Neuralign© and the Science of Reading

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Executive Summary

Reading is a complex skill that is essential to modern life. Unfortunately, even with proper instruction, approximately 5-10% of people struggle to acquire adequate literacy skills. Most of those who struggle with reading have deficits in key cognitive processes (e.g., phonological awareness, attention, sensory processing). Because reading difficulties have multiple causes and correlates, struggling readers may benefit from interventions that train a combination of phonological processing, cognitive, and attentional skills. Additionally, compared to offline interventions, digital interventions (i.e., that are available on computers, tablets, or online) may deliver accessible but high-quality instruction of core reading skills. Digital interventions may also engage students who are used to fast-paced media experiences, increasing motivation for those who have had longer-term difficulties. Finally, digital interventions may be more cost-effective than private tutoring.

In this report, we describe how Neuralign©, an online cognitive training program designed for people with dyslexia and other reading difficulties, is supported by research on literacy development. The Neuralign© program consists of digital game-based instruction to train phonological skills, cognitive skills, and attentional skills in an engaging and motivating environment. Many features of the intervention are likely to support improved reading. However, more work is needed to understand how best to combine various aspects of reading practice to maximize beneficial effects in a short-term intervention.

Many aspects of the Neuralign© program are grounded in specific research evidence, whereas other features have not received enough attention from researchers to allow an accurate evaluation of their impact. The features of the program that have the most research support are the ones that help students practice letter-sound connections, segmenting, and blending words. It seems very likely that this practice will be helpful and support their reading progress. However, more research on the amount, sequencing, and intensity of this practice would be useful; further research could explore the practical concerns about time investment relative to benefit or the optimal game design and spacing of practice. Some students might benefit from a less intensive but more prolonged intervention, others may need more practice than is currently provided. Increasing the variety of the words used in the cognitive training might also enhance benefits. Manipulating these features and collecting data about learning trajectories could provide useful benchmarks for improving the fit between student and intervention. Research on other aspects of the intervention, especially with respect to the speeded reading and comprehension components, could also be useful in determining who benefits most. In summary, although there many aspects of the program which have clear support from research, other features are hard to evaluate with that lens.

Reading Acquisition and Difficulties

The goal of reading is to understand the meaning of a text. According to the Simple View of Reading (Gough & Tunmer, 1986), reading comprehension is a combination of decoding and language comprehension. The Reading Systems Framework (Perfetti & Stafura, 2014) includes three constructs that are involved in the reading process: general cognitive skills (i.e., attention, memory, perception), language processes (i.e., decoding, word identification, activating word meanings), and knowledge (i.e., general, linguistic, orthographic). Most recently, the Active View of Reading (Duke & Cartwright, 2021), adds motivation, cultural knowledge, and self-regulation to the predictors of reading acquisition. Together, these frameworks can be used to understand the reading process and develop or refine interventions that will help students to acquire this complex skill.

Gaining a better understanding of reading acquisition and reading difficulties is critical for better instruction and targeted interventions. For example, **decoding** is a core skill for learning to read. Decoding is the mapping of sounds (phonology) to the letter(s) in a written word (orthography). Although poor decoding is not the only source of reading difficulties, decoding difficulties necessarily restrict the development of reading skills. Other possible causes of reading difficulties are problems with short-term memory, visual attention, or auditory processing (Galuschka et al., 2014; Hulme & Snowling, 2013; Rayner et al., 2001; Snowling et al., 2020). These cognitive factors may also contribute to poor decoding skills. Regardless of which of these factors is predominant, weak decoding prevents students from accessing words in text and is therefore a key target for remediation.

Dyslexia refers to a specific learning disorder that involves reading. The *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.; DSM–5; American Psychiatric Association, 2013) classifies dyslexia as a neurodevelopmental disorder, which means it has an early onset, is heritable, and has life-long consequences. For a person to receive a diagnosis of dyslexia, they must have had problems with reading accuracy and fluency, poor decoding, and poor spelling that persisted for a minimum of six months despite targeted interventions. Although difficulty connecting sounds and letters is considered a central issue in dyslexia, it is possible to have dyslexia without having phonological deficits (Hulme & Snowling, 2013; Pennington, 2006; Rayner et al., 2001; Snowling et al., 2020). Other possible causes of dyslexia include problems with vision (e.g., tracking or focusing), attention, working memory, and/or processing speed (Alt et al., 2022; Pasqualotto & Venuti, 2020; Rayner et al., 2001; Sala & Gobet, 2020; Snowling et al., 2020).

Not everyone who struggles with reading is dyslexic. Although researchers and clinicians typically use absolute thresholds to diagnose dyslexia, the reading difficulties of children below the diagnostic threshold are not categorically different from those of children who are above the threshold (Peters & Ansari, 2019). Accordingly, in research studies, dyslexia is often use to label students with extreme difficulties with reading whereas the term "reading difficulties" captures a larger group of students whose challenges are similar but less severe. Moreover, dyslexia and reading difficulties often co-occur with other learning difficulties or disorders. Approximately 40% of children with dyslexia have co-occurring difficulties such as dyscalculia, ADHD, anxiety, depression, or language disorders (Moll et al., 2020; Peters & Ansari, 2019). Therefore, understanding the nature and extent of students' reading and cognitive difficulties rather than having an official diagnosis is key to choosing an appropriate intervention.

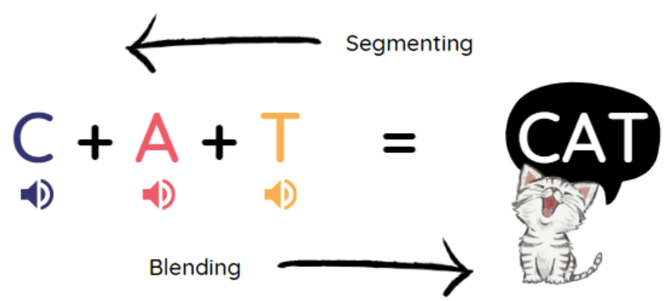
Decoding as a Key Reading Skill

Decoding is a critical skill for learning to read. It involves activating the meaning of a word using letter-sound knowledge to connect phonological, visual, and semantic representations in memory. Decoding involves phonological processes, including phonological awareness, phonemic awareness, and phonics. Other terms, such as phonics, phonemic awareness, and phonological awareness are commonly used to describe the key skills involved in decoding. Although similar, these are not equivalent concepts and the term '**phonological processes**' may be used as an umbrella construct to describe language-related sound perception.

Phonological awareness is the ability to perceive and manipulate the sounds of spoken words (Konza, 2011; Melby-Lervåg et al., 2012). Interventions targeting phonological awareness may include rhyming activities or segmenting sentences into words. For example, phonological awareness supports being able to hear that "cat" and "bat" rhyme or being able to hear "Whatdoesthefoxsay" and segment all of these sounds into individual words "What does the fox say?".

Part of phonological awareness, **phonemic awareness** is the specific ability to perceive the separate phonemes that make up words (Konza, 2011). For example, "cat" can be broken down into three sounds: /k/, /a/, and /t/. Interventions that target phonemic awareness may include **segmenting** (separating the individual sounds of a word) and **blending** (putting individual sounds together) (see Figure 1).

Figure 1. Blending and Segmenting



Phonics refers more specifically to the relation between phonemes (smallest unit of sound) and graphemes (smallest unit of writing) and thus phonics interventions help students link letters and sounds, for example, learning that the letter C stands for the sound /k/.

Most reading programmes that involve decoding include training in phonics, phonemic awareness, and phonological awareness, with the larger goal of improving links between written and spoken language.

Although most people with reading difficulties experience challenges using phonological processes to decode words, research has identified other challenges. Visual problems may also interfere with decoding. Reading fluency and reading comprehension are also influenced by phonological, visual, and working memory/attentional limitations (Castles et al., 2018), motivation, and active self-regulation of cognition (Burns et al., 2023; Duke & Cartwright, 2021).

Neuralign© and the Science of Reading

The following section shows the mappings between key reading skills and the Neuralign© cognitive therapy and reading exercise games have been designed to target and train these skills.

What is Neuralign©?

Neuralign© is a digitally delivered cognitive training program designed for people with dyslexia and other reading difficulties. The structure of the intervention is shown in Figure 2. The program consists of 13-15 weeks of game-based instruction designed to train phonological skills, cognitive skills, reading fluency, reading comprehension, and attention. It includes three weeks of cognitive training that is intended to enhance reading pathways in the brain, plus 10 weeks of reading exercises that target fluency and comprehension. The cognitive training portion of the program and the reading exercises each include decoding training and practice. The game-based and fast-paced activities are intended to enhance students' success and therefore increase motivation and engagement.

