https://doi.org/10.2352/ISSN.2470-1173.2019.3.SDA-654

A Comprehensive Head-mounted Eye Tracking Review: Software Solutions, Applications, and Challenges

Qianwen Wan, Department of Electrical and Computer Engineering, Tufts University, Medford, MA, USA
Aleksandra Kaszowska, Department of Psychology, Tufts University, Medford, MA, USA
Karen Panetta, Department of Electrical and Computer Engineering, Tufts University, Medford, MA, USA
Holly A Taylor, Department of Psychology, Tufts University, Medford, MA, USA
Sos Agaian, Computer Science, The City University of New York, New York City, NY, USA

Abstract

Head-mounted eye-tracking (E-T) technology allows for monitoring and recording people's eye movements in a completely unobtrusive fashion. It has been effectively used to accelerate human behavior research in a wide variety of areas. Motivated by the growing importance/applications of head-mounted eye tracking technology, this work provides a comprehensive review for researchers who are trying to find the most effective strategies for their research and applications. The goal of the paper is to provide the reader with a survey of state-of-art head-mounted eye tracking technology, present commercially available wearable eye tracking equipment, software solutions for eye tracking data analysis techniques reported in the literature, and large-scale eye tracking data visualization methods for researchers from varying backgrounds. Example applications adopting head-mounted eye tracking are described, such as human-machine interaction, cognitive psychology, medical applications, and augmented reality. Finally, discussion of limitations and expectations for head-mounted eye tracking analysis methodology is also investigated.

1. Introduction

Investigating eye movements dates back to 1960s and is supported by a rising trend technology - that is eye tracking sensor technology. Eye-tracking technique has been effectively use in psychology related fields for several decade (see table 1). Eye-tracking sensor technology can monitor where a person is looking while completing complex tasks. Generally speaking, all present eye tracking technology allows for tracking human's eyes focus, which provides indicators of humans' mental status, attention, awareness, and presence. Al-Rahayfeh and Faezipour published a comprehensive survey in 2013 on eye tracking and head movement detection [1]. The survey includes eye gaze detection and tracking algorithms, eye tracking applications and review of commercial products. Recently, Sridharan introduced real-world task inference using eye tracking and corresponding software solutions in his Ph.D. thesis [2]. This work provides information on different case studies and objects classification methods to improve manual annotation of region-of-interest efficiency. Duchowski's book [3] is utilized as a standard textbook on eye-tracking technology for students and researchers who are interested in psychology, marketing, industrial engineering, and computer science. M Chita-Tegmark [4] provided a review and meta-analysis of eye-tracking studies focusing on social attention research. Alemdag reviewed eye tracking methodology on multimedia learning research [5].

Head-mounted eye tracking devices have received increasing attention from both academia and industrial community because they allow the participants to move around freely without compromising the quality of captured eye gaze information. Wearable eye tracking devices can be used to investigate natural viewing behavior in any real-world environment with high robustness and accuracy.

Motivated by the growing importance of head-mounted eye tracking technology, this work provides a comprehensive review for researchers who are trying to find the most effective head-mounted eye tracking strategies for their applications. The paper is organized as follows. Different commercially available head-mounted eye tracking products are outlined in section 2. Fields of applications for head-mounted eye tracking are described briefly in section 3. Section 4 discusses several software solutions for eye tracking data analysis techniques reported in the literature. Large-scale eye tracking data visualization methods for researchers from varying backgrounds are described in section 5. The limitations and challenges existing in current eye tracking data analysis software solutions are presented in section 6. Finally, section 7 draws the conclusions.

2. Popular commercial head-mounted eye tracking products

Current commercially available infrared eye tracking equipment can be categorized into stationary remote eye trackers and head-mounted mobile eye trackers. Stationary remote eye trackers are widely used in traditional indoor human-machine interaction research since the 1980s, such as reading assignment, web searching, and gaming.

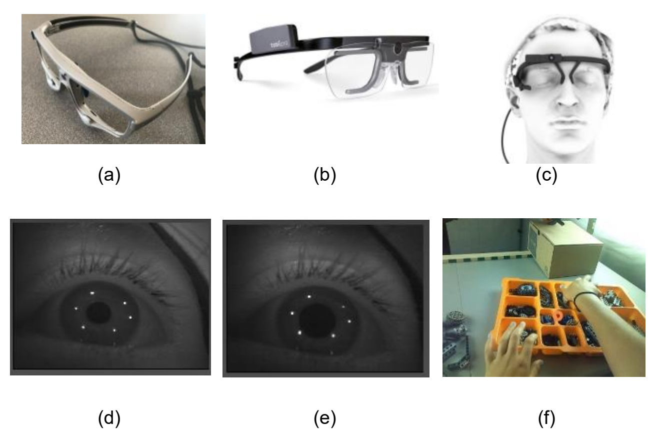


Figure 1. Example images of different head-mounted eye trackers. (a) SMI [1]; (b) Tobii pro glasses 2 [2]; (c) Pupil [3]; eye image as captured by the eye tracker (d) (e); (f) is the captured gaze point overlaid scene video while participants doing an indoor human problem solving study, the orange circle is showing where the participant is looking at.

