

Reading Time as Evidence for Mental Models in Understanding Physics

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Abstract. We present results of a reading study that show the usefulness of probing physics students' cognitive processing by measuring reading time. According to contemporary discourse theory, when people read a text, a network of associated inferences is activated to create a mental model. If the reader encounters an idea in the text that conflicts with existing knowledge, the construction of a coherent mental model is disrupted and reading times are prolonged, as measured using a simple self-paced reading paradigm. We used this effect to study how “non-Newtonian” and “Newtonian” students create mental models of conceptual systems in physics as they read texts related to the ideas of Newton's third law, energy, and momentum. We found significant effects of prior knowledge state on patterns of reading time, suggesting that students attempt to actively integrate physics texts with their existing knowledge.

Keywords: physics education research, reading, situation model, misconceptions, recruitment of prior knowledge

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INTRODUCTION

Remembering what we read is strongly influenced by a) our prior knowledge [1], and b) attentional allocation to construct a coherent representation [2]. Science students often fail to learn from reading a text that contradicts their ideas [3]. This may be because they do not allocate attention to resolve these contradictions. Supporting this idea, there is evidence that students with preconceptions learn better from refutational texts that explicitly acknowledge and then refute those preconceptions [4]. It is generally believed that the way in which a text is processed online (i.e., during reading) will affect what is remembered offline (after reading) [5]. However, we know of only one study [6] that has examined students' online and offline processing of a physics text in a single study. Surprisingly, this study showed a) no difference in online processing between groups of physics students who had different (pre-identified) knowledge states, and b) clear evidence of recruitment of prior knowledge in offline processing, even when the text that had just been read contradicted that prior knowledge.

In the constructivist view, students activate (or “recruit”) prior knowledge to interpret their experiences. According to the construction-integration model [7, 8], students learning from text attempt to construct a *situation model*, which is a mental representation of the text, integrating ideas given directly by the text with knowledge-based inferences. For example, if you read the sentence, “all the buildings collapsed except for the mint,” you might generate the inference “earthquake.” “Earthquake” then becomes part of your mental model

of the situation. In this view, inferences are activated promiscuously as part of a neural network. The network then uses the available information to cycle through a series of iterations and relaxes into a final state where a smaller subset of inferences deemed appropriate to the situation remain activated. What remains activated in the network is dependent on the knowledge base of the reader and the contents of the text that is being read.

Research in narrative understanding has shown that when readers encounter statements that conflict with their situation model, they will take longer to read these statements [9]. For example, readers slow down when information (e.g., Mary orders a hamburger) is introduced into the text that is inconsistent with the situation model introduced earlier in the text (e.g., Mary is a vegetarian) — even if these facts are spatially distant in the text. Thus reading time can be a sensitive probe of a) whether a reader has constructed a situation model, and b) the nature of the situation model that has been constructed. So it is perhaps surprising that an earlier attempt to demonstrate this effect in science learning was unsuccessful.

Our general research questions related to learning in physics are: In light of the null result of [6], do students' prior knowledge states have any noticeable effect on their processing of a physics text when they read it? In other words, if students recruit ideas that conflict with the text that they are reading, do they exhibit prolonged reading time? Additionally, can we use differences in reading time to understand something about the nature of the meaning that students construct? Finally we wish to explore the connections between students' online and offline processing.

METHOD

Participants

We recruited roughly 150 educational psychology undergraduate students from a large Midwestern university for a reading study. Approximately half of this group were eliminated because they did not meet the prior knowledge criteria for participation in phase 2 of our study. The remaining 75 students were invited to participate in phase 2 and 30 students from this group chose to participate. The “misconception” group consisted of 16 students (henceforward designated “non-Newtonian”), while the “non-misconception” group consisted of 14 students (henceforward designated “Newtonian”). Students were assigned to each group based on criteria described in the procedures section below. Newtonian and non-Newtonian subjects did not differ on WAIS vocabulary measures [10] $F(1,26) < 1$.

Materials and Procedures

The experiment was divided into two phases. In the screening phase (phase 1) the 150 participants were divided into three groups based on their answers to four Newton’s third law questions from the FCI [11]: Those who could answer all four Newton’s third law questions correctly (Newtonian), those students who consistently answered that the bigger or faster moving object exerted more force and/or passive or stationary objects don’t exert forces (non-Newtonian), and those students who gave a mixed response of correct and incorrect answers to the four Newton’s third law questions.