Figure 2. Structure of the Neuralign© Intervention

The Neuralign program is divided into three overlapping units.

Cognitive Therapy:

Comprised of 15 1-hour sessions that must be completed over 3-5 weeks (with no more than 3 days between sessions). There are 5 difficulty levels, with each session increasing in difficulty.

Reading Exercises:

Comprised of 15- to 30- minute sessions, with 5 sessions a week, lasting 10 weeks. The schedule varies throughout the week, alternating between reading comprehension activities (on days 1, 3, and 5) in which students must read a short text and answer related questions, and reading stories (on days 2 and 4) in which students must read either 2 short stories, or read for a duration of 10 minutes. On all days, cognitive memory games are played before and after the reading activity.

Reading exercises begin after the 15th and final Cognitive Therapy session.

Speed Reading:

Comprised of 1-minute sessions, with 5 sessions a week, lasting 10 weeks. Students read the same story for their 5 weekly sessions, with a new story each week.

Neuralign© is intended to integrate training of phonics and executive functioning through a targeted multisensory approach which may help strengthen brain pathways essential for fluent reading. The program was designed to foster student engagement and motivation by integrating reading and cognitive training with dynamic computer games. The games have multiple simultaneous auditory, visual, and processing demands, and include a point system that is designed to motivate students to persist. Results from a recent survey in which parents shared their children's experiences with Neuralign© (Douglas et al., 2022) shows that the games were the favourite feature of this program. The ten Neuralign© Cognitive Therapy games are named for countries. For some games, the imagery connects to the country name to representative themes or images, such as windmills in Holland, and fish and coral reefs in Australia. In the reading exercises portion of the intervention, which includes oral reading that is timed and answering questions about texts (see Figure 2), memory games are included to maintain motivation. A brief description of each game is shown in Appendix A (Cognitive Therapy) and Appendix B (Reading Exercises).

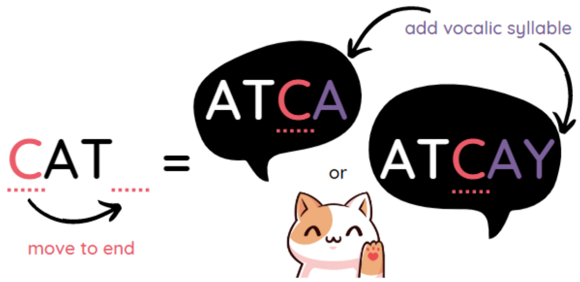
Reading Skills Targeted in Neuralign©

Phonological Processes

Decoding activities are common to most of the games in the Neuralign© Cognitive Therapy. Seven of the 9 games (exceptions are Morocco and Switzerland), centre around decoding skills, requiring users to read target words to score points while playing the game. More specifically, some games target phonological processes by focusing on blending or segmenting letters and letter combinations. To help students practice detecting and differentiating phonemes, some of these games employ the use of minimal pairs. **Minimal pairs** are words that vary by one sound. For example, "cat" and "bat" vary by one sound: the /k/ and /b/. Another game targets phonological awareness by focussing on syllables, using a variation of Pig Latin. **Pig Latin** (see Figure 3) is a pseudo-language consisting of moving the initial consonant (or cluster) to the end of the word and adding a vocalic syllable at the end.

Neuralign© Cognitive Therapy games that target phonological processes are Australia, Canada, China, Egypt, Holland, Scotland (rainy and sunny).

Figure 3. Pig Latin



Executive Functions

Executive functions are the processes involved in the control of cognition and behaviour, although they can be difficult to measure and target in interventions because they must be embedded within other tasks (Miyake & Friedman, 2012). Working memory, cognitive flexibility, and inhibitory control are the three executive functions involved in the reading process, and they each have different roles (Christopher et al., 2012; Park & Mackey, 2022; Pasqualotto & Venuti, 2020). The Neuralign© objective is to combine executive function practice with reading. As such, all games involve executive functions to some degree. In general, research on training executive functions shows evidence of near transfer (i.e., the trained activities improve), but rarely shows evidence of far transfer (i.e., to academic skills; Katz et al., 2018; Park & Mackey, 2022; Pasqualotto & Venuti, 2020; Sala & Gobet, 2020). However, more research is needed on the effect of training executive functions and core reading skills together.

Working memory (the ability to temporarily store and manipulate relevant information) is important for reading at all levels, from decoding to reading comprehension (Christopher et al., 2012; Seigneuric & Ehrlich, 2005). Visual-spatial and verbal working memory systems are separate. Although both systems are involved in reading, verbal working memory has the stronger role. Readers use verbal working memory to decode words and temporarily store words and phrases as they process sentences (Baddeley, 2003; Pasqualotto & Venuti, 2020). Once children have mastered the ability to read individual words, their working memory skills further predict their reading comprehension skills (Seigneuric & Ehrlich, 2005).

Working memory training is always embedded in a context, because working memory tasks requires people remember *something* (e.g., a sequence of numbers, a list of words, a spatial pattern). Therefore, it is impossible to separate the effects of working memory from those of other processes involved in the task (e.g., number processing when remembering numbers, reading processes when remembering words or letters). For reading, interventions targeting executive functions typically focus on training working memory because it is central to reading. Despite the wealth of correlational evidence that working memory is related to reading, the effectiveness of training working memory to address reading problems is unproven.

Working memory training sometimes supports better performance on very similar tasks as those that were trained, that is, near transfer (Peijnenborgh et al., 2016), however, there is no conclusive evidence that training significantly improves participants' working memory skills more generally (far transfer), or that training improves reading skills (Melby-Lervåg et al., 2016; Melby-Lervåg & Hulme, 2013; Sala & Gobet, 2017, 2020). However, training working memory in the context where it will be used, for example, training working memory and reading simultaneously, may result in overall better transfer to reading than training reading alone (Pasqualotto & Venuti, 2020; Peijnenborgh et al., 2016).

Neuralign© Cognitive Therapy games that target working memory in reading contexts are Australia, Canada, China, Holland, Morocco, Scotland, and Switzerland. Neuralign© Reading Exercise games target working memory in reading contexts (Wordbuilder Holland) and separately from reading (Memory Cards Colour Hopper, and Pathfinder).

Inhibitory control, the ability to suppress irrelevant information to maintain focus on relevant stimuli, is crucial for reading comprehension (Borella et al., 2010; Christopher et al., 2012; Gernsbacher & Faust, 1991). For example, when reading, readers need to ignore distracting stimuli from the environment (e.g., phone notifications), wayward thoughts (e.g., wondering what's for dinner), or the different senses of a word (e.g., crane could refer to a bird or to a machine). There are many kinds of inhibitory control, including environmental (extrinsic), internal attentional (intrinsic, mind wandering), and cognitive distractions (memory, knowledge). Each type of inhibitory control may require different cognitive processes.

Most Neuralign© Cognitive Therapy games involve extrinsic visual (Australia, China, Egypt, Holland) or audiovisual (Canada, Morocco, Scotland, Switzerland) distractions. The reading exercise game, Wordbuilder Holland, also focusses on extrinsic visual distractors. Australia and Egypt also require inhibition of cognitive distractions, which is typically the kind of inhibitory control associated with reading specifically (vs. attentional problems more generally). For example, semantic distractions occur when a word has more than one meaning, for example, "Shamika went to the bank to join her friend for a boat ride." In this sentence, a more familiar meaning of the word bank, a financial institution, has to be inhibited so the less familiar meaning, the side of a river, can be activated so that the sentence makes sense.

Cognitive flexibility (the ability to shift between tasks) is important primarily for reading comprehension; shifting is important because reading requires simultaneously decoding words and understanding their meaning (Cartwright, 2007, 2012; Colé et al., 2014).

Neuralign© Cognitive Therapy games that target cognitive flexibility are Australia and Egypt. There is much less research about specific role of cognitive flexibility in reading compared to working memory and inhibitory control.