Table 1. A Comprehensive Head-mounted Eye Tracking Review: Software Solutions, Applications, and Challenges

Head-mounted eye tracking technology	Category	Related work
Popular devices used by researchers from varying backgrounds	SMI, Tobii pro glasses 2, Pupil	[1-3]
Fields of application	• Cognitive psychology • Infant and child education • Augmented reality and virtual reality • Marketing and consumer • Human machine interaction • Sports • Medical and clinical applications	[4-11] [12-22] [23-35] [36-45] [46-54]. [55-58] [59-62]
Visualization methods	• Heatmap visualization • Scanpath visualization • AOI visualization	[63] [64] [65, 66] [67]
Analysis approaches	• Commercial software • Manual annotation on areas-of-interest	[1-3] [67-73]
Software solution limitations and challenges	• No commercially available eye tracking analysis systems that enables the automatic categorization of what people looked at without manual tagging AOIs. • No automatic visual analytic tools that can present information about *where*, *what*, and for *how long* all together in a dynamic scene video. • No automated data fusion approach existed that can fuse the audio data collected from the concurrent head-mounted eye trackers associate with the eye tracking video analysis.	

This technology significantly reduces participants' range of movement and often requires participants to sit still to ensure the quality of the collected data.

On the other hand, the head-mounted mobile eye tracking technology allows researchers to investigate human eye movements without many restrictions, opening up the range of possible recordings that stationary eye tracking could never fit. With the arrival of this technology, researchers can monitor "where" and "what" humans are looking at while they are interacting with the real-world, communicating with other people, manipulating common objects and completing specific daily tasks [6].

SMI head-mounted eye tracker is a popular head-mounted eye-tracking device that is often adopted by cognitive scientists and psychologists, though SMI is no longer commercially available since August 2017. Figure 1 (a) shows a picture of SMI eye tracker. Another popular head-mounted eye tracker is released by Tobii along with the Tobii Studio eye tracking data analysis software. Tobii is used a lot in education research and marketing usability applications. Figure 1 (b) shows a picture of Tobii eye tracker. The most commonly used open source eye tracking technology is developed by pupil labs [74]. Pupil labs [75] not only develops open source software eye tracking platforms and build accessible hardware but also provide tracking add-ons for the latest augmented reality (AR) and virtual reality (VR) headsets. Astonishing number of head-mounted eye tracking devices are market available, information and comparison about different devices can be found in [46].

Eye Tracker Hardware: Head-mounted eye tracking glasses have a frontal scene camera recording the field of view (FoV) in front of the participant and save it as video recordings, and infrared cameras directed at participants' eye to track the distance between the center of the pupil and position of artificially illuminated corneal reflections.

Calibration: Eye tracker calibration is a process that determines where in the scene someone is looking at (focusing at) by training and forming a mathematical correspondence between the location within the scene and the vector between the pupil's center and corneal reflections before the experiments.

3. Fields of applications for head-mounted eye tracking

Cognitive psychology: Head-mounted eye trackers were used to measure the cognitive load of interviewers while problem-solving on a whiteboard during technical interview process in industry for reducing bias in hiring practices [4]. A eye tracking solution using SMI eye tracking glasses for psychological research is discussed in [5]. Different experimental psychology research fields that require unconstrained eyes, head and hand movements suggested to use head-mounted eye tracking technology, such as visual searching, reading, natural tasks, scene viewing, and information processing in complex cognitive tasks. Research investigating how designers approached user experience and usability when working with different end users combines concurrent think aloud and eye tracking protocols were introduced in [6]. Researchers used head-mounted eye tracking devices to record unconstrained speech and eye movements elicited in purposefully controlled fashion.

Table 2. Commonly used eye-tracking measures in a two-dimensional framework. The eye tracking measures mentioned in table below are also used for head-mounted eye tracking technology (Table 1 from [76]).

Fixation	Saccade	Mixed
Temporal		Total reading time
Total fixation duration	Saccade duration	First pass time
Gaze duration		Re-reading time
Average fixation duration		
First fixation duration		
Time to first fixation		
Revisited fixation duration		
Proportion of fixation duration		
Spatial		
Fixation position	Saccade length	Scanpath pattern
Fixation sequence		
Count		
Fixation count	Saccade count	
Average fixation count	Saccade count	
Revisited fixation count		
Probability of fixation count		

Eye movements of a group of geologists engaged in a field study across California were examined while extracting environmental clues [7]. This project stems from the notion that exploring patterns of eye movements and fixations for the purpose of offering insights to the development of perceptual expertise. Wearable eye trackers have been used to study cognitive status in on-road driving applications [8] for tracking the eye movements of a driver navigating a test route while completing various driving tasks. Trends using head-mounted eye tracking technology in cognitive science and neurophysiological studies were demonstrated in [9], such as studying the relationship between saccadic eye movements and cognitive processes. Head-mounted eye tracking techniques were utilized to validate the cognitive load advantage to visual presentation of simple arithmetic and memorization tasks [10]. Head-mounted eye tracking technologies for investigating research on spatial cognition, geographic information science and cartography were detailed in [11]

Infant and child education: Head-mounted eye tracking technology was used in investigating infants' visual exploration [12]. The study measured infant's eye movements with/without mother's speech and visual guidance during spontaneous, unconstrained, natural interactions with caregivers, objects, and obstacles. The limitations and advances of using head-mounted eye tracking devices for understanding early human behavior development by researching young infants' corneal reflection, visual tracking, point of gaze, and the latency of gaze shifts were discussed in [13]. Developmental psychologists who study infants' looking behavior depend on the use of mobile eye tracking technology in order to gain insights of infants' everyday interactions, learning paradigms, and early vision deprivation [14] [15]. The visual evidence for language learning of ambiguous and unambiguous words was under investigated using head-mounted eye tracking devices [16]. Head-mounted systems were used to understand how information from eye-movements, characteristics such as interest in objects, time spent on objects, frequency of visits, and sequences in which content is consumed, could be used to infer learners' level of interests and support the learning process in the context of attention-related tasks [17] [18]. The user's meta-cognitive behavior during interaction with an environment for exploration-based learning was measured using head-mounted eye tracking devices [19]. In the recent years, various technologies (such as collaborative software, cloud computing, screen-casting, virtual classroom) adapting head-mounted eye tracking systems to facilitate e-learning development efficiency [20] [21] [22].

