Mapping students' self-reported cognitive load, situational engagement, and attentional-cognitive states in an online multimedia learning module

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This study investigated relationships between online learners' self-reported attentional and cognitive states, cognitive load, situational engagement, and learning gains from a multimedia instructional module on Newton's second law. Students (N=896) estimated time spent in four states: on-screen/on-task, off-screen/on-task, on-screen/off-task (mind wandering), and off-screen/off-task. Most time was spent on-screen/on-task (62.4%). Mind wandering time negatively correlated with engagement, germane load, and learning gains. On-task time positively correlated with engagement and germane load, but off-screen/on-task time unexpectedly negatively related to germane load. Off-task time correlated negatively with engagement/germane load and positively with extraneous load. However, no attentional state significantly predicted learning gains besides mind wandering's negative impact. Self-reports revealed relationships generally aligning with cognitive load theory, though some findings differed from expectations. The results underscore examining attentional-cognitive states' influence on cognitive load, engagement, and multimedia learning outcomes.

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I. INTRODUCTION

Online learning is ubiquitous and will remain so for the foreseeable future. However, a key issue with online learning is gauging and maintaining learners' attention [1–4]. Lack of sustained attention to online learning materials reduces learning [5, 6]. Effective online instruction should maintain learners' attention [7, 8].

Researchers have only begun to operationalize what we mean by "students' attention span," which is related to the more rigorously tested theoretical construct of sustained attention [9]. Further, the interplay between learners' attention and learning is complex. Learners' attentional states are not always aligned with their external gaze, but can instead be oriented internally to either on- or off-task thoughts [10, 11]. Additionally, just because a learner's gaze has left their learning materials, does not mean they are off-task. They could be engaging in behaviors such as note taking or thinking deeply about what they just read, which can be valuable to learning.

D'Mello [12] has shown that a student may be looking at online learning materials on their computer screen, but not thinking about them, because they are mind-wandering [13, 14]. Research has shown that when learners are engaged in a cognitively demanding task, such as watching an online lecture, their attention can decline over time [5]. Specifically, the demand for sustained attention depletes limited cognitive resources [15], such as executive control of attention, which leads to more mind-wandering [16]. That, in turn, squanders working memory resources, increasing extraneous cognitive load, decreasing engagement and reducing learning outcomes. In this study we probed learners' self-reported visual attentional and cognitive states, their levels of cognitive load, and their situational engagement, while they completed an online multimedia instructional module on Newton's second Law. Our goal was to study how these three factors : attentional-cognitive state, cognitive load, and situational engagement are correlated with each other and learning.

II. LITERATURE REVIEW

This work extends prior research on the role of visual attention in problem-solving in PER [17–22]. The underlying assumption in previous work is that visual attention is evidence of cognition. This work, extends our most recent work in which we relax this assumption to measure attentional and cognitive states [23].

D'Mello [12] has created a way of encapsulating a learner's attentional and cognitive states in a 2x2 matrix. In this framework, learners can transition between four attentional states that consider both the overt and covert aspects of attention (Fig. 1). Namely, the learner can either be looking at the online materials (on their computer screen), or looking away from them. Also, the learner can either be thinking about the learning materials (i.e., on-task), or not (i.e., off-task).

In the 2x2 matrix, **Quadrant 1** (Q1) Top Left: The learner is looking at the learning environment (on-screen), while thinking about it (i.e., on-task). **Quadrant 2** (Q2) Top Right: The learner looks away from the learning environment (off-screen), but thinks about it (on-task) such as taking notes or using a calculator to solve a relevant problem. **Quadrant 3** (Q3) Bottom Left: The learner looks at the learning environment (on-screen) but is not thinking about it (off-task), such as mindless reading or mind wandering. **Quadrant 4** (Q4) Bottom Right: The learner is neither looking at the learning environment (off-screen) nor thinking about it (off-task), such attending to their cell phone.

The relationship between visual attention and learning can be mediated by cognitive load. The demand for visual attention can overload a learner's limited working memory capacity impairing learning [24, 25]. The inherent complexity of a to-be-learned concept constitutes its intrinsic cognitive load. Relevant information that is attended to constitutes germane cognitive load, which facilitates learning by allowing learners to create schemas and situational models and encode information into long-term memory [25, 26]. However, attending to irrelevant information increases extraneous cognitive load, which depletes executive attentional control resources. Extraneous cognitive load, in turn, increases mind-wandering, which squanders working memory capacity needed for learning [10, 15] thus impairing learning [25]. In summary, the cognitive load literature [24, 25] emphasizes the importance of guiding learners' attention to relevant information to optimize instructional efficacy. This highlights the challenge for educators that online learners' overt visual behaviors may inadequately reflect the covert fluctuations in their cognitive engagement [27, 28].

