Relating Neural Mechanisms for Learning to Instructional Techniques in Online Learning Environments

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1. Introduction

As the coronavirus pandemic forced educational activities into a virtual format, changes to the infrastructure of online learning were done as quickly as possible. Many traditional teaching strategies do not translate well to an online environment, and the situation presented an immediate need to improve the delivery of instruction in virtual classes in order to foster successful learning in this format. Engagement with content, instructors, and other learners has been linked to greater understanding of learned subjects but is simultaneously one of the more difficult achievements to attain in a virtual learning environment (**Martin & Bollinger, 2018**). There are specific cognitive conditions that instructors, whether in-person or virtual, should induce in their students to promote successful engagement with the course. These “events of instruction” include, but are not limited to, capturing learners’ attention, introducing of learning objectives, recalling prior knowledge on the topic, practicing of new concepts, and providing feedback (**Gagné et al., 1992**) In any mode of course delivery, instructors who use these methods have been successful in delivering meaningful and engaging content to their learners.

Cognitive engagement with content of many forms has been well documented, as most healthy brains follow a pattern of activation called the attention-narrowing hypothesis. This is a network of visual and attentional brain regions that activate synchronously to allow for increased concentration on desired material and decreased concentration on stimuli in the background. In the attention-narrowing hypothesis, engaging stimuli evoke activation of the right prefrontal and bilateral temporoparietal cortices, which allow for attention narrowing in order to process rare or novel events (**Bledowski et al., 2004**). The intention of focusing on learning in class, or to another stimulus one consciously labels as salient, requires top-down cognition, which is the process of guiding one’s selective attention to that stimulus while ignoring other stimuli.

Learners' engagement with material presented in class is a combination of processing driven by the stimulus, which would be the instructor or course content, and driven by the cortex in a top-down manner. Top-down processing initiates the dorsolateral fronto-parietal network, a pathway that allows for voluntary selective attention to process specific visual and spatial information (**Bledowski et al., 2004**). Additionally, the attention-narrowing hypothesis requires selective dismissal of unimportant stimuli, which usually includes decreased processing of peripheral vision. As shown in previous fMRI research on engagement, this specific ignoring is achieved by decreased activation in the anterior calcarine sulcus, which is a region involved in processing the visual periphery (**Bezdek et al., 2017**).

Although the present study is concerned with the virtual learning experience, much related previous research on cognitive engagement with material has been done on participants viewing suspenseful film clips. Suspense is a useful tool to study engagement because people can quickly be captivated by effective narrative, and one's cognitive abilities concentrate to follow the story told by the plot line (**Green & Brock, 2000**). The pattern of narrowed attentional scope to the subject, as well as impaired attention to details (for example, the subject's clothing), that viewers experience during suspenseful moments comes from an emotional emphasis on the threat of a negative outcome (**Bezdek & Gerrig, 2016**). This experience is commonly referred to as "transportation" and is a powerful tool in persuasion of viewers; the present study will investigate whether course instruction can have the same engaging effect on the brain. However, material learned in a class cannot be categorized as narrative, but rather as rhetoric focusing on framing and argument. Since engagement is often reduced in rhetorical argument, as opposed to in narrative, which increases engagement, instructors of virtual classes have a more difficult task than filmmakers do to engage their learners or viewers. Based on this research, selecting instructional methods that optimize learners' attention in a manner similar to a story-telling narrative may allow for greatest engagement with virtual classes and learning of material.

Engagement in the classroom, virtual or otherwise, has many benefits for learners in higher education, other than its academic advantages. Many students who engage consistently with their online courses also have connections with other aspects of the collegiate experience, as compared to their disengaged counterparts (**Pu-Shih et al., 2010**). Often, in education at all levels, engagement is strongly associated with motivation, meaning that enhancing motivation often can lead to increased engagement with course content. Active learning is the best strategy to enhance motivation, but instructors must be creative in how to provoke inquiry and collaboration in the virtual learning environment (**Blumenfeld et al., 2006**). The present study aims to identify which conditions of learning are most effective in inducing attention-narrowing neural mechanisms and to compare those instructional strategies to the ones that are associated with strongest memory of the content.