Augmented reality and virtual reality: A head-mounted eye tracker was intergraded into a binocular eye tracking virtual reality system for aircraft inspection training in [23]. A virtual reality scene that is currently displayed to a user wearing the head-mounted system through detecting the direction in which the user is looking in the scene, via eye tracking was established in [35]. Gaze typing via virtual keyboard, real-time facial reenactment and eye gaze control in a head-mounted virtual reality system using mobile eye tracking technology is described in [24-28]. Head-mounted eye tracking can assess visual attention and has opened up many possibilities for virtual reality based therapy while VR technology recently has become popular tool for therapists to use as an immersive environment for patients [29]. Head-mounted eye tracking camera enables sensing and conveying facial expressions and user emotions during social interaction in virtual reality settings [30]. [31] introduced electroencephalographic eye-tracking as an additional interaction channel to record real-time pupil position for head-mounted virtual reality and augmented reality devices in gaming and entertainment industries. Head-mounted virtual and augmented reality near-eye displays require accurate eye tracking technology to create the possibilities to take us to new places, provide instant and spatially-aware access to information, hence improving navigation capability [32]. Combination of using head-mounted eye-tracking technology and user-worn virtual reality system was proposed as a novel tool to facilitate research in human movement and movement disorders [33]. Head-mounted eye tracking technology is predicted as the "hands-free" human machine interaction tool for next generation virtual reality and augmented reality gameplay filed [34].

Marketing and consumer: In [36] [37], grocery store experiments were described to investigate the possible region-of-interests of costumers using a head-mounted mobile eye tracker. The interplay between store familiarity, visual attention, and navigational fluency to precede and influence unplanned purchases of 100 retailer store shoppers wearing Tobii head-mounted eye trackers were examined in [38]. The power of using head-mounted eye tracking systems in marketing research and economics theory was discussed in [39]. In [40], different types of heuristics to meet shopping goals were investigated by monitoring how a customer's visual attention is influenced by their shopping goal at a gas station, a sports store, and a grocery store. The combination of virtual reality settings with head-mounted eye tracking provides a unique opportunity for shopper research in particular to shopper assistance [41]. A head-mounted eye-tracking case study was conducted in [42] to demonstrate that retailers can attract consumers' visual attention through various practices, such as providing relevant information, orienting consumers around, and offering an eco-friendly product assortment. [43] outlined case studies investigating the relationship between costumers' visual search patterns and shopping choice making process in supermarkets. A review of using eye tracking measurement for understanding of consumers' needs and desires were given in [44]. [45] examined associations between broad personality traits and human gaze behavior when buying a car or viewing car dealer advertisements.

Human machine interaction: For ideal human machine interaction systems, the most effective mean is through the behavior of the eye gaze [47]. Since early 20s, wearable, and lightweight eye gaze trackers became increasingly used for HCI studies [46]. A new "hands-free" method for aerial border surveillance, search and rescue missions using head-mounted eye tracking technology was offered in [48]. Searching and rescue soldiers are suggested to wear head-mounted eye trackers to better complete their mission by analyzing region-of-interests online and offline, investigating the workload through think-aloud-protocol and training through gaze path guidance. Gaze based command and control is largely used for people with severe disabilities who requiring hands-free alternative in everyday life [49]. An electrooculography based systems head-mounted eye tracking system shows great potential value for interacting with computers and devices by recognizing the user's eye movements [50]. Orbits [51] proposed a novel eye gaze based human machine interaction technique that enables hands-free input on smart watches, which was tested using example music player application. A low-cost head-mounted eye tracking solution was proposed to improve the human machine interaction with iPad applications [52]. Personal viewing devices, such as an augmented reality devices, virtual reality glasses, scope simulators, monocular simulators, binoculars simulators, or telescope simulators, can be integrated with eye tracking technology to create a more immersive human machine interaction experience [53]. Chittaro, L. and Sioni, R. combined eye tracking technology in mobile head-mounted device to effectively select menu items in [54].

Sports: Head-mounted eye tracker was proposed to find the evidence for predictive control of eye movements in sports [55] of two skilled squash players. Visual fixation of obstacles of both adults and children were measured using wearable eye tracking devices while they were during free, unfettered locomotion such as jumping, walking and running [56]. This study aimed to provide evidence to support the role of foveal vision in guiding action such as navigation, locomotion and sports. Head-mounted eye trackers have been successfully used in live sports to explore the vision and gaze behaviors of athletes; advice and solutions for using wearable eye trackers investigating exercise and sports psychology have been provided in [57, 58].

Medical and clinical applications: Clinical research on mental health monitoring, regarding mental disorders, using mobile eye tracker was demonstrated in [59]. Head-mounted eye tracking device was advocated for as a rapid, user friendly, and field-ready technique for the purpose of diagnosing and monitoring improvement of symptoms following mild traumatic brain injury [60]. Head-mounted eye-tracking technology is used as a robust and accurate approach for better understanding the role of vision during real-world tasks in older people with Parkinson's disease [61]. [62] gives an insight into different studies utilizing eye imaging in eye disease and other medical applications.

