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Visual Attention in Face-to-Face and Computer Supported Communication

PhD Thesis

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Auxiliary supervisor: *dr Kazimierz Zieliński*

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Podziękowania

Chciałabym podziękować mojej promotorce Izabeli Krejtz za wsparcie merytoryczne, jak i osobiste podczas całej dotychczasowej drogi naukowej, od pojawienia się pierwszej myśli o doktoracie, po zakończenie tej przygody i podtrzymywanie wiary, że pójście dalej naukową ścieżką ma sens. Dziękuję również promotorowi pomocniczemu, Kazimierzowi Zielińskiemu za wsparcie podczas przeprowadzania badań.

Następnie, opiekunowi naukowemu, Krzysztofowi Krejtz za pomoc na każdym kroku doktoratu, umożliwienie pracy w międzynarodowych zespołach, jak również za przekazanie wiedzy analitycznej, która przyczyniła się do dotarcia do wyników prezentowanych w tej pracy.

W szczególności dziękuję też asystentom badawczym, bez których nie udałoby mi się przeprowadzić badań; całemu labkowi, z którym mogłam dzielić codziennie czas oraz wszystkim wspaniałym naukowcom, z którymi mogłam dzielić pasję badawczą podczas tych czterech lat.

Dziękuję również moim bliskim, rodzicom i przyjaciołom za nieustanną wiarę we mnie, wyrozumiałość i siłę jaką mnie obdarzyli, żeby pokonać wszystkie przeciwności.

Abstract

Computer supported communication has become an integral part of our daily routines. Despite decreased non-verbal communication and face-to-face contact with partners of collaboration, people learned how to remotely work together. The consequences of decreased gaze communication on collaboration quality in remote settings are not fully investigated yet. The present PhD project intended to examine, in three eye tracking experiments, the role of visual attention during face-to-face and computer supported communication. The project has three interrelated aims: (1) examining the relationship between interaction quality and gaze patterns in remote and face-to-face collaboration; (2) facilitating workspace awareness among collaborators by visualization of collaboration partner's gaze; (3) investigating the process of visual attention and information acquisition during online lectures. Additionally, as a part of the project I validated the use of webcam eye tracking to study visual attention dynamics (4).

(1) In the first study, the participants' visual attention mechanisms were analyzed during decision-making in the context of natural resource management in three experimental conditions: in-person collaboration, remote collaboration, and single user condition. I predicted that collaboration would guide users' visual attention to task-relevant information facilitating decision-making. As expected, during collaboration participants directed their attention to key elements during natural resource management task problem solving. In contrast to remote collaboration, in-person collaboration yielded a more optimal strategy of decision-making. Finally, in-person collaboration was found to be less cognitively demanding and of higher quality than remote collaboration. These findings could be used to improve social interaction and collaborative decision-making more broadly in remote settings.

(2) In the second study, collaborating pairs, differing in self-focused attention, solved logical problems in remote and co-located settings, with and without partner's real-time gaze visualization. In general, participants solved less problems in the remote than co-located collaboration. In line with predictions, gaze visualization enhanced joint attention of collaboration partners and evaluation of the collaboration quality. Self-focused participants benefited most from the visualizations in remote condition. As a result, we suggest that introducing visualization of a partner's gaze to remote computer-mediated systems may trigger a more partner-oriented perspective during remote collaboration.

(3) In the third study, students' visual attention was registered via a webcam eye tracker during online lecture. The study aimed at examining the relationship between visual attention distribution and effectiveness of online learning. I observed a positive correlation between knowledge acquisition and students' focal attention and its dynamics, with fixation duration - a sign of visual processing depth - being longer for those who retained more from the lecture. Compared to students who remember less, those who remember more from the lecture spent more time focusing on the lecturer's presentation and lecture's image than on self image and other students. Finally, the assimilation of course material was related to subjective ratings of concentration and cognitive load during the lecture. The insights from the study may inform designers of online learning platforms on how to arrange elements of the interfaces to promote focal attention.

(4) Finally, in the fourth study, I validated the use of webcam eye tracking for studying cognitive processes. We compared results of a visual search task obtained from a webcam eye tracker to a stationary eye tracker. Despite higher measurement error of the webcam eye tracker, both measurements yielded effects in line with theoretical expectations of the face-in-the-crowd effect. For example, time to first fixation toward happy faces was significantly shorter than toward sad faces suggesting the happiness-superiority effect. I also observed the switch from

ambient to focal attention depending on the complexity of visual stimuli. The findings support the use of webcam eye tracking to study dynamics of visual attention during cognitive processes.

Taken together, the present project suggests that insights from the analyses of visual attention dynamics may provide the basis for enhancing communication in both in-person and remote settings. The project provides support for the effectiveness of collaboration in promoting joint attention during remote and in-person collaboration. Interface designers may employ subtle graphical gaze cues (such as color or blinking) to draw users' attention to the collaboration interface's most important elements in order to improve the effectiveness of remote collaboration. The project evaluated also the influence of reduced communication with teachers on knowledge assimilation efficacy during online lectures. We showed that the level of information assimilation is correlated with the dynamics of visual attention during online learning. The results can be used in designing interfaces to help students focus on relevant information, or real-time recommender systems informing about the level of collaboration partners' concentration. To conclude, broadening the knowledge about dynamics of visual attention during computer-mediated communication is a step to develop gaze-based solutions tailored to remote interactions.

Streszczenie po polsku

Interakcja za pośrednictwem komputera stała się integralną częścią codziennych czynności. Pomimo obniżenia jakości komunikacji niewerbalnej i kontaktu twarzą w twarz z partnerami współpracy, ludzie nauczyli się, jak zdalnie współpracować. Konsekwencje ograniczenia sygnałów niewerbalnych – takich jak komunikacja za pomocą spojrzenia – na jakość współpracy w warunkach zdalnych nie są jednak w pełni zbadane. Niniejszy projekt doktorski ma na celu sprawdzenie w trzech eksperymentach okulograficznych roli uwagi wzrokowej podczas komunikacji twarzą w twarz oraz komunikacji zdalnej przy użyciu komputera. Praca ma trzy powiązane ze sobą cele: (1) zbadanie związku pomiędzy jakością interakcji a wzorcami spojrzenia w zdalnej i bezpośredniej współpracy; (2) wzmocnienie świadomości przestrzeni roboczej wśród współpracowników poprzez wizualizację kierunku spojrzenia partnera; (3) zbadanie procesu przetwarzania wzrokowego i przyswajania informacji podczas wykładów online. Dodatkowo, w ramach projektu przeprowadzono walidację rejestracji ruchów oczu z wykorzystaniem kamery internetowej (webcam eye tracker).

