Measuring Cognitive Engagement with Eye-Tracking: An Exploratory Study

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Abstract. In this paper, we focus on objectively measuring cognitive engagement using eye-tracking techniques. Specifically, we analyze both gaze-based and pupil-based eye movement data to assess attention and absorption—two key dimensions of cognitive engagement. These ocular behaviors serve as complementary indicators of cognition, providing a more comprehensive representation of cognitive engagement. Using these objective measures, we examine how navigation style influences cognitive engagement with an 18-page web-based medical decision aid (DA). Our findings demonstrate that evaluating cognitive engagement through the objective measures of attention and absorption offers a more holistic understanding of user engagement. Furthermore, because the system used in our study supports emotionally taxing decision-making, our results extend the measurement of cognitive engagement to contexts beyond those driven by affective states such as flow.

Keywords: Cognitive engagement · Eye-tracking · Attention and absorption

1 Introduction

In information system (IS) research, *cognitive engagement* is often associated with the concept of *flow* [1]. *Flow* refers to a positive affective state characterized by experiencing intense concentration, loss of time awareness, and a sense of total control [2]. For example, in emergency response literature, optimal cognitive engagement with a decision aid (DA) during crisis is linked to the experience of flow. When faced with emergency situations, experienced decision-makers often achieve a state of flow, characterized by *calm alertness* and *focused attention* [3]. Similarly, cognitive engagement, in the user engagement scale (UES) is measured as focused attention, a construct grounded in the concept of flow [4]. Focused attention items in the UES evaluate the flow experience by asking users if they felt time passed quickly while using a system. In a similar fashion but more thoroughly, cognitive engagement in the acceptance literature is captured with a self-reported scale measuring the experience of flow along five dimensions: *temporal dissociation* (the inability to register the passage of time while engaged in interaction),

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focused immersion (the experience of total engagement where other attentional demands are ignored), *heightened enjoyment* (the pleasurable aspects of the interaction), *control* (the user's perception of being in charge of the interaction), and *curiosity* (the extent to which the experience arouses an individual's sensory and cognitive curiosity) [5–7]. Despite the strong association between cognitive engagement and flow in the IS literature, some studies acknowledge that cognitive engagement can occur without the presence of flow [8].

In a recent comprehensive multidisciplinary framework for explaining involvement with an activity cognitive engagement is conceptualized along two distinct dimensions: attention and absorption [9]. Within this framework, attention is described as "*a state of awareness, concentration, and focus*" [9–11], while absorption is defined as a state of flow, characterized by "*a pleasant feeling of being captivated and fully immersed, to the extent of losing track of time*" [9, 12, 13]. Because cognitive engagement is predominantly assessed using self-reported scales, this multidisciplinary framework emphasizes the need to develop objective measures for capturing cognitive engagement in future research. Furthermore, recognizing that engagement is not a static phenomenon but evolves over time [14], the framework highlights the importance of studies that explore the dynamic nature of cognitive engagement.

In this paper, we aim to address the call for objectively measuring cognitive engagement and exploring its dynamic nature through eye-tracking methodology. While we adopt the conceptualization of cognitive engagement as a two-dimensional construct proposed by the multidisciplinary framework of engagement, we expand it to include affective states beyond the traditional concept of flow.

2 Background

Engagement with technology typically reflects an individual's willingness to interact with and remain involved in a system [15]. Flow, as a state that compels individuals to stay engaged or re-engage in an activity, has often been used as a key metric for predicting the likelihood of continued technology use. However, there are many situations where users may be fully immersed in using a system without experiencing flow. For example, completing a task such as reporting business-related expenses in an organizational system may not induce flow and may even evoke negative emotions (e.g., frustration or upset) despite users being fully invested in completing the task and likely to continue using the system in the future. In such cases, relying on flow to measure engagement is unlikely to yield accurate results.

Supporting this argument, a recent study examining user engagement with a suicide prevention app revealed that ratings for the focused attention dimension of the User Engagement Scale (UES) were relatively low. However, objective measures, such as the quality scores of textual entries, and qualitative feedback indicated that users were adequately involved with the app [16]. Given that participants in this study used the app during their visit to an emergency department due to suicide risk, it is unreasonable to expect that their engagement with the app would foster a flow experience. Thus, the findings of this study support the argument that cognitive engagement can occur even in the absence of flow. Hence, we extend the definition of absorption to make it applicable regardless of the valence of a user's affective state during an activity. We define absorption as *a state characterized by being captivated and immersed in an activity*.