4. Software solutions for eye tracking data analysis techniques reported in the literature

To understand eye movement measures, a commonly used eye-tracking indices according to two dimensions was summarized in [76]. The eye tracking measures mentioned in table 2 are also widely used for head-mounted eye tracking technology.

While there has been a significant success deploying head-mounted eye tracking technology in both academic and commercial research, analyzing the collected large-scale eye tracking data remains a challenge.

Eye tracking data analysis tools have been developed in order to provide a more efficient way to understand the recorded eye tracking data, such as manual annotation on areas-of-interest [68-70], and manual gaze point labeling systems [67, 71-73]. In order to ensure high accuracy, most existing software solutions for annotating the collected eye tracking data rely heavily on human manual labor. Usually, researchers would go frame by frame to annotate the areas-of-interest (AOI), or just simply play/stop a video stream while watching through the entire eye tracking video and label the AOI. In other word, researchers will manually assign a semantic meaning to where the human eye gaze falls (See figure 3); hence the information about what, where and how long of an eye movement event occur will be collected.

Example commercial software solutions for analyzing head-mounted eye tracking data recommended by psychology experts and education researchers are shown in Figure 2 below.

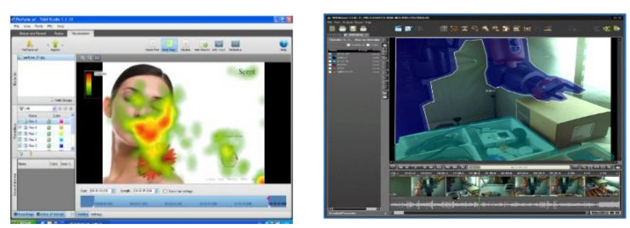


Figure 2. Example commercial software solutions for analyzing head-mounted eye tracking data recommended by psychology experts.

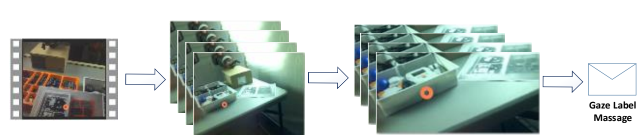


Figure 3. An illustration for manual AOI labeling: a recorded video is converted to frames, area-of-interests are detected based on gaze points' location using recognition algorithms and the object being viewed is determined.

5. Large-scale eye tracking data visualization methods for researchers from varying backgrounds

Data visualization methods for eye tracking technology is an interdisciplinary challenge that has become crucial due to the large application range among different fields [66]. Large-scale eye tracking data visualization methods for researchers from varying backgrounds can be typically categorized into heatmap visualization, scanpath visualization and AOI visualization. Goldberg and Jonathan [63] visualized eye tracking data in a 2D space representing time on one axis of a coordinate system and eye tracking data on the other axis. Kurzhals and Weiskopf [64] presented robust motion-compensated attention maps using optical flow information to adjust fixation data based on the fixated moving object. Scanpath visualization incorporates fixations and saccades in creating a "viewing path" while a person is looking at a scene. In a typical scanpath visualization, each fixation is indicated by a symbol such as a circle, where the radius often corresponds to the fixation duration. Saccades between fixations are represented by connecting lines between these circles [65]. AOI (area-of-interest) based visualization techniques also consider the annotation of the regions or objects on the stimulus that are of special interest to the observer. Kurzhals and Hlawatsch [67] described a visual analytics approach to implemented an semi-automatic area-of-interest annotation process by image-based, automatic clustering of eye tracking data integrated in an interactive labeling and analysis system. Some example graphic user interface to demonstrate the commonly used eye tracking data visualization techniques are shown in Figure 4.

(a) Heatmap visualization

(b) Scanpath visualization

(c) AOI annotation analysis

Figure 4. Example of commonly used eye tracking data visualization techniques.

6. Discussion of limitations of head-mounted eye tracking methodology

This section will present the limitations and challenges existing in current eye tracking data analysis software solutions.

Manually tagging massive eye movement data is time prohibitive, prone to human error, and a well-known obstacle to utilizing mobile eye tracking technology. As we demonstrated in section 3, analyzing collected eye tracking data poses a particular analytic challenge for automatically obtaining information on where and what a person is looking at in a specific scene. However, currently there is no commercially available eye tracking analysis systems that enables the automatic categorization of what people looked at without manual tagging AOIs in the video; and moreover, there are no automatic visual analytic tools that can present all three aspects in a dynamic scene video: where, what, and for how long participants were looking. Lack of reliable and user-friendly solutions for automating video data analysis limits possibilities for utilizing mobile eye tracking technology in exploring large-sample data, effectively limiting the scope of possible advancements in our understanding of how people interact with the surrounding world.

Another big limitation existing in eye tracking data analysis is that no automated data fusion approach existed to fuse the audio data collected from the concurrent head-mounted eye trackers associate with the eye tracking video analysis. Lacking automatic speech prosody method and speech-to-text semantic analysis limits possibilities for utilizing mobile eye tracking technology in exploring multi-channel eye tracking data through think-aloud-protocol.

7. Conclusion

Wearable eye tracking technology opened a new way to conduct research in unconstrained environment settings; motivated by the growing importance of head-mounted eye tracking technology, this work provides a comprehensive review on head-mounted eye tracking technology. This work, for the first time, present a review contains the state-of-art head-mounted eye tracking equipment, software solutions for eye tracking data analysis and visualization, head-mounted eye tracking applications, and challenges and limitations in software solutions in head-mounted eye tracking multi-modal data analysis and fusion. We believe our presented review will provide valid suggestions and advice for researchers who are trying find the most effective strategies for their research and applications.