Other Factors Targeted in the Neuralign© Program

Magnocellular pathway

Some researchers have proposed that dyslexia is caused by impairments in the dorsal visual pathway, more specifically, the magnocellular cells, which are important for detecting motion and visual attention (Franceschini & Bertoni, 2019; Gori et al., 2016; Lawton, 2016; Lawton & Shelley-Tremblay, 2017; Stein, 2001, 2019). For example, Stein (2019) has argued that developmental dyslexia is caused by poor temporal processing due to impairments with magnocellular cells. Some researchers have investigated the role of other visual deficits in reading by studying the effects of action video games (Franceschini & Bertoni, 2019) and figure/ground motion discrimination (Lawton, 2016; Lawton & Shelley-Tremblay, 2017) on reading abilities and high-level cognitive functioning. Whether there is a causal relation between dyslexia and disordered visual processing is controversial and there is no consensus as to who is affected or how much variability in these processes may account for reading difficulties.

Some researchers have found correlations between visual processes and dyslexia but failed to find evidence of causality. For example, Hutzler et al. (2006) found no causal link between magnocellular pathways and reading difficulties in dyslexics and Olulade et al. (2013) showed that visual magnocellular dysfunction is most likely a consequence of poor reading skills, rather than the cause. Even in studies where children with dyslexia were responsive to motion discrimination training such as Lawton and Shelley-Tremblay (2017), typical readers also showed improvement, weakening the argument that visual difficulties are the cause of dyslexia. Other theorists have argued that, even if visual deficits may sometimes be related to reading difficulties, the effects would be minimal compared to other explanations (Rayner et al., 2001; Vellutino et al., 2004). In summary, the evidence that visual processes are causally linked to dyslexia is controversial and more research is needed to understand exactly how visual and phonological factors may interact to influence reading.

Neuralign© games have specific patterns which rotate in the background and are intended to activate magnocellular cells to help users improve figure/ground motion discrimination.

Timing

Timing is important in learning to read because reading involves matching the correct symbols with rapidly changing speech sounds (Hahn et al., 2014). Synchronicity is important for multisensory integration and visual training with feedback can improve the temporal precision of multisensory tasks (Stevenson et al., 2013). To the extent that reading problems are caused by difficulties with auditory processing, it is possible that managing auditory presentation speed could assist struggling readers in matching sounds to symbols. More research is needed to determine the effectiveness of delayed audio and visual cues in improving reading ability.

Neuralign© games have delayed audio and visual cues in many games. For example, delays are inserted between each phoneme verbally presented in Canada. Although the games are not adaptive to individual users, as the program progresses (e.g., session 13 versus session 3), the auditory delay is reduced.

Spelling

There is a strong relation between spelling and reading because they both rely on the relations between letters and sounds and the development of orthographic representations (Ehri, 2000; Moats, 2005; Moll et al., 2014; Perfetti 1997). However, spelling is more difficult than reading because it involves *production* of an orthographic pattern whereas reading requires *activation* of phonology from orthography.

Spelling is not the central focus of the Neuralign© program (only Scotland targets this skill). However, two reading exercise games include spelling practice: Silly Machine and Wordbuilder Holland.

Fluency

Reading fluency has been studied extensively, though there are still questions as to how exactly one goes from a novice reader to a fluent reader. **Reading fluency** is defined as the fast and accurate reading of a text, including fast and accurate word decoding, proper sentence prosody, and at a conversational rate (Hudson et al., 2008). During the acquisition process, after decoding starts to increase in accuracy, reading fluency is the next significant hurdle for developing readers (Hudson et al., 2005; Schreiber, 1980). Many interventions have been developed to help readers become fluent. Most commonly, **repeated reading** interventions are used to help improve students' reading fluency (Hudson et al., 2020; Samuels 1979; Schreiber 1980). Meta-analyses have shown that repeated reading is the most effective intervention for improving reading fluency in children with learning disabilities (Hudson et al., 2020; Stevens et al., 2017). However, meta-analyses have also shown that interventions requiring an equal amount of non-repetitive reading may produce similar outcomes as repeated reading for word accuracy and reading comprehension for students in grades 6-12 (Wexler et al., 2008). Similarly, both repetitive and non-repetitive repeated reading interventions support reading fluency for students in grades K-12 (Zimmerman et al., 2021).

The Neuralign© program includes some fluency practice for users. Speed Reading consists of repeated reading sessions that begin after the 9th Cognitive Therapy session. Each session lasts one minute. Users must complete five sessions a week, in which they read the same text. The sessions last 10 weeks, with a new text introduced each week. Thus, Neuralign© includes elements of both repeated reading and non-repetitive reading. In the Speed Reading sessions, users are presented with a text on screen and are instructed to read the text aloud and then click the last word they read when the minute is up. Without feedback or support, however, it is unclear how useful the repeated reading is for increasing fluency. Although accuracy and speed are usually the focus of intervention, it is important to also consider the importance of proper prosody: A meta-analysis by Wexler et al. (2008) found that interventions in which students listened to models of good reading before they read a passage consistently improved fluency outcomes.

Reading Comprehension

As mentioned previously, the objective of reading is comprehension of a text. Being able to garner meaning from text is especially hampered by decoding difficulties as well as other factors such as attention, memory, perception, knowledge, or fluency (Gough & Tunmer, 1986; Perfetti & Stafura, 2014).

Interventions therefore typically focus on targeting key skills, seek to reduce anxiety or improve affect and self-concept, or use a multifactor approach to target all aspects of the reading process. A recent meta-analysis has shown that instruction of proper strategies and background knowledge is more effective at supporting reading comprehension in struggling readers in elementary through high school than instructional enhancements such as graphic organizers or technology (Filderman et al., 2022).

The Neuralign© Reading Exercises component begins after the 15th and final Cognitive Therapy session, and has students alternate between reading comprehension activities and reading practice. During the reading comprehension activities, students read a short text and respond to related questions (multiple choice, with immediate feedback). In the reading practice, students read short stories for a duration of 10 minutes.

Conclusions

The Neuralign© program takes a multifactor game-based approach to targeting reading difficulties. Based on an analysis of the research on reading interventions, we found evidence that many features of the program are consistent with this research. In particular, the features of the program that are consistent with research on reading:

1. Include decoding practice, supporting segmenting and blending. Children need to already know letter sounds to benefit from the games which are focussed on these skills.
2. Employ the use of fast-paced game formats and a reward system to engage and motivate students.
3. Provide fluency practice through reading exercises consisting of repeated readings (one minute) of the same text over five days.
4. Provide practice reading short texts and answering questions (with immediate feedback for correctness) through reading exercises.

Other features of Neuralign© which may be important for dyslexic readers have not received as much research attention and thus were difficult to evaluate. In particular, the design of Neuralign© assumes that presenting words in a visually and auditorily complex environment and with distracting moving stimuli may stimulate magnocellular pathways. Moreover, intensive experience with the cognitive therapy in a short time frame is assumed to help brain pathways which are underdeveloped in dyslexic individuals to improve, helping them benefit from training.

However, very few studies in the literature have addressed these factors (compared to the phonological and fluency aspects of dyslexia) and thus we could not identify clear guidelines for parameters that might maximize any effect. Additional research on how various aspects of visual and auditory stimulation might enhance word processing would be useful. Furthermore, despite working memory, selective attention, and inhibitory processing being a major focus of the games, there is little research evidence that these skills improve with short-term interventions; it would be useful to determine whether integrating these activities into the reading practice supports development of these skills.

Combined, the various features of Neuralign© are intended to help students with reading difficulties, dyslexia, and other learning difficulties to persist and practice reading. Non-cognitive factors (i.e., motivation, self-efficacy, anxiety) are also correlates of reading (Guthrie et al., 1999; Macdonald et al., 2021; Pollack et al., 2021; Ramirez et al., 2019) and reading interventions that target affective and motivational factors in the context of cognitive skills may also support reading improvement. However, evidence to support this view is scarce.

The Neuralign© program was designed to provide an engaging and motivating environment in which to practice skills essential for improving reading ability. In the user survey, users reported that they especially liked the games and that the program is computer based which allows for independent reading practice (Douglas et al., 2022). Practice is essential to improve reading ability and increased opportunities to do so (and in positive and stimulating environments) may be beneficial for students' overall abilities and attitudes towards reading. However, more research on the amount, sequencing, and intensity of this practice would be useful in optimizing learning gains through game – and program – design.

Based on our current evaluation of the program and the existing literature, it is our opinion that some aspects of the program could be improved. For example, fluency practice is underdeveloped in the intervention. Fluency practice is most helpful when it involves reading aloud to support prosody as well as repeated decoding; this aspect of the intervention has not really capitalized on existing research. If students do the fluency practice alone, it is not clear if they are reading aloud with proper prosody or accuracy. It is also easy for students to not read at all, and simply select a word at random at the end of the session. If students are not monitored during this portion of the exercises, then they may not follow the instructions. Finally, having the opportunity to hear the text read aloud might increase the value of fluency practice.

