computer lessons.

Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1. Posted text with overview of individual RTI findings

Table S1. Summary of individual RTI profiles by diagnosis and group (A or B)

References

Aleven, V., Beal, C., & Graesser, A. (2013). Introduction to special issue on advanced learning technologies. *Journal of Educational Psychology*, *105*, 929–931.

Barnett, A., Henderson, S., Scheib, B., & Schulz, J. (2007). *Detailed assessment of speed of handwriting (DASH)*. UK: Pearson.

Bear, D., Ivernezzi, M., Templeton, S., & Johnston, F. (2000). *Words their way: Word study for phonics, vocabulary, and* *spelling instruction* (2nd ed.). NJ: Merrill: Upper Saddle River.

Berninger, V. (2007). *Process Assessment of the Learner, 2nd Edition. Diagnostic for Reading and Writing* (PAL-II RW). San Antonio, TX: The Psychological Corporation. Now Pearson.

Berninger, V. (2009). Highlights of programmatic, interdisciplinary research on writing. *Learning Disabilities Research and Practice*, *24*, 68–79.

Berninger, V., & Richards, T. (2010). Inter-relationships among behavioral markers, genes, brain, and treatment in dyslexia and dysgraphia. *Future Neurology*, *5*, 597–617.

Berninger, V., Richards, T., Grabowski, T., Askren, K., Mestre, Z., Boord, P., . . . Nagy, W. (2015). *Neurobiological profiles differentiating dysgraphia, dyslexia, and oral and written language learning disability (OWL LD)*. The Dyslexia Foundation Conference: San Francisco.

Bitan, T., & Booth, J. (2012). Offline improvement in learning to read a novel orthography depends on direct letter instruction. *Cognitive Science*, *36*, 896–918.

Bloom, L., & Lahey, M. (1978). *Language development and language disorders*. New York: John Wiley & Sons.

Cheung, A., & Slavin, R. (2012). How features of educational technology applications affect student reading outcomes: A meta-analysis. *Educational Research Review*, *7*, 198–215.

Cristia, J., Ibarrarán, P., Cueto, S., Santiago, A., & Severin, E. (2012). Technology and child development: Evidence from one laptop per child program. InterAmerican Development Bank Department of Research and Chief Economist Working Paper Series IDB-WP 384.

Duncan, A. (2014). Retrieved from www.disabilityscoop.com/2014/06/24/most-deficient-special-ed/19466

Fry, E. (1996). *Spelling book. Level 1–6. Words most needed plus phonics*. Westminster, CA: Teacher Created Materials, Inc. Retrieved from: www.teachercreated.com.

Graham, S., & Hebert, M. A. (2010). *Writing to read: Evidence for how writing can improve reading. A carnegie corporation time to act report*. Washington, DC: Alliance for Excellent Education.

Henry, M. (2010). *Unlocking literacy. Effective decoding and spelling instruction* (2nd ed.). Baltimore: Paul H. Brookes Publishing.

James, K., Jao, J. R., & Berninger, V. (in press). C. MacArthur, S. Graham, & J. Fitzgerald (Eds.), *The development of multi-leveled writing brain systems: Brain lessons for writing instruction Handbook of Writing Research*. New York: Guilford.

Katusic, S. K., Colligan, R. C., Barbaresi, W. J., Schaid, D. J., & Jacobsen, S. J. (2001). Incidence of reading disability in a population-based birth cohort, 1976–1982, Rochester, Minnesota. *Mayo Clinic Proceedings*, *76*, 1081–1092.

Katusic, S. K., Colligan, R. C., Weaver, A. L., & Barbaresi, W. J. (2009). The forgotten learning disability – epidemiology of written language disorder in a population-based birth cohort (1976–1982), Rochester, Minnesota. *Pediatrics*, *123*, 1306–1313.

MacArthur, C. (2009). Reflections on writing and technology for struggling writers. *Learning Disabilities Research and Practice*, *24*, 93–103.

MacArthur, C., Graham, S., & Fitzgerald, J. (Eds.). (in press). *Handbook of writing research*. New York: Guilford.

Mather, N., Hammill, D., Allen, E., & Roberts, R. (2004). *Test of silent word reading fluency* TOSWRF. Austin, TX: Pro-Ed.

Mather, N., Roberts, R., Hammill, D., & Allen, E. (2008). *Test of orthographic competence* (*TOC*). Austin, TX: Pro-Ed.

