International Society of the Learning Sciences

Capturing Learners' Interactions with Multimedia Science Content Over Time during Game-based Learning

Daryn A. Dever, Allison M. Banzon, Nikki Anne M. Ballelos, Roger Azevedo
ddever@knights.ucf.edu, amacey@knights.ucf.edu, nikkianne.ballelos@ucf.edu, roger.azevedo@ucf.edu
University of Central Florida

Abstract: Learners demonstrate difficulties effectively deploying self-regulated learning (SRL) strategies while using game-based learning environments (GBLEs). Features designed to scaffold and support learners' SRL with GBLEs may limit autonomy and impact their performance. However, the effectiveness of limiting autonomy as individual learners engage in SRL over time (i.e., throughout a 90-minute learning session) has been largely unexplored. Therefore, this study examines how learners' prior knowledge and varying levels of autonomy (i.e., full versus partial) moderate the relationship between fixation durations over time on different information representations (i.e., books and research articles, conversations, posters) that are either considered relevant or irrelevant to the pre-test. Undergraduate students (N=82) learned with Crystal Island, a microbiology GBLE. Results identified interaction effects between (1) fixation durations and representations on learning gains and (2) text relevance, type of representation, and relative game time as well as a moderating effect of autonomy.
Keywords: Game-based Learning, Autonomy, Multimedia, Self-regulation, Eye Tracking

Autonomy and SRL during game-based learning

Game-based learning environments (GBLEs) incorporate tasks and game elements while allowing learners full autonomy (i.e., complete control over actions; Bandura, 2001) to enhance learning, motivation, and cognitive engagement (Plass, Homer, Mayer, & Kinzer, 2020; Taub, Sawyer, Smith, Rowe, Azevedo, & Lester, 2020). Because of the open-ended nature of GBLEs, learners must engage in self-regulated learning (SRL) to monitor and adapt their learning strategies to meet goals (Winne & Azevedo, in press). However, as learners typically lack the SRL skills needed to successfully interact with GBLEs (Josephsen, 2017), GBLEs embed scaffolds (e.g., guidance through restricted autonomy) to support learners' use of SRL processes and strategies (Josephsen, 2017).

GBLEs must balance the level of autonomy afforded to learners to simultaneously increase motivation through full autonomy and scaffold learning by restricting autonomy (Dever & Azevedo, 2019; Dever, Azevedo, Cloude, & Wiedbusch, 2020). For example, Crystal Island, a microbiology GBLE, limits autonomy by dictating the order in which learners interact with game elements (e.g., informational text) and forcing learners to engage with all information. However, regardless of the level of autonomy, learners must use SRL strategies to select relevant information from the text, organize the information into a mental model, and integrate their mental models with prior knowledge. As such, it is important to consider how limited autonomy moderates learners' interactions with GBLE elements by capturing process-oriented data as learners monitor and regulate learning processes. This study focuses on how learners' gaze fixations on different information representations (i.e., large paragraphs of text, conversations, posters) within Crystal Island contribute to learning gains, change over time, and are related to representation relevance, learners' autonomy, and prior knowledge.

Capturing SRL via eye-tracking methodology

Eye-tracking methodologies are utilized to capture learners' cognition and SRL strategy use (Azevedo, Taub, & Mudrick, 2018; Catrysse, Gijbels, Donche, De Maeyer, Lesterhuis, & Van den Bossche, 2018; Mayer, 2019). Fixation durations, which are defined as relatively still gaze for at least 250ms, and saccades are regularly used (see Cloude, Dever, Wiedbusch, & Azevedo, 2020) to quantify learners' underlying cognitive processes (e.g., reading; Bolzer, Strijbos, & Fischer, 2015; Catrysse et al., 2018l Cutumisu, Turgeon, Saiyera, Chuong, González Esparaza, MacDonald, & Kokhan, 2019). For example, time fixating on in-game texts indicates when learners are monitoring their understanding of text and capture the total time learners need to process information. These gaze behaviors further indicate learners' ability to accurately and efficiently apply SRL strategies. For example, learners fixating on irrelevant text for a long period of time may indicate the learner has not made an appropriate or efficient content evaluation (i.e., inaccurate metacognitive monitoring). Yet, accurately identifying relevant from irrelevant information is influenced by the multimedia material where accuracy increases when information is represented by multiple modalities (e.g., text and picture versus solely text; Azevedo & Dever, in press; Butcher, 2014; Mayer, 2019, in press). Within this paper, we use eye-tracking data to explore this relationship between information representations and SRL.

