A New Approach to Cognitive Metrics: Analysing the Visual Mechanics of Comprehension using Eye-Tracking Data in Student Completion of High-Stakes Testing Evaluation

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1 Context

Reading is arguably the most critical skill for life success. Australia, like other Anglophone nations, has high proportions of children and adults with serious literacy weakness. It is common for up to 30% of students at primary and secondary school to be experiencing significant reading weakness (Knight and Galletly 2011; Masters 2009; National Assessment Program Literacy and Numeracy (NAPLAN) 2010; Program for International Student Assessment (PISA) 2007, 2009).

In addition, almost half of all Australians over the age of 15 have literacy skills below a minimum level needed to manage the literacy requirements of a modern society (Australian Bureau of Statistics 2008).

Australian teachers are increasingly being held to account for their students' literacy and numeracy progress through the NAPLAN. To improve their students' literacy performance, teachers, schools, and educational systems have devised specific literacy teaching strategies and focussed these strategies toward improving NAPLAN scores. However, current strategies have not been informed by research about the interactive visual and cognitive mechanics and the processes of comprehension that students actively use as they complete the literacy comprehension component of the NAPLAN tests. The research presented here uses a new methodology that focusses on the visual and cognitive mechanisms used by students when responding to comprehension tasks that require interpretive and critical level responses. This new research has the capacity to underpin comprehension strategies for teacher use.

"It [comprehension] remains the key longitudinal and developmental goal of all school reading instruction" (Luke et al. 2011, p. 151). The research revolves around capacity building for teachers with a very clear purpose of relevance for

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students with literacy difficulties. Currently, there is insufficient knowledge of how the skills and processes that students use to comprehend language interact. To better understand the precise and deliberate role of students' eye movements and emotions interacting with cognitive and metacognitive strategies in the processes involved in reading comprehension, the research will provide timely, reliable, and valid knowledge on the interaction of students' skills and processes required for successful comprehension. The outcomes will facilitate teachers and policy makers to plan and allocate resources to effectively assist students in achieving literacy outcomes.

2 Reading Comprehension

Reading comprehension is a complex cognitive process that engages both early literacy skills (including accurate word recognition, fluent access to word meaning, recognition of syntactic cues to sentence meaning) and sophisticated literacy (automatic and self-regulating) level processing of information (Knight and Galletly 2011). Sinatra and Pintrich (2003) describe the change that occurs as the "goal-directed and conscious initiation and regulation of cognitive, metacognitive, and motivational processes to bring about a change in knowledge" (p. 6). The reader makes inferences and creates connections between the text and the real world of their situated social and cultural practice so as to construct a mental representation and generate meaning from the ideas presented in the text (Kintsch 1998; Knight and Galletly 2011; Luke et al. 2011; McNamara and Magliano 2009; Snow 2010). During such cognitively demanding tasks, other factors that need to be considered in any analysis include the role of reader emotions, the nature of the task being undertaken and their motivation for completing the task.

Reading, thus, involves deciphering, comprehending and evaluating written texts to engage with the message it communicates. Gough and Tunmer's (1986) Component Model of Reading proposes that reading comprehension starts from two essentials which follow developmental patterns of attainment: Reading Accuracy (the recognition or pronunciation of the spoken words corresponding to written words including decoding and word recognition) and Language Comprehension, which comprises thinking and reasoning skills as well as vocabulary and literal and inferential comprehension.

The Component Model of Reading supports research evidence as to the nature and operation of cognitive and linguistic processes in reading and is embedded within the sociocultural milieu that typifies readers' lives. It acknowledges that research has shown that the fundamentals of word recognition processes and of language comprehension processes are different.

Although the Component Model of Reading describes the elements of reading comprehension, it does not consider how the processes operate and interact when students formatively appraise a text during comprehension. To consider how the processes interrelate, we focus on the Construction–Integration (CI) Model (Kintsch 1998) of comprehension.

The CI Model (Kintsch 1998) argues that discourse comprehension consists of a construction phase (a propositional network is constructed) and an integration phase where the network is integrated into the reader's memory to make inferences (propositions) that promote understanding. The CI Model assumes that multiple levels of memory representations (surface code using decoding and syntax cues, proposition base, and mental models to integrate information) are generated as part of the comprehension process (Graesser 2007). As inferences can be tracked through eye-tracking data where gaze patterns illustrate the processes used by readers to comprehend text and answer questions, this research will investigate the mechanics of the processes involved in reading comprehension.

3 Eye Movements During Reading

The fovea is the only part of the retina that is useful for reading, with visual accuracy being most favourable at the centre and decreasing toward the edge (Rayner 2009). The eyes move in small steps (saccades), with the perceptual abilities of the eyes dependent on the number of letters in a word. As gaze advances by only approximately seven to nine letters (Rayner 1998), individuals consciously process only a very small subset of the visual inputs. The eyes shift around with the outcome that "reading is nothing but the word-by-word mental restitution of a text through a series of snapshots" (Dehaene 2009, p. 17). Dehaene proposes the brain does not stop at a single-letter level but rather the visual system automatically regroups letters into higher-level graphemes, which are in turn automatically regrouped into syllables and whole words, suggesting that multiple levels of analysis coexist as meaningful reading and comprehension occurs.