Subjects who were identified as Newtonian or non-Newtonian in phase 1 (about 75 students) were invited by email to participate in phase 2. Thirty students responded and participated in phase 2. In the reading phase of this study (phase 2), subjects were asked to read (on a computer screen) a collection of 29 passages (four segments each) that accurately described different physical situations involving interactions between two equal or unequal sized objects. (See Table 1 for examples.) Subjects were told in the instructions that all passages they were about to read were true. The passages were read segment by segment, self-paced by the reader, who advanced to the next segment by hitting the space bar. As subjects advanced, the previous segment disappeared. Reading time for each segment was recorded by the computer. The last segment of each passage was designated as the “target” segment. These segments were designed to either agree with or conflict with each subject’s prior knowledge. Subjects’ reading times on the target segments were used in our analysis. After each passage, subjects were asked

to rate their understanding of the ideas in the passage on a 1–5 scale. We refer to this as a “judgment of learning,” or JOL. Immediately after subjects had read all 29 passages they were asked to answer a 16-question true/false quiz about a new set of scenarios probing understanding of Newton’s third law.

In the passages, the relative size of the two interacting objects was either equal, e.g., “two equal mass sumo wrestlers,” or different, e.g., “a bowling ball collides with a bowling pin.” All scenarios involved either a collision happening or about to happen, or a situation where the two objects were pushing against each other for an extended period of time. The 29 passages included 6 Newton’s third law passages where the two objects were of unequal size, and 3 Newton’s third law passages where the two objects were of equal size. In addition to the 9 Newton’s third law passages, subjects were given 8 energy passages and 8 momentum passages as well as 4 Newton’s second law passages. The energy and momentum passages served both to test certain factors involved in processing of the text and as distracters. The energy and momentum sentences were deliberately chosen to be intuitively obvious to the non-Newtonians and therefore some passages may appear vague to a physics expert. The Newton’s second law passages served only as distracters and were not included in any analysis.

Subjects were randomly assigned to one of two conditions; a refutational condition, or a non-refutational condition. Examples of the refutational and non-refutational modes may be found in Table 1. Energy, momentum and Newton’s second law passages did not have a refutational mode. Thus all subjects read the same energy, momentum, and Newton’s second law distracters.

Hypotheses and Predictions

1. If students recruit prior knowledge and construct a situation model when they read a physics text:
 - (a) Non-Newtonian students should read N3uneq target segments significantly slower than Newtonian students.
 - (b) Non-Newtonian students should read N3uneq target segments significantly slower than they read N3eq segments.
 - (c) Newtonian students should read N3uneq and N3eq target segments without any significant difference in time.
2. We hypothesize that there is a linguistic element to students’ models of the idea of force. Namely, non-Newtonian students see force, energy and momentum as properties of motion of an object and roughly equivalent in meaning [12]. In the situation model view, when asked to compare which object

TABLE 1. Reading passages examples. // Denotes each new segment in the reading sequence. The target segments, which were used in our analysis, are indicated in bold.

Description	Example(s)
Newton's third law, unequal sized objects (N3uneq)	(Non-refutational mode): A mosquito is flying towards a bus that is coming the other way. // When the mosquito collides with the bus, // compare the force that the mosquito exerts on the bus with the force that the bus exerts on the mosquito. // Physics says the mosquito and the bus exert equal forces on each other. (Refutational mode): A mosquito is flying towards a bus that is coming the other way. // Some people think that when the mosquito collides with the bus, // the force that the mosquito exerts on the bus is less than the force that the bus exerts on the mosquito. // However, the mosquito and the bus exert equal forces on each other.
Newton's third law, equal sized objects (N3eq)	Two equally heavy sumo wrestlers are trying to push each other out of the ring. // The two remain locked in battle in the middle, not moving at all. // Consider how much force each sumo wrestler exerts on the other. // It is true that each wrestler exerts the same amount of force on the other.
Energy	A stunt man plans to smash through a wall with his monster truck. // As the truck roars towards the wall, // consider the energy of the truck compared to the energy of the wall. // The energy of the truck is a good deal more than the energy of the wall.
Momentum	With a hammer, you are hitting a nail into a piece of wood. // Just before the hammer connects with the nail, // think about the momentum of the hammer compared to the momentum of the nail. // The hammer has much more momentum as compared to the momentum of the nail.
Newton's second law (N2)	A 200-pound sumo wrestler is pushing against a 300-pound sumo wrestler. // As the bigger wrestler pushes the smaller wrestler out of the ring, // consider how much force each wrestler exerts on the floor. // The bigger sumo wrestler exerts more force on the floor than the smaller wrestler.

exerts more force, students may generate an inference like “bigger object has more force therefore bigger object exerts more force.” If students see force, energy and momentum as synonymous, students should generate similar inferences about energy and momentum, e.g., “a bigger object has more energy.” We predict that non-Newtonian students will read energy and momentum targets quicker than the N3uneq targets since energy/momentum targets will match their situation model.

3. If there is a simple relationship between online and offline processing:
 - (a) We predict that non-Newtonian students who score higher on the quiz will show more evidence of hesitation on target sentences that contradict their naïve ideas about force.
 - (b) If the refutational mode leads to more learning among non-Newtonians, we should see more hesitation over N3uneq targets in the refutational mode, and correspondingly higher performance on the quiz.