(1) W pierwszym badaniu analizowano mechanizmy uwagi wzrokowej podczas podejmowania decyzji w zarządzaniu zasobami naturalnymi w trzech warunkach eksperymentalnych: współpracy twarzą w twarz, współpracy zdalnej i pracy indywidualnej. Przewidywaliśmy, że podczas działań wspólnych uwaga wzrokowa badanych będzie kierować się na informacje istotne dla zadania, co ułatwi podejmowanie optymalnych decyzji. Zgodnie z oczekiwaniami, przy działaniach wspólnych uwaga partnerów współpracy skupiała się na kluczowych elementach zadania. Co więcej, w przeciwieństwie do współpracy zdalnej, współpraca twarzą w twarz prowadziła do bardziej optymalnej strategii podejmowania decyzji i okazała się mniej obciążająca poznawczo, niż współpraca zdalna. Wyniki te mogą być wykorzystane do wypracowania technik podnoszących jakość interakcji społecznych i wspólnego podejmowania decyzji we współpracy zdalnej.

(2) W drugim badaniu pary uczestników rozwiązywały problemy logiczne w warunkach współpracy zdalnej i kolokacyjnej, z i bez wizualizacji spojrzenia partnera w czasie rzeczywistym. Badani gorzej rozwiązywali problemy logiczne w warunku współpracy zdalnej niż kolokacyjnej. Wizualizacja spojrzenia zwiększała wspólną uwagę partnerów i jakość współpracy. Co więcej, uczestnicy charakteryzujący się większym skoncentrowaniem uwagi (self-focused attention) na sobie skorzystali najskuteczniej z wizualizacji w warunku zdalnym. Wprowadzenie wizualizacji spojrzenia partnera do zdalnych systemów komputerowych może podnosić perspektywę zorientowaną na partnera podczas zdalnej współpracy.

(3) W trzecim badaniu uwaga wzrokowa studentów podczas wykładów online była rejestrowana za pomocą kamery internetowej. Badanie miało na celu sprawdzenie związku pomiędzy dystrybucją uwagi wzrokowej a efektywnością uczenia się online. Zaobserwowano dodatnią korelację między wynikiem testu wiedzy wypełnianego po wykładzie a uwagą wzrokową studentów i jej dynamiką, przy czym czas trwania fiksacji – wskaźnik głębokości przetwarzania wzrokowego – był dłuższy u tych, którzy więcej zapamiętali z wykładu. Porównując studentów, którzy mniej zapamiętali z wykładu, z tymi, którzy zapamiętali więcej, mogliśmy zauważyć, że druga grupa spędziła więcej czasu, skupiając się na prezentacji i wizerunku nauczyciela niż na wizerunku własnym i innych studentów. Co więcej, przyswojenie materiału z kursu było związane z subiektywnymi ocenami koncentracji i obciążenia poznawczego podczas wykładu. Spostrzeżenia płynące z badania mogą pomóc projektantom platform edukacyjnych, dać wskazówki jak rozmieścić elementy interfejsu, aby podnosić poziom skoncentrowanej uwagi.

(4) Czwarte badanie miało na celu zwalidowanie metody śledzenia uwagi wzrokowej za pomocą kamerki internetowej i zweryfikowanie, czy metoda ta może być wykorzystywana do badania procesów poznawczych. Porównaliśmy wyniki z kamerki internetowej w zadaniu na wyszukiwanie twarzy o określonej emocji w tłumie innych twarzy (face-in-the-crowd task) z wynikami uzyskanymi ze stacjonarnego okulografu. Pomimo wyższego błędu pomiarowego kamerki internetowej, oba pomiary dały efekty zgodne z teoretycznymi oczekiwaniami. Na przykład, czas do pierwszej fiksacji w kierunku szczęśliwych twarzy był znacząco krótszy niż w kierunku smutnych twarzy, co sugeruje efekt wyższości szczęścia. Zaobserwowaliśmy również przełączanie się z uwagi rozproszonej na uwagę skoncentrowaną w zależności od złożoności bodźców wizualnych. Wyniki te wspierają wykorzystanie śledzenia oczu przez kamerę internetową do badania dynamiki uwagi wzrokowej podczas procesów poznawczych.

Podsumowując, projekt dostarczył nowej wiedzy sugerującej, że analiza dynamiki uwagi wzrokowej może stanowić podstawę do wzmocnienia komunikacji współpracowników. Projekt dostarcza wsparcia dla skuteczności współpracy w podnoszeniu wspólnej uwagi podczas współpracy zdalnej i twarzą w twarz. Projektanci interfejsów mogą wykorzystać subtelne graficzne wskazówki dotyczące spojrzenia (takie jak kolor lub miganie), aby zwrócić uwagę użytkowników na najważniejsze elementy interfejsu w celu poprawy efektywności współpracy zdalnej. W projekcie badano również zależność pomiędzy ograniczeniem komunikacji z wykładowcami a skutecznością przyswajania wiedzy podczas wykładów online. Wykazaliśmy, że poziom przyswajania informacji jest skorelowany z dynamiką uwagi wzrokowej podczas nauki online. Wyniki mogą być wykorzystane w projektowaniu interfejsów pomagających studentom skupić się na istotnych informacjach lub systemów informujących w czasie rzeczywistym o poziomie koncentracji partnerów do współpracy. Podsumowując, poszerzenie wiedzy na temat dynamiki uwagi wzrokowej podczas komunikacji za pośrednictwem komputera jest krokiem do opracowania rozwiązań opartych na spojrzeniu, dostosowanych do zdalnych interakcji.

Table of Contents

1. Series of articles

On the basis of my PhD research project, in collaboration with co-authors, I have prepared four empirical articles. Two of them are already published in conference proceedings, one is accepted for publication in a scientific journal, and the last paper is submitted for publication. All venues for my work are on the Ministry of Education and Science's list.

- **Wisiecka, K.,** Konishi, Y., Krejtz, K., Zolfaghari, M., Kopainsky, M., Krejtz, I., Koike, H., Fjeld, M. (2023) Supporting Complex Decision-Making. Evidence from an Eye Tracking Study on Large-Screen Collaboration. *ACM Transactions on Computer-Human Interaction*. http://doi.org/10.1145/3581787

  my contribution (70%) included: hypotheses, study design, measurement, literature review, article preparation
  MNISW: 140

- **Wisiecka, K.,** Mayer, S., Schweigert, R., Krejtz, I., Nielek, R., Bulling, A., Krejtz, K. Enhancing Computer-Mediated Collaboration with Gaze Visualization among Self-Focused Individuals. *Computers in Human Behaviour.* (under review).

  MNISW: 140 **my contribution: 75%**
- hypotheses, study design, measurement, analyses, literature review, article preparation

- **Wisiecka, K.,** Krejtz, K., Krejtz, I. & Duchowski, A. (2022). Dynamics of visual attention during online lectures - evidence from webcam eye tracking. In T. Bastiaens (Ed.), Proceedings of EdMedia + Innovate Learning (pp. 1220-1230). New York City, NY, United States: Association for the Advancement of Computing in Education (AACE). Retrieved July 8, 2022. ISBN 978-1-939797-65-0. from https://www.learntechlib.org/primary/p/221437/.