In summary, although there many aspects of the program which have clear support from research, further research is needed to accurately determine the importance of other design elements.

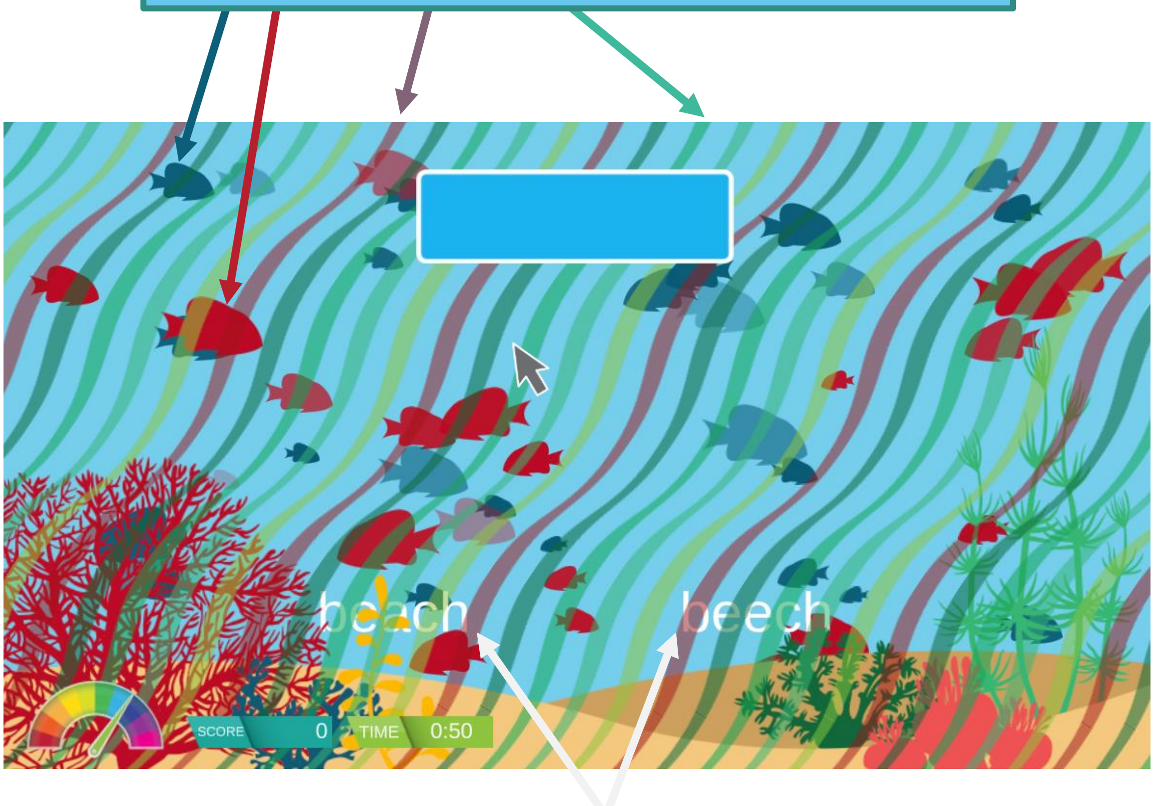
Appendix A: Neuralign© Cognitive Therapy Games

Australia:

In this game, a homophone is presented verbally, followed by a sentence containing the homophone. The homophone is repeated verbally, and two homophones are presented on the screen. For example, “Beach. We grabbed our swimsuits and went to the beach. Beach.”

Visual Selective Attention:

The user must ignore simultaneous visual distractors (i.e., flashing fish, scrolling waves overlay).



Working Memory / Cognitive Flexibility / Inhibition:

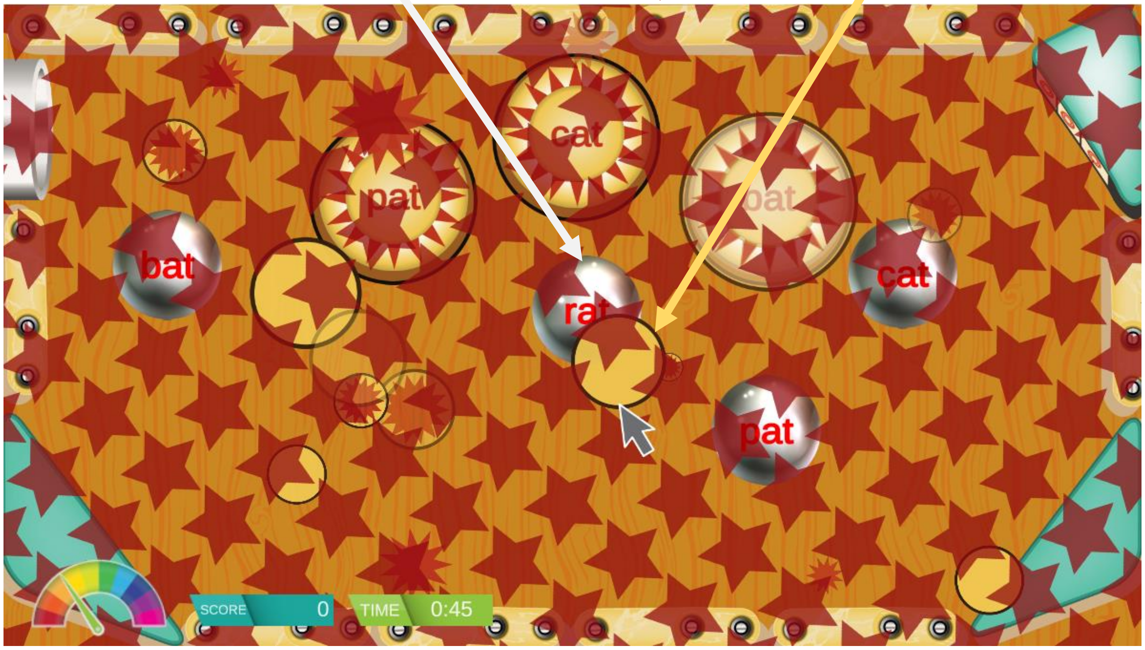
The user must simultaneously read and decode the homophones presented to the screen and understand their meaning. They must then inhibit the irrelevant meaning to select the appropriate word for the context.

Canada aka Pinball:

In this game, a word is presented verbally, one phoneme at a time. Balls bounce around bumpers labelled with minimal pairs and the user must click on the appropriately labelled ball and drag it to the correct bumper.

Audio/Visual Selective Attention:

The user must ignore simultaneous audio distractors (i.e., pings and beeps of balls hitting bumpers) and visual distractors (i.e., scrolling stars overlay, flashing circles, moving balls with incorrect responses).



Verbal Working Memory:

The user must remember the individual segmented sounds to blend them together to form a complete word while simultaneously locating the appropriate word on the balls moving across the screen.

Blending:

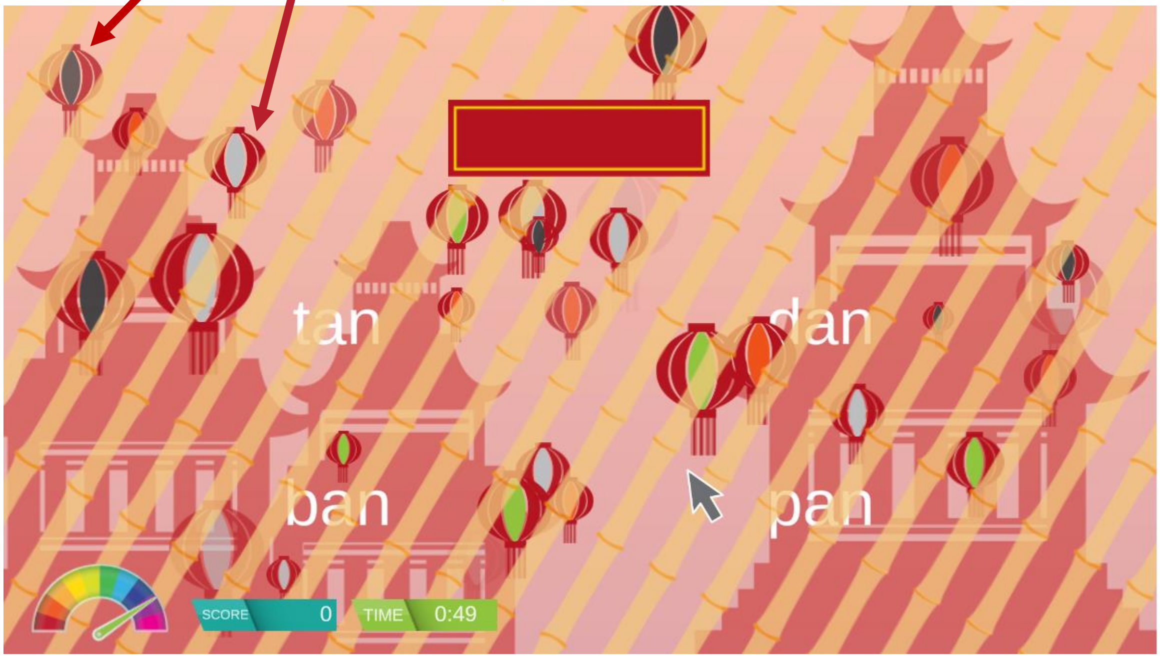
The user must blend together the individual, segmented sounds of the word to select the appropriately labelled bumper. As the game progresses, the delay between sounds is reduced.