Acknowledgment

This work is supported by the Tufts University School of Engineering, Center for Applied Brain and Cognitive Sciences (CABCS) under award numbers A452001 ARM981. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the CABCS.

References

[1] https://www.smivision.com/.

[2] https://www.tobiipro.com/product-listing/tobii-pro-glasses-2/.

[3] https://pupil-labs.com/store/.

[4] M. Behroozi, A. Lui, I. Moore, D. Ford, and C. Parnin, "Dazed: measuring the cognitive load of solving technical interview problems at the whiteboard," in Proceedings of the 40th International Conference on Software Engineering: New Ideas and Emerging Results, 2018, pp. 93-96.

[5] M. L. Mele and S. Federici, "Gaze and eye-tracking solutions for psychological research," Cognitive processing, vol. 13, pp. 261-265, 2012.

[6] Q. W. Aleksandra Kaszowska, Karen Panetta, William C. Messner, Holly A. Taylor, "You can't always know what you need: A concurrent think aloud and eye tracking analysis of a tool design

process," presented at the International Meeting of the Psychonomic Society, Amsterdam, 2018

[7] J. B. Pelz, T. B. Kinsman, and K. M. Evans, "Analyzing complex gaze behavior in the natural world," in Human Vision and Electronic Imaging XVI, 2011, p. 78650Z.

[8] M. Sodhi, B. Reimer, J. Cohen, E. Vastenburg, R. Kaars, and S. Kirschenbaum, "On-road driver eye movement tracking using head-mounted devices," in Proceedings of the 2002 symposium on Eye tracking research & applications, 2002, pp. 61-68.

[9] M. Hayhoe and D. Ballard, "Eye movements in natural behavior," Trends in cognitive sciences, vol. 9, pp. 188-194, 2005.

[10] J. M. Klingner, "Measuring cognitive load during visual tasks by combining pupillometry and eye tracking," Stanford University, 2010.

[11] P. Kiefer, I. Giannopoulos, M. Raubal, and A. Duchowski, "Eye tracking for spatial research: Cognition, computation, challenges," Spatial Cognition & Computation, vol. 17, pp. 1-19, 2017.

[12] J. M. Franchak, K. S. Kretch, K. C. Soska, and K. E. Adolph, "Head-mounted eye tracking: A new method to describe infant looking," Child development, vol. 82, pp. 1738-1750, 2011.

[13] G. Gredebäck, S. Johnson, and C. von Hofsten, "Eye tracking in infancy research," Developmental neuropsychology, vol. 35, pp. 1-19, 2009.

[14] J. M. Franchak, K. S. Kretch, K. C. Soska, J. S. Babcock, and K. E. Adolph, "Head-mounted eye-tracking of infants' natural interactions: a new method," in Proceedings of the 2010 Symposium on Eye-Tracking Research & Applications, 2010, pp. 21-27.

[15] R. N. Aslin, "How infants view natural scenes gathered from a head-mounted camera," Optometry and vision science: official publication of the American Academy of Optometry, vol. 86, p. 561, 2009.

[16] F. Huettig and G. T. Altmann, "The online processing of ambiguous and unambiguous words in context: Evidence from head-mounted eye-tracking," The on-line study of sentence comprehension: Eyetracking, ERP and beyond, pp. 187-207, 2004.

[17] M. Pivec, C. Trummer, and J. Pripfl, "Eye-tracking adaptable e-learning and content authoring support," Informatica, vol. 30, 2006.

[18] S. Asteriadis, P. Tzouveli, K. Karpouzis, and S. Kollias, "Estimation of behavioral user state based on eye gaze and head pose—application in an e-learning environment," Multimedia Tools and Applications, vol. 41, pp. 469-493, 2009.

[19] C. Conati and C. Merten, "Eye-tracking for user modeling in exploratory learning environments: An empirical evaluation," Knowledge-Based Systems, vol. 20, pp. 557-574, 2007.

[20] J. L. Soler, J. Ferreira, M. Contero, and M. Alcañiz, "The power of sight: using eye tracking to assess learning experience (LX) in virtual reality environments," INTED2017 Proceedings, pp. 8684-8689, 2017.

[21] Ö. Sümer, P. Goldberg, K. Stürmer, T. Seidel, P. Gerjets, U. Trautwein, et al., "Teachers' Perception in the Classroom," arXiv preprint arXiv:1805.08897, 2018.

[22] R. G. Lupu and F. Ungureanu, "A survey of eye tracking methods and applications," Buletinul Institutului Politehnic din Iasi, Automatic Control and Computer Science Section, vol. 3, pp. 72-86, 2013.

[23] A. T. Duchowski, V. Shivashankaraiah, T. Rawls, A. K. Gramopadhye, B. J. Melloy, and B. Kanki, "Binocular eye tracking in virtual reality for inspection training," in Proceedings of the 2000 symposium on Eye tracking research & applications, 2000, pp. 89-96.

[24] J. Thies, M. Zollhöfer, M. Stamminger, C. Theobalt, and M. Nießner, "Demo of FaceVR: real-time facial reenactment and eye gaze control in virtual reality," in ACM SIGGRAPH 2017 Emerging Technologies, 2017, p. 7.

[25] R. Cucchiara, A. Bulling, K. Kunze, and J. Rehg, "Eyewear Computing–Augmenting the Human with Head-Mounted Wearable Assistants," 2016.