  MNISW: 70 **my contribution: 85%**
- hypotheses, study design, measurement, analyses, literature review, article preparation

- **Wisiecka, K.,** Krejtz, K., Krejtz, I., Sromek, D., Cellary, A., Lewandowska, B., Duchowski, A. (2022). Comparison of Webcam and Remote Eye Tracking. *ACM Symposium on Eye Tracking Research and Applications, ETRA'22*. http://doi.org/10.1145/3517031.3529615

  MNISW: 70 **my contribution: 80%**
- hypotheses, study design, measurement, analyses, literature review, article preparation

1.1 Additional achievements

1.1.1 Articles without those mentioned in the section 1

1. Krejtz, K., Szczeciński, P., Pawłowska, A., Rutkowska-Siuda, D., **Wisiecka, K.**, Milczarski, P., Hłobaż, A., Duchowski, A., Krejtz, I. (2023). A unified look on cultural heritage. Comparison of aggregated scanpaths between experts and non-experts in architecture. *ACM Symposium on Eye Tracking Research and Applications, ETRA'23*. (accepted for publication).

2. Krejtz, K., Krejtz, I. **Wisiecka, K.,** & Duchowski, A. (2022). Entropy of eye movements while reading code or text. *The Tenth International Workshop on Eye Movements in Programming 2022, EMIP'22.* pp. 8-14. https://doi.org/10.1145/3524488.3527365.

3. **Wisiecka, K.** (2021). Gaze and heart rate synchronization in computer-mediated collaboration. In *ACM Symposium on Eye Tracking Research and Applications, ETRA'21*. https://doi.org/10.1145/3450341.3457992.

4. Holas, P., Kowalczyk, M., Krejtz, I., **Wisiecka, K.,** Jankowski, T. (2021). Self-compassion mediates the relationship between self-esteem and social anxiety symptoms in socially anxious individuals. *European Psychiatry, 64*(S1). https://doi.org/10.1192/j.eurpsy.2021.1639.

5. Holas, P., Kowalczyk, M., Krejtz, I., **Wisiecka, K.,** & Jankowski, T. (2021). The relationship between self-esteem and self-compassion in socially anxious. *Current Psychology*, 1-6. https://doi.org/10.1007/s12144-021-02305-2

6. Krejtz, I., Krejtz, K., **Wisiecka, K**., Abramczyk, M., Olszanowski, M., Duchowski, A. (2020). Dynamic facial expressions recognition among deaf people. *Journal of Deaf Studies and Deaf Education.*10-21. https://doi.org/10.1093/deafed/enz036

7. Banasik, N., Wieland, L.,**Wisiecka, K.**, Popovic, L., Piper, J., Camilleri, L. (2020). Individual variability in caregivers' beliefs about using ironic expressions in child-directed speech. *PlosOne. 15*(2), https://doi.org/10.1371/journal.pone.0228538

8. Holas, P., Krejtz, I., **Wisiecka, K**., Rusanowska, M., Nezlek, J. (2020). Modification of attentional bias to emotional faces following Mindfulness-Based Cognitive Therapy in people with a current depression. *Mindfulness. 1*-11. https://doi.org/10.1007/s12671-020-01353-2

9. Krejtz, K., **Wisiecka, K**., Krejtz, I., Holas, P., Olszanowski, M., Duchowski, A. (2018). Dynamics of emotional facial expressions recognition in social anxiety. In *ACM Symposium on Eye tracking research & applications.* https://doi.org/10.1145/3204493.3204533

10. **Wisiecka, K**., Holas, P., Krejtz, I., Kowalczyk, M., Lusińska, K., Sobol, M. (2018). Mindfulness-Based Interventions and mechanism of visual attention among socially anxious people. *Research and Development of Young Scientists in Poland. Social Sciences and Humanities* III, 95-103

11. Grochowska, A., Młyniec, A., **Wisiecka, K**., Józefowicz, E., Ponikowska, K., Ozimek, A., Ślęzak, P., Krejtz, K. How Does Personality Affect Perception of Advertising Messages? The Big Five Model and Advertising Responses: A Meta-Analysis. *International Journal of Advertising.* (under review).

12. Kowalczyk, M., Kornacka, M., **Wisiecka, K**.,Młyniec, A., Redeł, A., Szwykowska-Ziemniak, M., Krejtz, I., The Relationship between Oral Contraceptives and Executive Functioning. A

Systematic Review, Meta-Analysis and Guide of Unified Methodological Practices. *European Psychologist.* (under review).

1.1.2 Research projects

1. ***Friendly city. Supporting the independence of the visually impaired people in the use of public transport networks in Łódź, including the application of location information and local architectural monuments.*** Principal investigators: Aneta Pawłowska, Krzysztof Krejtz, Izabela Krejtz, SWPS University & University of Lodz, NCBiR Grant - research coordinator, data scientist

2. ***A platform segmenting users and advertising messages based on mobile applications and personality traits.*** Principal investigators: Alicja Grochowska, Artur Zawadzki. SWPS University & Spicy Mobile, NCBiR Grant - data scientist (data analysis, preparation of preliminary reports on statistical analysis, preparation of test procedures)

3. ***The impact of inhibition on the link between daydreaming and maladaptive emotional regulation - a study with ecological momentary assessment and eye-tracking measures.*** Principal investigator: Monika Kornacka. SWPS University & Universite Grenoble Alpes, France, Polonium, NAWA (2020-2021) PPN/BFR/2019/1/00049 - researcher (co-investigator)

4. ***Developing and Validating the Focal Attention Span Test (FAST).*** Principal investigator: Krzysztof Krejtz. SWPS University, Regional Initiative of Excellence at SWPS University, 2020 - research assistant (meta-analysis preparation - literature collection, data preparation, analyses)

5. ***Understanding the relation between vegetarianism as social identity and mental well-being.*** Principal investigator: John Bruce Nezlek, SWPS University, Opus: 018/31/B/HS6/02822 - scholarship holder (literature review, help in developing the measurements, organizing and running focus groups, supervising group of students assisting in the project)

6. ***Associative learning mechanisms: functional organization of the amygdala in humans.*** Principal investigator: Iwona Szatkowska, Institute of Experimental Biology, Polish Academy of Science, Opus 8: 2014/15/B/HS6/03658 - research assistant (conducting fMRI measurements)

7. ***The impact of aging on making decisions and making judgments: Identification of restrictions related to age and compensatory mechanisms.*** Principal investigator: Sędek Grzegorz, SWPS University, Opus 9: 2015/17/B/HS6/04185 - scholarship holder (programming eye-tracking procedures, conducting the research and analyses)

