Advanced Eye-tracking Metrics for Analyzing Joint Visual Attention and Joint Mental Attention

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Abstract

Wearable eye-tracking devices have rapidly evolved, providing researchers with innovative ways to capture and analyze multimodal interactions. In collaborative environments, individuals share visual attention and mental attention which affect the efficiency and success of the collaborative task. Synchronized eye-tracking studies can be employed during these collaborative tasks to understand Joint Visual Attention (JVA) and Joint Mental Attention (JMA). Here we aim to evaluate oculomotor plant features extracted from saccadic eye movements, traditional positional gaze metrics, and advanced eye metrics such as ambient/focal coefficient κ, Index of Pupillary Activity (IPA), Low/High Index of Pupillary Activity (LHIPA), and Real-time Index of Pupillary Activity (RIPA) to study the JVA and JMA between two individuals. By leveraging modern wearable eye-tracking devices, we step beyond single-user eye-tracking studies to monitor and assess how individuals distribute attention, share information, and coordinate tasks in group settings. This research aims to explore the dynamic relationships between visual attention, mental attention, and teamwork while offering new insights to improve more synchronized collaboration in digital environments.

CCS Concepts

• **Human-centered computing → Empirical studies in HCI**.

Keywords

Eye-tracking, Multi-user, Advance gaze measures, Joint attention

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1 Introduction

Collaborative work often relies on effective communication and coordination of attention between individuals. Recent advancements in wearable eye-tracking technology have provided an opportunity to explore these mechanisms more deeply, using detailed eye-tracking data along with other sensory data [20]. Joint Visual Attention (JVA) [19] and Joint Mental Attetion (JMA) [18] are two scenarios associated with collaborative interactions in physical as well as digital environments[7, 9].

JVA is the phenomenon in which two or more people focus their eyes on the same object, event, or place, knowing that they are both looking at the same target. JVA has been widely studied in developmental psychology for language learning [2, 10] and relied on gaze data to analyze and quantify JVA between individuals [1, 17]. Introducing the coefficient κ [15] and scan path similarity [3] will provide a promising approach to deeply understanding JVA by capturing both spatial and temporal alignment of eye movements between individuals.

JMA involves two or more individuals sharing the same cognitive focus, where they not only direct their attention to the same task or object but also align their thinking, understanding, and mental processes. This coordination of cognitive efforts help teams to work together more efficiently, ensuring they are mentally synchronized while engaging in tasks like problem-solving, learning, or decision-making. The pupillary activity of human eye is considered as an indicator for cognitive load [6, 8, 14]. Changes in pupil size, driven by the autonomic nervous system, reflect fluctuations in attention, processing effort, and emotional states, offering insights into the mental alignment between individuals during collaborative tasks [16]. Pupil diameter and pupil dilation are the commonly used eye-tracked measures to understand the cognitive load or working memory capacity of individuals [8, 14]. Dushowski et al. derived two advanced eye-tracked measures IPA [6] and LHIPA [5] which are computed using a wavelet-based method. The authors demonstrated the sensitivity of these measures to the measurement of cognitive load. The lack of research utilizing advanced eye movement measures to understand JMA motivated us to explore this topic further.

We hypothesize that the characteristic movements of the human eye and advanced metrics derived from traditional measures may be utilized to observe JVA and understand JMA in collaborative environments. Identifying these metrics could allow systems to respond appropriately by improving and enhancing their ability to support more synchronized collaboration, allowing for better communication, shared understanding, and overall task efficiency among users.

1.1 Research Questions

We will investigate the following research questions.

(1) Can we use ambient/focal coefficient and scan path similarity to calculate JVA?

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(2) Can traditional positional gaze metrics and advanced eye metrics be used to understand JMA?
(3) Can we derive an aggregate measure using advanced eye metrics to quantify JMA?
(4) Is there a relationship between JVA and JMA in collaborative interactions between a dyad?

2 Methodology

We plan to investigate the JVA and JMA between two individuals working together in a collaborative physical environment using advanced eye-movement measures. The proposed study consists of five main steps; (1) Data collection, (2) Obtain traditional gaze metrics and advanced pupillary activity measures, (3) Calculate JVA, (4) Analyze JMA using advanced eye-movement metrics, and (5) Explore the relationship between JVA and JMA between a dyad during a collaborative task.