[26] J. P. Hansen, V. Rajanna, I. S. MacKenzie, and P. Bækgaard, "A Fitts' law study of click and dwell interaction by gaze, head and mouse with a head-mounted display," in Proceedings of the Workshop on Communication by Gaze Interaction, 2018, p. 7.

[27] D. Nister, V. Thukral, D. Nijemcevic, and R. Bhargava, "Eye-typing term recognition," ed: Google Patents, 2016.

[28] C. Elmadjian, P. Shukla, A. D. Tula, and C. H. Morimoto, "3D gaze estimation in the scene volume with a head-mounted eye tracker," in Proceedings of the Workshop on Communication by Gaze Interaction, 2018, p. 3.

[29] O. H.-M. Lutz, C. Burmeister, L. F. dos Santos, N. Morkisch, C. Dohle, and J. Krüger, "Application of head-mounted devices with eye-tracking in virtual reality therapy," Current Directions in Biomedical Engineering, vol. 3, pp. 53-56, 2017.

[30] S. Hickson, N. Dufour, A. Sud, V. Kwatra, and I. Essa, "Eyemotion: Classifying facial expressions in VR using eye-tracking cameras," arXiv preprint arXiv:1707.07204, 2017.

[31] M. P. Dietrich, G. Winterfeldt, and S. von Mammen, "Towards EEG-based eye-tracking for interaction design in head-mounted devices," in Consumer Electronics-Berlin (ICCE-Berlin), 2017 IEEE 7th International Conference on, 2017, pp. 227-232.

[32] A. Maimone, A. Georgiou, and J. S. Kollin, "Holographic near-eye displays for virtual and augmented reality," ACM Transactions on Graphics (TOG), vol. 36, p. 85, 2017.

[33] B. Quinlivan, J. S. Butler, I. Beiser, L. Williams, E. McGovern, S. O'Riordan, et al., "Application of virtual reality head mounted display for investigation of movement: a novel effect of orientation of attention," Journal of neural engineering, vol. 13, p. 056006, 2016.

[34] M. Alcaniz, "A Proposal for the Selection of Eye-Tracking Metrics for the Implementation of Adaptive Gameplay in Virtual Reality Based Games," in Virtual, Augmented and Mixed Reality: 9th International Conference, VAMR 2017, Held as Part of HCI International 2017, Vancouver, BC, Canada, July 9-14, 2017, Proceedings, 2017, p. 369.

[35] E. Larsen, F. Umminger, X. Ye, N. Rimon, J. R. Stafford, and X. Lou, "Methods and systems for user interaction within virtual reality scene using head mounted display," ed: Google Patents, 2018.

[36] T. P. Keane, N. D. Cahill, J. A. Tarduno, R. A. Jacobs, and J. B. Pelz, "Computer vision enhances mobile eye-tracking to expose expert cognition in natural-scene visual-search tasks," in Human Vision and Electronic Imaging XIX, 2014, p. 90140F.

[37] K. M. Evans, R. A. Jacobs, J. A. Tarduno, and J. B. Pelz, "Collecting and analyzing eye tracking data in outdoor environments," Journal of Eye Movement Research, vol. 5, p. 6, 2012.

[38] T. Otterbring, E. Wästlund, and A. Gustafsson, "Eye-tracking customers' visual attention in the wild: Dynamic gaze behavior

moderates the effect of store familiarity on navigational fluency," Journal of Retailing and Consumer Services, vol. 28, pp. 165-170, 2016.

[39] J. N. Lahey and D. Oxley, "The power of eye tracking in economics experiments," American Economic Review, vol. 106, pp. 309-13, 2016.

[40] E. Wästlund, T. Otterbring, A. Gustafsson, and P. Shams, "Heuristics and resource depletion: eye-tracking customers' in situ gaze behavior in the field," Journal of Business Research, vol. 68, pp. 95-101, 2015.

[41] M. Meißner, J. Pfeiffer, T. Pfeiffer, and H. Oppewal, "Combining virtual reality and mobile eye tracking to provide a naturalistic experimental environment for shopper research," Journal of Business Research, 2017.

[42] H. Guyader, M. Ottosson, and L. Witell, "You can't buy what you can't see: Retailer practices to increase the green premium," Journal of Retailing and Consumer Services, vol. 34, pp. 319-325, 2017.

[43] E. Wästlund, P. Shams, and T. Otterbring, "Unsold is unseen… or is it? Examining the role of peripheral vision in the consumer choice process using eye-tracking methodology," Appetite, vol. 120, pp. 49-56, 2018.

[44] P. Rosa, "What do your eyes say? Bridging eye movements to consumer behavior," International Journal of Psychological Research, vol. 8, pp. 90-103, 2015.

[45] T. C. Stratmann, U. Gruenefeld, and S. Boll, "EyeMR: low-cost eye-tracking for rapid-prototyping in head-mounted mixed reality," in Proceedings of the 2018 ACM Symposium on Eye Tracking Research & Applications, 2018, p. 90.

[46] M. Cognolato, M. Atzori, and H. Müller, "Head-mounted eye gaze tracking devices: An overview of modern devices and recent advances," Journal of Rehabilitation and Assistive Technologies Engineering, vol. 5, p. 2055668318773991, 2018.

[47] L. Yin and M. Reale, "Real time eye tracking for human computer interaction," ed: Google Patents, 2016.

[48] Q. Wan, A. Kaszowska, A. Samani, K. Panetta, H. A. Taylor, and S. Agaian, "Aerial Border Surveillance for Search and Rescue Missions Using Eye Tracking Techniques," in 2018 IEEE International Symposium on Technologies for Homeland Security (HST), 2018, pp. 1-5.