Murphy, K. R., Myors, B., & Wolach, A. (2009). *Statistical power analysis* (3rd ed.). New York: Routledge.

Nagy, W., Diakidoy, I., & Anderson, R. (1993). The acquisition of morphology: Learning the contribution of suffixes to the meaning of derivatives. *Journal of Reading Behavior*, *25*, 155–170.

Pearson, P. D., Ferdig, R., Blomeyer, R., & Moran, J. (2005). The effects of technology on reading performance in the middle school grades: A meta-analysis with recommendations for policy. Learning Point Associates, sponsored under government contract number ED01-CO-0011.

Pearson. (2009). *Wechsler individual achievement test* (3rd ed.). San Antonio, TX: Pearson.

Richards, T. L., Grabowksi, T., Askren, K., Boord, P., Yagle, K., Mestre, Z., . . . Berninger, V. (2015). Contrasting brain patterns of writing-related DTI parameters, fMRI connectivity, and DTI-fMRI connectivity correlations in children with and without dysgraphia or dyslexia. *Neuroimage: Clinical*, *8*, 408–421.

Semel, E., Wiig, E. H., & Secord, W. A. (2003). *Clinical evaluations of language fundamentals 4th edition: Examiner's manual*. San Antonio, TX: Harcourt Assessment, Inc.

Shadish, W., Cook, T., & Campbell, D. (2002). *Experimental and quasi-experimental designs for generalized causal inference*. Boston: Houghton Mifflin Co.

Silliman, E., & Berninger, V. (2011). Cross-disciplinary dialogue about the nature of oral and written language problems in the context of developmental, academic, and phenotypic profiles. *Topics in Language Disorders*, *31*, 6–23. Retrieved from http://journals.lww.com/topicsinlanguagedisorders/Fulltext/2011/01000/Cross_Disciplinary_Dialogue_about_the_Nature_of.3.aspx

Singson, M., Mahony, D., & Mann, V. (2000). The relation between reading ability and morphological skills: Evidence from derivational suffixes. *Reading and Writing: An Interdisciplinary Journal*, *12*, 219–252.

Stocco, A., Yamasaki, B., Natalenko, R., & Prat, C. (2014). Bilingual brain training: A neurobiological framework of how bilingual experience improves executive function. *International Journal of Bilingualism*, *18*(1), 67–92. doi:10.1177/1367006912456617; Retrieved from http://ijb.sagepub.com/content/early/2012/08/22/1367006912456617

Torgesen, J., Wagner, R., & Rashotte, C. (1999). *Test of word reading efficiency*. Austin, TX: Pro-Ed.

Troia, G. (Ed.). (2009). *Instruction and assessment for struggling writers. Evidence-based practices*. New York: Guilford.

Tyler, A., & Nagy, W. (1989). The acquisition of English derivational morphology. *Journal of Memory and Language*, *28*, 649–667.

Tyler, A., & Nagy, W. (1990). Use of derivational morphology during reading. *Cognition*, *36*, 17–34.

Venezky, R. (1970). *The structure of English orthography*. The Hague: Mouton.

Venezky, R. (1995). From orthography to psychology to reading. In V. Berninger (Ed.), *The varieties of orthographic knowledge. II Relationships to phonology, reading, and writing* (pp. 23–46). Dordrecht: Kluwer Academic Press. Now Springer.

Venezky, R. (1999). *The American way of spelling*. New York: Guilford.

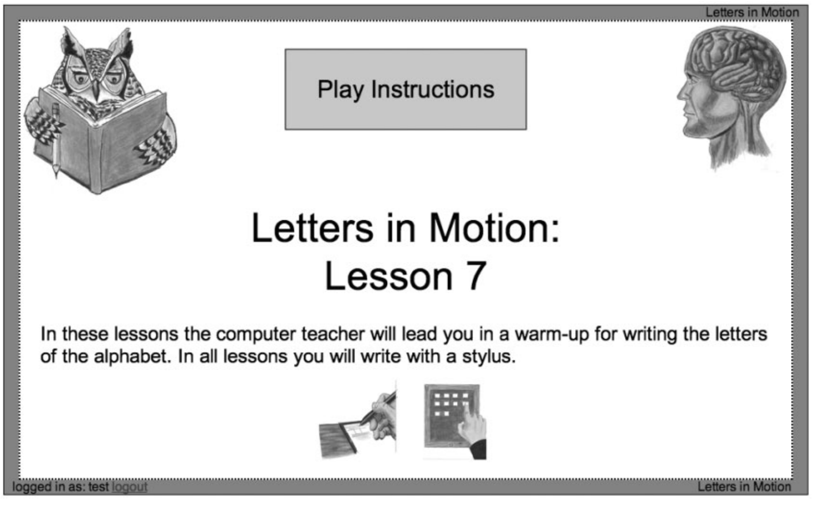
Woodcock, R., McGrew, K., & Mather, N. (2001a). *Woodcock-Johnson III psychoeducational cognitive test battery*. Itasca, IL: Riverside.