8. ***The relationship between menstrual cycle and anxiety and cognitive functioning - the moderating role of oral hormonal contraceptive use.*** Project supervisor: Izabela Krejtz, Principal investigator: Melanie Kowalczyk. SWPS University, Preludium 19: 2020/37/N/HS6/02571 - data scientist (meta-analysis preparation)

9. ***Adaptive functions of the self concept in the dynamic-structural approach.*** Principal investigator: Tomasz Jankowski, Catholic University of Lublin, , Opus 10: 2015/19/B/HS6/02216- research coordinator (conducting measures, supervising MBCT groups, eye-tracking data analyses)

10. ***Long-term music training and reading skills, eye-tracking measures***. Project supervisor: Izabela Krejtz. Principal investigator: Agata Rodziewicz, SWPS University, Preludium 11: 2016/21/N/HS6/02845- research assistant (coordination of student assisting in the project, analyses)

11. ***The impact of gratitude on mental well-being and affect in women with breast cancer***

and women with depression. Project supervisor: Izabela Krejtz, Principal Investigator: Joanna Sztachańska. SWPS University, Preludium 11: 2016/21/N/HS6/02840 - coordinator of assistants team

12. ***Willpower and decisions, magnetic resonance imaging.*** Project supervisor: Magdalena Marszał-Wiśniewska, Principal investigator: Wojciech Zajkowski, SWPS University, Diamond Grant MNiSW, 2015 - research assistant (recrutation, conducting interviews)

13. ***Examination of the neuronal basis of temperamental traits with application standardized dynamic stimuli (Emotional Films Database)***. Project supervisor: Krystyna Rymarczyk. Principal investigator: Pamela Sobczak, SWPS University, Institute of Experimental Biology, PAN. Diamond Grant MNiSW, 2015 - research assistant (conducting recrutation and measurements)

14. ***The impact of cognitive function training on susceptibility to visual illusions.*** Principal investigator: Hanna Bednarek, SWPS Uniwersytet, Opus 9: 2015/17/B/HS6/04183 - research assistant (conducting measurements and analyses)

15. ***Content analysis of texts written by people suffering from depression. Looking for linguistic indicators specific for depressed people and changes in their functioning triggered by psychological interventions.*** Project supervisor: Izabela Krejtz. Principal investigator: Natalia Rohnka. SWPS University. BST, 2016 - research coordinator (supervising participants on online research platform)

16. ***The development of social competence, and the understanding of irony***. Project supervisor: Natalia Banasik, Junior Research Program, Cyprus, 2017/18 - co-investigator

1.1.3 Selected conferences

1. Grochowska, A., Młyniec, A., **Wisiecka, K**., Józefowicz, E., Ponikowska, K., Ozimek, A., Ślęzak, P., Krejtz, K. (2021). How Does Personality Affect Perception of Messages? The Big Five Model and Advertising Responses: A Meta-Analysis. *The 19th International Conference on Research in Advertising (ICORIA, 2021)*

2. Participation in Doctoral Symposium at ACM Symposium on Eye Tracking Research and Applications, ETRA'21. Online presentation: *Gaze and Heart Rate Synchronization in Computer-Mediated Collaboration.*

3. **Wisiecka K.,** Mayer S., Schweigert R., Krejtz I., Nielek R., Bulling A., Krejtz K. (August, 2019). *Joint and Self-Focused Attention in Computer-Supported Collaboration - the Role of Gaze Visualization.* Poster presented at the European Conference of Eye Movements, Alicante, Spain.

4. **Wisiecka, K.**, Krejtz, I., Holas, P., Rusanowska, M., Nezlek, J. (March, 2019). *Modification of Attentional Bias to Emotional Faces Following Mindfulness-Based Cognitive Therapy among People with a Current Depression.* Poster presented at the International Convention of Psychological Science (ICPS), Paris, France.

5. **Wisiecka, K.**, Krejtz, I, Krejtz, K., Holas, P., Kowalczyk, M., Olszanowski, M., Duchowski, A. (June, 2018). *Happiness superiority effect during dynamic emotion recognition among socially anxious people.* Poster presented at 9th European Conference on Positive Psychology, Budapest, Hungary.

6. XVI Congress of the Polish Association of Social Psychology, Poznań, (September, 2019). Symposium: Social information processing – from infancy to pathology. Using eye-tracking techniques to understand how people perceive and interpret social events. Coordinator: dr hab. Anna Zajenkowska. Presentation: *Effectiveness of mindfulness training in reducing attentional biases in clinical depression – evidence from eye-tracking studies.*

2. Introduction

Collaboration can be defined as the process of two or more people, entities, or organizations working together to complete a task or achieve a goal (Marinez-Moyano, 2006). Collaboration is also a process where co-workers who see different aspects of a problem can constructively explore these alternative aspects and search for solutions transcending each individual's view (Wood, 1991).

In recent years, however, collaboration has had various facets and forms as people started to have more computer-supported interactions with collaboration partners with limited face-to-face contact. It triggered the need to develop solutions that enable collaborators to feel comfortable with the systems to maintain online relationships during remote communication. The challenge to create a collaborative online workspace is critical not only from a technological, but also a psychological perspective. Several meta-analyses showed that technology support could be an effective solution for promoting retention of interaction and problem-solving during collaboration (e.g., Li and Ma, 2010; Roseth et al., 2008).

The outset to struggle with limitations in existing systems is to understand the cognitive processes during computer-supported communication and different needs resulting from remote communication settings or individual differences. However, there is a lack of empirical evidence about the psychological nature of face-to-face and remote collaboration. The existing technological solutions for remote communication may benefit from understanding of attentional processes and mechanisms that are imperceptible or even unconscious during collaboration, e.g., platforms for online meetings.

2.1. The importance of collaboration

Collaboration may trigger processes that do not occur in individual work and can yield unique strategies and novel problem descriptions (Schwartz, 1995; Shirouzu et al., 2002). Collaboration has a strong potential to tackle problems posed in decision-making. However, just working in a group does not necessarily guarantee success. Often, there can be difficulties in group work leading to time wasted, discouragement, and, in the end, lack of progress (Barron 2003). The success of problem-solving varies significantly among groups, even when group members have comparable knowledge levels (Hogan et al. 1999; Webb et al. 2013). Barron (2003) points out the importance of capitalizing on the "potential of distributed reasoning". In this process, the most important is to coordinate the collaboration partners' cognitive resources, that is e.g. their level of knowledge, concentration, and distribution of attention.

