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ORIGINAL ARTICLE

A review of eye-tracking applications as tools for training

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Abstract Substantial literature exists regarding how eye-tracking systems can be used to measure cognitive load and how these measurements can be useful for adapting training in real time. Much of the published literature discusses the applications and limitations of the research and typically provides recommendations for improvement. This review assesses these articles collectively to provide a clearer solution for implementing eye-tracking systems into a training environment. Although limitations exist for using eye tracking as an interface tool, gaze and pupillary response have been successfully used to reflect changes in cognitive load and are starting to be incorporated into adaptive training systems, although issues are still present with differentiating pupil responses from simultaneous psychological effects. Additionally, current eye-tracking systems and data analysis software have proven accurate enough for general use, but issues including system cost and software integration prevent this technology from becoming commercialized for use in common instructional settings.

Keywords Eye tracking · Cognitive load · Instruction · Adaptive e-learning

1 Introduction

1.1 Traditional training is outdated

Although University administrators may find large classes to be more economical and more homogeneous in terms of instruction, there are drawbacks in terms of the amount of time required on the instructor's behalf and the quality of education (Crull and Collins 2004). Large classes may overburden teachers, limit class discussions, and reduce the number of assignments (Longmore et al. 1996). Time management and organization also become critical issues in large-class instruction (Lewis 1994). Consequently, in more complex educational settings, such as at the university level, allowing or encouraging interaction may be particularly difficult to sustain because the time commitment required jeopardizes course completion (Saroyan and Snell 1997). There is a need for the ability to provide personalized, focused instruction to large classes in order to improve the level of student interest and immersion in instructional content. Specifically, practitioners (Berry 2000; Coné and Robinson 2001; Rossett 2002) and researchers (Brown and Ford 2002; Salas et al. 2002; Steele-Johnson and Hyde 1997) agree that technological advances are dramatically altering the training and development landscape (Welsh et al. 2003) and may improve some of the challenges faced by educators who have large class sizes, are not co-located with their students, or who have few resources. In response, organizations are transitioning to e-learning [the use of computer network technology, primarily over an intranet or through the Internet, to deliver information and instruction to individuals (Welsh et al. 2003)] for a variety of reasons, including the desire to (1) provide consistent, worldwide training; (2) reduce delivery cycle time; (3) increase learner convenience; (4) reduce information overload; (5) improve tracking; and (6) lower expenses (Welsh et al. 2003).

1.2 Improvements in e-learning

Extending this to military applications, the solution of offsetting the inadequacies of training large numbers of

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trainees via traditional methodologies (like lectures) is transitioning to the electronic domain. Meta-analyses of the literature support the conclusion that technology is, on average, slightly more effective than the classroom and that studies tend to report better results for technology-delivered training than for classroom training (Welsh et al. 2003). This ensures that all trainees are receiving consistent training across multiple locations quickly and in less time (Welsh et al. 2003). Initial investment in e-learning technologies often deters its widespread implementation, utilizing both information technology and staff to ensure success. Specific costs include development costs to design and build the courses as well as hardware and software costs to allow users to access the training (Kramer 1991; Kumar 2007; Oonk et al. 2003; Oyekoya and Stentiford 2006; Welsh et al. 2003).

Recent developments in e-learning have yielded vast improvements in electronic instruction by transitioning instruction from a static interface to a dynamic regime that can adapt to each individual, but this evolution is accompanied by additional complications such as how and when to present feedback and the effects of these interruptions. Initial deployment of e-learning systems focused on presenting information to the user with little or no feedback [information given to learners about the accuracy of their response (Mory 2003)] and testing the amount of information he or she retained (Welsh et al. 2003). Self-reported measures can be used to identify subjective levels of cognitive load during an activity, but these measures have questionable accuracy and do not support real-time changes. However, recent studies have shown that obtaining psychological information from the user via psychophysiological responses (physical reactions to psychological changes) can be used to transform static e-learning interactions into dynamic ones (Coyne et al. 2009; Gutl et al. 2005; Rapp 2006). This capacity of an e-learning environment to react and adapt to the user's psychophysiological responses is referred to as adaptive e-learning. The benefit of this dynamic learning environment is that feedback can be administered in real time during instruction, and the presentation of information can be adapted to the needs of the user. One such system, AdeLE (Adaptive e-Learning with Eye tracking) has the ability to exploit real-time eye-tracking information from the user to detect cognitive load levels (varying degrees of mental effort required during a task (Paas et al. 1994)) and to dynamically adapt instruction to promote efficient information transfer (Gutl et al. 2005). Applications of this technology are demonstrated via studies highlighting the importance of knowing when to present interruptions during training and its negative effects on trainees when involved in minimal mental activity as compared to high mental activity (DeLeeuw 2009; Mewhort et al. 2010; Nordahl and Korsgaard 2010). In other words, there are optimal opportunities to interrupt learners; if information about one's mental activity is available, interruptions can be used effectively to guide the user to pertinent information without hindering information retention. Thus, the goal is to identify a method by which real-time psychophysiological response data can be collected, analyzed, and implemented without compromising the learning experience. It is therefore the focus of this review to determine whether an eye-tracking system that measures psychophysiological responses, specifically gaze direction (where the user is looking) and pupil dilation (the pupil diameter of the user), to indicate attention (applying mental effort toward an object) and varying levels of cognitive load can be effectively used in a training environment by utilizing this information in real time.