Another factor that affects visual attention and learning is situational engagement. Higher situational engagement is associated with increased visual attention and better learning outcomes [29]. Lower situational engagement is linked to more frequent and prolonged periods of mind-wandering [13, 14, 29, 30]. When situational engagement wanes, learners have increased response times and make more mistakes, suggesting impaired comprehension [5]. However, as was mentioned above, the relationship between overt visual behaviors and covert attentional states is complex. Learners can mind-wander while still looking at the learning materials, such as during "mindless reading" [13, 28]. Conversely, looking away briefly, such as when taking notes, does not necessarily indicate disengagement [27].

Given our 2x2 attentional-cognitive state matrix [12], and literature on mind wandering, cognitive load, and situational engagement, we pose these research questions: RQ1) What is the self-reported proportion of time online learners spend in each of the four quadrants when completing an online instructional module? RQ2) How does the time in each quadrant correlate with the learning gains on the instructional module? RQ3) How does the self-reported time in each quadrant correlate with cognitive load types, situational engagement and learning?

FIG. 1: The 2x2 Matrix denoting four attentional cognitive states [12].

	Looking at learning materials (computer)	**Looking *elsewhere***
Thinking about learning content (On-task)	**Quadrant 1 (Q1):** Overt sustained attention (On-task) ● Focused attention ● Alternating attention ● Divided attention	**Quadrant 2 (Q2):** Covert sustained attention (On-task) ● Note-taking ● Using calculator ● Looking away while thinking hard, etc.
NOT thinking about learning content (Off-task)	**Quadrant 3 (Q3):** Covert ***in***attention (mind wandering)(Off-task) ● Tune outs ● Zone outs	**Quadrant 4 (Q4):** Overt ***in***attention (Off-task) ● Texting ● Fidgeting ● Staring off into space, etc.

III. METHODS

All of the data collected in this study, except for the pre- and post-tests are based on self-reports from the participants. This study was conducted with students enrolled in a first-semester calculus-based physics course for future engineers and scientists in spring 2024 at a large U.S. Midwestern land grant university. The class had an enrollment of 1453 students. The vast majority of these students had completed high school physics. The population consisted of about 20% women, 10% international students, and 8% underrepresented minorities.

The materials consisted of a pre-test, a multimedia learning module, and post-test. The multimedia module was about 15 minutes long and was created using the backward design strategy of Wiggins and McTighe [31] and was consistent with Mayer's [32] principles of multimedia learning. The module focused on reviewing Newton's II Law, free-body diagrams, and solving problems based on these concepts. During the module, participants were presented with occasional "mind-wandering prompts" in which they were explicitly asked to indicate whether or not they were mind-wandering, by responding "Y" (yes) or "N" (no) on the keyboard. The pre-test and post-test each had 28 multiple choice items that included both conceptual questions and questions that required an application of the problem-solving strategies presented in the module. After completing the post-test, students had to answer questions where they had to estimate the proportion of time they spent in each quadrant of the 2x2 matrix in Fig. 1. They also completed a cognitive load survey [33] and a situational engagement survey [34].

Students completed the online module and associated pre-test, post-test and surveys in a single online session in Week 5 of the semester, after they had completed instruction in the class pertaining to Newton's Laws. The duration for the entire module (including the pre-test, post-test, and surveys) was estimated to be about 45 minutes. One week prior to completing the module, students had completed the first of three exams administered in the course. The exam covered material that was also covered on the online module. Participants who completed the online module received extra credit equal to 1% of the course grade.

IV. RESULTS & DISCUSSION

Of the 1453 students enrolled in the course, 1180 completed the online study. Upon closer examination of the data, we eliminated all but N = 896 participants due to incomplete or corrupted data.

Studying the instructional module produced a statistically significant ($p < 0.05$) improvement from the pre-test (Mean = 71%, S.E. = 5%) to the post-test (Mean = 83%, S.E. = 3%). Thus, overall the module facilitated learning (See Fig. 2).

Results of the time spent in four quadrants of the 2x2 attentional-cognitive matrix is shown in Fig. 3.

Participants reported spending most of their time on the screen and thinking about the material (Mean(Q1) = 62.4%, 95% CI [61.0%, 63.0%]), followed by on screen and not thinking about it (Mean(Q2) = 11.6%, 95% CI [10.6%, 12.6%]), off-screen and thinking about the material (Mean(Q3) = 16.6%, 95% CI [15.6%, 17.6%]), and least time on off-screen and not thinking about the material (Mean(Q4) = 9.7%, 95% CI [8.7%, 10.7%]) respectively. The self-reported time estimation in the four quadrants are comparable to those reported in the a lab study using the same materials and learning assessments [35]. However, this study and the lab study (N (self-reported estimates) = 34) had significantly different numbers of participants making a statistical comparison unfeasible.