2. Non-Newtonian students read N3uneq targets significantly slower ($\bar{t} = 3.6$ seconds) than N3eq targets ($\bar{t} = 2.4$ seconds): $p < 0.001$, $n = 16$.
3. Newtonians' reading times on the N3uneq ($\bar{t} = 2.3$ s) and N3eq ($\bar{t} = 2.8$ s) targets did not differ significantly, but tended in the opposite direction relative to non-Newtonians, $p = 0.07$, $n = 14$.
4. Non-Newtonian students read N3uneq targets significantly slower ($\bar{t} = 3.6$ seconds) than the equivalent energy ($\bar{t} = 2.6$ seconds) and momentum ($\bar{t} = 2.9$ seconds) targets. $p = 0.0015$ and $p = 0.014$ respectively.
5. Conversely, Newtonians read N3uneq targets significantly faster ($\bar{t} = 2.3$ seconds) than equivalent energy (3.0 seconds) and momentum ($\bar{t} = 3.2$ seconds) targets. $p < 0.01$ and $p < 0.001$ respectively.
6. There was no significant difference between non-Newtonians' and Newtonians' reading of the energy and momentum targets ($p > 0.15$).

Offline and Online Processing

RESULTS AND ANALYSIS

Online Processing

1. Non-Newtonian students read N3uneq targets significantly slower than the Newtonians did: $\bar{t} = 3.6$ seconds versus $\bar{t} = 2.3$ seconds, $p < 0.0001$, two tailed, unequal variance t-test, $n = 30$.

The Newtonians' average score on the true/false quiz was 15.7 out of 16. On the other hand the average score of the non-Newtonians was 8.7, or 4.7 out of 12 if we subtract out four questions where the objects presented were of equal size. (All non-Newtonians answered these four questions correctly.) Here the statistical null hypothesis is that if students randomly guess true or false they should get 6 out of 12. An average score of 4.7 places

this group at $0.1 < p < 0.2$ on a binomial sampling distribution — their responses are not significantly below random guessing.

In the non-Newtonian group:

1. There is no effect of refutation on reading time for N3uneq targets, nor on quiz performance.
2. Although some students showed they were confused by N3uneq targets (from JOL ratings), there was no correlation between JOL and reading time on N3uneq targets. (Pearson $R = 0.229$, $n = 16$, $p = 0.394$ - two-tailed t test).
3. There is no evidence of correlation between reading time on N3uneq targets and performance on the post-reading true/false quiz (Pearson $R = 0.162$, $n = 16$, $p = 0.548$).
4. There is a significant positive correlation (Pearson $R = 0.568$, $n=16$, $p = 0.022$) between non-Newtonian students' JOL on N3uneq passages and performance on the T/F quiz. In other words, students who rated their understanding higher performed better on the quiz.

CONCLUSIONS

In contrast with [6], we found evidence of online processing when students read a physics text. It is clear from the differential reading times that non-Newtonian students and Newtonian students are generating inferences (and therefore recruiting prior knowledge) and forming a situation model. When non-Newtonian students read the N3uneq targets, they hesitate over those target segments that contradict their inferences and read target segments that agree with their inferences (N3eq) significantly faster. Newtonian students appear to be reading target segments that are consistent with their prior-generated inferences (as evidenced by their quicker reading time).

Our prediction that non-Newtonians would read energy and momentum targets faster than N3uneq targets is confirmed by our data. This is consistent with the idea that students with “non-Newtonian” conceptions of force and motion and Newton’s third law have difficulty with the meaning of the term “force,” confusing it with “energy” and “momentum” as properties of an object and/or its motion [12].

Interestingly, Newtonians read the Newton’s third law targets more quickly than comparable targets about energy and momentum. We propose one possible explanation for this result: Situation model theory suggests that, depending on existing knowledge structures, individuals generate inferences as they read so as to create a globally coherent representation of the situation. In this view, students who have relatively rich knowledge sys-

tems about energy and momentum will activate a wider array of inferences when reading about these concepts. For example, a student with sufficient physics knowledge might question “what forms/types of energy are we talking about?” “Momentum is a vector,” “the passage does not tell me which object is moving faster, therefore I’m not sure which object has more momentum.” The greater number of inferences generated means that it will take the neural network longer to relax into a single state, hence the longer reading times amongst the Newtonians.

There is evidence of online processing (differential reading times) but there is no correlation between reading time and quiz performance. Our data clearly show that, at a perceptual level, non-Newtonian students are surprised by statements that contradict their situation model. Further evidence about how ideas in the text are integrated into students’ knowledge is inconclusive, and only suggestive. The correlation between JOL and quiz performance suggests that metacognition may be playing a role. Confusion arising from the text is insufficient for any learning to take place. Students also make conscious decisions to either accept or reject the ideas that they’ve just read, based on possible factors such as their epistemological beliefs, the manner in which they have framed the experimental situation, and so on. In future research we hope to explore the interaction of students’ metacognition with their online and offline processing of the text they are reading.

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