To further understand the relationship between engagement and attention, the present study examines how well the brain follows the attention-narrowing hypothesis while watching instructional videos that have been categorized in various conditions of learning. Participants in the study watch a series of quality, asynchronous instructional videos taught by a Georgia Tech professor while in an fMRI scanner because this technique measures whole-brain activity in real-time and will allow for specific brain regions to be identified as more or less active than at a resting state. Levels of engagement with the instructional videos are measured by brain activity and self report by the participants. Additionally, a memory test is conducted directly after the first viewing of the instructional videos and again one week later. Further investigation of instructional strategies that induce high cognitive engagement and whether they also aid in memory storage, recall, and retention will occur in the future. fMRI data from the present study is compared to data from previous studies showing the effects of suspense on the attention-narrowing hypothesis, which have already defined the brain areas active during cognitive engagement in order to show an association between the instructional method and engagement.

2. Literature Review

The brain may narrow our attentional focus in response to many different cues, one of those being narrative suspense. As opposed to rhetoric, narrative arguments are more powerful in their ability to captivate and persuade the viewer through story telling; this experience is called transportation. During an experience of effective narrative suspense, the cognitive abilities are highly focused on the suspense, resulting in high engagement with the material (**Green & Brock, 2000**). In fact, the brain follows a well-defined network to focus attention, called the attention-narrowing hypothesis. In this activation pattern, decreased processing of the visual periphery and decreased activation of the default mode network allows the brain to direct their attention to the salient stimulus, which has been studied using fMRI to measure brain activation to a suspenseful video clip (**Bezdek et al., 2017**). The brain network that is active when people successfully attend to suspenseful material includes the bilateral temporo-parietal junction and right prefrontal cortex. This salience network is stimulus-driven and responds most successfully to rare events. The dorsolateral fronto-parietal network is a related network that is active in voluntarily shifting spatial and visual attention in top-down processing (**Bledowski et al., 2004**). One reason why people are so captivated by suspense is that the brain often focuses on potential negative outcomes. Though suspense combines the hope for a positive outcome with the fear of a negative outcome, emotions tend to emphasize the threat of a negative outcome, which drives engagement and attention (**Bezdek & Gerrig, 2016**). The structural-affect theory defines the timeline of suspense in two events: Initiating Events, in which the viewer is aware that a negative outcome, which the viewer does not prefer, is possible, and Outcome Events, in which the negative outcome either occurs or is avoided (**Brewer & Lichtenstein, 1982**). The current study seeks to analyze brain activity during engagement with rhetorical, rather than narrative, material, as participants watch instructional videos on new content.

Cognitive engagement with material other than suspense is highly sought after in school and learning environments. One of the main factors separating virtual courses from the success of teaching students in a traditional, in-person course is maintaining the attention of learners and consistently making them feel engaged with the course, despite distractions in the environment where they are learning. Engagement with educational materials has been linked to motivation, which is determined by value, competence, relatedness, and autonomy. Active learning strategies have been found to enhance motivation and engagement. Challenges to increasing motivation and cognitive engagement include authenticity, inquiry, and collaboration (**Blumenfeld et al., 2006**), which are subsequently the challenges of online learning. The components of virtual classroom engagement include (1) learner-to-learner engagement, which fosters a sense of community and alleviates boredom and isolation; (2) learner-to-instructor engagement, which correlates strongly with successful learning outcome; and (3) learner-to-content engagement, which increases critical thinking and greater subject understanding (**Martin & Bollinger, 2018**). Additionally, a characteristic of students who engage effectively with the online classroom is additional engagement with the collegiate environment in other ways (**Pu-Shih et al., 2010**).

The current study applies prior knowledge of the attention-narrowing hypothesis to cognitive engagement in an online learning environment. Just as suspenseful film clips have been shown to induce the brain to narrow attention to focus on the material, the current study compares whether the same brain activity occurs while watching instructional videos, especially during times when participants report feeling most engaged. As popularity of online classes rises, understanding engagement with that content becomes increasingly more important. Overcoming hurdles of learners' engagement in the online classroom by understanding what triggers the brain to narrow focus has implications in improving the virtual learning experience.