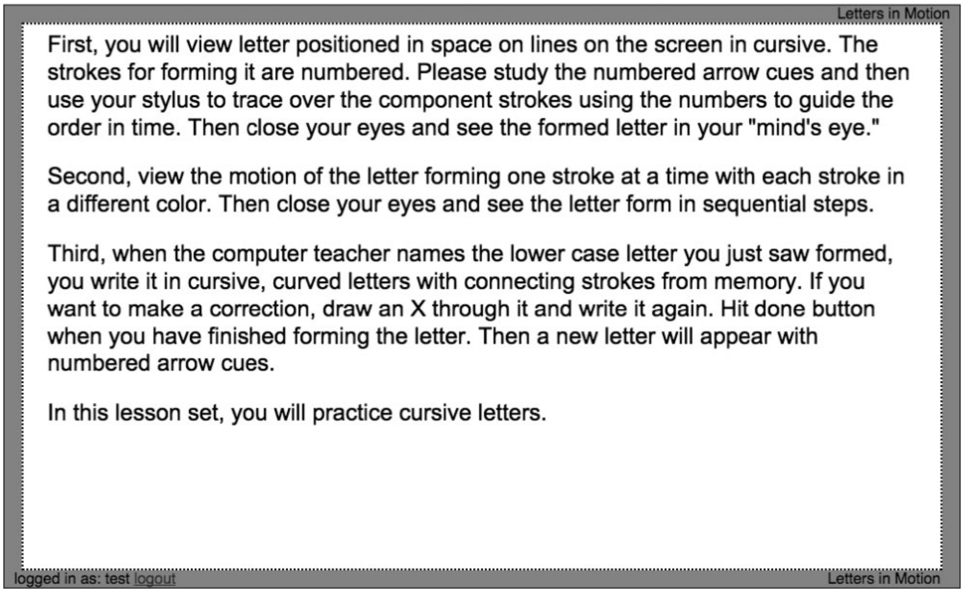
Woodcock, R., McGrew, K., & Mather, N. (2001b). *Woodcock-Johnson III achievement battery*. Itasca, IL: Riverside.