Previous research with Crystal Island

Recent studies in Crystal Island utilize eye-tracking data to understand learners' in-game behaviors, deployment of SRL processes, and learning gains (Syal & Nietfeld, 2020; Taub, Mudrick, Azevedo, Millar, Rowe, & Lester, 2017). Dever et al. (2020) compared log-file with eye-tracking data and examined how learners interact with relevant versus irrelevant text in Crystal Island. Their findings suggest that learners' eye-tracking data provides a better indication of how learners interact with information throughout a GBLE compared to log files. Cloude et al. (2020) found moderating relationships between fixations and information gathering actions within Crystal Island where learners with less prior knowledge had a positive relationship between interactions and fixation durations. Taub et al. (2017) used eye-tracking data to examine learners' use of SRL processes where results found that eye-tracking data was essential to capturing the quality of learners' processing through fixation durations. While these studies used eye-tracking data to provide evidence on learners' in-game behaviors and SRL processes associated with heightened knowledge acquisition, they do not address these relationships over time. This current study uses eye-tracking data to assess learning gains in relation to autonomy, prior knowledge, and text representations over time within Crystal Island to examine how these constructs influence learners' SRL strategies while interacting with multimedia materials in a GBLE.

Theoretical frameworks

To examine the relationship between learners' SRL processes, specifically content evaluation, and the cognitive processes required to select and comprehend multimedia material, both Mayer's (2019, in press) CTML and Winne's (2018) COPES models are used to ground this study. CTML is centered around three cognitive processes: (1) selecting relevant visual and auditory information; (2) organizing the selected visual and auditory information into mental models; and (3) integrating mental models together with prior knowledge to construct a cohesive representation of information (Mayer, 2019). These processes are assumed to be linearly structured, limited by learners' cognitive resources, and elicited by learners' active processing of multimedia.

COPES details learners' conditions, operations, evaluations, and standards as they engage in SRL throughout learning (Winne, 2018). Within this paper we examine the conditions, operations, and products that influence learners' interactions with different representations of information. Conditions refer to the types of resources and constraints that are available to a learner through internal (e.g., prior knowledge) or external/environmental (e.g., limited versus full autonomy) factors (Winne, 2018). Conditions can significantly influence learners' deployment of SRL strategies during learning. For example, Taub, Azevedo, Bouchet, and Khosravifar (2014) found that learners with high prior knowledge had a greater number of and duration on SRL strategies than learners with low prior knowledge. Operations are the internal cognitive processes that a learner continuously deploys while learning with a GBLE which, when combined with conditions, results in products, or the new understanding of the content based on information presented in the GBLE (i.e., learning gains).

Current study

Limited research has examined how learners' interactions with information representations change over time as a result of prior knowledge, autonomy, and learners' SRL abilities. The goal of this study is to add to this area by examining learners' fixation durations on relevant versus irrelevant types of representations over time and how learners' prior knowledge and autonomy throughout the environment are related to this interaction by examining three research questions. The first research question focuses on learners' products: To what extent does the proportion of time learners spend on different representations influence learning gains? Supported by CTML, we propose that the greater amount of time learners spent reading information from non-player character (NPC) dialog and posters relative to their total time in game and accounting for the type of representation will increase learning gains. The second research question focuses on learners' operations: How does relative game time, relevance of the text to the pre-test, type of representation, and their interactions account for the variation of fixation durations within and between learners? We propose that (1) the variation in fixation durations within and between learners will be increasingly accounted for as we add these variables within our model, and (2) as relative game time increases, fixation durations across all types of relevant representations will increase at a greater rate than fixation durations on all types of irrelevant representations. The third research question focuses on learners' conditions: How does autonomy and prior knowledge moderate the effects between relative game time, relevance of the text to the pre-test, type of representation, and learners' fixation duration? Supported by previous literature (Dever et al., 2020; Sawyer, Rowe, Azevedo, & Lester, 2018; Taub et al., 2014), we propose that learners with high prior knowledge and limited autonomy will have greater fixation durations on relevant representations over time than learners with lower prior knowledge and full autonomy.