China:

In this game, a target word is presented verbally, one phoneme at a time. The target and three minimal pairs are presented visually, and the user must click on the target word and drag it to the answer box.

Visual Selective Attention:

The user must be able to ignore simultaneous visual distractors (i.e., flashing lanterns, scrolling bamboo overlay).



Blending:

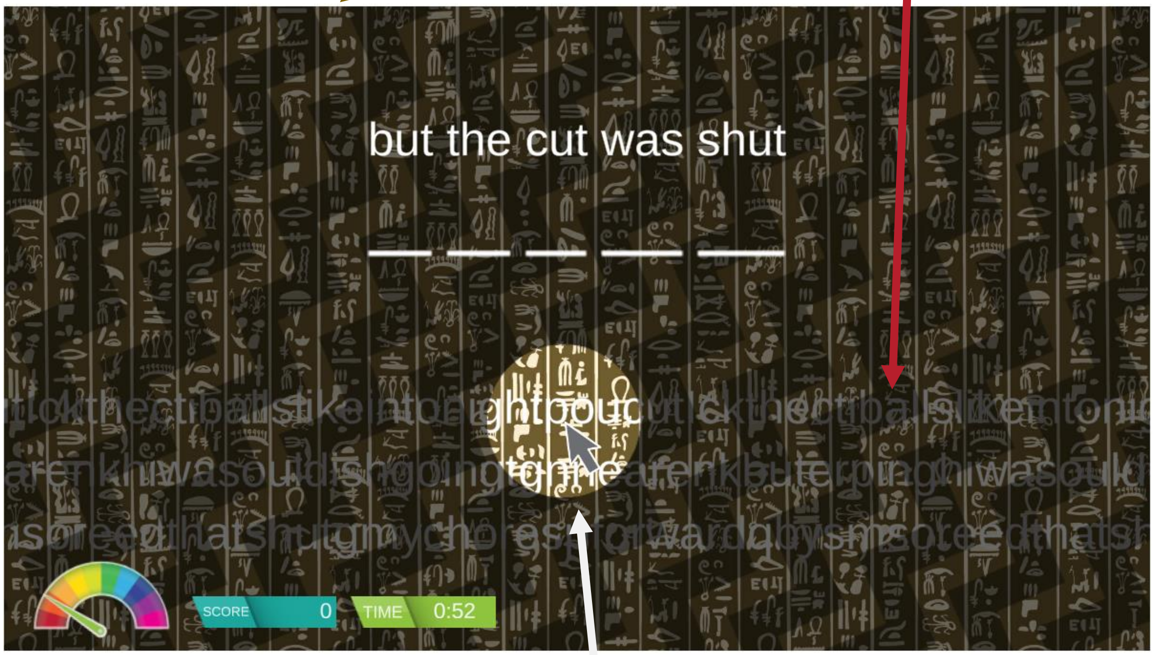
Minimal pairs are laid out across the screen as segmented sounds of the target word are being heard. The user must blend them together to select the word. As the game progresses, the delay between sounds is reduced.

Egypt:

In this game, a sentence is presented verbally (in all difficulties) and visually (up until P3). The user must search through scrolling text on the bottom of the screen and find the words that make up that sentence.

Visual Selective Attention:

The user must ignore simultaneous visual distractors (i.e., scrolling overly of zigzags, irrelevant words in the scrolling list).



Working Memory / Cognitive Flexibility / Inhibition:

The user must use their flashlight (cursor) to look through the scrolling text at the bottom of the screen and locate the words that make up that sentence. They must drag and drop the appropriate words in the correct order to recreate the sentence. Words are hidden within two* lines of scrolling text across the bottom of the screen (top line scrolls to the left, and the bottom line scrolls to the right). The user must be able to decode the strings of letters within the scrolling texts to identify the correct words.

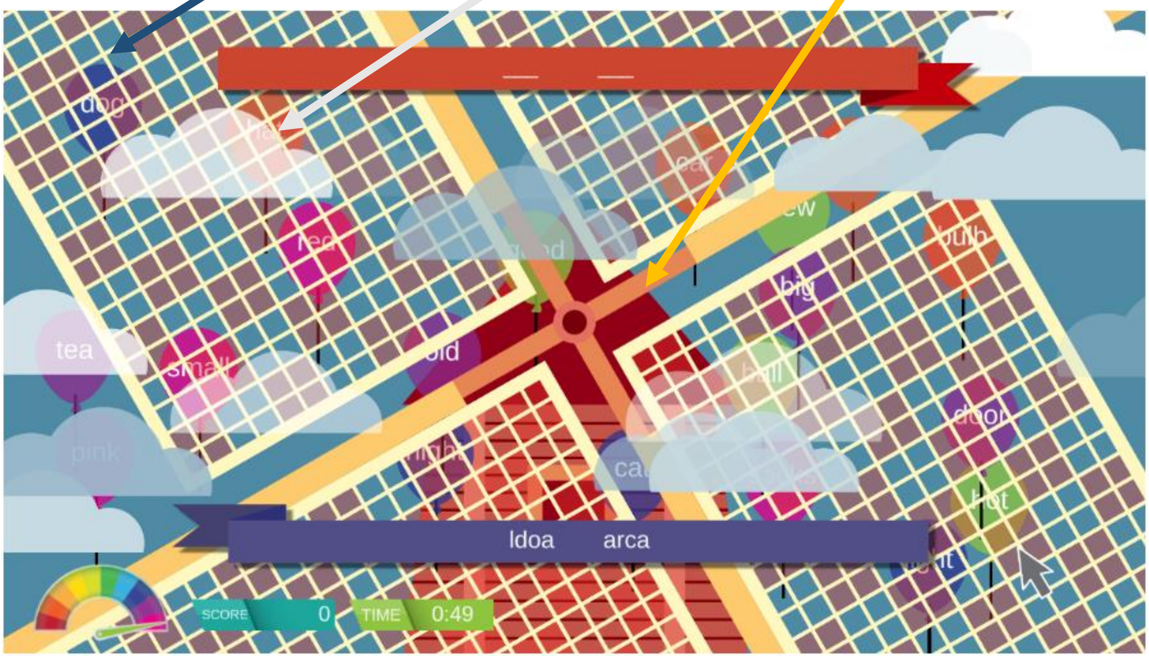
*Starting at P2-Session 4, 3 lines of scrolling text appear.

Holland:

In this game, a target word is presented visually on the screen. There are many balloons slowly moving across the screen with words presented in either English or Pig Latin. The user must then select the balloon which corresponds to the prompt.

Visual Selective Attention:

The user must be able to ignore the simultaneous visual distractors (i.e., moving balloons filled with incorrect responses, flashing clouds, and rotating windmill blades).



Segmenting:

The user must be able to segment the word into syllables to form the correct Pig Latin or English word.