1.3 Overview

For the purposes of this review, an eye-tracking system will refer to any set of monitoring tools that can measure gaze direction, fixation duration, pupil dilation, or a combination of those. The primary benefit of an eye-tracking system is that it provides a constant stream of information about the user in real time that can be used to assess the user's mental state (changes in baseline mental functionality) and/or where they are focusing their attention (Liu and Chuang 2010). To indicate the user's mental state, the positions and the number of fixations, the fixation duration, and the saccade length (the distance a gaze direction traverses between fixations) are the most common variables (Liu and Chuang 2010). To measure attention allocation, the duration of eye fixations, the number of fixations, and the amount of re-fixations (fixating on an area or object multiple times) reveal patterns describing how a user's attention is directed to a given region or visual area of the computer screen (Liu and Chuang 2010). In the recent literature, fixations have been used successfully to gauge the level of image complexity (Crosby et al. 2001) and problem complexity (Jazbec et al. 2006) as well as to identify the part of a screen or slide that is viewed during instruction (Guan 2002; Liu and Chuang 2010; Pierce 2009; Schrammel et al. 2009).

In addition to fixations, pupil response has gained significant popularity in terms of indicating a user's cognitive load. Inferring cognitive load from pupil responses is known as "pupillometrics," a term invented by Hess (1965) to describe a research field (started in 1960) encompassing the effects of psychological influences, perceptual processes, and mental activities upon the pupil size. Pupil size, or the diameter of the pupil, is correlated with the level of cognitive load that the user is experiencing (Guan 2002). Marshall (2002) defines the index of cognitive activity as a new method for evaluating cognitive load from pupil dilation. The index typically is reported as the average number of abrupt discontinuities in the signal per second over a designated period of time (Marshall et al. 2003).

Much of the work that has been done to investigate the validity and applications of eye-tracking systems tends to overlap, leading to some generalities that can be made to steer future research into areas that have not yet been investigated. There is a significant quantity and variety of information regarding the effects of different modalities of instruction on cognitive load and eye-tracking measurements, but there does not appear to be a comprehensive overview and analysis combining all of this information at once. For example, presentation formats comparing written text with spoken text (DeLeeuw et al. 2010; Schmidt-Weigand 2006; Schmidt-Weigand et al. 2010a, b) and static images with animations (Arguel and Jamet 2009; Bétrancourt et al. 2008; Guan 2002; Kühl et al. 2011) have been investigated numerous times, each with similar outcomes. However, it would be helpful to see all of this information listed together and compared with one another to aid in finding similarities and differences as well as determining new directions for future research.

1.4 Purpose of this review

Regardless of whether cognitive load levels are too high or too low, both of these conditions are generally agreed upon to result in decreased performance (Paas et al. 2004), such as longer interaction times, decreased accuracy, or reduced information transfer. Acquiring a greater level of performance necessitates achieving a moderate level of cognitive load, which requires some method in order to determine the user's cognitive load level: For the purposes of this review, methodologies are focused on eye-tracking measures. In response to the need to better understand the usefulness of eye tracking across a variety of settings, a review of the literature was performed to identify areas of research involved with the development and application of eye-tracking systems and to find limitations, contradictions, and recommendations for future research and applications. The applications of eye-tracking systems were limited to those involving instructional scenarios that use eye tracking to supplement or enhance education by measuring cognitive load and using that information appropriately. This review can help to elucidate how individual components of a learning system can affect the end goal of user performance and inform eye-tracking use for adapting training in real time by assessing cognitive load.

2 Method

Three search engines were used to obtain relevant literature: Google Scholar®, Science Direct®, and Inspec®. The search for articles used the following query items—"eye tracking", "learning", and "cognitive load"—and was limited to only those published between 2000 and 2010. It was decided to restrict the review's focus to the past decade worth of literature due to the opinion that publications prior to this time frame likely would be irrelevant unless they were cited in more recent publications. It is also expected that any research before the year 2000 is outdated due to improved theories, technology, and applications. The search resulted in a total of 1068 across search engines (see Table 1). Rejection criteria and their respective statistics are provided in Table 2. Inclusion criteria were relevancy and whether the article focused on learning, cognitive load, or eye tracking.