Methods

Participants
Undergraduates (N = 139) from a large North American public university were randomly assigned to either the full, partial, or no agency conditions that varied in the autonomy afforded (see Crystal Island). Only 82 participants ($Range_{age}$: 18-26, M_{age} = 20.1, SD_{age} = 1.69; 68.3% female), split between full (n = 47) and partial (n = 35) agency conditions, were included in our analyses. Participants were removed if they had missing data and measurement errors in eye-tracking calibration (n = 25) or belonged to the no agency condition (n = 32).

Crystal Island: A GBLE for microbiology
Crystal Island, a GBLE set on a remote island, aims to cultivate learners' SRL and scientific reasoning skills by introducing microbiology content through a problem-solving scenario. Learners must identify an unknown disease infecting island residents by reading informational content (e.g., books, research articles, dialogue with NPCs, posters), completing concept matrices corresponding to informational content, filling out a diagnosis worksheet, and scanning food items. Agency conditions were embedded within Crystal Island. Full agency did not restrict participants' interactions with the environment, generalizable to the majority of GBLEs. Partial agency consisted of a predetermined path (i.e., "Golden Path") that restricted the participants' choice of actions to provide learners support and optimize their learning outcomes. No agency required learners to watch a playthrough of Crystal Island. Learners in this condition could not directly interact with any video (e.g., pause, rewind) or game features.

Experimental procedure
At the start of the experimental session, participants signed an informed consent and were calibrated to the eye tracker. Participants then completed a demographic questionnaire, a microbiology content knowledge pre-test, and several self-report measures. Following pre-task measures, participants started the learning session. As participants interacted with Crystal Island, eye-tracking data were collected. Once a correct diagnosis was identified and submitted, participants completed post-task measures including a microbiology post-test similar to the pre-test and self-reports. Participants were then thanked and compensated, receiving $10 an hour (up to $30).

Apparatus
Gaze behavior data were captured using an SMI RED250 eye tracker with 9-point calibration at a sampling rate of 250 samples per second (s). The SMI eye tracker captured fixation durations, saccades, and regressions on pre-identified areas of interest (AOIs) which are boundaries that contain the object on which the participants fixate.

Coding and scoring

Reading
Reading duration and instances were operationalized as learners' fixation duration (i.e., relatively stable eye movements for at least 250ms) on different types of representations using AOIs overlaid on top of each representation. Types of information representations refer to NPCs (informative text, uninformative visual), books and research articles (informative text, no visual), and posters (informative and uninformative text and visual). Books and research articles are combined as both representations contain large paragraphs of text.

Learning gains
Normalized change scores (Marx & Cummings, 2007) are used to identify learning gains, or the differences between pre- and post-test scores, while controlling for the prior knowledge of each participant.

Relevance of representations
Individual representations were evaluated for relevance to the pre-test where if a representation contained information addressed in the pre-test, the representation was classified as relevant (see Table 1). If the representation did not hold any information addressed in the pre-test, the representation was labeled as irrelevant. This classification is based on priming literature (see McNamara, 2005) assuming that participants will identify information as more instructionally relevant based off of the pre-test domain-related questions and is needed for the post-test.

Table 1: Relevance of representations

Representation	Total #	# Relevant Representations
Books & Research Articles	21	12
NPC Dialog	9	3
Posters	10	4

Relative game time

As each participant varied in their total game duration, relative game time was calculated by dividing the time in game participants fixated on content by the participants' total game duration, scaling instances from 0 to 1 so that all participants could be compared. This measure was found to first look at a continuous scaling of time to normalize all participants' time in game, which ranged from 39.7 to 135.8 minutes.