2.1.1. Workspace awareness and shared reality

According to the theory of distributed cognition (Flor &, Hutchins, 1991), the social context and the artifacts present in the environment result in a cognitive system distributed among actors engaged in a collaborative activity. One of the concepts of creating a distributed cognition during collaboration is enhanced workspace awareness. Workspace awareness is the up-to-the-moment understanding of another person's interaction with a shared workspace (Gutwin et al. 1996). This involves knowledge about where others are working, what they are doing, and what they will do next. Therefore, workspace awareness enables the creation of a shared reality which is a process of experiencing a commonality of inner (mental) states with others which includes shared ground to exchange ideas and knowledge on particular issues (Echterhoff et al., 2009, Shteynberg, 2015; Higgins, 1992). This allows for an efficient flow and communication required for optimal collaboration (McCraty and Childre, 2010). The processes described above can be explained by observing both behavioral and physiological processes along with verbal and non-verbal signals occurring during collaboration (Dumas, 2011, McCraty, 2017). Collaboration success is based on distributed cognition that comes from verbal and non-verbal communication signals.

2.1.2. Verbal and non-verbal communication

Gestures, a non-verbal communication channel, sometimes represent our thoughts and emotions more effectively than language (Jamalian and Tversky, 2012). Also, facial expressions and gaze direction are essential during communication and collaboration (e.g., Miller, 1959; Buck, 1994; Motley and Camden, 1988). Face and gaze are important means of communication that provide information about a partner's intentions, emotional state, and direction of attention.

During collaboration, people share focus on an object, both in indicating to each other their course of attention and in responding to each other’s signals. Individuals can either indicate things physically (deictic gestures), verbally (describing the object of interest), or by using their body (position and orientation). Partners in social interaction need to demonstrate awareness that they are working on something in common via non-verbal signals, such as gaze direction (Tomasello et al. 1995).

Mutual gaze and gaze-following represent processes involving two individuals. Following another individual’s gaze to a novel focus of visual attention creates a situation of joint attention. Perception of eye direction is a core process of joint attention, a fulcrum of social cognition (Dumas, 2011). Joint attention is a particularly interesting aspect of social gaze while mutual gaze and gaze-following represent dyadic processes involving two individuals, it represents a triadic interaction involving a ‘referential triangle’ of two individuals and some third entity (e.g., object, person, task) in the environment (Carpenter et al., 1998). As people look where they attend and where they intend to act, joint attention is considered a fundamental developmental milestone and essential to an understanding of other minds and building shared reality to collaborate. Joint attention is associated with many overlapping concepts in the cognitive sciences: shared cognition, intersubjectivity, grounding processes in conversation, joint problem-solving, and distributed cognition (e.g., Barron and Roschelle 2009; Echterhoff et al. 2009).

While there are many methods to study communication during interaction, such as head movements (Cognolato et al. 2018; Müller et al. 2018; Yu and Smith 2017) and gesture analysis (Gullberg and Holmqvist 1999; Kendon 1988), I chose to use mobile eye tracking to examine gaze patterns during face-to-face and remote communication and collaboration. This enabled me to register participants’ attention allocation during task performance as a measure of shared visual workspace (Fussell et al. 2000).

3. Supporting Collaboration on Complex Decision

Wisiecka, K., Konishi, Y., Krejtz, K., Zolfaghari, M., Kopainsky, M., Krejtz, I., Koike, H., Fjeld, M. (2023) Supporting Complex Decision-Making. Evidence from an Eye Tracking Study on Large-Screen Collaboration. *ACM Transactions on Computer-Human Interaction*. http://doi.org/10.1145/3581787

(a) In-person collaboration (b) Remote collaboration (c) Single user

Figure 1: Study participants collaborating on the system interface resolving a natural resource management task (Reindeer Task, Moxnes 2014) in (a) in-person collaboration, (b) remote collaboration, and (c) single user condition. Each participant is wearing a mobile eye tracking device.

In this study, we looked at the visual mechanics of collaboration during decision-making in the context of sustainability in natural resource management that are under danger of overuse and depletion. We selected a reindeer rangeland management challenge for our natural resource dynamic simulation. The framework of this task is typical of many natural resource management projects, such as mitigating climate change (Derwisch and Kopainsky 2011; Moxnes 2004). A few studies have examined the possibility of multiplayer System Dynamic - based simulations (SD - based simulations), most of SD-based simulation activities were created for and tested on single users (Happach and Schoenberg 2017). In our work, we fill this gap by using an eye tracking technique to investigate collaborative decision-making on large displays. We looked into how visual attention is processed during group decision-making in face-to-face and remote collaboration, and single user condition. We observed a cognitive mechanism underlying workspace awareness during computer-supported collaboration by observing eye movements during cooperation.

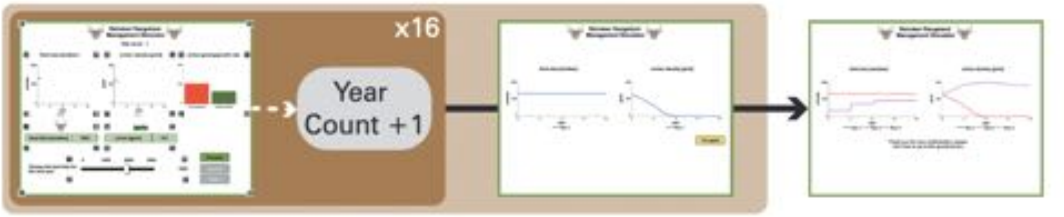
3.1 Hypotheses and design

In relation to the three experimental conditions - in-person collaboration, remote collaboration, and single-user condition - the current study included four key hypotheses. First, making a decision collaboratively requires a great deal of cognitive effort, which can be seen in the traits of eye movement fixations (Duchowski et al. 2020; Krejtz et al. 2020). Second, we hypothesized that cooperation would direct partners' visual attention to the most crucial visual features given in simulation control areas, which in turn would affect how the system is understood and how decisions are made. Third, we aimed to see how partner distance affects the distribution of visual attention and the process of collaborative decision-making (in-person vs. remote collaboration condition). In contrast to the single-user scenario, we predicted that collaboration would result in more successful task-solving. We specifically expected that in-person collaboration would encourage a decision-making approach similar to the best approach discovered through a dynamic model simulation, which can be seen at the behavioral level in participants' decisions captured with system logs. Then, anticipating to see differences favoring in-person decision-making, we evaluated the subjective quality of collaboration, task workload, and usability as a self-reported dependent variable.