Accepted articles (319 total, 243 of which were journal articles, 76 of which were dissertation or Masters theses) were categorized by learning (117), eye tracking (108), or cognitive load (94). Further revisions and rejections were conducted based on the goals of each article: instruction (pertaining to use by instructors), validation (determining the usefulness of a product or idea), cognition (the amount of cognitive load the user experiences or how he or she thinks), interface design (the layout or physical design of the educational tools), review (gathering and interpreting literature regarding a specific topic), eye tracking (promoting the evolution of eye-tracking technology or use), human–computer interaction (how the user manipulates the educational tools), and task performance (how much a user improves his or her skills completing a task). Some of these goals overlapped, but the purpose of separating the literature into these goals was to help with initial organization and aid in the analysis, structure, and focus. These were not intended to be definitive classifications or limitations of the literature that was reviewed. Further analysis of the literature allowed organization of the articles by what

Table 1 Results of search queries using different search engines

Database	Articles
Google scholar	917
Science direct	149
Inspec	2
Total	1,068

Table 2 Article rejection statistics

Criteria	Articles
Duplicate	159
Irrelevant	446
Improper format	97
Unavailable	40
Foreign language	7
Total	749

measurements were taken and by what means. Criteria for assessing the contribution of the article were statements regarding changes between the control and experimental conditions or correlations between two dependent variables. Specifically, if gaze data or pupil response measurements were found to objectively identify differing levels of cognitive load, attention, or other psychological responses, the article was given further consideration for inclusion.

3 Results

3.1 Comparison to other methods

It is useful to become aware of how eye-tracking data compare to other forms of psychological measurement, since combinations of data may allow for the distinction of different psychological factors. Listed below are some of the measures that were compared to eye-tracking measures.

- Retrospective think-aloud usability method (RTA) (Zhiwei et al. 2006).
  - Fixation data correlated with what participants reported about the experiment.
- Skin conductivity and mouse click pressure (Ikehara and Crosby 2005).
  - Skin conductivity decreased with increased difficulty.
  - Z-scores of eye movements (saccade length) decreased with increased difficulty.
  - Pressure applied when clicking increased with increased difficulty.
- Keyboard and mouse behavior (Mueller et al. 2008).
  - Changes in eye-tracking measures correlated with increase keystrokes and mouse clicks.
- Heart rate variability (HRV) (Lin and Imamiya 2006; Urry et al. 2009).
  - Higher heart rate variability correlated with increased saccade speed.
- Electroencephalograph (EEG) (Marshall et al. 2003).
  - Increased mental activity corresponded to increase ICA measures (based on pupil size).

One instance where pupil measures were not useful was in a task designed to test user's cognitive ability with an inverted visuomotor tracking task (Kobori and Abe 2009), which led the authors to suggest that the inversion-evoked cognitive load reflects changes in motor task and is not merely a response to high errors. Furthermore, it was shown that pupil response was incapable of predicting user self-explanation (Conati and Merten 2007). It is clear from the above-listed verification mechanisms that combinations of measurement methods may provide additional objective support and reduce errors (Lin et al. 2008). However, it is implicit from the lack of supporting literature that these comparisons to existing methods require additional testing to lead to a clear consensus regarding whether or not other data collection methodologies can be replaced by eye-tracking measurements.

Regarding data collection, every eye-tracking system has unique ways of collecting and analyzing data. In most cases, the data that are being collected can be analyzed via software either in real time in order to be used in adaptive training systems or after the experiment to see general trends in the data. Time required for analysis can be lengthy without the aid of software, but most eye-tracking systems come with built-in data analysis software to output pupil radius measures, area of interest plots, etc., thus making data analysis relatively fast, whether it is done for individual users or for groups.

Although there are few articles that describe how eye-tracking measures compare to other methods of psychophysiological response data collection, there exists literature supporting the use of eye-tracking data as a single tool for data collection. The remainder of this document will focus on two specific types of measurements that can be obtained from an eye-tracking system: gaze and pupil response. Gaze will refer to the direction that a user is looking, and pupil response will refer to the diameter and changes in diameter of the users' pupils.

3.2 Gaze applications

Literature regarding the applications and benefits of using gaze data (gaze direction, fixation duration, and saccades) has been grouped according to the application of the measurement as shown in Table 3 along with the relevant citations. The sections following the table will discuss the merits and generalizations of the listed articles to extend their results to more broad applications.

Generally, gaze measurements are useful for indicating levels of cognitive load and have been applied to reading comprehension and presentation design. In addition, information regarding the user's focus of attention has been used to gauge distracting elements and the effectiveness of cueing. Also, human–computer interaction using gaze as a selection methodology is generally successful, particularly for image selection or for large screens. The following sections are organized to provide a logical progression of how the information obtained from gaze measurements can be used: from approximating cognitive load levels, to using