Verbal Working Memory:

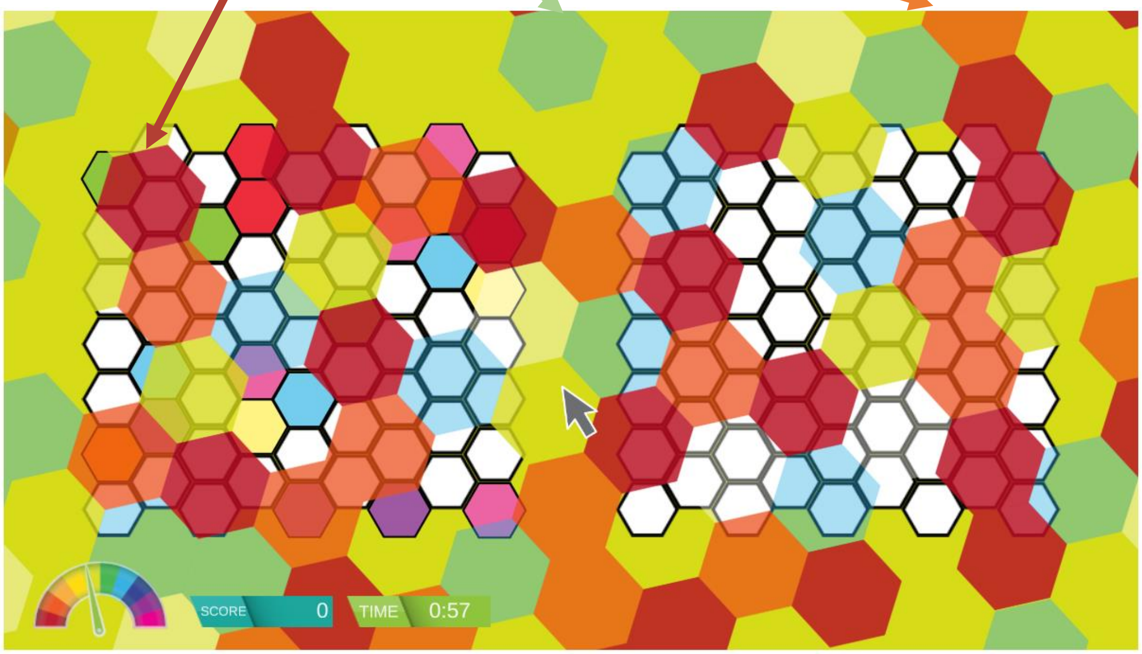
The user must be able to retain the segmented sounds and reorder the syllables to select the correct Pig Latin or English word.

Morocco aka Mosaic:

In this game, the user must move coloured hexagons from a honeycomb pattern on the left side of the screen to a recreate the same pattern on the right side of the screen.

Audio/Visual Selective Attention:

The user must ignore simultaneous auditory distractors (i.e., clicks) and visual distractors (i.e., rotating overlay of hexagons).



Visuospatial Working Memory:

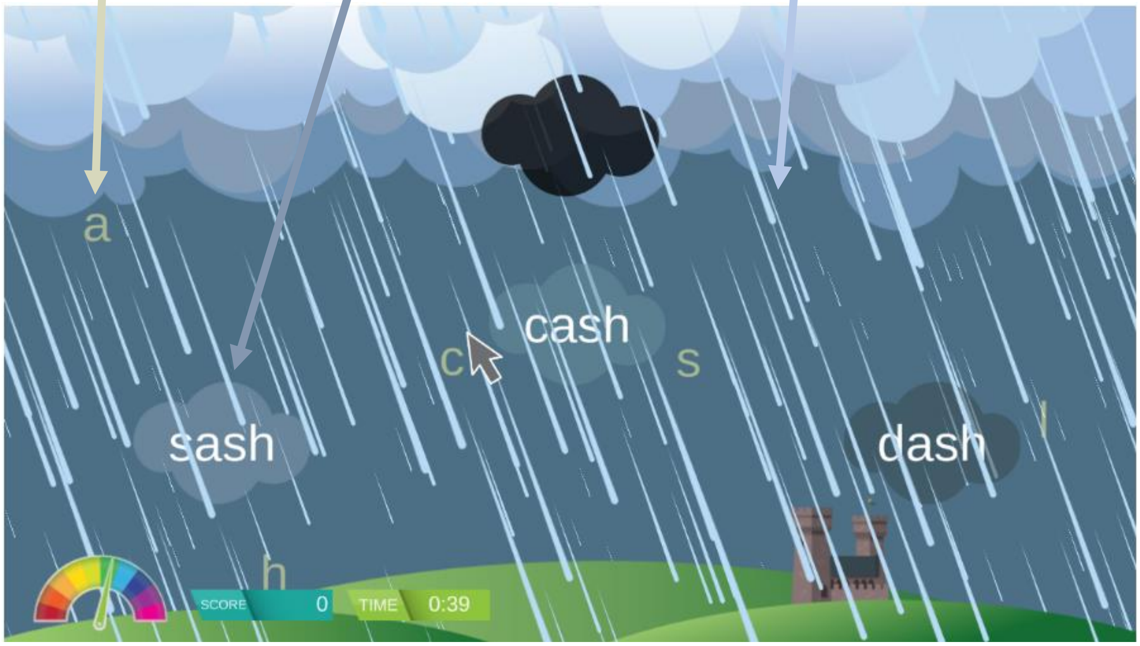
The user must retain the previous positioning of the hexagons in the pattern while recreating it on the other half of the screen.

Scotland (Sunny/Rainy):

In this game, a word is presented verbally, one phoneme at a time, and letters fall like raindrops down the screen. The user must first drag the target word to the blank cloud at the top of the screen. The target word is then verbally repeated, and the user must drag each to spell out the target word.

Audio/Visual Selective Attention:

The user must ignore simultaneous auditory distractors (i.e., rain) and visual distractors (i.e., moving clouds with incorrect responses, raindrops, incorrect falling letters).



Blending / Segmenting / Spelling:

The user must blend the sounds together to select the target word. Then the user must segment the sounds and select the letters which make up the target word as they fall like raindrops. The must correctly order the letters to spell out the word.

Verbal Working Memory:

The user must retain the word while simultaneously segmenting the sounds which make up the word. They must also retain these sounds as they search through the multiple letters that are falling like raindrops across the screen.

Switzerland aka Bees:

In this game, the user must move bees from a honeycomb pattern on the left side of the screen to a recreate the same pattern on the right side of the screen.

Audio/Visual Selective Attention:

The user must ignore simultaneous auditory distractors (i.e., buzzing of bees) and visual distractors (i.e., rotating overlay of hexagons, flapping wings of bees).

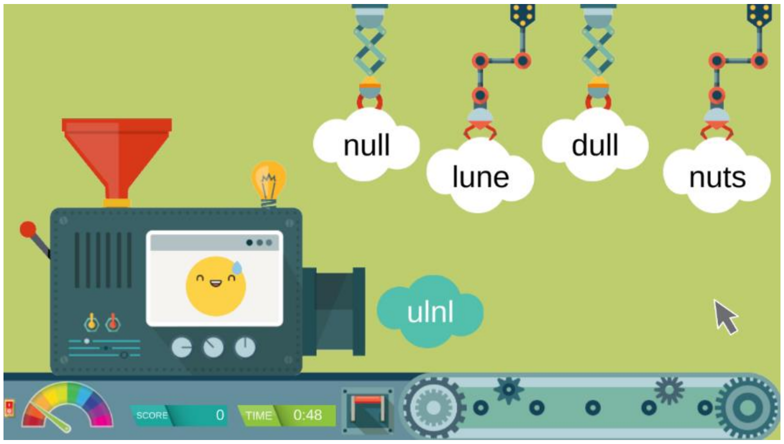
Visuospatial Working Memory:

The user must retain the previous positioning of the bees in the pattern while recreating it on the other half of the screen.