To study cognitive engagement without achieving a state of flow, we used a medical decision aid (DA) designed to support emotionally challenging decisions. This DA is specifically developed for surrogates responsible for making informed decisions on behalf of their nonresponsive loved ones in neurosciences Intensive Care Units (neuroICU). Such decisions require processing a substantial amount of complex medical information regarding treatment options and their potential consequences. This includes descriptions of treatments that can artificially prolong a patient's life using intrusive mechanical devices, as well as options that avoid intrusive procedures to prioritize patient comfort for the remainder of their natural life. In this context, achieving a state of flow is neither relevant nor appropriate for fostering cognitive engagement with the system. Instead, an ideal level of cognitive engagement is characterized by the extent to which the system effectively involves users in actively and thoroughly processing the critical information necessary to inform their decisions.

2.1 Measuring Cognitive Engagement with Eye Movements

Grounded in a multidisciplinary framework for engagement with an activity, we measure cognitive engagement along two dimensions: attention and absorption [9]. For attention, we adopt the framework's definition as "*a state of awareness, concentration, and focus*" [9–11]. We extend the framework's definition of absorption to ensure it is not confined to a positive affective state. Specifically, we define absorption as *a state characterized by being captivated and fully immersed in an activity*.

To objectively capture attention and absorption during technology use, we utilize eye-tracking technology. For sighted individuals, visual information is predominantly processed through the eyes, making eye tracking the gold standard for measuring how we attend to information in our visual field [17]. Grounded in the eye-mind assumption—which posits that what we look at is sent to the brain for processing [18]—visual attention has been reliably measured using gaze-based eye movement behaviors. The raw gaze data collected by eye trackers is typically filtered to identify clusters of slow movements called fixations. These slow eye movements represent the focus of attention, as we slow down our gaze to capture detailed visual information about objects that attract our attention [17, 19]. Because gaze streams reveal where and how individuals direct their attention over time [17], they offer objective data for measuring cognitive engagement and tracking its fluctuations over time.

Measuring absorption, however, is relatively underexplored in the IS eye-tracking literature. In the broader eye-tracking field, absorption is closely related to the concept of arousal, which is often captured through pupil-based changes. Arousal, defined as the state of being alert and responsive to stimuli [20], is a fundamental cognitive process underlying information processing behavior. Being captivated and immersed in an activity inherently requires an individual to be both alert and responsive to stimuli. Supporting this argument, a recent study suggests that changes in pupil size offer an opportunity to measure absorption unobtrusively using eye-tracking sensors [21].

3 Methodology

3.1 Study Design and Process

To evaluate which of the two 18-page web-based medical decision aid (DA) prototypes facilitated better cognitive engagement, we conducted an eye-tracking study. Both prototypes contained identical content but differed in navigation style: one used a top navigation bar, while the other featured a left navigation bar. Fourteen participants were recruited for the study and were randomly assigned to review one of the two prototypes while their eye movements were tracked. We utilized the Tobii X300 eye-tracking device to capture participant eye movements. The eye tracker was integrated into the screen resembling a standard monitor thus enabling unobtrusive gaze capture. Also, since the Tobii X300 does not require participants to remove glasses or contact lenses, it facilitated a natural and comfortable environment for studying viewing behavior. Owing to the effect of light on pupil size, as in prior pupillometry studies, we ensured that lighting conditions remained constant.

After using the DA, we utilized two selected items from a prior engagement survey to measure participants' perceptions of attention and absorption [8]. These items asked participants to rate the extent to which: 1) the DA held their attention, and 2) they felt fully absorbed while reviewing the DA, using a 7-point scale. Additionally, participants were invited to provide qualitative feedback about their experience with the DA.

3.2 Eye Movement Metrics

To investigate the progression of cognitive engagement over time, we defined each page of the DA as an area of interest (AOI) and we calculated attention and absorption for each page individually. The DA was designed to be viewed sequentially, from the first page to the last, to optimize information acquisition. As a result, mapping engagement across the 18 pages of the DA provided an effective proxy for tracking the progression of cognitive engagement over time.