3. Methodology

3. 1 Data Collection

Human participants in the experiment will watch a series of lectures while having their brains scanned in a functional magnetic resonance imaging (fMRI) scanner. This machine measures the changing hemodynamic signals in the brain to determine which regions are active during various time points in the lecture videos. Participants have first undergone various screening techniques to make sure they are compatible with the Siemens 3T fMRI scanner. Screening also ensures that the participants are naïve to the subject material being taught by using a survey to see which computer science classes they have taken. In the first session, they lay supine in the scanner as they undergo a structural scan and watch a series of lecture videos. These videos cover 55 minutes of introductory content on Human-Computer Interaction (HCI), as taught by Dr. David Joyner, a Georgia Tech professor in the College of Computing and the Executive Director of Online Education. Each short video has been labeled with one of the Nine Events, as described by Gagne, according to which is being employed by the instructor.

After each short video, participants were asked to rate how engaged they felt with the content while watching the video. A rating of 1 meant that the participant felt dis-engaged with the content, was thinking about something else, or felt like they were falling asleep; a rating of 4 meant that the participant felt engaged with the content and wanted to learn more. These ratings serve as a subjective measure of cognitive engagement with each piece of content that displays one of the Nine Events. Participants held one 4-button box in the right hand to respond with their cognitive engagement on the scale of 1-4 while in the scanner. There were 10 runs, each with 2-5 videos. After exiting the fMRI scanner, the participants took a short memory test on Qualtrics over the content presented in the videos watched in the scanner.

Approximately one week later, participants returned for the second session of the experiment. First, they completed a memory test over the content, which is very similar to the previous test given directly after the first session; however, the second memory test also contains several short-answer questions, as well as the previous multiple-choice questions, to assess whether participants remember the HCI content on a level of deeper understanding. The participants then watched the lecture videos for a second time on a testing computer in the laboratory. Instead of using the 4-button box to respond with their engagement, the participants used a slider mouse wheel to respond moment-to-moment with their subjective engagement rating on a scale of 1-100, which are recorded at 10 Hz.

3.2 Data Analysis

Data from the fMRI scan, as well as subjective engagement ratings, must be pre-processed and processed in order to determine areas of brain activation in participants at various time points. MRI data were processed using tools from the Analysis of Functional NeuroImages suite of programs **(AFNI; http://afni.nimh.nih.gov/afni)** and FMRIB Software Library **(FSL; http://www.fmrib.ox.ac.uk)**, both of which are open-source software tools to process fMRI data (**M. Bezdek, personal communication, September 23, 2021**).

3.2.1 Pre-processing. First, the raw data were converted from DICOM to NIfTI format, which makes the T1 anatomical scan data usable for pre-processing. Next, the anatomical data were fitted to a 3D image and re-oriented to the RPI space for processing in FSL. Skull-stripping was then performed with the 3dSkullStrip function, allowing for the erasure of the skull bones in order to isolate the brain images.

The functional data were processed for fitting, re-orientation, and skull-stripping before a slice-time correction was then performed with 3dTshift. Motion correction was performed to the average of the time series using 3dTstat and 3dvolreg functions to correct for head movement. Finally, the anatomical data were combined with the functional data using a Gaussian filter, which was applied for spatial smoothing. This step minimizes spatial specificity but allows for analysis of multiple individuals' scans, making results applicable to a general population. The combined anatomical-structural scan is then registered with FSL FLIRT for linear transformation to the Montreal Neurological Institute (MNI) 152 standard space to warp multiple T1 scans. At this point, the data is smooth and in a standard space for formal processing.