Model building and estimation

Our model examines how fixation duration, the outcome variable, was related to several observation- and individual-level variables (see Table 2). Several leveraging outliers ($N = 72$), i.e., data that falls approximately 1.5 interquartile ranges below or above the first and third quartile of data respectively, from the observations were removed from analyses. Fixation duration values were transformed through natural logs to normalize the data (skew and kurtosis < |2|) and reduce heteroscedasticity. As such, geometric means for fixation durations are interpreted within results. Two-level multilevel linear growth models analyzed our hierarchically structured data with observations (i.e., level one, $N = 4274$) nested within individual learners (i.e., level two, $N = 82$) where each learner had approximately 52 observations (Range: 25-75). Observation-level variables included relative game as a latent time variable with a random slope in all growth models. To interpret model intercepts, relative game time values were forced to zero to exemplify learners' first interactions with representations as learners cannot fixate on a representation when they first enter the game. Pre-test relevancy (irrelevant versus relevant) and type of representation (i.e., NPC, books and research articles, posters) were added as fixed effect observation-level variables. Individual-level variables included pre-test scores and conditions.

Table 2: Definitions of variables included in the models.

Level	Variable	Definition	Effects
Observation-Level (Level 1)	Relative Game Time	Proportion of time learners initiate an action.	Random
	Representation	Book or Research Article, NPC, Poster	Fixed
	Relevance	Representation contains information related to a question on the pre-test (1). Representation does not contain information related to a question on the pre-test (0).	Fixed
Individual-Level (Level 2)	Condition	Full Autonomy (1); Restricted Autonomy (0).	Fixed
	Prior Knowledge	Raw scores on the domain knowledge pre-test quiz.	Fixed

Five models were calculated using maximum likelihood estimation within R (R Core Team, 2019) utilizing packages 'lme4' (Bates, Maechler, Bolker, & Walker, 2015), 'jtools' (Long, 2020), and 'emmeans'

(Lenth, 2020) for model building and analysis. The unconditional means model was estimated first. Based on this model, the intraclass correlation coefficient was 0.05, suggesting that about 5% of the variation in fixation duration on representations within Crystal Island is between learners and about 95% is within learners. There was a statistically significant variation between learners ($t(82.64) = 75.14$, $p < .01$). Thus, it is reasonable to proceed with multilevel linear growth models. The next four models were built with: (1) an unconditional growth model; (2) level one predictors and their interactions; (3) predictors from (2) and level two predictors; and (4) predictors from (3) and cross-level interactions. Tests of model fit were calculated using maximum likelihood estimates.

Model 4: $Y_{ti} = \pi_{0i} + \pi_{1i}(RelativeGameTime) + \pi_{2i}(TypeofRepresentation) + \pi_{2i}(PretestRelevance)$
$+\pi_{3i}(RelativeGameTime^{*}TypeofRepresentation$
$+ \pi_{4i}(RelativeGameTime^{*}PretestRelevance)$
$+ \pi_{5i}(RelativeGameTime^{*}TypeofRepresentation^{*}PretestRelevance) + e_{ti}$

$$\pi_0 = \beta_{00} + r_0$$
$$\pi_1 = \beta_{10}$$
$$\pi_2 = \beta_{20}$$
$$\pi_3 = \beta_{00} + \beta_{01}(Condition) + \beta_{02}(PriorKnowledge)$$
$$\pi_4 = \beta_{10}$$
$$\pi_5 = \beta_{20}$$

Results

Research question 1: To what extent does the proportion of time learners spend on different representations influence learning gains?

A multiple linear regression was run and, while the overall model was not significant ($p > .05$), there was a significant interaction effect for proportion of time fixating on NPCs ($t(485) = 8.99$, $p < .05$) where as proportion of time on NPCs increased by one unit, normalized change scores increased by 0.48 points. As the proportion of time fixating on books and research articles increased by one unit, normalized change scores increased by approximately 1.28 points compared to the proportion of time fixating on NPCs ($t(485) = 2.81$, $p < .01$). Proportion of time on posters did not significantly relate to learning gains. In sum, the proportion of time spent on NPCs as well as books and research articles were positively related to normalized change scores.