To measure attention to the DA objectively, we calculated the total fixation duration for each participant and averaged them across participants for each page (TFD_{Avg} expressed in seconds). This eye-movement metric represents the average amount of time spent visually processing the pages of the DA. Using averages instead of total values helps minimize noise caused by individual differences [22]. Higher fixation duration values often indicate deliberate engagement with content, such as reading text or analyzing visuals [22]. To measure absorption objectively, we calculated the average pupil diameter in z-scores ($PD_{z\text{-score}}$) for each participant on each page [21]. An identical page in both prototypes (Page 0) was used as the baseline. So, to study the progression in pupillary response across pages, $PD_{z\text{-score}}$ was calculated based on the mean and standard deviation of average pupil data from Pages 0–18. This approach helped implicitly baseline-correct as well as control for inter-subject variability in pupil responses [21, 23].

3.3 Analysis

For the statistical analysis, we visualized the distribution of data for outliers and employed log transformation, if necessary. Based on whether or not the data was normally distributed and checking for homogeneity of variance where required, we conducted a two-way Analysis of Variance (ANOVA) without replication. This enabled us to test for differences between designs as well as across pages of the DA.

In addition to the above analysis, we conducted Spearman's correlation test to explore potential relationships between attention and absorption. These two dimensions of cognitive engagement represent distinct aspects of the construct. Similarly, the objective measures of attention and absorption in our study—represented by a gaze-based metric (fixation duration) and a pupil-based metric (pupil diameter), respectively—are known to reflect complementary cognitive processes [24].

4 Results

Table 1 presents the results of the ANOVA comparing differences in cognitive engagement across the 18 pages of the DA and between the two navigation designs of the prototypes. Attention, measured objectively as TFD_{Avg}, showed a higher average value for the prototype with the left navigation style compared to the one with the top navigation style. Similarly, absorption, measured objectively as $PD_{z\text{-}score}$ showed a higher average value for the prototype with the left navigation style compared to the one with the top navigation style. The differences in attention were significant both across the pages of the DA and between the two navigation designs. In contrast, absorption showed significant differences only across the pages of the DA. Qualitative feedback supported these results.

Table 1. Results of ANOVA for objective measures.

Metrics for Attention & Absorption	Mean (SD) TopNav	LeftNav	p-value for Differences (across pages)	(between designs)
TFD_{Avg}	49.80s (38.07)	55.54s (40.22)	**<0.001**	**<0.001**
$PD_{z\text{-}score}$	-0.16 (0.35)	-0.12 (0.41)	**0.01**	0.53

Figures 1 and 2 illustrate the trends in cognitive engagement across both prototypes over time (pages 1–18). Figure 1 presents fixation duration, representing the amount of time users spent fixating their gaze on each page. The trend reflects viewing behavior in response to content density—pages with more content elicited longer fixation durations, indicating thorough reviewing behavior. Figure 2 displays level of absorption for each page, with peaks in the trend corresponding to pages that included images or visual elements such as graphs and charts. For example, page 3 featured an image of a ventilator, while page 8 contained a diagram representing the two different goals of care. Page 10 included images of patients with tubes attached to their bodies, and page 11 had images that included faces. Although page 18 did not have images, it contained a worksheet for

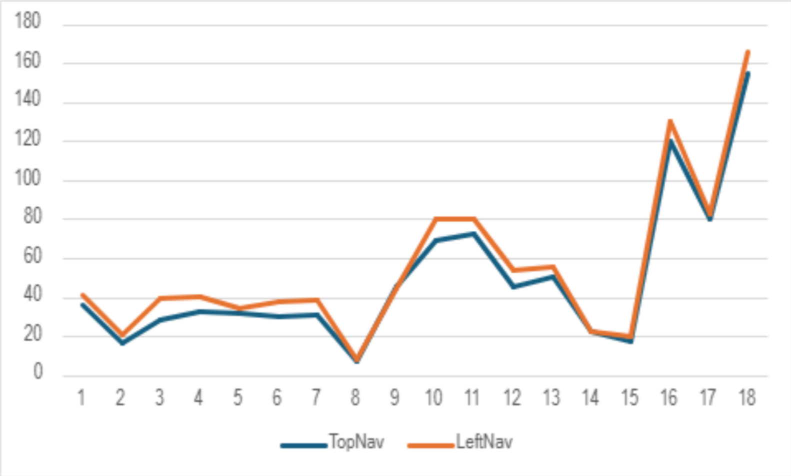

Fig. 1. The trend in attention (TFD_{Avg}) to the DA over time.