3.2.2 Processing First, the Generate Stimulus Files program is applied to correlate questions from the memory test to time points in the videos, which have already been designated as one Event from Gagne's Nine Events of Instruction. The convolver function was applied to the data to combine the hemodynamic response function from fMRI with a down-sampled rate of MRI acquisition. This was used with the rate of change in the continuous slider mouse ratings to create a predictive level of activation based on engagement, which can later be applied to each brain voxel in an individual to determine which areas are active when the participant feels engaged with the content. The processing also included nuisance regressors, such as head movement in six directions and low-level visual properties (hue, saturation, luminance, edges, and optical flow).

3.3 Statistical Analysis

A General Linear Model was performed in order to obtain β-values from each voxel that can compare previously established areas of interest with patterns of brain activity. The design matrix includes a calculated β-value for the engagement slope. which acts as the regressor of interest, in addition to the nuisance regressors. A censor file was applied to erase time points with a large amount of participant head movement or time points without video playing. A first-level analysis was completed on each participant, and group-level analysis allows for us to determine systematic activation regions (**M. Bezdek, personal communication, September 23, 2021**).

4. Results

The following results come from data taken from 5 participants, 3 of which will ultimately serve as pilot data for the experiment once complete. Each of these individuals completed the 2-part series of the experiment.

4.1 Behavioral Data Results

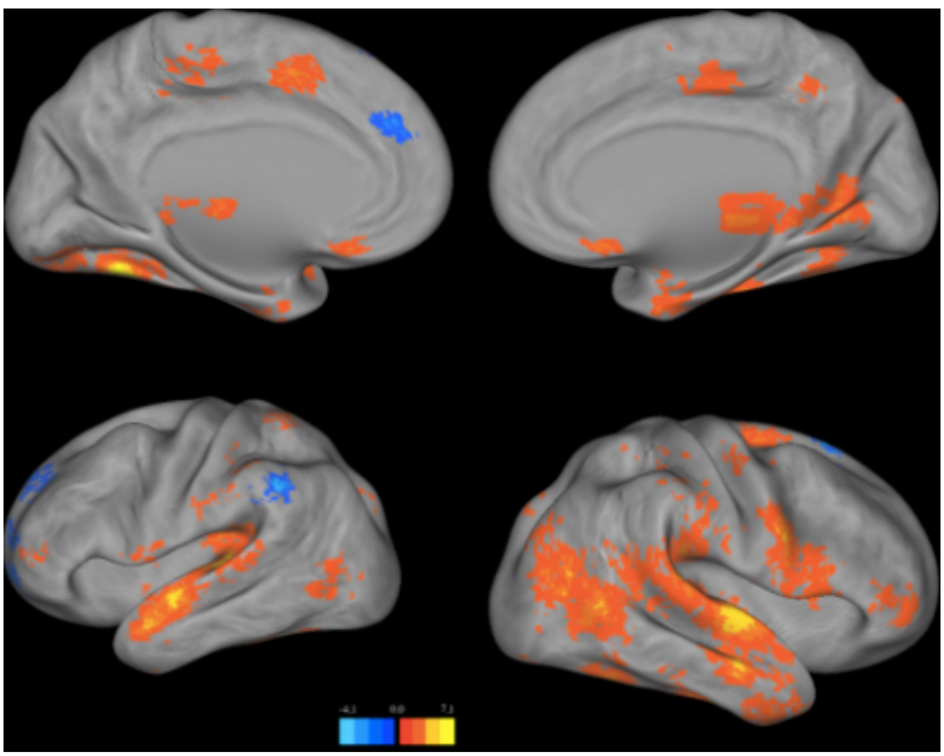
Engagement ratings collected for each video during session 1 are ranked on a scale of 1-4, with 1 being the lowest level of subjective engagement and 4 being the highest. These engagement ratings correlate positively ($r = 0.41$, $p < 0.001$) with the average continuous mouse ratings that were collected during session 2. Additionally, engagement from the continuous mouse ratings were higher during times related to participants' correct answers than the times related to participants' incorrect answers.