[49] P. Majaranta and A. Bulling, "Eye tracking and eye-based human–computer interaction," in Advances in physiological computing, ed: Springer, 2014, pp. 39-65.

[50] Z. Jin and S. Laszlo, "Wearable head-mounted, glass-style computing devices with EOG acquisition and analysis for human-computer interfaces," ed: Google Patents, 2018.

[51] A. Esteves, E. Velloso, A. Bulling, and H. Gellersen, "Orbits: Gaze interaction for smart watches using smooth pursuit eye movements," in Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology, 2015, pp. 457-466.

[52] A. Lopez-Basterretxea, A. Mendez-Zorrilla, and B. Garcia-Zapirain, "Eye/head tracking technology to improve HCI with iPad applications," Sensors, vol. 15, pp. 2244-2264, 2015.

[53] Y. Boger, M. Machlin, and Y. Korakin, "Apparatus, systems and methods for providing motion tracking using a personal viewing device," ed: Google Patents, 2018.

[54] L. Chittaro and R. Sioni, "Selecting Menu Items in Mobile Head-Mounted Displays: Effects of Selection Technique and Active Area," International Journal of Human–Computer Interaction, pp. 1-16, 2018.

[55] K. Chajka, M. Hayhoe, B. Sullivan, J. Pelz, N. Mennie, and J. Droll, "Predictive eye movements in squash," Journal of Vision, vol. 6, pp. 481-481, 2006.

[56] J. M. Franchak and K. E. Adolph, "Visually guided navigation: Head-mounted eye-tracking of natural locomotion in children and adults," Vision research, vol. 50, pp. 2766-2774, 2010.

[57] R. M. Discombe and S. T. Cotterill, "Eye tracking in sport: A guide for new and aspiring researchers," Sport & Exercise Psychology Review, vol. 11, pp. 49-58, 2015.

[58] A. Moran, M. Campbell, and D. Ranieri, "Implications of eye tracking technology for applied sport psychology," Journal of Sport Psychology in Action, pp. 1-11, 2018.

[59] M. Vidal, J. Turner, A. Bulling, and H. Gellersen, "Wearable eye tracking for mental health monitoring," Computer Communications, vol. 35, pp. 1306-1311, 2012.

[60] B. Caplan, J. Bogner, L. Brenner, D. X. Cifu, J. R. Wares, K. W. Hoke, et al., "Differential eye movements in mild traumatic brain injury versus normal controls," Journal of Head Trauma Rehabilitation, vol. 30, pp. 21-28, 2015.

[61] S. Stuart, L. Alcock, A. Godfrey, S. Lord, L. Rochester, and B. Galna, "Accuracy and re-test reliability of mobile eye-tracking in Parkinson's disease and older adults," Medical engineering & physics, vol. 38, pp. 308-315, 2016.

[62] K. Harezlak and P. Kasprowski, "Application of eye tracking in medicine: A survey, research issues and challenges," Computerized Medical Imaging and Graphics, vol. 65, pp. 176-190, 2018.

[63] J. H. Goldberg and J. I. Helfman, "Visual scanpath representation," in Proceedings of the 2010 Symposium on Eye-Tracking Research & Applications, 2010, pp. 203-210.

[64] K. Kurzhals and D. Weiskopf, "Space-time visual analytics of eye-tracking data for dynamic stimuli," IEEE Transactions on Visualization and Computer Graphics, vol. 19, pp. 2129-2138, 2013.

[65] J. H. Goldberg and X. P. Kotval, "Computer interface evaluation using eye movements: methods and constructs," International Journal of Industrial Ergonomics, vol. 24, pp. 631-645, 1999.

[66] T. Blascheck, K. Kurzhals, M. Raschke, M. Burch, D. Weiskopf, and T. Ertl, "State-of-the-art of visualization for eye tracking data," in Proceedings of EuroVis, 2014.

[67] K. Kurzhals, M. Hlawatsch, C. Seeger, and D. Weiskopf, "Visual analytics for mobile eye tracking," IEEE transactions on visualization and computer graphics, vol. 23, pp. 301-310, 2017.

[68] H. Y. Tsang, M. Tory, and C. Swindells, "eSeeTrack—visualizing sequential fixation patterns," IEEE Transactions on Visualization and Computer Graphics, vol. 16, pp. 953-962, 2010.

[69] K. Kurzhals, F. Heimerl, and D. Weiskopf, "ISeeCube: Visual analysis of gaze data for video," in Proceedings of the Symposium on Eye Tracking Research and Applications, 2014, pp. 43-50.

[70] R. Netzel, M. Burch, and D. Weiskopf, "Interactive scanpath-oriented annotation of fixations," in Proceedings of the Ninth Biennial ACM Symposium on Eye Tracking Research & Applications, 2016, pp. 183-187.

[71] P. Yin, H. Qiao, W. Wu, L. Qi, Y. L. Li, S. Zhong, et al., "A Novel Biologically-inspired Visual Cognition Model—Automatic Extraction of Semantics, Formation of Integrated Concepts and Re-selection Features for Ambiguity," IEEE Transactions on Cognitive and Developmental Systems, vol. PP, pp. 1-1, 2017.

[72] D. F. Pontillo, T. B. Kinsman, and J. B. Pelz, "SemantiCode: Using content similarity and database-driven matching to code wearable eyetracker gaze data," in Proceedings of the 2010 Symposium on Eye-Tracking Research & Applications, 2010, pp. 267-270.