Table I below shows the Spearman's correlation coefficients between our various measures: proportion time allocated to each of the quadrants, engagement, cognitive load types, and normalized learning gain.

FIG. 2: Percentage correct on the Pre- and Post-Tests

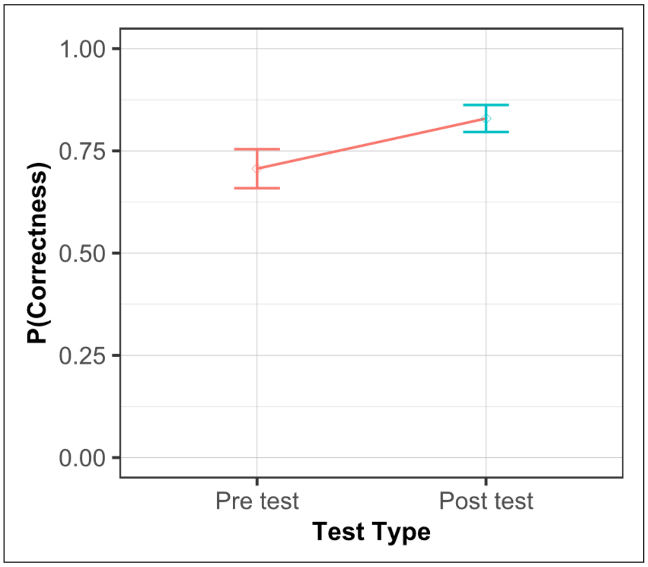
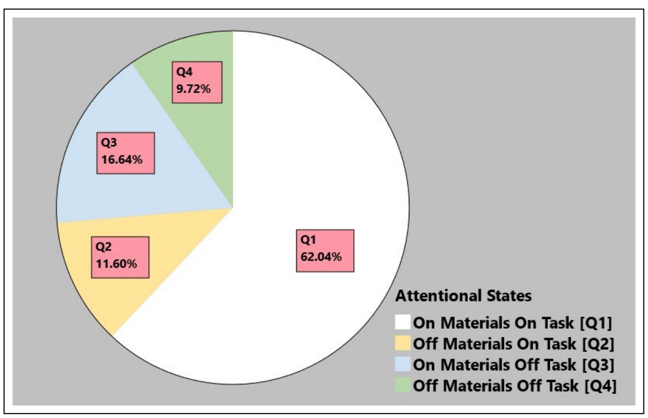


FIG. 3: Percent time allocation in the four attentional-cognitive states



The self-reported proportion of time spent in Q1 (looking at the screen and thinking about the learning materials) correlated positively with both engagement and germane cognitive load, and correlated negatively with extraneous cognitive load. These results are as expected in that students who claimed to be engaged with the materials also claimed to have spent more time on task with those materials.

That self-reported time in Q2 (looking away from the screen but thinking about the learning materials) correlated positively with both intrinsic cognitive load and extraneous cognitive load. This too is expected because if students are trying to understand content that is either inherently difficult (i.e., high intrinsic cognitive load) or difficult due to the way it is presented (extraneous cognitive load), then students are more likely to either look away to seek help from other resources, or to distribute their cognitive load to other tools, such as by using calculator or engage in note-taking.

The self-reported time in Q3 (looking at the screen but not thinking about the learning materials) namely mind wandering, correlated negatively with both engagement and germane cognitive load. This is expected because when students are disengaged or uninterested in the learning materials, they are more likely to mind wander. Consequently, and consistent with our results, students who mind wandered were also more likely to show lower normalized learning gains.

Finally, the self-reported time spent in Q4 (looking away from the screen and not thinking about the learning materials) correlated negatively with both engagement and germane cognitive load, but correlated positively extraneous cognitive load. This indicates that learners who looked away from the screen while not thinking about the learning materials were disengaged, did not put in effort into learning, and perceived the material as confusing.

V. CONCLUSIONS, LIMITATIONS & FUTURE WORK

The use of online multimedia learning modules in completely asynchronous distance education or as supplements to face-to-face classroom learning is becoming more commonplace. With the increasing prevalence of studying online learning materials, it is important to understand how learners engage with them, the time they spend thinking about them, the cognitive load they experience, and the impact it has on their learning. Thus, the current study has focused on the relationships between the attentional and cognitive states of learners, their different types of cognitive load, their levels of situational engagement, and their learning outcomes. Our overarching goal was to investigate how these three cognitive constructs (attention, cognitive load, and engagement) are related to each other, and their relationships with learning.