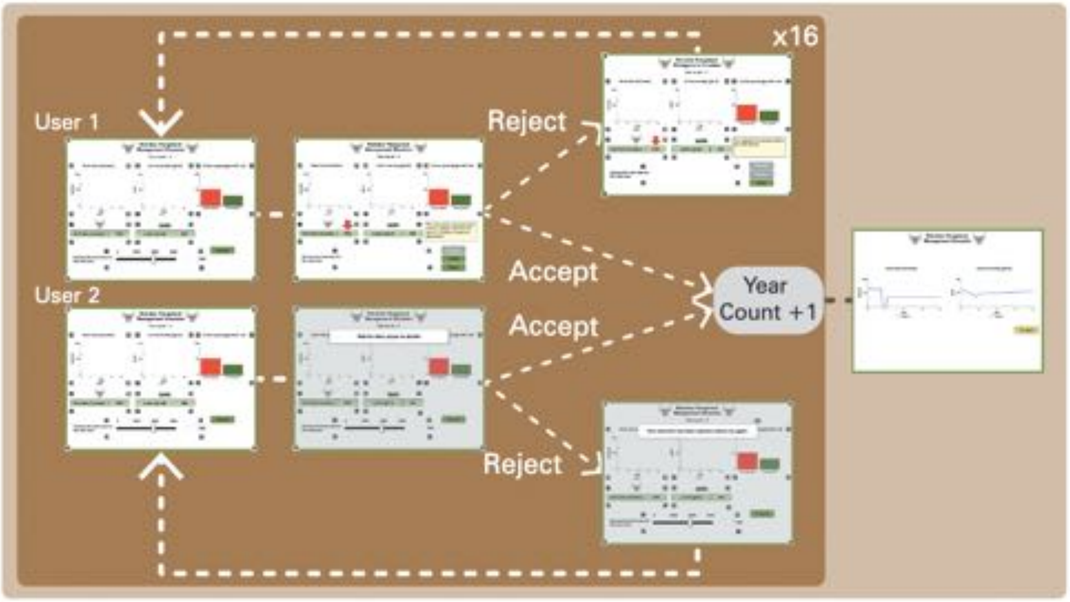
We conducted a mixed-design eye tracking experiment to fulfill the objectives of the study and test the hypotheses. A total of 71 students volunteered to participate in the experiment

(30 Females, $M_{age} = 26.52$, $SD_{age} = 5.12$). Participants were randomly assigned to one of three experimental conditions: single user (17 individuals), in-person collaboration (13 pairs), and remote collaboration (14 pairs). The collaborating pairs were of the same sex. For the experimental task we used an SD-based simulation task developed by Moxnes (2004), see Figure 2.

The study's triangulation of data from three sources - self-report questionnaires, behavioral choices recorded in simulation system logs, and attentional distribution recorded by eye tracking devices allowed for more thorough analysis of the results. Similar mixed-method techniques have been employed in the past to examine collaboration, such as by Mayer et al. (2018). Therefore, analyses were divided into three parts: (a) depth of information processing (hypothesis 1), visual attention distribution (hypothesis 2), (b) simulation outcome analyses (hypothesis 3), and (c) subjective assessments of task workload, system usability, and collaboration quality (hypothesis 4).



(a) Simulation task workflow used in a single-user experimental condition.



(b) Simulation task workflow used in remote and in-person collaboration experimental conditions.

Figure 2: Simulation task workflow in all experimental conditions (single user, in-person collaboration, and remote collaboration). The the user interface displays data such as herd size, lichen density, and lichen grazing rate. This data is presented in two ways: as a graph over time and as a numerical display. There are two input areas at the bottom of the user interface; one for users to enter their decisions on reindeer herd size and the other for users to interact with collaboration partners in the collaboration condition. The participants could enter the number of reindeer using either a slider or numeric input. Once they proposed their decision using the propose button, they were directed to a waiting page where they had to wait for the other collaboration partner to decide on the proposed number. The collaboration partner was notified that a number for the reindeer herd had been proposed. They could either accept or reject the proposed number using consensus buttons. If they were in agreement, they clicked the accept button, which advanced the simulation by one year. The reject button was used if the collaboration partner did not agree, whereby the partner who had proposed the number was notified and they had to agree upon a new number for the reindeer herd. Participants made sixteen decisions in the simulation task as described above.

3.2 Main results

We examined the visual attention distribution and depth of processing over simulation control and decision-making regions of interest to test the hypotheses concerning attentional bias to critical information and provide insight into decision-making. The average fixation period on decision-making areas of simulation was significantly longer for participants in all three experimental conditions than it was for simulation control AOIs. Considering the "eye-mind assumption" of Just and Carpenter (1976), this may imply that making decisions required more cognitive effort than reading simulation control graphs.

According to the second hypothesis, participants in both collaboration situations spent more time looking at the lichen density graph when analyzing simulation control graphs than they did at the other two graphs. This was notably evident in the condition involving in-person collaboration, as participants paid more attention to the lichen density graph than they had in the other two conditions. Understanding the concepts underpinning the simulation task required understanding of the lichen density graph. Participants' focus was equally split among the simulation control graphs in the single-user condition.

In general, participants' choices for herd size resulted in a lichen density that was close to the optimal solution. Notably, participants in the single user and in-person conditions appeared to adopt a slightly different approach from those in the remote condition that were closer to optimal decision-making strategy.

Despite the fact that all participants gave the system a comparable rating for usability, those who participated in the in-person collaboration and single user conditions said they felt less workload to do than those who worked remotely. Participants who worked together in-person rather than remotely reported higher collaboration quality and a sense of greater control over the simulation. Based on the findings, we hypothesize that higher satisfaction with collaboration was caused by a better task understanding, which is reflected in attention bias toward the most significant information and the best outcome of one's own judgments.

3.3 Conclusions and future studies

Altogether, the data allow us to draw the conclusion that remote and in-person collaboration enabled users to concentrate more on the information needed to manage the simulation than in the single-user scenario. The results are consistent with the concept of collaboration given by Roschelle and Teasley (1995) as the process of creating a common understanding through engagement with others and a dedication to problem-solving. Importantly, compared to distant collaboration, in-person collaboration allowed for even higher attention to focus on important information. Additionally, decisions made by users and their results were closest to optimal when participants worked together in-person. Thus, when compared to alternatives (without any instructional help) for single users, the in-person collaboration examined in our research appears to have improved understanding (Moxnes, 1998, 2004). The degree of shared understanding and commitment in task-solving may be attributed to the limited availability of non-verbal signals of communication during remote collaboration, such as gaze communication (Pfeiffer et al. 2013) or mimicking others' non-verbal behavior and postures (Shockley et al. 2003). Settings for remote collaboration seem to lack a number of partnership coordination activities, such as directing both partners' attention to the same visual stimuli by gesturing, pointing, or eye contact (Clark and Krych 2004). Therefore, it is necessary to look for solutions that allow nonverbal communication in an online workspace.

In order to increase the effectiveness of remote collaboration, interface designers may use subtle graphical gaze cues (such as color or blinking) to direct users' attention to the collaboration interface's most crucial components. By doing this, they will be able to activate the bottom-up mechanisms of visual attention (Posner 2011) and reduce chaotic attention distribution.