Research question 2: How does relative game time, relevance of the text to the pretest, type of representation, and their interactions account for the variation of fixation durations within and between learners?

To answer this question, we utilize Models 1 and 2. Model 1, the unconditional growth model, includes time as a level-1 predictor of learners fixation duration. The average fixation duration at participants' initial interaction with text is approximately 31.19s (SE = 0.06) and decreases by approximately 67% (i.e., 20.81s; SE = 0.11) for every unit increase in relative game time. This model (BIC = 14379, D = 14329) is significantly better in terms of fit than the unconditional means model (BIC = 14582, D = 14557) wherein adding time, the model explains approximately 11% of individual-level variance in fixation duration ($\chi 2(3) = 227.41$, $p < .01$). Model 2 (BIC = 12623, D = 12506) examined the extent to which level 1 variables contribute to variation in learners' fixation durations. This model is a significantly better fit than the unconditional growth model ($\chi 2(8) = 1822.8$, $p < .01$). Holding all other variables constant, the average fixation duration is 104.58s (SE = 1.08, $t(301.39) = 60.69$, $p < .01$). There was a main effect for relative game time where, holding all variables constant, fixation durations decreased 89% (i.e., 93.08s) for every unit increase in relative game time (SE = 16.15; $t(653.86) = -13.36$, $p < .01$). There was a main effect where, when text was relevant, fixation durations were greater than those on irrelevant text by approximately 25.9% (i.e., 27.04s; SE = 1.96; $t(4186.66) = 3.37$, $p < .01$). There were significant differences between the type of representation and their effect on fixation durations. In comparison to book and research article observations and holding all other variables constant, fixation durations are lower on both NPCs and posters by approximately 85.6% (i.e., 89.55s; SE = 6.49; $t(4200.02) = -26.8$, $p < .01$) and 91.5% (i.e., 95.65s; SE = 9.01; $t(4210.62) = -28.31$, $p < .01$) respectively.

Holding all variables constant, there were significant two-way interactions between relative game time, NPCs ($t(4211.68) = 11.85$, $p < .01$), and posters ($t(4209.54) = 8.86$, $p < .01$) compared to book and research articles. Books and research articles (by 92.6% or 96.89s; SE = 14.45; see Figure 1) decreased at a greater rate over time than posters (by 44.4% or 46.43s; SE = 7.68). NPCs did not have a significant decrease in fixation durations over time. There was a significant interaction effect for pre-test relevancy and relative game time where fixation durations on relevant text were lower over time than fixation durations on irrelevant text by approximately

56.4% (i.e., 58.98s; SE = 11.63; $t(4182.43) = -4.65$, $p < .01$). When examining a three-way interaction and controlling for all observation-level variables, fixation durations on relevant posters (SE = 9.75; $t(4180.03) = 2.65$, $p < .05$) and NPCs (SE = 40.01; $t(4176.82) = 6.70$, $p < .01$) increased over time by 53.7% (i.e., 56.19s) and 206% (i.e., 215.94s) respectively compared to fixations on books and research articles. As relative game time increased, fixations decreased on relevant books and research articles by 95.1% (i.e., 99.50s; SE = 17.85) and posters by 54.3% (i.e., 56.83s; SE = 10.73). Over time, fixation durations decreased on irrelevant books and research articles by 88.9% (i.e., 92.95s; SE = 16.67) and posters by 32.3% (i.e., 33.78s; SE = 6.46).

In sum, fixation durations generally decreased at a greater rate over time for representations that were relevant to the pre-test than irrelevant. However, there were only significant interaction effects on fixation durations between books and research articles (regardless of relevancy to the pre-test) and posters relevant to the pre-test where fixation durations decreased over time.