Table 3 Applications of gaze measurements

Application	Measure	Citations
Indicating cognitive load	Direction	Waniek and Ewald (2008), Bednarik (2005), Murray (2000), Pierce (2009)
	Duration	She and Chen (2009), Van et al. (2005), Crosby et al. (2001)
	Saccades	Di Stasi et al. (2010), Irving et al. (2009), Unsworth et al. (2004)
Reading comprehension	Direction	Bohan (2008), Ifenthaler et al. (2008), Knoeferle and Crocker (2009), Mitchell et al. (2010), Poulter et al. (2005), Wengelin et al. (2009), Heuer (2009), Raidt (2008), Traxler (2009), Buscher et al. (2008), Nicholson (2007), Salmerón et al. (2010), Holsanova et al. (2009), Prendinger et al. (2009)
	Duration	Doherty et al. (2010), Schmidt-Weigand et al. (2010a, b)
	Saccades	Schnitzer and Kowler (2006)
Presentation design	Direction	Alacam (2010), Brunyé and Taylor (2009), Huang et al. (2008), Josephson and Holmes (2006), Liu and Chuang (2010), Loboda and Brusilovsky (2010), Dabbish and Kraut (2004), Gilman and Underwood (2003), Lorigo et al. (2008), Meyer et al. (2010), Schrammel et al. (2009), Bednarik and Tukiainen (2006), Körner (2004), Cook et al. (2008), Nesbit et al. (2007), Patrick et al. (2005), Schmidt-Weigand (2006), Slykhuis et al. (2005), Rouet et al. (2008), Bednarik et al. (2005)
	Duration	Kuo et al. (2009), Yecan et al. (2007), Guan (2002)
Distraction and attention guiding	Direction	Atkins et al. (2006), DeLeeuw (2009), DeLeeuw et al. (2010), Fisher et al. (2009), Gilland (2008), Memarovic (2009), Yulan et al. (2007), Fuller (2010), Sodhi et al. (2002), Boucheix and Lowe (2010), Ozcelik et al. (2010), Teodorescu (2004), Groen and Noyes (2010), de Koning et al. (2010), Feil (2009), Murphy (2007)
	Saccades	Stuyven et al. (2000), Vandierendonck et al. (2008), Seidlits et al. (2003)
Human–computer interaction	Direction	Mollenbach et al. (2010), Huang and Snedeker (2009), Alaçam and Dalcı (2009), Kammerer et al. (2008), Kumar et al. (2007), Porta and Turina (2008), Wang et al. (2001), Adams et al. (2008), Kumar (2007), Oyekoya and Stentiford (2005, 2006), Sibert and Jacob (2000), Smith et al. (2005), André et al. (2006), Surakka et al. (2004), Duchowski et al. (2002), Sennersten et al. (2007), Baldauf et al. (2010), Bulling et al. (2008)
	Duration	Pan and Soto (2010), Špakov (2005)

cognitive load levels to gauge reading comprehension and presentation design, to using presentation design to purposefully distract or attract the user's attention based on cognitive load levels, to using the user's attention to interact with the computer.

3.2.1 *Indicating cognitive load*

Cognitive load theory emphasizes that the limitations of working memory [temporary storage of information for immediate use (Sweller et al. 1998)] can impede knowledge acquisition and schema construction (relationships between concepts) (Paas et al. 2004). It is an instructional theory that aims to provide parameters for optimizing cognitive load, or the load that performing a particular task imposes on the learner's cognitive system (Paas et al. 1994), associated with learning complex cognitive tasks (Paas et al. 2005). For these reasons, the ability for a system to accurately detect cognitive load without inadvertently affecting it is critical for optimizing adaptive learning systems.

Evidence from the literature supports the use of eye-tracking systems to effectively indicate cognitive load during learning exercises. Specifically, the user's gaze (direction and duration) has been reported to correlate with depth of learning (She and Chen 2009; Van et al. 2005), complexity (Crosby et al. 2001; Waniek and Ewald 2008), and mental workload (Bednarik 2005; Murray 2000; Pierce 2009). In all of these studies, the fixation behavior of the user was linked to his or her levels of cognitive load and general understanding of the learning material, whereby longer fixation durations (on average) correlated with higher learning and higher cognitive load. To apply fixation data to an adaptive e-learning system, the fixation durations for important objects can be calculated in real time and be set to trigger a feedback mechanism to draw the user's attention back to the relevant area if the user's fixation duration does not meet a calculated threshold. The fixation data can also be used to estimate the user's cognitive load over time, allowing developers to control the complexity of content presented in order to maintain moderate cognitive load levels to reduce the likelihood of overloading or underloading (too much or too little load, respectively) the user.

Similar to fixations, saccades have also been used as an indicator of cognitive load. Saccades, defined as ballistic eye movements that occur on very short timescales between fixations (Sibert and Jacob 2000), have also been demonstrated to correlate with changing levels of cognitive load: Higher cognitive load levels correlated with higher saccade peak velocities (Di Stasi et al. 2010) and more saccade errors (Irving et al. 2009). However, some have suggested that saccades alone are insufficient for isolating working memory because no cognitive function is occurring during a saccade (Unsworth et al. 2004). Comparing fixation data to saccades, the ability to gauge cognitive load is likely better suited for fixation data since little or no information is being retained or processed during saccades. It should be noted that saccades and fixations are related measures. Saccades occur between fixations. So if the number and durations of fixations increase, then the number of saccades should decrease. This relationship between data measures needs to be considered during statistical analysis if both fixations and saccades are to be used.