Our first research question (RQ1) focused on the self-reported proportion of time participants spent in each quadrant. Students self-reported spending the vast majority (roughly 60%) of their time both attending to the learning materials and thinking about them (i.e., in Q1 in Figure 1). The remainder of their time was roughly evenly split between the other three quadrants in our 2x2 attention and cognition space. Our second research question (RQ2) focused on the correlation between the proportion of time in each quadrant and learning gains on the instructional module. The only statistically significant correlation with learning gains was the proportion of time spent in Q3, namely the time students spent mind wandering, which, as expected, correlated negatively with learning. Our third research question (RQ3) focused on the correlation between the self-reported time in each quadrant with cognitive load types, situational engagement, and learning. We found significant positive correlations between the proportion time spent both looking at the materials and thinking about them (i.e., Q1) with both engagement and germane cognitive load. This is expected because students who are spending time on task are more likely to be engaged with the materials. We also found significant

TABLE I: The Spearman's correlation coefficient between measures: TQ1 (% time ON materials & ON task); TQ2 (% time OFF materials & ON task); TQ3 (% time ON materials & OFF task); TQ4 (% time OFF materials & OFF task); ENG (Situational Engagement); ICL (Intrinsic Cognitive Load); GCL (Germane Cognitive Load); ECL (Extraneous Cognitive Load); NLG (Normalized Learning Gain). * represents p < 0.05, ** represents p < 0.001.

	TQ1	TQ2	TQ3	TQ4	ENG	ICL	GCL	ECL	NLG
TQ1	.	.	.	.	.	.	.	.	.
TQ2	-0.57**	.	.	.	.	.	.	.	.
TQ3	-0.68**	0.11**	.	.	.	.	.	.	.
TQ4	-0.78**	0.31**	0.42**	.	.	.	.	.	.
ENG	0.24**	-0.06	-0.18**	-0.23**	.	.	.	.	.
ICL	0.00	0.09*	-0.04	-0.01	0.19**	.	.	.	.
GCL	0.35**	-0.12**	-0.34**	-0.35**	0.37**	0.08	.	.	.
ECL	-0.17**	0.07*	0.16**	0.18**	-0.13**	0.37**	-0.25**	.	.
NLG	0.04	-0.05	-0.08*	-0.05	-0.03	-0.11**	0.12**	-0.06	.

negative correlations between time spent looking at the materials but mind wandering (i.e., Q3) with both engagement and germane cognitive load. Time spent looking away from the materials, but thinking about them, such as while note taking (i.e., Q2) correlated positively with both the intrinsic and extraneous cognitive load caused by the materials. Additionally, time spent looking away from the materials, but thinking about them (Q2) was negatively correlated with germane cognitive load. That finding was not expected, because note-taking and various other generative learning activities (e.g., summarizing, mind-map drawing, etc.) would create germane cognitive load, and often occur while looking away from the learning materials but thinking about them [36]. Finally, as expected, the time spent neither looking at the learning materials, nor thinking about them (i.e., Q4) correlated negatively with engagement and germane cognitive load and positively with extraneous cognitive load.

In summary, our results are largely, but not entirely, consistent with cognitive load theory and its relationship to learners' attentional-cognitive states. Although we found an expected negative relationship between learning and mind wandering (i.e., Q3), we found no statistically significant dependence of learning on time in the other three quadrants (Q1, Q2, and Q4), or on engagement, which was quite unexpected. This work underscores the importance of examining the effect of attentional and cognitive states on cognitive load, engagement, and learning.

The main limitations of this study lie in the fact that apart from the learning gain measures, all of our attentional-cognitive states, cognitive load, and engagement measures were self-reported. As with any study that relies on self-reports, it is likely that participants either did not recall the time they spent in various quadrants or were unwilling to candidly report this information. There are several avenues for extending this work. First, the data could be analyzed to determine the influence of pre-test scores on the outcome measures (attentional and cognitive states, cognitive load, and engagement). A regression analysis including multiple model comparisons could be used to determine which combination of these parameters can best predict learning. Finally, rather than rely on self-reported data alone, we could also measure mind wandering through the interaction of the learners with the mind wandering prompts that were embedded in the instructional unit, which could provide an independent measure of the extent of mind wandering, and the features of the instructional materials that might cause or inhibit mind wandering in multimedia learning. Finally, eye-tracking could be used to validate the self-reported quadrant survey by indicating the proportion of time participants are looking at the screen. It would be interesting to investigate how that coincides with the sum of quadrants Q1 and Q3. Such work would extend and complement our previous research in a lab study on this topic [35].

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