4.2 fMRI Data Results in General

The rates of change of the continuous mouse ratings were correlated with areas of brain activation. The brain regions that are active during moments when subjective engagement with the material was increasing include the lateral occipito-temporal cortex and ventral attention network ($p < 0.001$) (**Figure 1**). The brain regions that are less active during times of higher engagement ratings include nodes of the default mode network ($p < 0.001$). Raw engagement, as opposed to the rate of change of mouse ratings, showed greater brain activation in the lateral temporal cortex.

Figure 1.

Brain Activation during Positive Engagement Slope



Note. The image above shows brain regions that are active during times when the participants' subjective engagement ratings on the mouse are increasing. Brain regions active here include the lateral occipito-temporal cortex, which is involved in higher-order visual processing and association, and the ventral attention network, which is involved in re-orienting to newly salient stimuli.

Beta-values for each brain voxel were derived from a General Linear Model for each participant, then a group T-test was performed to test for which beta-values are reliably different from zero across the 5 participants (**Figure 2**). The threshold was an uncorrected p-value of 0.01, which is typically a wider threshold than desired; however, this was necessary to find potentially significant patterns of activation because of the small population (**M. Bezdek, personal communication, November 28, 2021**). No significant clusters were found at higher thresholds.

Figure 2.

Pattern of Activation, as Related to Increases in Subjective Engagement

Region	t-value at peak activation	Size (voxels)	MNI Coordinates of peak voxel		
			x	y	z
Right superior temporal gyrus	27.14	376	60	-12	-15
Left superior temporal gyrus	17.34	166	-48	-12	-9
Right lateral occipito-temporal cortex	15.25	115	69	-54	-3
Left lateral occipito-temporal cortex	10.46	35	-54	-72	0
Right inferior frontal gyrus	17.98	66	60	12	27
Right middle frontal gyrus	22.22	31	48	48	0
Left inferior parietal lobule	-15.02	9	-51	-48	36

Note. The table above shows specific areas of brain activation and their significance level (t-value) during times in which participants reported increases in engagement with the videos. The brain activation data is from the participants' Session 1 in the fMRI, and increases in subjective engagement were measured during Session 2 using the continuous sliding mouse ratings. The cluster size threshold was 30 voxels; however, the left inferior parietal lobule is shown here to show deactivation using the negative t-value in a node of the Default Mode Network.

4.3 fMRI Data Results for Gagne's Nine Events **(Figure 3)**

Event 1 is "gaining attention of the learners." During points of the video that the instructor employed this strategy, activation was measured in primary visual and primary auditory regions.

Event 2 is "informing learners of the objectives." During this event, a similar pattern to Event 1 concerning primary auditory activation was observed. Less primary visual processing was noted in Event 2 than in Event 1. Event 2 only occurs in two instances during the video time course, though, so there is little data supporting these observations.

Event 3 is "stimulating recall of prior learning," and participants showed activity along the dorsal and ventral streams during this event. During the times when the instructor was using Event 3, the videos use visual tools to stimulate recall memory.

Event 4 is "presenting the stimulus," and this Event encompasses most of the videos' content. There was an increase in brain patterns of selective attention during information presentation.

Event 5 is "providing learning guidance." During this event, participants showed deactivation in the medial activation cortex, implying a depression of visual processing in order to focus attention. This brain region is also close to the language centers of the brain, and the videos include a large amount of lecture content that participants must process.

Events 6-9 are not represented well in the instructional videos, and the activation of brain regions was not consistent among multiple participants. These Events are "eliciting performance (practice),” “providing feedback,” “assessing performance,” and “enhancing retention and transferring to the job.”

Figure 3.