Fixations and saccades can occur for a variety of reasons in a multitude of visual media. Three main types of media presentation that will be discussed are text, images, and animations. With specific reference to text, eye-tracking systems have been combined with text-based instruction and interaction to gauge different cognitive processes. Now that a foundation for the relationship between fixations and cognitive load has been presented, this information can be applied to real-world training systems which will be discussed in the following sections.

3.2.2 Reading comprehension

A process which lies upon the boundary between saccades and fixations is reading; it requires recognition of characters or combinations thereof in order to process language. The duration of each fixation can vary for many reasons, including language comprehension difficulty (Bohan 2008; Doherty et al. 2010; Ifenthaler et al. 2008; Knoeferle and Crocker 2009; Mitchell et al. 2010; Poulter et al. 2005; Schnitzer and Kowler 2006) and written language production (Wengelin et al. 2009), whereby longer fixations indicate a greater level of cognitive processing. In a training system, fixation data can be used to gauge the user's difficulty with the reading material and adapt the material to heighten or reduce cognitive load levels. For instance, if the user's cognitive load levels are too low, pop-up windows can be used to ask questions for the user to answer, thus forcing the user to concentrate on the material and critically contemplate a response in order to proceed. If cognitive load levels are too high, then presenting the user with a shortened version of the reading material that merely summarizes the text will allow the user to quickly review and clarify the material and may also act as a brief resting period.

Fixations while reading have additionally been used in conjunction with spoken text and dialogue to understand how auditory information affects the user's gaze toward text (Heuer 2009; Schmidt-Weigand et al. 2010b) or objects (Raidt 2008). Knowing which words were viewed (Traxler 2009), feedback could be generated to improve future reading or searching (Buscher et al. 2008). Types of feedback that would be applicable to this scenario based on fixation data would be to highlight important words or sentences that have been skipped, provide definitions for words that resulted in higher fixations (implying the word may not be understood), or to provide in-depth explanations of concepts that may have been missed for text that should have required higher cognitive load and did not. The type of feedback should avoid requiring human interaction or input, as disfluency (reduction of language processing ability) may occur (Nicholson 2007).

Extending the analysis of text-only reading to combined text and picture reading, fixation data have provided insight into the effects of information presentation, such as providing graphical overviews before reading text to improve comprehension (Salmerón et al. 2010) and improving user performance (via information retention and application) by satisfying spatial contiguity between text and illustrations (Holsanova et al. 2009). Fixations on specific portions of a graphic can be used to infer the user's understanding of the graphic based on whether he or she is looking at relevant areas of it and by the level of cognitive load accompanied by these fixations. The body of text associated with the graphic can then be tailored to identify crucial components of the graphic that were or were not examined or be more or less descriptive in nature if cognitive load levels are too high or low respectively.

Although it has been suggested that gaze is not a complete predictor of intention (what a person wants or wants to bring about in the environment) or of uncertainty (Prendinger et al. 2009), the majority of the literature indicates that the general application of gaze data is sufficient under most circumstances. Developing the applications for which fixation information can be used further, particular attention can be given to how the information is being presented.

3.2.3 Presentation design

The physical layout of an instructional interface has been shown to play a role in the user's ability to use and understand the interface and the displayed information. From a graphical standpoint, the layout of information has been correlated with effort metrics (like information retention and fixation duration) using gaze data (Alacam 2010; Brunyé and Taylor 2009; Huang et al. 2008). Gaze data have also been used to show how the presentation of information affects how much information is transferred (Josephson and Holmes 2006; Liu and Chuang 2010; Loboda and Brusilovsky 2010) and whether information is overbearing (Dabbish and Kraut 2004). These findings are relevant to training for their applicability to optimizing the amount of content to display on a screen without causing the user to become overloaded. Ideally, a screen can be designed to only show as much information to the user as necessary to complete the task, whether by hiding unnecessary details or by allowing the user to choose what content is displayed and when it should appear, flight simulators for example. Alternatively, portions of a screen can be obscured to reduce the potential of overloading the user too quickly (for a complex graphic or map) and can be sequentially revealed so that schemas can be constructed between the regions that were and were not obscured.

Part of the user's capabilities lies in how they perceive and respond to visualizations. There may be an underlying perceptual effect whereby the mental representation of the information is altered by the surrounding information or the means by which the information is presented (Gilman and Underwood 2003; Kuo et al. 2009; Lorigo et al. 2008; Meyer et al. 2010; Schrammel et al. 2009). Therefore, gaze information can be used to measure the amount of attention given to surrounding graphics or regions to ascertain the level of concentration the user has toward the objective. Also, cognitive load levels can be measured while different presentation formats are used (videos, slides, text) to determine which format is best suited for each user (Bednarik and Tukiainen 2006; Guan 2002; Körner 2004; Nesbit et al. 2007; Patrick et al. 2005; Schmidt-Weigand 2006; Slykhuis et al. 2005; Yecan et al. 2007). Differences in prior knowledge can also be determined by how the user analyzes a graphic (Cook et al. 2008), whether he or she fixates more upon the complicated intricacies of a graphic or the overall design.