Appendix

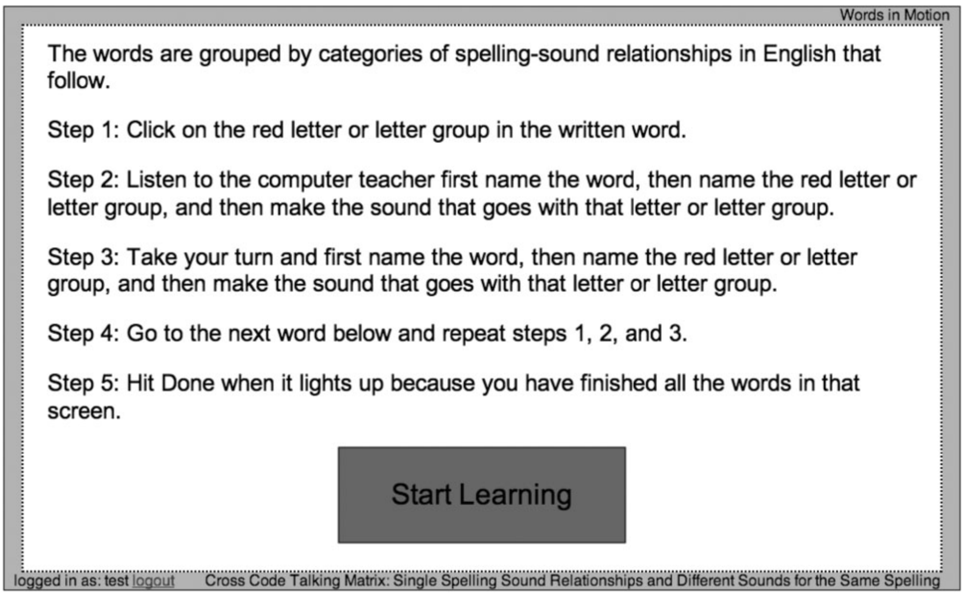
Selected screen shots

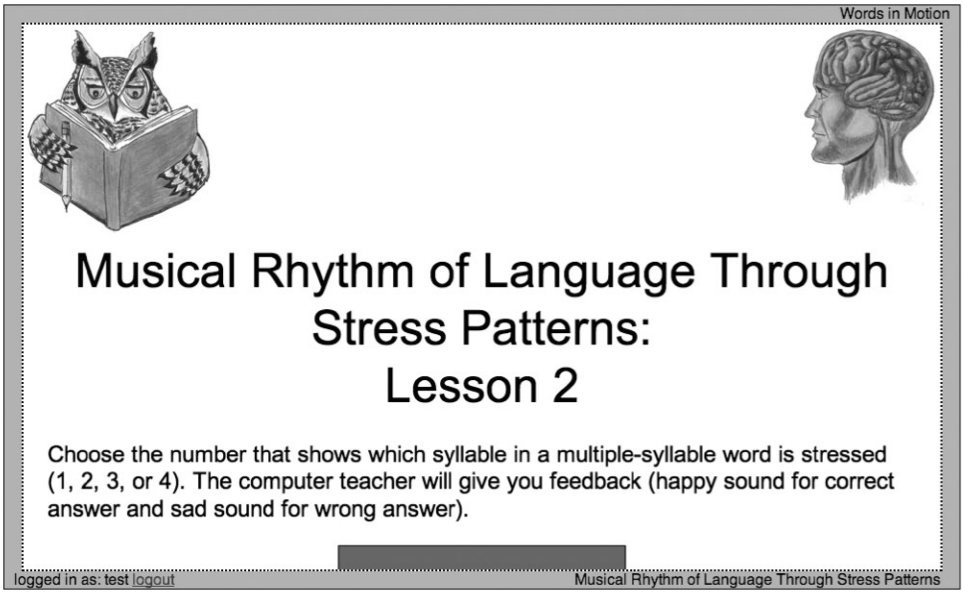
*Letters in Motion (LIM) in HAWK * = (Help Assistance in Writing Knowledge)*™