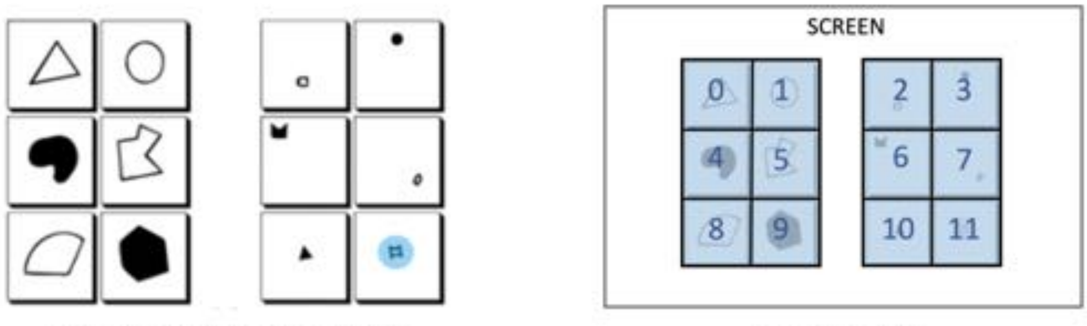
In this study, we looked at how people collaborated on big interactive screens. This research may be expanded to include relatively common small screens, such as tablets or smartphones, where it may be more difficult to maintain workplace awareness.

The current work may also be expanded by including new technologies, such as haptic or tangible input devices (Fjeld et al. 2007; Patten et al. 2001), that could improve workspace awareness. The importance of awareness in collaborative workspaces mixing real-world and virtual settings is another area worth researching (Kudo et al. 2021) .

Our research offers suggestions for developing ICT-based systems for teamwork that are collaborative, such as remote teamwork or computer-supported collaboration, which could result in new technological advances. Our findings are applicable to large-scale collaborative problem-solving in related fields like logistics simulation, smart grid design, and natural resource planning.. It can assist in influencing how collaborative technologies for networks, communities, groups, and organizations are designed in the future.

4. Gaze visualization and self-focused attention in computer supported collaboration

Wisiecka, K., Mayer, S., Schweigert, R., Krejtz, I., Nielek, R., Bulling, A., Krejtz, K.
Enhancing Computer-Mediated Collaboration with Gaze Visualization among
Self-Focused Individuals. *Computers in Human Behaviour.* (under review).



(a) An example of the Bongard's Problem

(b) Areas of Interest

Figure 3: a) An example of the Bongard's Problem with a Gaze Visualization point (cyan circle). The correct answer: figures on the images on the left are big. b) Areas of Interests (AOIs). Each AOI corresponds to one image.

In face-to-face interactions, nonverbal cues like gaze cueing and reciprocal eye contact are essential to establishing joint attention. By observing and tracking the partner's eye direction to a shared reference, collaboration performance can be improved (Pfeiffer et al. 2013; Schneider et al. 2018). Compared to face-to-face cooperation, little is known about gaze communication during computer-supported collaboration. Given that non-verbal communication is reduced in computer-supported collaboration (Hadwin et al. 2018), interaction partners' gaze directions could improve the quality of their collaboration. Evidence for this claim comes from eye-tracking experiments, which show that knowing participants' gaze directions improves the quality of computer-supported collaboration (Ishii and Kobayashi 1992; Soller et al. 2005; Velichkovsky 1995). These studies provide information about the attentional patterns of two or more collaborators, indicating the role of gaze-based solutions in enhancing quality of interaction. Until now, gaze visualization in computer-supported collaboration has also been linked favorably to performance (Velichkovsky 1995), coordination (Serim et al. 2018), and searching behavior (Siirtola et al. 2019; Zhang et al. 2017). However, different methods of gaze visualization or individual diffrences that may influence real-time gaze communication have not yet been thoroughly investigated (D'Angelo and Gergle 2018).

Gaze cue perception is influenced by the reciprocity of social contact (Bayliss et al. 2013; Schilbach et al. 2013). The "gaze-cueing effect" (Driver et al. 1999) suggests improved performance at areas to which one's gaze was directed. In face-to-face communication, synchronization of gaze-cueing results in higher joint attention and better cooperation outcomes (Pfeiffer et al. 2013). However, successful gaze-cueing can only be achieved if both/all participants can inhibit their own perspective (self-focused attention inhibition) (Samson et al. 2005). It may be more difficult to unite attention with a partner when working remotely, according to our theory on self-focused attention restriction.

A propensity to focus attention on either internal or external stimuli is known as attentional focus (Astle and Scerif 2009; Posner and Petersen 1990). High attentional focus on internal stimuli (self-focus attention, Ingram 1990) influences the absorption of social cues. Because of their propensity to become more easily distracted while collaborating, people with high self-focus attention may benefit from gaze visualizations.

According to Kaplan and Berman (2010), high levels of self-focused attention are linked to reduced endogenous attentional control and a decreased capacity to direct the individual's attention to something that doesn't particularly (internally) interest them (Morecraft et al. 1993). It diverts focus away from the current task, which may make it more difficult to complete it successfully (Spurr and Stopa 2002). The distance between collaborators and the absence of non-verbal contact during remote collaboration further impede the management of attention in highly self-focused individuals. When participating in remote and in-person collaboration, including gaze visualizations as exogenous cues can help participants focus on other people's perspectives and improve the effectiveness of their work.

4.1 Hypotheses and design

In our study, we looked at the quality of computer-supported collaboration during logical problem-solving in co-located and remote settings, as well as at the impact of gaze visualization projection. Additionally, we considered self-focus attention differences that might affect gaze communication. In general, we anticipated that the projection of gaze visualization would improve problem-solving efficiency as assessed by task accuracy (H1). Additionally, we hypothesized that gaze visualization would enhance joint attention as evaluated by reciprocal gaze fixations (H2). Finally, we predicted that the degree of self-focused attention would moderate the relationship between accuracy and joint attention (H3).

We conducted a 2x2x2 laboratory experiment where participants worked in pairs to solve Bongard Problems while their eye movements were being monitored to test these predictions. Participants (24, age: *M* = 20.86, SD = 1.7) solved half of the problems with gaze visualization and the other half without gaze visualization (the independent within-subjects variable ‘visualization’: control vs. gaze visualization). The independent within-subjects variable ‘setting’ is related to the collaborative environment; participants solved half the problems remotely and the other half in person (Setting: co-located vs. remote). Using the Self-Consciousness Scale (SCS-R) (Scheier, 1985) as a pre-screening tool, we classified participants into low and high self-focused attention groups, yielding a between-subjects independent variable called *Self-Focused Attention* (low vs. high). They completed 32 Bongard Problems (see Figure 3).

4.2 Main results

In general, the findings supported our main hypotheses, however, the influence of gaze visualization varied by group and cooperation setting. Compared to conditions without gaze visualization, adding a partner's gaze visualization led to better results in solving Bongard Problems and higher levels of joint attention. Participants with high levels of self-focused attention who collaborated remotely benefited the most from gaze visualization. The mixed design enabled us to observe that despite the importance of direct contact during co-located collaboration, the accuracy of solved problems in this setting appeared to be also enhanced by gaze visualization. However, the effectiveness of gaze visualization in each setting was differentiated by self-focused attention level. Low self-focused individuals benefited from gaze visualization more in co-located setting, whereas high self-focused in remote setting. The difference between groups in co-located settings might be related to a higher ability to absorb social cues, both off-screen and on-screen among low self-focused individuals than among high self-focused individuals. Contrary, in the remote setting, without face-to-face social cues, the performance of high self-focused individuals decreased, and gaze visualization improved their performance more than among the low self-focused group.