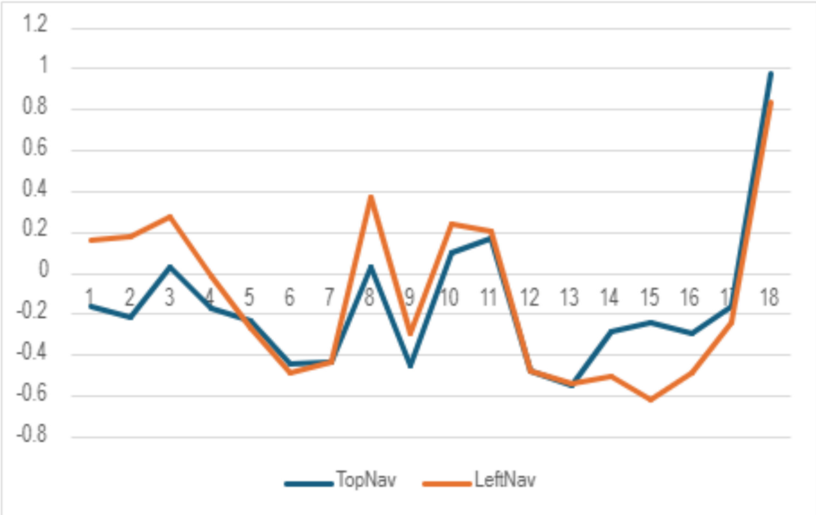

Fig. 2. The trend in absorption (PD $_{z\text{-score}}$) elicited by the DA over time.

deciding on survival or death for their loved one, which surrogates had to prepare for a meeting with their doctor to finalize their decision.

The results for page 8 are particularly interesting because they reflect that attention and absorption are different constructs. This page contained a relatively simple diagram displaying the two choices available to the surrogate: either artificially keeping their loved ones alive or deciding to end their suffering. The relative brevity of the content on this page is reflected by a dip in fixation duration in Fig. 1. However, despite its brief content, this page invoked alertness and responsiveness, as reflected by a spike in pupil dilation (PD) for page 8 in Fig. 2.

We found no significant correlation between attention and absorption metrics in our study, regardless of the prototype design. As shown in Table 2, the results indicate no relationship between the two dimensions of cognitive engagement in this context.

Table 2. Results from correlation analysis for attention and absorption

Metric Pairs	TopNav (r)	p-value	LeftNav (r)	p-value
TFDavg vs PDz-score	0.13	0.60	0.17	0.51

The self-reported ratings for attention, with mean scores of 2.14 and 3.14 on a 7point scale (where 1 represents the highest level of attention and 7 the lowest), indicated that attention was rated in the high to medium range. Similarly, the ratings for absorption (3.14 and 4.14) fell within the higher end of the medium range. However, the differences in ratings between the two prototype designs were not statistically significant indicating that the two prototypes were equally engaging (Table 3).

Table 3. Results of t-test for self-reported measures

	Mean (SD)		
	TopNav	LeftNav	
Perceived Attention	2.14(0.90)	3.14 (1.77)	t-Stat = 1.33, df = 12, p = 0.20
Perceived Absorption	3.14(2.12)	4.14 (1.86)	t-Stat = 0.94, df = 12, p = 0.37

5 Discussion

When measuring cognitive engagement objectively through eye movements, we found significant differences between the two designs. Our results showed that the left navigation design resulted in significantly more attention to the DA pages. However, our analysis did not reveal significant differences in cognitive absorption between the two designs. This may be because both designs contained the same content, differing only in navigation style. As a result, both DA prototypes appeared to keep participants equally captivated in processing the critical information required to inform their decisions.