Eye-tracking methodologies enable researchers to track a reader's eye movements, as well as their fixations as a text is read (Rayner 1998). Saccadic movements between sentences and fixation times provide insights into comprehension activity. Where a reader directs their attention is revealed by saccadic movements, how much attention is allocated is revealed by fixations, while regressions can indicate comprehension difficulties (Mikkila-Erdmann et al. 2008).

4 Eye-Tracker Literature

Reading then is a complicated process during which readers must control their eye movements to accommodate incoming printed information. Research has established that an interaction occurs between the text and the reader (Kintish 1988) and that language factors such as word frequency, text difficulty and the reader's background knowledge influence eye-movement patterns during reading (Rayner 2009). When reading complex English orthography (the range and irregularity of the spelling patterns used in English words), most students in English-speaking countries take several years to become proficient readers, and at least 6 years to reach adult

proficiency, in comparison to readers from other countries which have a transparent orthography (Aro 2004; Knight and Galletly 2011).

Decades of reading studies using eye-tracking methodologies have focussed on experimental research. The narrow dimension of this research has led to an emphasis on the micro-aspects of reading individual words and phrases. Research on eye-movement control has reported that readers of alphabetic writing systems tend to fixate longer when a word appears less frequently (White 2008); with readers' eye movements also affected by word type (Carpenter and Just 1983); and word predictability (Frisson et al. 2005). Fixation time on a word can also be influenced by variables such as phonological properties (Ashby 2006) and word familiarity (Williams and Morris 2004).

As students gain reading accuracy skills and become proficient readers, their eye-movement behaviours undergo substantial changes. McConkie et al. (1991), for example, reported that the average fixation duration decreased from first grade to fifth grade, whilst the mean saccade length increased over the same period. It has also been reported that the number of fixations per word decreases continuously as well as a reduction in regression rates and an increase of word skipping as reading skills improve (Kaakinen et al. 2003).

Most studies have focussed on individual aspects of the reading components, rather than how students coordinate the mechanics to creating meaning. Some recent research has established that how much is processed during reading varies as a function of the skills of the reader, the difficulty of the text, and the purpose of the task (Rayner 2009). For example, the amount of preview benefit readers obtain (leading to fluency and comprehension) whilst engaged in the reading process varies as a function of the difficulty of the fixated word. If the fixated word is difficult to process, readers get little or no preview benefit from the word to the right of fixation (White et al. 2005). Most competition between words is solved automatically and unconsciously by skilled readers, while in some cases only the context permits understanding and/or pronunciation.

5 Methodology

The research explored skilled and weak readers' eye-movement patterns as they completed NAPLAN reading passages and answered comprehension questions that all students in Australian schools complete a number of times during their school life.

5.1 Aims

The research was designed to map the eye-movement behaviour of students, with data on the following variables being analysed:

1. What is happening when reading the text
2. Rereading habits

3. What students read first
4. Structure of reading scan
5. Collect data on students' emotions as they complete the tasks

5.2 Sample

Fifteen students in year 7 (aged 12–13) from a regional primary school in Queensland were involved in the study. Seven students were regarded as skilled readers (top achievement band) and eight were weak readers (bottom achievement band) based on their scores in the Australian NAPLAN test completed 2 years earlier. School tests and current teacher ratings supported the grouping of students into the skilled and weak reader categories.

5.3 Instrument

The NAPLAN tests assess skills in literacy and numeracy developed over time through the school curriculum. Knowledge and interpretation of language conventions in context are drawn upon in many reading comprehension questions. NAPLAN can involve students making decisions under complex, ambiguous constraints where the text presents a high load of information which needs to be continually processed and filtered. In year 7, reading texts usually includes a wide range of genres that may use scientific vocabulary and varied sentence structures requiring readers to understand the meaning of words as well as interpret the intention of a narrator, the motivation of a character, and an author's viewpoint.

The NAPLAN comprehension questions are designed such that students are required to use inferential and critical analysis skills to successfully complete the questions. In the experimental situation, students were provided with an online magazine test format that contained a range of texts that illustrated different writing styles. Students read the texts provided and then chose an answer from comprehension questions, which contained four alternative responses.

5.4 Apparatus

Eye movements are directly observable. Previously, the structure of experimental studies, together with unsophisticated eye tracker technology, has precluded studying the interactivity between eye movement and information processing patterns.

Sophisticated eye tracking is particularly useful to this study as it can provide direct, online, sensitive, and non-invasive indexes of processing. User experience (UX) research methodologies generate ways of collecting student strategy data using Tobii eye tracker hardware and software, with the allocations of gaze during an activity monitored and quantified. Saccades and fixations during the task provide information about the interactive processes occurring during the task.