To support the utility of gaze information with respect to attention and interface design, systems have been developed such as GazeTracker (Rouet et al. 2008) and Jeliot-3 (Bednarik et al. 2005), which can be used to integrate text and pictures in dynamic interfaces. The ability to take gaze information and apply it to an adaptive interface may provide an advantage over traditional methods of instruction by possibly improving the amount of information transfer and retention by monitoring cognitive load levels and ensuring these are not too high or too low. There are only a few such systems being investigated according to the literature, so the true potential of such systems require much more investigation.

In order for an interface to be adaptive, some aspects of the presentation must change, either by actively changing what the user sees or by changing the presentation of future content. Whether or not these changes are noticeable to the user may be thought of as distracting elements or as attention guidance. Luckily, the impact of these elements has been investigated using eye-tracking systems.

3.2.4 *Distraction and attention guiding*

When designing a user interface, one may consider simplifying the visual stimuli that are presented in order to reduce distracting elements and to avoid increasing extraneous cognitive load (unnecessary load caused inefficient instructional design) (Bétrancourt et al. 2008; Nimwegen 2008; Sweller et al. 1998). Although some research has indicated that distracting and unnecessary elements cause disruptions and interference to cognition (Atkins et al. 2006) and saccades (Stuyven et al. 2000; Vandierendonck et al. 2008), a similar study has shown that users will fixate upon distractors less often when extraneous cognitive load is increased (DeLeeuw 2009; DeLeeuw et al. 2010). This effect was observed by using gaze data to calculate the frequency and duration of observing distracting elements during different periods of extraneous cognitive load. From these studies, it cannot be speculated whether or not increasing one's extraneous cognitive load will induce a greater level of concentration and focus toward relevant elements of the interface. One may hypothesize that increasing the extraneous cognitive load will detract from working memory, and the amount of information transfer and retention will be hindered. Therefore, it is recommended that more research is required in order to determine whether the presence or absence of distracting elements have any effect on information transfer to the user.

A multitude of environments and conditions exist wherein a person is required to multitask during an operation or procedure. These circumstances can occur during simple tasks such as writing or talking, or during more complex tasks such as driving or flying. In the field, vehicles can be used for transporting equipment and units or for tactical maneuvers. For these reasons, the ability to detect driver or pilot distraction can assist in ensuring effective vehicular control and minimizing the potential for erroneous decision making and catastrophic consequences. Multiple studies have examined the effects of distractors on the driver's attention (Fisher et al. 2009; Gilland 2008; Memarovic 2009) and have been shown to detect driver distraction with accuracies as high as 81 % (Yulan et al. 2007). Some studies have shown that, while driving, increased level of visual difficulty worsened driving performance (Fuller 2010) and that visual tunneling occurred (Sodhi et al. 2002), indicated by a decrease in peripheral vision performance and a narrower angle of vision. These driving studies focused on an increase in intrinsic cognitive load caused by making the driving tasks more difficult and resulted in poorer task performance compared to the control groups. From these assumptions, it would be prudent to suggest a study in which distraction was tested with varying levels of intrinsic and extrinsic cognitive load. The results of such a study may provide insight into the processes involved in distraction in terms of different types of cognitive load and how to best control the user's attention using different levels of intrinsic and extraneous cognitive load. It should also be noted that although these studies focused on driving, the results are applicable to other scenarios like flying an aircraft or steering a robot.

Similar in principle to distraction, attention guiding (also known as gaze guiding) is an alternative means to minimize distraction and to ensure that appropriate information is being investigated. The fundamental idea behind gaze guiding is to highlight or accentuate a region of text or a portion of an image or animation in order to differentiate it from its surroundings, thus making it evident for the user to view that particular area. This has been applied in educational settings wherein the presence of gaze guiding had a positive influence on the gaze direction (Boucheix and Lowe 2010; Ozcelik et al. 2010; Teodorescu 2004) and saccades (Seidlits et al. 2003). Stemming from this effect, gaze guiding has been shown to improve task performance (Groen and Noyes 2010), although its effect on cognitive load has been contested (de Koning et al. 2010; Feil 2009; Murphy 2007), so more evidence is necessary to solidify any conclusions.

Up to this point, the primary consideration of eye-tracking system applications has been to detect psychophysiological responses to environmental stimuli and correlate them with psychological effects in order to gauge information transfer. If this information instead was used as a control mechanism, similar measures such as gaze direction and fixation duration could be applied to human–computer interaction for novel training purposes.