Comparing perceived attention and absorption between the two designs revealed relatively positive engagement ratings for the DA, but the differences were not statistically significant, indicating that both designs were perceived as equally engaging. However, qualitative feedback aligned with the eye movement analysis results, showed that the left navigation was perceived as more engaging than the top navigation. These findings are not surprising, as detecting statistically significant differences often requires larger sample sizes. Therefore, in formative studies, which typically involve smaller sample sizes, qualitative feedback becomes crucial for providing rich context to interpret inconclusive results. Notably, eye movement data from the same small sample size yielded significant findings. This is because the dataset for each participant included eye movement metrics across 18 pages of the DA, offering the depth and richness needed to generate meaningful insights in formative studies.

Our analysis revealed that engagement varied significantly across the pages of the DA, regardless of navigation style. This finding, indicating that some pages were more engaging than others, is not surprising, as each page provided a different type of information. Figure 2 illustrates the trend in absorption across pages. Notably, the peaks or spikes in the trend correlate with pages containing images or visual descriptions, suggesting that visual content may enhance engagement with the DA.

The exploratory analysis of the correlation between TFD_{Avg} and $PD_{z\text{-}scores}$ did not reveal any significant results, indicating that attention and absorption, as represented by these two variables, were independent of each other in our study. This interpretation is further supported by the differing trends in Figs. 1 and 2, which demonstrate that attention and absorption represent two distinct dimensions of cognitive engagement.

Our findings suggest that fixation duration is a suitable measure for capturing attention. Similarly, when focusing on capturing alertness and responsiveness, our results show that changes in pupil size provide an effective metric for objectively measuring absorption. Additionally, our study supports the argument that the concept of engagement extends beyond flow to include other affective states [8]. Given the emotionally taxing nature of the DA, engagement in our study occurred without the experience of flow, a finding further supported by the qualitative feedback on participants' experiences with the DA.

From an HCI perspective, our results suggest that interface layout, particularly the navigation design, can significantly influence users' cognitive engagement. Our findings indicate that the spatial arrangement of navigational cues can facilitate a more thorough exploration of content—an important insight for interfaces that present dense or critical information, such as medical decision aids, training materials, or data-driven dashboards.

Moreover, measuring engagement through attention and absorption highlights the importance of considering both where users look and how they respond to the content. For instance, a balanced visual design that minimizes clutter, allows sufficient whitespace and structures content in a logical flow is likely to enhance not only attention but also absorption. These design adjustments help prevent users from feeling overwhelmed by extraneous elements or disengaged due to a poor layout.

Incorporating eye movement data into cognitive engagement measurements can be a valuable tool in iterative design cycles. This approach enables UX practitioners to make data-driven decisions about design optimizations, ultimately resulting in more intuitive and user-centered products. Our study further supports this argument with the results of self-reported measures. While we did not find significant differences in perceived engagement between the two designs, the eye movement data revealed that one design was significantly more engaging than the other. This finding is particularly important in the early stages of development, where designers often optimize user experience through a series of iterative studies, each with small sample sizes [25].

5.1 Limitations and Future Research

The results of our study are exploratory and should not be considered definitive. Although the small sample size of fourteen participants limits the ability to generalize these findings to a broader audience, the significant results suggest that measuring engagement with eye movements shows promise. Nonetheless, larger and more diverse samples would strengthen the robustness and generalizability of our findings. We utilized only two eye movement metrics to measure attention and absorption; incorporating additional metrics could further refine and expand our results. Our study focused on a more traditional information system, but future research could test these components using advanced interactive and relational information systems. Moreover, more sophisticated models, such as Mixed Models could be employed to analyze these eye-tracking metrics in real-time, providing deeper insights into UX optimization and cognitive engagement. While we initially focused on the cognitive aspect of engagement, this represents just a foundational step in developing a more refined measurement model for engagement.

6 Conclusion

User engagement with a system can be measured objectively through eye movements, which reflect attention and responsiveness to content. While fixation duration indicates the level of attention given to information, pupil size provides insight into how immersed users are in processing that information. By using an emotionally taxing decision aid (DA), our study supports expanding the definition and measurement of absorption to contexts that do not necessarily involve enjoyable activities. Our results show that measuring both attention and absorption together via eye movements offers a more nuanced and comprehensive understanding of how cognitive engagement unfolds over time.

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