6 Results

Early results show that skilled readers had increased reading times in comparison to weak readers. Early data report that skilled readers scanned continuously and consistently from the comprehension questions to the text, suggesting that when skilled readers come to what they believe to be a critical part of a text that aligns with answering comprehension questions, they return to previous sections of the text in an attempt to resolve any ambiguity that may have arisen from the text.

Figure 1 displays heat maps produced for a skilled and a weak reader on one of the tasks. In the heat map of the skilled reader, the map shows that the student has scanned the whole text on cockroaches (with paragraph 3 being the most intense) and also shows comprehensive reading of the comprehension questions. This student's reading behaviours included comprehensive scanning of the whole text to begin with and an alignment between comprehension questions and sections of the text. The most concentrated attention displayed in the heat map is looking at the alternative responses to answer the comprehension questions.

In contrast, the heat map of the weak reader as displayed in Fig. 1 is quite different. Neither the whole passage nor all of the alternative responses to the comprehension questions have been read. Most intensity is focussed on the early paragraphs and alternative responses in the comprehension questions. The reading behaviour of the individual suggested that the reading level was too difficult and the student "gave up". Other reading behaviours of the student included only linear reading left to right and top to bottom, no scanning of the whole text, and a focus on individual words.

7 Discussion

The early results have been used to develop an appreciation of the interactive processes of how learners "prime" text elements to gain an understanding of text and answer comprehension questions. These preliminary investigations of skilled and weak readers have been used to formulate a model which attempts to understand the mechanics used by students to comprehend text.

7.1 Mechanics of Reading

From our initial early research, we have conceptualised a framework for understanding how students interrogate text by measuring the components that represent the mechanics of reading comprehension. Underpinning the model are theories of the Component Model of Reading and the construction/integration model of comprehension discussed earlier.

Fig. 1 Heat maps of a skilled and weak reader

Fig. 2 Mechanics of reading

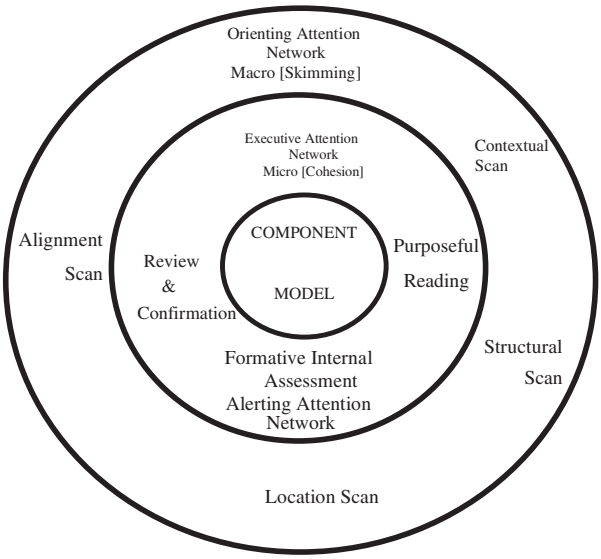

Figure 2 represents a diagrammatic representation that aims to scope reading comprehension by using a number of constructs that constitute comprehension processes needed for interpretive, critical, and creative levels of comprehension. Attention network theory (Posner and Petersen 1990) offered a theoretical framework to clarify the attentional processes that occur during a task. Posner and Petersen propose that there are three specific functionally and anatomically distinct attentional networks that learners use, and we have integrated them into the model by hypothesizing that readers' cognitive processes operate in the attention networks which act as mechanisms to comprehend text. Firstly, at the macro-level, an orienting attention network (Posner and Peterson 1990) operates when readers orient to the task by using structural scanning (headings and illustrations), location scanning (entire page and questions), and alignment scanning (interaction of questions and text that is operationalised by an individual in different texts and different formats). At the executive attention network level (Posner and Peterson 1990), micro-level mechanics are used by readers to decipher the text and guide purposeful reading. As this transpires, readers also actively coordinate comprehension questions and distracters by scanning (and re-scanning) and reading (and rereading) searching for alignment and confirmation of responses to the text. Posner and Peterson (1990) categorise this practice as functioning in an alerting attention network.

8 Conclusion

This research has demonstrated the usefulness of eye-tracking methodology in focussing on the visual and cognitive mechanisms used by students when responding to comprehension tasks. The results have been informally shared with practitioners

who have supported the findings as relating to some existing teaching strategies and practices aimed at improving students' comprehension skills.

The model emerging from the research appears to provide early, reliable, and valid knowledge on the interaction of students' skills and processes required for successful comprehension. We acknowledge that more work is needed to enhance and refine the model and look forward to a large-scale study to test students' reading behaviours as they respond to comprehension tasks. It is anticipated that the outcomes will enable teachers and policy makers to plan and allocate resources to effectively assist students in achieving literacy outcomes.

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