(In)Active Brain Regions during Nine Events

	Gagne’s Nine Events of Instruction	(In)Active Brain Regions from fMRI Results	Specific Brain Regions (See Figure 2)
Event 1	Gain attention of the learners	Primary visual cortex, primary auditory cortex	Lateral occipito-temporal cortex (bilateral)
Event 2	Inform learners of the objectives	Primary auditory cortex	Superior temporal gyrus (bilateral)
Event 3	Stimulate recall of prior learning	Dorsal visual stream, ventral visual stream	Lateral occipito-temporal cortex, coordination with multiple other regions
Event 4	Present the content	Selective attention pattern	Inferior and middle frontal gyri
Event 5	Provide learning guidance	*Deactivation* in medial activation cortex	Left inferior parietal lobule
Event 6	Elicit performance (practice)	N/A	N/A
Event 7	Provide feedback	N/A	N/A
Event 8	Assess performance	N/A – Participants took post-test 1 after fMRI scan.	N/A
Event 9	Enhance retention and transfer to the job	N/A – Participants took pre-test 2 after fMRI scan.	N/A

Note. The above chart shows which general brain regions were activated or deactivated during timepoints of the instructional video content correlating to one or more of Gagne’s Nine Events of Instruction. Brain regions active during Events 6-9 were unable to be successfully assessed due to low number of participants and inability to measure these while in the fMRI scanner. Additionally, the more specific brain regions that became activated or deactivated during increases in participants’ engagement are in the right column. More details can be found about this in Figure 2.

5. Discussion

Due to the difficulty of obtaining data from human participants during the pandemic, the low number of participants whose data was analyzed limits the conclusions that can be made about the results; however, a few interesting trends have emerged, and these will be the targets for upcoming analysis with the next group of participants.

There is a notable amount of overlap in brain regions active during times of increasing engagement with the instructional videos as was previously found during increasing engagement with suspenseful film viewing, as noted in the study published by Bezdek (2017). These brain regions are the lateral occipito-temporal cortex, which is involved in higher-order visual processing and association, and the ventral attention network, which allows for re-orientation to changing, salient stimuli. The fMRI results imply that participants are focusing their attention on the videos' instructional content and processing it in a similar way to watching an engaging movie.

The decreased activation in nodes of the default mode network, as shown during times of higher engagement ratings, is a finding consistent with previous suspense studies, such as **Bezdek et al., 2017**. This finding implied that the participants are exerting attention to the instructional video, an externally focused task. Deactivation of the default mode network allows the brain to pay attention to the salient stimulus and less attention to peripheral details.

Overall, Events 4 and 5 that were studied using fMRI with the Human-Computer Interaction (HCI) course that the participants were watching. These Events are common to teaching lecture-based courses, and online courses are more likely to be lecture-based, as student-student or student-professor interaction is difficult virtually. Implications from results from Events 1-3, though consistent among participants, are limited because of the few instances of these Events being employed by the instructor of the HCI course.

The main challenge of online classes is the virtual environment, and by extension, the real environment where learners take their classes. The course material and its instruction must be cognitively engaging in order to stimulate the brain's attention-narrowing hypothesis. Activating this network will increase attention to the class and decrease attention to external distractors in their environments, which could be at home or in a loud, shared workspace. If instructors can effectively employ the Nine Events as they teach virtually, there is greater chance that learners will feel engaged with the course and its material. Events 3 and 4 have shown to be the most effective instructional strategies in inducing activation in the occipito-temporal cortex and ventral attention network. This means that instructors who utilize Events 3 and 4 may be most successful in enhancing learning and promoting better long-term memory of the coursework. Once more data has been collected and analyzed, results will be more conclusive and will be able to be applied directly in virtual classrooms.

5.1 Future Directions

The immediate next step in this experiment is to recruit more participants for the experiment. The data presented above only accounts for 5 participants, which does not lead to powerful enough results to draw definitive conclusions. More data should allow for examination of which Events of Instruction are predictive of learners' strong memory of the material.

The data from the memory tests will then be examined more closely. One way to test how effective the lecture is at inducing true learning will be to correlate activity during Event 4 with participants' memory score. Memory and learning outcomes are likely to follow learners' subjective engagement, which is also likely to be related to brain activity.

Once this study is complete, the deliverable findings will be implemented directly into the Georgia Tech classroom. Our team in Dr. Schumacher's Cognitive Neuroscience laboratory has been collaborating with Dr. Harmon's teams in Georgia Tech Professional Education and the Center for 21st Century Universities to develop an experiment that will allow us for improvements to the virtual classroom at Georgia Tech and beyond.

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