[73] T. Nakamura and T. Nagai, "Ensemble-of-Concept Models for Unsupervised Formation of Multiple Categories," IEEE Transactions on Cognitive and Developmental Systems, vol. PP, pp. 1-1, 2017.

[74] https://pupil-labs.com/pupil/.

[75] M. Kassner, W. Patera, and A. Bulling, "Pupil: an open source platform for pervasive eye tracking and mobile gaze-based interaction," in Proceedings of the 2014 ACM international joint conference on pervasive and ubiquitous computing: Adjunct publication, 2014, pp. 1151-1160.

[76] M.-L. Lai, M.-J. Tsai, F.-Y. Yang, C.-Y. Hsu, T.-C. Liu, S. W.-Y. Lee, et al., "A review of using eye-tracking technology in exploring learning from 2000 to 2012," Educational research review, vol. 10, pp. 90-115, 2013.

Author Biography

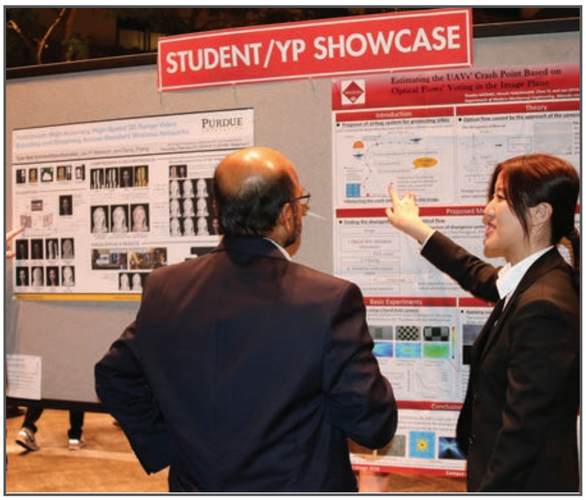
Qianwen Wan received her B.S. in information engineering from Wuhan University of Technology (Wuhan, China), B.S. in law from Wuhan University (Wuhan, China), and M.S. in electrical and computer engineering from Tufts University (Medford, MA, USA). She is currently pursuing her Ph.D. in electrical and computer engineering at Tufts University. Her current research interests include designing automated tools for cognitive science, analyzing mobile eye tracking data, facial recognition, image and video processing, and machine-learning applications.

Aleksandra Kaszowska received her B.A. from Clark University (Worcester, MA) and M.S. from Tufts University (Medford, MA) in Psychology. She is currently working towards her Ph.D. in Experimental Psychology and Cognitive Science at Tufts University. Her research interests focus on utilizing eye tracking and think aloud protocols for investigating cognitive processes underlying decision making, problem solving, and strategy selection in a variety of contexts.

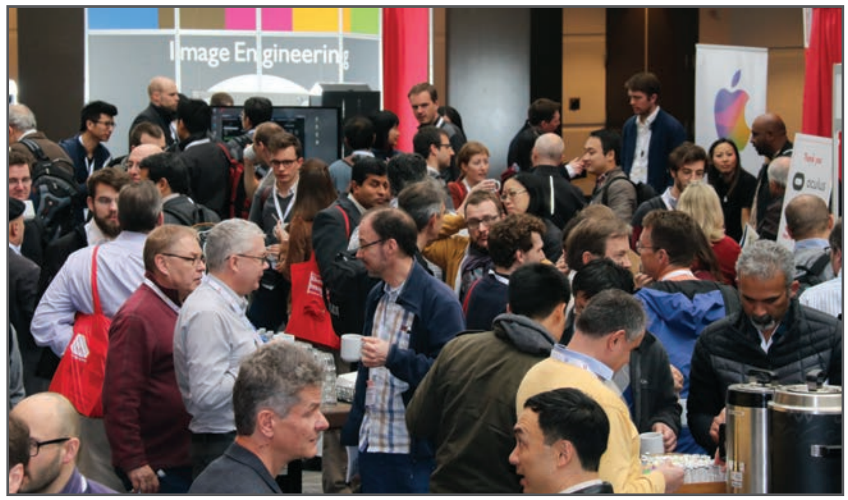
Karen Panetta received the B.S. degree in computer engineering from Boston University, Boston, MA, and the M.S. and Ph.D. degrees in electrical engineering from Northeastern University, Boston. Dr Panetta is currently a Dean of Graduate Engineering Education and a Professor in the Department of Electrical and Computer Engineering and Adjunct Professor of Computer Science at Tufts University, Medford, MA, and Director of the Dr Panetta's Vision and Sensing System Laboratory.

Holly A. Taylor received her B.A. in Mathematics from Dartmouth College (Hanover, NH) and her Ph.D. in Cognitive Psychology from Stanford University (Stanford, CA). She is currently a full professor of Psychology, and adjunct professor of Mechanical Engineering, and co-director of the Center for Applied Brain and Cognitive Science at Tufts University.

Sos Agaian is currently a Distinguished Professor at The City University of New York/CSI. His research interests include computational vision and machine learning, large scale data analytic analytics, multi-modal data fusion, signal/image processing modeling, multimodal biometric and digital forensics, 3D imaging sensors, information processing and security, and biomedical and health informatics. He is a Fellow of the SPIE, a Fellow of IEEE, Fellow of the IS&T, and a Fellow of the AAAS.



STUDENT/YP SHOWCASE
PURDUE



AR is a fundamental and transformative interface and platform.
20+ years from my initial working demo to today's AR displays
Optimistic that it won't take another 20 to reach ubiquitous consumer AR!
My first working AR prototype
Today's platforms
Ubiquitous consumer AR