3.2.5 Human–computer interaction

Gaze data from an eye-tracking system generally will consider fixation duration as an indicator of selection. One study reported fixation durations of 78.81 and 131.45 ms for short and long gaze gestures, respectively (Mollenbach et al. 2010). Particular instances where gaze-based interaction was useful were visual selection (Huang and Snedeker 2009; Alaçam and Dalcı 2009; Kammerer et al. 2008; Pan and Soto, 2010) and text entry (Kumar et al. 2007; Porta and Turina 2008), although the utility of such a system depends heavily on interface design (Alaçam and Dalcı 2009; Kammerer et al. 2008). One such system that was developed is called EASE (eye assisted selection and entry) (Wang et al. 2001), which uses gaze data to infer the selection of objects and text.

Comparing the eye-tracking method of input to other methods, namely the mouse, it has been stated that the eye-tracking interface was similar or superior in performance for image identification and selection in terms of speed (Adams et al. 2008; Kumar 2007; Oyekoya and Stentiford 2005, 2006; Sibert and Jacob 2000; Smith et al. 2005) and could correctly classify the subject's choice of selection at least 81 % of the time (André et al. 2006). Although an accuracy of 81 % is much less than that of a mouse, this becomes a question of whether the improvement in speed and lack of accuracy merits classifying the eye-tracking method of selection similar to a mouse, but this is highly situation-dependent. For instance, if the user's hands are already occupied with other motor devise and a mouse is incapable of being used, then 81 % accuracy may be considered acceptable if alternative means are slower or simply unavailable. These studies can be considered benchmarks for future improvements to the techniques implemented for selection using eye-tracking systems. Alternatively, if instead of fixation duration the selection method required a physical response such as facial muscle contraction (Surakka et al. 2004) or blinking (Špakov 2005), the user is likely to become fatigued, and the eye-tracking method of input will result in inferior performance compared to that of the mouse. Overall, it is suggested that fixation duration is better suited for gaze-based human–computer interaction, but its efficacy is dependent on the interface design and the situation in which the system is used.

Extending the use of eye-tracking systems further, eye-tracking systems have been incorporated into immersive settings such as 3D virtual environments (Duchowski et al. 2002), gaming platforms (Sennersten et al. 2007), and in the field (Baldauf et al. 2010). The last setting mentioned utilized an eye-tracking system called KIBITZER which combined GPS data and gaze direction in the field to determine what object the user may be viewing so that information regarding the object could be downloaded and presented to the user. This particular system has potential applications in training to assist in carrying out missions and identifying objects in unfamiliar territory. Also, it has been shown that eye-tracking measurements could be made in the presence of noise, such as walking (Bulling et al. 2008).

3.2.6 Conclusions

The use of gaze measurements in training settings have a wide variety of applications: indicating cognitive load, assessing reading comprehension, designing instructional materials, gauging user distraction and attention, attention guiding, and human–computer interaction. The majority of the literature suggests that the use of gaze data in these applications is successful in detecting changes in cognitive load and assessing attentional focus, which allows for the possibility of utilizing this information in adaptive training systems. Specifically, increased fixation durations will generally correspond to increases in cognitive load and attentional focus. Also, the user's gaze information can be used to determine what information is being observed and which is not, allowing for an adaptive training system to guide the user's attention to pertinent information. Recommendations for the improved application of eye-tracking technology in training environments include minimizing costs of the systems to increase the cost-to-benefit ratio to make these systems more accessible, investigating the ability of correlating fixation data to cognitive load measures further by assessing how presentation adaptation affects information transfer and retention, and developing ways to integrate eye-tracking data usage into commercially available programs intuitively.

3.3 Pupil-response applications

Literature regarding the applications and benefits of using pupil response data (pupil dilations or combinations of pupil response data with other measurement types, such as heart rate variability or skin conductance) has been grouped according to the application of the measurement as shown in Table 4 along with the relevant citations. The sections following the table will discuss the merits and generalizations of the listed articles to extend their results to more broad applications.

To summarize the findings from Table 4, changes in pupil diameter were found to be indicative of behavioral responses to arousal (a heightened sense of alertness or excitement), clarity (a sense of understanding), and frustration (being annoyed or upset), but the ability to differentiate one behavioral response from another remains unexplored. In addition, some adaptive interfaces and adaptive e-learning environments have been developed, which utilize pupil response in conjunction with other psychophysiological measurements, but these systems should undergo universal testing to ensure their effectiveness.

3.3.1 Indicating cognitive load

Evidence is present in recent literature, whereby changes in cognitive load were reported to be indicated by changes in pupil response (Bailey et al. 2007; King 2009; Klingner et al. 2010; Piquado et al. 2010; Rudmann et al. 2003; Verney et al. 2004). One author in particular states that pupillary dilation response may be a more stable measure of cognitive ability compared to other methods (Silva 2009). The reports show that as cognitive load increased, pupil diameter also increased. Careful consideration was taken to isolate the effects of cognitive load from other factors that are known to affect pupil response like brightness changes. In terms of data analysis, one study employed an averaging technique to accurately detect shifts in cognitive load by averaging pupil responses for similar events (Jeff Klingner 2010), thus attempting to avoid pupil response artifacts not associated with cognitive load. Some suggested applications of pupil response data are that information can be incorporated into interface design (Ponton 2008), used to gauge the interface usability (Komogortsev et al. 2000), or employed to allow instructional media to adapt itself to the user in real time to promote higher learning.