We will begin by preprocessing the raw eye movement data obtained from wearable eye-tracking devices. Extracting raw data including (x, y) coordinates, timestamps, and pupil diameters. Next, we will use the Real-Time Advanced Eye Movements Analysis Pipeline (RAEMAP) [4, 11, 13] to compute both standard gaze metrics and advanced eye metrics, particularly ambient/focal coefficient κ, Index of Pupillary Activity (IPA), Low/High Index of Pupillary Activity (LHIPA). We will employ the existing methods to calculate the JVA [17] and extend the analysis by incorporating ambient/focal coefficient κ and analyzing the scan path similarity between the dyads. We plan to introduce an aggregate measure for multi-user pupillary signals which can be used as an indication of JMA by analyzing IPA and LHIPA.

We will conduct comprehensive experiments to obtain eye-tracking data from diverse collaborative tasks like collaborative visual search, collaborative digital document reading, and annotating. We will demonstrate the utility of advanced eye-movement measures to understand the collaborative behavior of individuals.

Table 1: Potential eye-tracking devices for the study.

Device	Supported data
PupilLabs Invisible[1]	Eye videos, Gaze, Fixations and saccades, Blink rate, Scene video
Aria Glasses[2]	Scene video, scene images, eye gaze, hand tracking data, audio data

2.1 Pilot study

I will conduct an evaluation study to observe the behavioral patterns of dyads in a collaborative environment.

2.1.1 Participants. We plan to recruit 25 pairs of individuals between 18 and 40 years by conducting a visual acuity test to record eye gaze metrics during a collaborative digital map reading task. During the task, participants will ask to work together to find a path between two fixed locations on a map visualized on a screen. We will plan the task with three difficulty levels (easy, medium, and hard) to observe how the pairs work together to achieve the goal.

2.1.2 Task procedure. We will provide wearable eye-tracking devices to both individuals and record eye-movement data along with other sensory data (depending on the eye-tracker) into the devices. Upon completion of the task, We will retrieve the data stored in the devices and feed data to RAEMAP to obtain traditional and advanced eye-movement metrics. We will collect the time series data for ambient/focal coefficient κ, IPA, and LHIPA to measure the JVA and JMA.

2.1.3 Evaluation. We will evaluate the obtained measurements for JVA using metrics such as gaze overlap, fixation similarity, and synchrony, and for JMA using metrics like task completion time, turn-taking and coordination, and task accuracy.

[1]https://pupil-labs.com/products/invisible
[2]https://www.projectaria.com/

3 Future work

We plan to extend the study to analyze the real-time JMA using (Real Time Index of Pupillary Activity) RIPA [12]. Further, we will incorporate multi-modal data (facial expressions, utterance, and conversational data) in conjunction with eye-tracking data to observe how the additional data correlate with eye-movement metrics to offer deeper insights into JVA and JMA between a dyad. We will conduct comprehensive user studies to investigate different behaviors of dyads and how they affect the JVA and JMA.

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References

[1] Sebastian Becker, Sergey Mukhametov, Philipp Pawels, and Jochen Kuhn. 2021. Using mobile eye tracking to capture joint visual attention in collaborative experimentation. In *Physics Education Research Conference 2021 Proceedings*. 39–44.
[2] Valerie Corkum and Chris Moore. 2014. Development of joint visual attention in infants. In *Joint attention*. Psychology Press, 61–83.
[3] Richard Dewhurst, Tom Foulsham, Halszka Jarodzka, Roger Johansson, Kenneth Holmqvist, and Marcus Nyström. 2018. How task demands influence scanpath similarity in a sequential number-search task. *Vision Research* 149 (2018), 9–23. https://doi.org/10.1016/j.visres.2018.05.006
[4] Andrew Duchowski. 2017. *The Gaze Analytics Pipeline*. 175–191. https://doi.org/10.1007/978-3-319-57883-5_15
[5] Andrew T. Duchowski, Krzysztof Krejtz, Nina A. Gehrer, Tanya Bafna, and Per Bækgaard. 2020. The Low/High Index of Pupillary Activity. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376394
[6] Andrew T. Duchowski, Krzysztof Krejtz, Izabela Krejtz, Cezary Biele, Anna Niedzielska, Peter Kiefer, Martin Raubal, and Ioannis Giannopoulos. 2018. The Index of Pupillary Activity: Measuring Cognitive Load vis-à-vis Task Difficulty with Pupil Oscillation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173856
[7] Shaun Gallagher. 2012. Interactive Coordination in Joint Attention. In *Joint Attention: New Developments in Psychology, Philosophy of Mind, and Social Neuroscience*. The MIT Press. https://doi.org/10.7551/mitpress/8841.003.0015 arXiv:https://direct.mit.edu/book/chapter-pdf/2276896/9780262303729_cdc.pdf
[8] Rahul Gavas, Debatri Chatterjee, and Aniruddha Sinha. 2017. Estimation of cognitive load based on the pupil size dilation. In *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. 1499–1504. https://doi.org/10.1109/SMC.2017.8122826

[9] Samantha EA Gregory and Margaret C Jackson. 2017. Joint attention enhances visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 43, 2 (2017), 237.