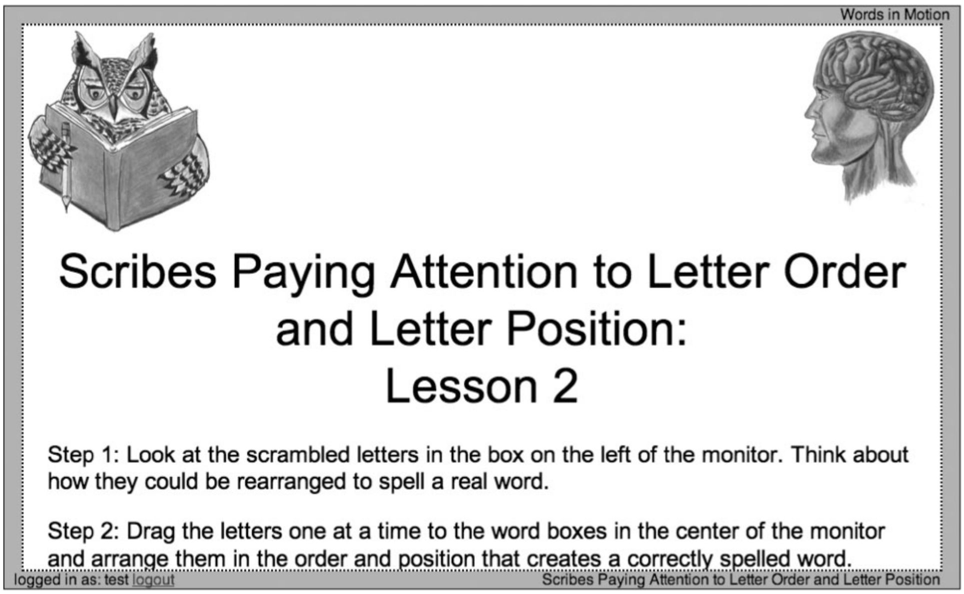


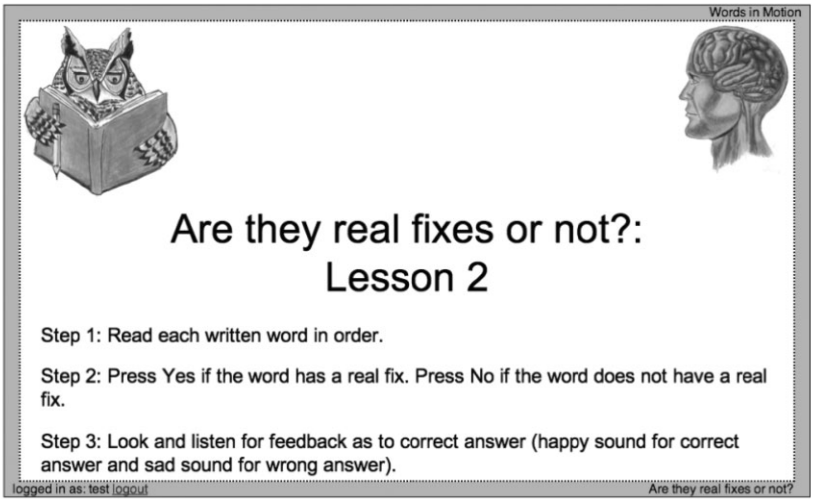


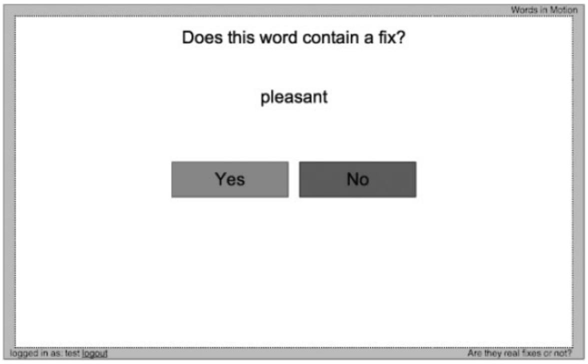
Words in Motion (WIM) in HAWK (Help Assistance in Writing Knowledge)™

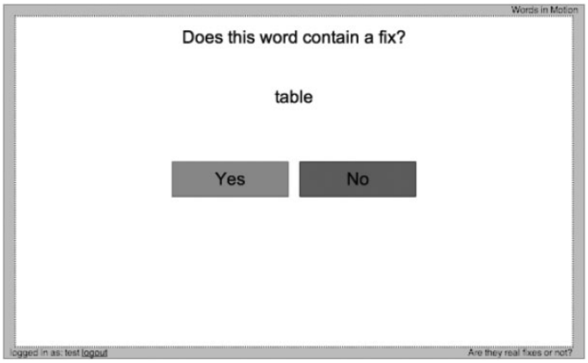



Words in Motion
Musical Rhythm of Language Through Stress Patterns: Lesson 2
Choose the number that shows which syllable in a multiple-syllable word is stressed (1, 2, 3, or 4). The computer teacher will give you feedback (happy sound for correct answer and sad sound for wrong answer).
logged in as: test logout
Musical Rhythm of Language Through Stress Patterns


Words in Motion
Scribes Paying Attention to Letter Order and Letter Position: Lesson 2
Step 1: Look at the scrambled letters in the box on the left of the monitor. Think about how they could be rearranged to spell a real word.
Step 2: Drag the letters one at a time to the word boxes in the center of the monitor and arrange them in the order and position that creates a correctly spelled word.
logged in as: test logout
Scribes Paying Attention to Letter Order and Letter Position


Words in Motion
Are they real fixes or not?:
Lesson 2
Step 1: Read each written word in order.
Step 2: Press Yes if the word has a real fix. Press No if the word does not have a real fix.
Step 3: Look and listen for feedback as to correct answer (happy sound for correct answer and sad sound for wrong answer).
logged in as: test logout
Are they real fixes or not?


Words in Motion
Does this word contain a fix?
pleasant
Yes
No
logged in as: test logout
Are they real fixes or not?


Words in Motion
Does this word contain a fix?
table
Yes
No
logged in as: test logout
Are they real fixes or not?

*Minds in Motion (MIM) in HAWK * = (Help Assistance in Writing Knowledge)™*