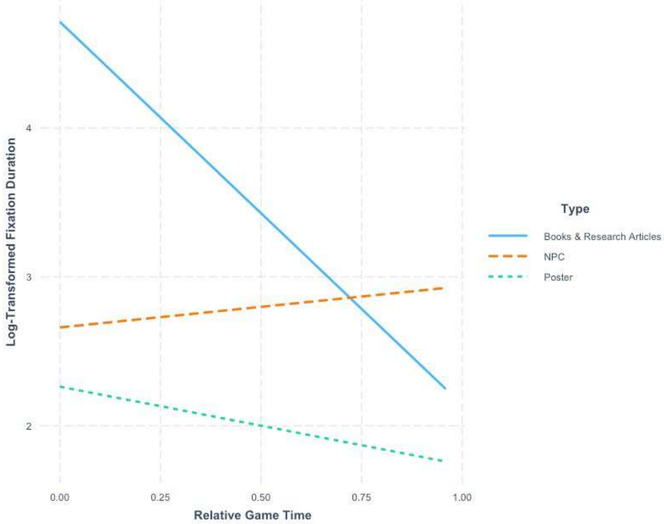

Figure 1. Interaction between relative game time, fixation durations, and type of representation.

Research question 3: How does autonomy and prior knowledge moderate the effects between relative game time, relevance of the text to the pre-test, type of representation, and learners' fixation duration?

Preliminary analysis on condition and learning gains using a t-test confirmed participants with partial agency (M = 0.45, SD = 0.27) had significantly greater learning gains than participants within the full agency condition (M = 0.32, SD = 0.26; $t(71.6) = 2.18$; $p < .05$). Because of this significant preliminary finding, Model 3 (BIC = 12640, D = 12506) added prior knowledge and condition as variables but these variables were not significant (ps > .01). Model 4 (BIC = 12608, D = 12466) examined the moderating effects of condition on the relationship between the type of representation and fixation duration. This model was a significantly better fit than Model 2 ($\chi 2(3) = 40.43$, $p < .01$), explaining approximately 44% of individual-level variance in fixation duration. Prior knowledge was initially included but removed due to non-significance. While there was no moderating effect (ps > .01) of condition on the relationship between NPCs and fixation durations over time, there was a three-way cross-level interaction effect where learners who were in the full agency condition had greater fixation durations on books and research articles over time compared to learners in the partial agency condition ($t(169.3) = 3.89$, $p < .01$). For every unit increase in relative game time, fixation durations on books and research articles increased by 97.4% (i.e., 101.84s; SE = 18.87) for learners with full autonomy than those with partial autonomy. For every unit increase in relative game time, fixation durations on posters decreased by 30.2% (i.e., 31.62s; SE = 5.86) for learners with full autonomy compared to those with partial autonomy. In sum, learners with more control during gameplay had increasingly greater fixation durations on books and research articles over time and lower fixation durations on posters compared to learners with restricted control, regardless of prior knowledge.

Discussion and future directions

The goal of this paper was to examine how learners' fixation durations on relevant and irrelevant types of representations changed over time and how prior knowledge and autonomy moderated this relationship. The first research question examined how learners' products were related to the proportion of time fixating on different types of representations. Results partially support our hypothesis where the proportion of time fixating on NPCs

 © ISLS

and books and research articles were positively related to learning gains, but there was no relationship between posters and learning gains. This is not in complete alignment with CTML (Mayer, 2019, in press) where NPCs have text, pictures, and audio, and posters have both text and pictures, but books and research articles only contain large blocks of text. Findings may be attributed to the breadth of knowledge contained within books and research articles where posters do not explain relationships between terms or constructs related to microbiology.

Results for the second research question did not confirm our hypothesis where, as relative game time increased, fixation durations tended to decrease. Interestingly, results showed an interaction between text and relevancy where fixation durations tended to decrease at a greater rate over time for posters and books and research articles that were relevant than texts that were irrelevant. This may be due to the presence of other instructional activities within Crystal Island such as completing concept matrices, filling out the worksheet, and scanning items (Azevedo et al., 2018). However, this result emphasizes learners' inability to consistently and accurately use SRL strategies, such as content evaluations, throughout the game (Taub et al., 2020).