[10] Jia Guo and Gary Feng. 2013. *How Eye Gaze Feedback Changes Parent-Child Joint Attention in Shared Storybook Reading?* Springer London, London, 9–21. https://doi.org/10.1007/978-1-4471-4784-8_2

[11] Gavindya Jayawardena. 2020. RAEMAP: Real-Time Advanced Eye Movements Analysis Pipeline. In *ACM Symposium on Eye Tracking Research and Applications* (Stuttgart, Germany) *(ETRA '20 Adjunct)*. Association for Computing Machinery, New York, NY, USA, Article 8, 4 pages. https://doi.org/10.1145/3379157.3391992

[12] Gavindya Jayawardena, Yasith Jayawardana, Sampath Jayarathna, Jonas Högström, Thomas Papa, Deepak Akkil, Andrew T. Duchowski, Vsevolod Peysakhovich, Izabela Krejtz, Nina Gehrer, and Krzysztof Krejtz. 2022. Toward a Real-Time Index of Pupillary Activity as an Indicator of Cognitive Load. *Procedia Computer Science* 207 (2022), 1331–1340. https://doi.org/10.1016/j.procs.2022.09.189 Knowledge-Based and Intelligent Information Engineering Systems: Proceedings of the 26th International Conference KES2022.

[13] Gavindya Jayawardena, Anne Michalek, Andrew Duchowski, and Sampath Jayarathna. 2020. Pilot Study of Audiovisual Speech-In-Noisenbsp;(SIN) Performance of Young Adults with ADHD. In *ACM Symposium on Eye Tracking Research and Applications* (Stuttgart, Germany) *(ETRA '20 Short Papers)*. Association for Computing Machinery, New York, NY, USA, Article 38, 5 pages. https://doi.org/10.1145/3379156.3391373

[14] Peter Kiefer, Ioannis Giannopoulos, Andrew Duchowski, and Martin Raubal. 2016. Measuring Cognitive Load for Map Tasks Through Pupil Diameter. In *Geographic Information Science*, Jennifer A. Miller, David O'Sullivan, and Nancy Wiegand (Eds.). Springer International Publishing, Cham, 323–337.

[15] Krzysztof Krejtz, Andrew Duchowski, Izabela Krejtz, Agnieszka Szarkowska, and Agata Kopacz. 2016. Discerning Ambient/Focal Attention with Coefficient K. *ACM Trans. Appl. Percept.* 13, 3, Article 11 (May 2016), 20 pages. https://doi.org/10.1145/2896452

[16] Sebastiaan Mathôt. 2018. Pupillometry: Psychology, Physiology, and Function. *J Cogn* 1, 1 (Feb. 2018), 16.

[17] Bertrand Schneider, Kshitij Sharma, Sebastien Cuendet, Guillaume Zufferey, Pierre Dillenbourg, and Roy Pea. 2018. Leveraging mobile eye-trackers to capture joint visual attention in co-located collaborative learning groups. *International Journal of Computer-Supported Collaborative Learning* 13, 3 (01 Sep 2018), 241–261. https://doi.org/10.1007/s11412-018-9281-2

[18] Barbora Siposova and Malinda Carpenter. 2019. A new look at joint attention and common knowledge. *Cognition* 189 (2019), 260–274. https://doi.org/10.1016/j.cognition.2019.03.019

[19] Michael Tomasello. 2014. Joint attention as social cognition. In *Joint attention*. Psychology Press, 103–130.

[20] Minqiang Yang, Yujie Gao, Longzhe Tang, Jian Hou, and Bin Hu. 2024. Wearable Eye-Tracking System for Synchronized Multimodal Data Acquisition. *IEEE Transactions on Circuits and Systems for Video Technology* 34, 6 (2024), 5146–5159. https://doi.org/10.1109/TCSVT.2023.3332814