Appendix B: Neuralign© Reading Exercise Games

Silly Machine:

In this game, the Silly Machine eats some letters and spits out a jumbled word. The user must then determine which word it represents and add the unordered letters to the correct word cloud.
Skills targeted: spelling

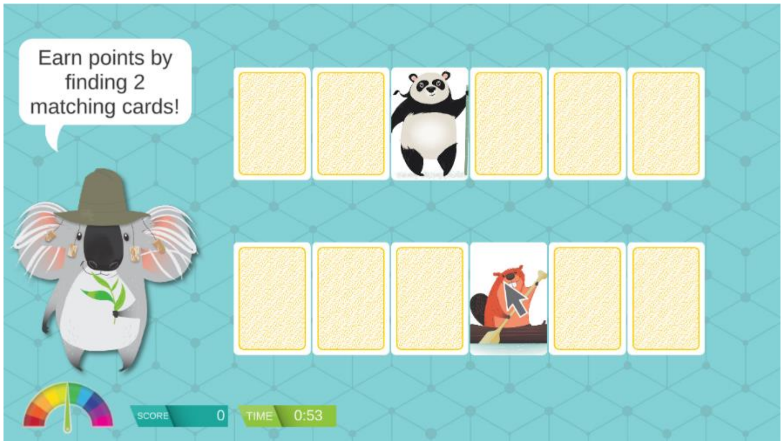


Wordbuilder Holland:

In this game, users must look at the 'core' word and find possible prefixes or suffixes in floating balloons that they could add to the core word to form another word.
Skills targeted: spelling, visual selective attention, working memory

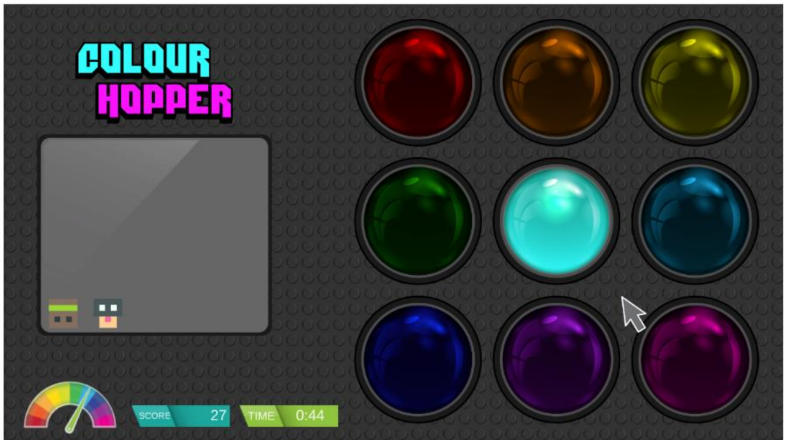
Memory Cards:

In this game, the user must click on cards to find the matching cards. Cards begin facedown, and when the user clicks on a card, it turns faceup. After two cards have been turned over, they get removed from the field if they are a matching pair or turned facedown if they are not. The user must remember the card values and locations to successfully pair them all up and remove them from the playing field.
Skills targeted: visuospatial working memory



Colour Hopper:

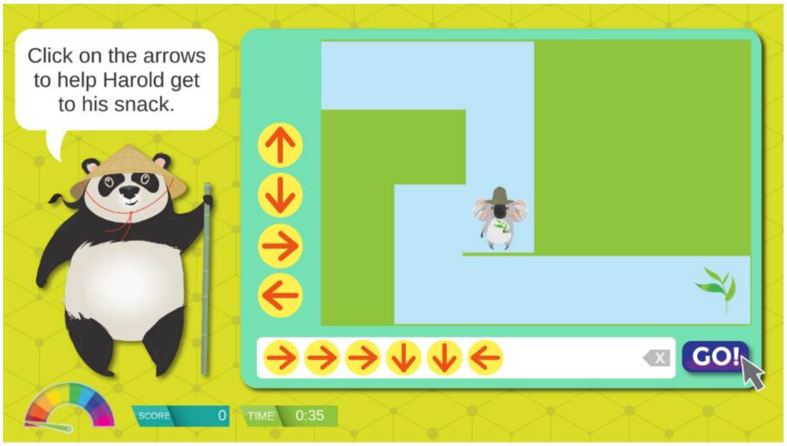
In this game, a light will activate with a sound. The user must then click on the same light. After each successful attempt, the pattern will continue with a new light added. The game begins with one light and goes up to a string of 15 lights.
Skills targeted: visuospatial working memory



Pathfinder:

In this game, the user must click on arrows to help the koala reach the end of the maze. The user must create the pattern of arrows *before* clicking on 'Go'. The arrows (up, down, left, right) must be clicked on individually and represent 1 unit of space. For example, to get to the koala's current position in the maze shown below, the right arrow must be clicked three times, the down arrow must be clicked two times.

Skills targeted: spatial awareness



References

Alt, M., Fox, A., Levy, R., Hogan, T. P., Cowan, N., & Gray, S. (2022). Phonological working memory and central executive function differ in children with typical development and dyslexia. *Dyslexia*, *28*(1), 20–39. https://doi.org/10.1002/dys.1699

American Psychiatric Association. (2013). *Diagnostic and Statistical Manual of Mental Disorders*. American Psychiatric Association. https://doi.org/10.1176/appi.books.9780890425596

Baddeley, A. (2003). Working memory and language: An overview. *Journal of Communication Disorders*, *36*(3), 189–208. https://doi.org/10.1016/S0021-9924(03)00019-4

Borella, E., Carretti, B., & Pelegrina, S. (2010). The Specific Role of Inhibition in Reading Comprehension in Good and Poor Comprehenders. *Journal of Learning Disabilities*, *43*(6), 541–552. https://doi.org/10.1177/0022219410371676

Cartwright, K. B. (2007). The Contribution of Graphophonological-Semantic Flexibility to Reading Comprehension in College Students: Implications for a Less Simple View of Reading. *Journal of Literacy Research*, *39*(2), 173–193. https://doi.org/10.1080/10862960701331902

Castles, A., Rastle, K., & Nation, K. (2018). Ending the reading wars: Reading acquisition from novice to expert. *Psychological Science in the Public Interest, 19*(1), 5–51. https://doi.org/10.1177/1529100618772271

Christopher, M. E., Miyake, A., Keenan, J. M., Pennington, B., Defries, J. C., Wadsworth, S. J., Willcutt, E., & Olson, R. K. (2012). Predicting word reading and comprehension with executive function and speed measures across development: A latent variable analysis. *Journal of Experimental Psychology: General*, *141*(3), 470–488. https://doi.org/10.1037/a0027375

Ehri, L. C. (2000). Learning to read and learning to spell: Two sides of a coin. Topics in language disorders, 20(3), 19-36.

Filderman, M. J., Austin, C. R., Boucher, A. N., O'Donnell, K., & Swanson, E. A. (2022). A meta-analysis of the effects of reading comprehension interventions on the reading comprehension outcomes of struggling readers in third through 12th grades. Exceptional Children, 88(2), 163-184. https://doi.org/10.1177/00144029211050860

Galuschka, K., Ise, E., Krick, K., & Schulte-Körne, G. (2014). Effectiveness of treatment approaches for children and adolescents with reading disabilities: A meta-analysis of randomized controlled trials. *PLoS ONE*, *9*(2). https://doi.org/10.1371/journal.pone.0089900

Gernsbacher, M. A., & Faust, M. E. (1991). The Mechanism of Suppression: A Component of General Comprehension Skill. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *17*(2), 245–262.

Gori, S., Seitz, A. R., Ronconi, L., Franceschini, S., & Facoetti, A. (2016). Multiple causal links between magnocellular–dorsal pathway deficit and developmental dyslexia. *Cerebral Cortex, 26*(11), 4356-4369. https://doi.org/10.1093/cercor/bhv206

Gough, P. B., & Tunmer, W. E. (1986). Decoding, Reading, and Reading Disability. *Remedial and Special Education*, *7*(1), 6–10.

Guthrie, J. T., Wigfield, A., Metsala, J. L., & Cox, K. E. (1999). Motivational and Cognitive Predictors of Text Comprehension and Reading Amount. In *SCIENTIFIC STUDIES OF READING* (Vol. 3, Issue 3).

Hudson, R. F., Lane, H. B., & Pullen, P. C. (2005). Reading fluency assessment and instruction: What, why, and how? *The Reading Teacher*, *58*(8), 702–714. https://doi.org/10.1598/RT.58.8.1

Hudson, R. F., Pullen, P. C., Lane, H. B., & Torgesen, J. K. (2008). The complex nature of reading fluency: A multidimensional view. *Reading & Writing Quarterly, 25*(1), 4-32. https://doi.org/10.1080/10573560802491208

Hudson, A., Koh, P. W., Moore, K. A., & Binks-Cantrell, E. (2020). Fluency interventions for elementary students with reading difficulties: A synthesis of research from 2000–2019. *Education Sciences, 10*(3), 52. https://doi.org/10.3390/educsci10030052

Hulme, C., & Snowling, M. J. (2013). Learning to Read: What We Know and What We Need to Understand Better. *Child Development Perspectives*, *7*(1), 1–5. https://doi.org/10.1111/cdep.12005

Hutzler, F., Kronbichler, M., Jacobs, A. M., & Wimmer, H. (2006). Perhaps correlational but not causal: No effect of dyslexic readers' magnocellular system on their eye movements during reading. *Neuropsychologia, 44*(4), 637-648. https://doi.org/10.1016/j.neuropsychologia.2005.06.006

Katz, B., Shah, P., & Meyer, D. E. (2018). How to play 20 questions with nature and lose: Reflections on 100 years of brain-training research. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(40), 9897–9904. https://doi.org/10.1073/pnas.1617102114

Konza, D. (2011). Phonological awareness. *Research into Practice*, *1*(1), 1–6.