The third research question examined how findings in research question two are affected by autonomy. Results did not support our hypothesis and contradicted prior works where learners with full autonomy had increasingly greater fixation durations on books and research articles over time and lower fixation durations on posters compared to learners with limited autonomy, regardless of prior knowledge (McCardle & Hadwin, 2015; Winne, 2018). Previous work has emphasized the relationship between autonomy and learning gains (Dever et al., 2020). Traditionally, limited autonomy is associated with greater learning gains (Dever & Azevedo, 2019; Dever et al., 2020; Sawyer et al., 2018). Between the first and third research question results, learners with full autonomy had greater fixation durations on books and research articles over time which is further associated with greater learning gains. When accounting for preliminary findings on autonomy and learning gains in the third research question, results from this study suggest that learners with full autonomy were not able to employ efficient or accurate SRL strategies while reading books and research articles whereas learners supported in their actions throughout gameplay had significantly less time interacting with information, but efficiently employed SRL strategies to achieve greater learning gains.

Findings from this current study partially validate the relationship between COPES and CTML where we find that learners' conditions and operations are directly related to their products, especially as we explore the role of different types of representations of information within GBLEs. This study serves as a baseline for future studies to further examine the relationship between COPES, autonomy, and information representations over time within GBLEs. Future studies should incorporate searching, monitoring, assembling, rehearsing, and translating processes into the COPES and CTML model over time within GBLEs to better understand how SRL strategies are used by learners over time (Azevedo & Dever, in press). From the results, we identify the need for adaptive GBLEs depending on learners' eye-tracking behaviors as they read information over time and between different types of representations, especially as we see mixed results compared to previous studies about the role of autonomy as a scaffold for acquiring information. Using adaptive GBLEs from learners' gaze behaviors has the potential to better support learners in navigating the environment, selecting relevant instructional text, and integrating this information to increase learning outcomes while supporting self-regulated learning.

References

Azevedo, R., & Dever, D. A. (in press). Multimedia learning and metacognitive strategies. In R. E. Mayer & L. Fiorella (Eds.) Cambridge handbook of multimedia learning (3rd ed.). Cambridge, MA: Cambridge University Press.

Azevedo, R., Taub, M., & Mudrick, N. V. (2018). Understanding and reasoning about real-time cognitive, affective, and metacognitive processes to foster self-regulation with advanced learning technologies. In D. H. Schunk & J. A. Greene (Eds.), Handbook on self- regulation of learning and performance (2nd ed.) (pp. 254-270). New York, NY: Routledge.

Bandura, A. (2001). Social cognitive theory: An agentic perspective. Annual Review of Psychology, 52, 1-26.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. Journal of Statistical Software, 67, 1-48. doi:10.18637/jss.v067.i01.

Bolzer, M., Strijbos, J., & Fischer, F. (2015). Inferring mindful cognitive- processing of peer-feedback via eye-tracking: Role of feedback-characteristics, fixation-durations and transitions. Journal of Computer Assisted Learning, 31, 422–434.

Butcher, K. (2014). The multimedia principle. In R. E. Mayer (Ed.), The Cambridge handbook of multimedia learning (2nd ed., pp. 174-205). Cambridge, MA: Cambridge University Press.

Catrysse, L., Gijbels, D., Donche, V., De Maeyer, S., Lesterhuis, M., & Van den Bossche, P. (2018). How are learning strategies reflected in the eyes? Combining results from self-reports and eye-tracking. British Journal of Educational Psychology, 88, 118-137.