3.3.2 Behavior detection

The behavioral stability of a person is highly subjective; it is possible for a person to mask one behavioral state using another, which can lead to impractical or illogical decision making. Objectively, measuring one's behavior has been investigated using eye-tracking systems. Measurements involving the relationship between pupil response and psychological stimuli have shown promise toward the capability of detecting states of arousal (Allard et al. 2010;

Table 4 Applications of pupil response

Application	Measure	Citations
Indicating cognitive load	Pupil response	Bailey et al. (2007), Klingner et al. (2010), Piquado et al. (2010), Verney et al. (2004), Silva (2009), Klingner (2010)
	Various systems	King (2009), Rudmann et al. (2003), Ponton (2008), Komogortsev et al. (2000)
Behavior detection	Pupil response	Allard et al. (2010), Mistry (2005), Muldner et (al. 2010), Partala (2005), Wong (2009), Bierman et al. (2004), McCuaig et al. (2010), Moresi et al. (2008), Wang et al. (2010)
	Various systems	Calvi et al. (2008)
Adaptive environments	Pupil response	Iqbal (2008)
	Various systems	Merten (2005), Gutl et al. (2005), Raphael et al. (2009a, b), Pompei et al. (2002)

Mistry 2005; Muldner et al. 2010; Partala 2005), conceptual clarity (Wong 2009), and frustration (Bierman et al. 2004; McCuaig et al. 2010; Moresi et al. 2008; Wang et al. 2010), but these behavioral definitions were loosely defined in the reviewed literature (if at all), and the ability to differentiate between these behavioral responses has not been clarified. Moreover, the capability of differentiating between behavioral states and changes in cognitive load requires further investigation. It is possible that these behavioral indicators could be incorporated into adaptive learning technologies to correctly administer feedback, which may result in improved task performance, but the ability to differentiate between behavioral states remains unresolved.

Although these studies have stated that their experiments have successfully used pupil response as an indicator of general changes in behavior as compared to a baseline, the fundamental problem that still exists is the fact that pupil response can be affected by more than just behavior, such as age, brightness, and cognitive load (Andreassi 1995; Janisse 1977).

3.3.3 Adaptive environments

Eye-trackers provide information that can and have been used in adaptive environments (Merten 2005), such as AdeLE (Adaptive e-Learning Environment) (Gutl et al. 2005), e5Learning (Calvi et al. 2008), I-NET (Interactive Neuro-Educational Technology) (Raphael et al. 2009a), and PPT (peak performance trainer) (Raphael et al. 2009b). In addition, a driving system was also investigated that could detect and respond to cognitive load levels (based on multiple sensors) that a user was under while driving (Pompei et al. 2002). The ability to adapt the user's environment based upon his or her psychological state, such as intelligent notification management (Iqbal 2008), may improve the user's task performance, but more research is required to verify this statement.

3.3.4 Conclusions

Pupil response measurements have been used to indicate cognitive load levels as well as behavioral responses to stimuli, but further investigation is still required in order to differentiate the effects from one another using pupil response measurements. Pupil response used in conjunction with other psychophysiological responses appears to yield greater confidence in terms of reflecting behavior and cognitive load, but again more research is necessary to confirm these results. Some research has employed the use of pupil response in order to adapt training for specific scenarios, but this research may be too specific to be applied generally.

4 Summary and recommendations

The use of eye-tracking systems has proven its versatility in terms of indicating cognitive load, influencing interface design, providing an alternative means of human–computer interaction, detecting behavioral response, and adapting presentation elements according to user data. Although there is a significant amount of supporting literature in these regards, some areas lack such support. Further research is specifically recommended for presentation, adaptation, intelligent notification, validation using other detection methods, and discerning different levels of cognitive load. In addition, continued exploration into the human psyche using eye-tracking systems has the potential to promote the use of such systems in commercialized settings and training environments because it allows for personalized training on a large, automated scale.

Eye tracking can be utilized to its full potential by incorporating it into adaptive training systems and heads-up displays by using gaze and pupil data to indicate cognitive load levels and attentional focus, which then can be used to adapt to the needs of the user. Personalizing an e-training program based on the user's cognitive load levels calculated from eye-tracking data will infuse the benefit of having a personal tutor into a mass-distribution environment, improving training by increasing information transfer and retention while making the most effective use of the trainee's time.

Additional recommendations for future research include hardware design to make eye-tracking systems more robust, inexpensive, and capable of installing and programming with ease. Development of training systems should begin by using eye-tracking to gauge user interactions with programs to gauge where, how, and when the instruction should or could be altered.

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