Lawton, T. (2016). Improving dorsal stream function in dyslexics by training figure/ground motion discrimination improves attention, reading fluency, and working memory. *Frontiers in human neuroscience, 10*, 397. https://doi.org/10.3389/fnhum.2016.00397

Lawton, T., & Shelley-Tremblay, J. (2017). Training on movement figure-ground discrimination remediates low-level visual timing deficits in the dorsal stream, improving high-level cognitive functioning, including attention, reading fluency, and working memory. *Frontiers in Human Neuroscience, 11*, 236. https://doi.org/10.3389/fnhum.2017.00236

Macdonald, K. T., Cirino, P. T., Miciak, J., & Grills, A. E. (2021). The Role of Reading Anxiety among Struggling Readers in Fourth and Fifth Grade. *Reading and Writing Quarterly*, *37*(4), 382–394. https://doi.org/10.1080/10573569.2021.1874580

Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology*, *49*(2), 270–291. https://doi.org/10.1037/a0028228

Melby-Lervåg, M., Lyster, S.-A. H., & Hulme, C. (2012). Phonological Skills and Their Role in Learning to Read: A Meta-Analytic Review. *Psychological Bulletin*, *138*(2), 322–352. https://doi.org/10.1037/a0026744.supp

Melby-Lervåg, M., Redick, T. S., & Hulme, C. (2016). Working Memory Training Does Not Improve Performance on Measures of Intelligence or Other Measures of "Far Transfer": Evidence From a Meta-Analytic Review. *Perspectives on Psychological Science*, *11*(4), 512–534. https://doi.org/10.1177/1745691616635612

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science*, *21*(1), 8–14. https://doi.org/10.1177/0963721411429458

Moats, L. C. (2005). How spelling supports reading. American Educator, 6(12-22), 42.

Moll, K., Ramus, F., Bartling, J., Bruder, J., Kunze, S., Neuhoff, N., ... & Landerl, K. (2014). Cognitive mechanisms underlying reading and spelling development in five European orthographies. Learning and instruction, 29, 65-77. https://doi.org/10.1016/j.learninstruc.2013.09.003

Moll, K., Snowling, M. J., & Hulme, C. (2020). Introduction to the Special Issue "Comorbidities between Reading Disorders and Other Developmental Disorders." *Scientific Studies of Reading*, *24*(1), 1–6. https://doi.org/10.1080/10888438.2019.1702045

Olulade, O. A., Napoliello, E. M., & Eden, G. F. (2013). Abnormal visual motion processing is not a cause of dyslexia. *Neuron, 79*(1), 180-190. https://doi.org/10.1016/j.neuron.2013.05.002

Park, A. T., & Mackey, A. P. (2022). Do Younger Children Benefit More From Cognitive and Academic Interventions? How Training Studies Can Provide Insights Into Developmental Changes in Plasticity. *Mind, Brain, and Education*, *16*(1), 24–35. https://doi.org/10.1111/mbe.12304

Pasqualotto, A., & Venuti, P. (2020). A Multifactorial Model of Dyslexia: Evidence from Executive Functions and Phonological-based Treatments. *Learning Disabilities Research & Practice*, *35*(3), 150–164. https://doi.org/10.1111/ldrp.12228

Peijnenborgh, J. C. A. W., Hurks, P. M., Aldenkamp, A. P., Vles, J. S. H., & Hendriksen, J. G. M. (2016). Efficacy of working memory training in children and adolescents with learning disabilities: A review study and meta-analysis. *Neuropsychological Rehabilitation*, *26*(5–6), 645–672. https://doi.org/10.1080/09602011.2015.1026356

Pennington, B. F. (2006). From single to multiple deficit models of developmental disorders. *Cognition*, *101*(2), 385–413. https://doi.org/10.1016/j.cognition.2006.04.008

Perfetti, C. A. (1997). The psycholinguistics of spelling and reading.

Perfetti, C., & Stafura, J. (2014). Word Knowledge in a Theory of Reading Comprehension. *Scientific Studies of Reading*, *18*(1), 22–37. https://doi.org/10.1080/10888438.2013.827687

Peters, L., & Ansari, D. (2019). Are specific learning disorders truly specific, and are they disorders? *Trends in Neuroscience and Education*, *17*(July). https://doi.org/10.1016/j.tine.2019.100115

Pollack, C., Wilmot, D., Centanni, T. M., Halverson, K., Frosch, I., D'Mello, A. M., Romeo, R. R., Imhof, A., Capella, J., Wade, K., al Dahhan, N. Z., Gabrieli, J. D. E., & Christodoulou, J. A. (2021). Anxiety, Motivation, and Competence in Mathematics and Reading for Children With and Without Learning Difficulties. *Frontiers in Psychology*, *12*(October), 1–13. https://doi.org/10.3389/fpsyg.2021.704821

Ramirez, G., Fries, L., Gunderson, E., Schaeffer, M. W., Maloney, E. A., Beilock, S. L., & Levine, S. C. (2019). Reading Anxiety: An Early Affective Impediment to Children's Success in Reading. *Journal of Cognition and Development*, *20*(1), 15–34. https://doi.org/10.1080/15248372.2018.1526175

Rayner, K., Foorman, B. R., Perfetti, C. A., Pesetsky, D., & Seidenberg, M. S. (2001). How psychological science informs the teaching of reading. *Psychological Science in the Public Interest*, *2*(2), 31–74. https://doi.org/10.1111/1529-1006.00004

Samuels, S. J. (1979). The method of repeated readings. *The reading teacher, 32*(4), 403-408. https://www.jstor.org/stable/20194790

Sala, G., & Gobet, F. (2017). Working memory training in typically developing children : A meta-analysis of the available evidence . *Developmental Psychology*, *53*(4), 671–685. https://doi.org/10.1037/dev0000265

Sala, G., & Gobet, F. (2020). Working memory training in typically developing children: A multilevel meta-analysis. *Psychonomic Bulletin and Review*, *27*(3), 423–434. https://doi.org/10.3758/s13423-019-01681-y

Schreiber, P. A. (1980). On the acquisition of reading fluency. *Journal of Reading Behavior*, *12*(3), 177–186. https://doi.org/10.1080/10862968009547369

Seigneuric, A., & Ehrlich, M. F. (2005). Contribution of working memory capacity to children's reading comprehension: A longitudinal investigation. *Reading and Writing*, *18*(7–9), 617–656. https://doi.org/10.1007/s11145-005-2038-0

Snowling, M. J., Hulme, C., & Nation, K. (2020). Defining and understanding dyslexia: past, present and future. *Oxford Review of Education*, *46*(4), 501–513. https://doi.org/10.1037/dev0000265

Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia, 7*(1), 12-36. https://doi.org/10.1002/dys.186

Stein, J. (2019). The current status of the magnocellular theory of developmental dyslexia. *Neuropsychologia, 130*, 66-77. https://doi.org/10.1016/j.neuropsychologia.2018.03.022

Stevens, E. A., Walker, M. A., & Vaughn, S. (2017). The Effects of Reading Fluency Interventions on the Reading Fluency and Reading Comprehension Performance of Elementary Students With Learning Disabilities: A Synthesis of the Research from 2001 to 2014. *Journal of Learning Disabilities*, *50*(5), 576–590. https://doi.org/10.1177/0022219416638028

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades?. Journal of child psychology and psychiatry, 45(1), 2-40. https://doi.org/10.1046/j.0021-9630.2003.00305.x

Wexler, J., Vaughn, S., Edmonds, M., & Reutebuch, C. K. (2008). A synthesis of fluency interventions for secondary struggling readers. *Reading and Writing*, *21*(4), 317–347. https://doi.org/10.1007/s11145-007-9085-7

Zimmermann, L. M., Reed, D. K., & Aloe, A. M. (2021). A Meta-Analysis of Non-Repetitive Reading Fluency Interventions for Students With Reading Difficulties. In *Remedial and Special Education* (Vol. 42, Issue 2, pp. 78–93). SAGE Publications Inc. https://doi.org/10.1177/0741932519855058