Cloude, E. B., Dever, D. A., Wiedbusch, M. D., & Azevedo, R. (2020). Quantifying scientific thinking using multichannel data with Crystal Island: Implications for individualized game-learning analytics. Frontiers in Education. doi: 10.3389/feduc.2020.572546
Computing, Vienna, Austria.
Cutumisu, M., Turgeon, K.-L., Saiyera, T., Chuong, S., González Esparza, L. M., MacDonald, R., & Kokhan, V. (2019). Eye tracking the feedback assigned to undergraduate students in a digital assessment game. Frontiers in Psychology. https://doi.org/10.3389/fpsyg.2019.01931
Dever, D. A., & Azevedo, R. (2019). Autonomy and types of informational text presentations in game-based learning environments. In S. Isotani, E. Millán, A. Ogan, P. Hastings, B. McLaren, & R. Luckin (Eds.), AIED'19: Proceedings of the 20th International Conference on Artificial Intelligence in Education (pp. 110-120). Amsterdam, The Netherlands: Springer.
Dever, D. A., Azevedo, R., Cloude, E. B., & Wiedbusch, M. (2020). The impact of autonomy and types of informational text presentations in game-based environments on learning: Converging multi-channel processes data and learning outcomes. International Journal of Artificial Intelligence in Education, 30, 581-615.
Josephsen, J. M. (2017). A qualitative analysis of metacognition in simulation. Journal of Nursing Education, 56, 675-678.
Lenth, R. (2020). Emmeans: Estimated marginal means, aka least-squares means. R package version 1.5.1.
Long, J. A. (2020). Jtools: Analysis and presentation of social scientific data. R package version 2.1.0.
Marx, J. D., & Cummings, K. (2007). Normalized change. American Journal of Physics, 75, 87-91.
Mayer, R. E. (2019). Computer games in education. Annual Review of Psychology, 70, 531-549.
Mayer, R. E. (Ed.) (in press). Cambridge handbook of multimedia learning (3rd ed.). Cambridge, MA: Cambridge University Press.
McCardle, L., & Hadwin, A. F. (2015). Using multiple, contextualized data sources to measure learners' perceptions of their self-regulated learning. Metacognition and Learning. doi:10.1007/s11409-014-9132.
McNamara, T. P. (2005). Semantic priming: Perspectives from memory and word recognition. New York, NY: Psychology Press.
Plass, Y. L., Homer, B. D., Mayer, R. E., & Kinzer, C. K. (2020). Theoretical foundations of game-based and playful learning. In J. L. Plass, R. E. Mayer, & B. D. Homer (Eds.), Handbook of game-based learning (pp. 3-24). Cambridge: The MIT Press.
R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical
Sawyer, R., Rowe, J., Azevedo, R., & Lester, J. (2018, July 15-18). Filtered time series analyses of student problem-solving behaviors in game-based learning [Paper presentation]. 11th International Conference on Educational Data Mining, Buffalo, NY, United States.
Syal, S., & Nietfeld, J. L. (2020). The impact of trace data and motivational self-reports in a game-based learning environment. Computers & Education, 157, 1-12. https://doi.org/10.1016/j.compedu.2020.103978
Taub, M., Azevedo, R., Bouchet, F., & Khosravifar, B. (2014). Can the use of cognitive and metacognitive self-regulated learning strategies be predicted by learners' levels of prior knowledge in hypermedia-learning environments? Computers in Human Behavior, 39, 356-367.
Taub, M., Mudrick, N. V., Azevedo, R., Millar, G. C., Rowe, J., & Lester, J. (2017). Using multi-channel data with multi-level modeling to assess in-game performance during gameplay with Crystal Island. Computers in Human Behavior, 76, 641–655. http://dx.doi.org/10.1016/j.chb.2017.01.038
Taub, M., Sawyer, R., Smith, A., Rowe, J., Azevedo, R., & Lester, J. (2020). The agency effect: The impact of student agency on learning, emotions, and problem-solving behaviors in a game-based learning environment. Computers & Education, 147. https://doi.org/10.1016/j.compedu.2019.103781
Winne, P. H. (2018). Theorizing and researching levels of processing in self-regulated learning. British Journal of Educational Psychology, 88, 9-20.
Winne, P. H., & Azevedo, R. (in press). Metacognition. In K. Sawyer (Ed.), Cambridge handbook of the learning sciences (3rd ed.) Cambridge, MA: Cambridge University Press.

Acknowledgments

This research was supported by funding from the Social Sciences and Humanities Research Council of Canada (SSHRC 895-2011-1006). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Social Sciences and Humanities Research Council of Canada. The authors would also like to thank members of the SMART Lab and the intelliMEDIA group at NCSU for their assistance and contributions.