Higher joint attention in remote collaboration for highly self-focused participants was surprisingly associated with decreased accuracy. Self-focused attention may lessen the partner's oriented perspective, supporting earlier findings (Smith and Greenberg 1981). Our findings go beyond these conclusions by demonstrating that high self-focused individuals cannot improve remote collaboration simply by gazing at the same targets simultaneously. Gaze visualization improved awareness of the other person's focus of attention, leading to increased accuracy and shared joint attention among high self-focused persons in a remote situation. Observing where the partner is looking, which is strengthened by gaze visualization, appears to be a key to improving collaboration among highly self-focused people.

4.3 Conclusions and future studies

By requiring participants to pay attention to their partner's attentional cues while collaborating, the current study offers insights into improved gaze communication. Here, the partner's gaze visualization promoted joint attention and the transition from self-focused to partner-focused attention. Therefore, gaze visualization aims to broaden the partner’s perspective in cooperative problem-solving, resulting in a better performance quality.

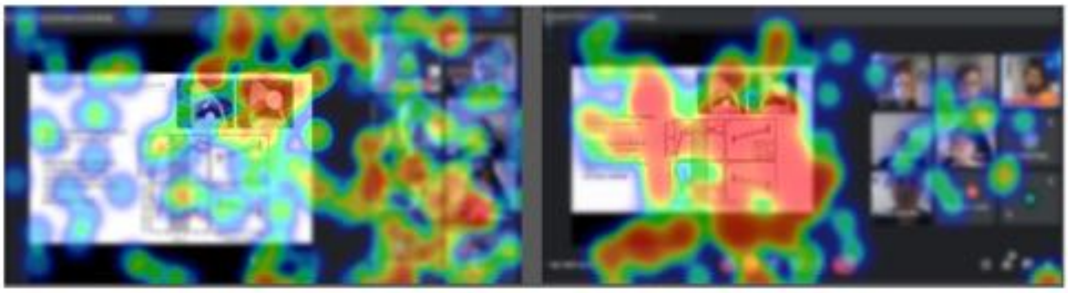
The current study has a twofold contribution. First, we support the effectiveness of gaze visualization in promoting joint attention during remote and in-person collaboration. Second, to the best of our knowledge, this is the first study registering how individual attentional focus differences affect collaboration when working remotely.

Although there is a wealth of research in the field of computer-supported collaboration, it is misleading that individual differences that have an influence on face-to-face collaboration were not studied thoroughly in this area. The present study supports the idea that gaze visualizations might be a way to enable people with higher levels of self-focused attention to focus on important details during distant cooperation.

Gaze visualization can help people with particular attentional tendencies during remote collaboration. Our results may be used as a basis for gaze-based solutions enhancing computer-supported collaboration for people with different individual characteristics. We hypothesize that existing online group work platforms or remote collaboration may benefit from enhancing gaze communication. In the coming years, considering each person's unique requirements, the solution based on the perception of eye direction may play a significant role in the development of remote cooperation and eye-tracking research.

5. Visual attention during online lectures

Wisiecka, K., Krejtz, K., Krejtz, I. & Duchowski, A. (2022). Dynamics of visual attention during online lectures - evidence from webcam eye tracking. In T. Bastiaens (Ed.), Proceedings of EdMedia + Innovate Learning (pp. 1220-1230). New York City, NY, United States: Association for the Advancement of Computing in Education (AACE). Retrieved July 8, 2022. ISBN 978-1-939797-65-0. from [https://www.learntechlib.org/primary/p/221437/.](https://www.learntechlib.org/primary/p/221437/)



a) Low score student

b) High score student

Figure 4: Heatmap of (a) a low score and (b) high score students' visual attention.

According to research (Haataja et al. 2021), eye contact between teachers and students is important in natural classroom settings. The mechanism of visual attention in an online environment is not well understood when compared to processes that naturally occur between teachers and students in a classroom (Haataja et al., 2021).

Second, more research must be done on the impact of screen distractions such as the students' own and other students' faces that are shown adjacent to the presentation. Research underlines the cognitive overload that can result from staring at a computer screen while learning (Mierlo 2012). Thirdly, we need to investigate how instructors and distractions alter the dynamics of visual attention, shifting it from ambient to focal. The dynamics of visual attention during synchronous online classes still require further study.

The present study evaluated the efficacy of knowledge assimilation in a setting where there is less eye contact and more external distraction than in a traditional classroom (Hollis and Was 2016). We observed how students distributed their visual attention throughout an online lecture and how well they retained the class content. Additionally, we verified if their level of information assimilation is correlated with the dynamics of their visual attention, specifically the ratio of ambient/focal attention.

Eye tracking is a helpful method for researching how people learn. This is because, both when we learn and when we execute professional work, we primarily acquire information through our eyes. The recording of visual attention may offer a singular source of information about the focus of a student's visual attention throughout the class, revealing what they value, which features of the online platform facilitate their ability to focus, and which attention indices are associated with effective learning.

According to Grindinger et al. (2010), assessments of eye movements may be conducted on fixation allocation or on the sequence of events (e.g., de Bruin et al. 2013). It is critical to record not only attentional distribution but also the time-ordered path (sequence) of visual attention when gathering information (Krejtz et al. 2014). Fixations and saccades interact dynamically during the visual processing process. Their characteristics are a reflection of the ambient and focal modes of attentional processing, with the latter being more serial than parallel in visual search. Attention shifts from parallel (ambient attention) to serial (focal attention) processing while taking in visual information (Velichkovsky et al. 2005). Deeper information processing and attention control happen with more focal attention (Pannasch et al. 2011). The dynamics of visual processing and information acquisition during online classes were examined in the current study using the ambient/focal attention measure.

The process of visual attention during real-time synchronous online learning is essentially unknown, despite the advancements in technology and the growth of online learning. In terms of the significance of the locations on the learner's screen, there is very little empirical background in this area. It's still unclear how the teacher's, owns', or even the students' faces adjacent to the presentation affect the learners' attention during online lectures. Does it foster a sense of shared cognition or divert the learners' attention?

5.1 Hypotheses and study design

In the current study, we sought to understand how online learners assimilate knowledge while taking social context into account. First, we looked at how much visual attention was paid to the presentation, the teacher, the other students, and one's own face as recorded by the webcam. Second, we contrasted the visual attention distribution across the groups that had low and high results on the knowledge exam conducted after the lecture. Third, we examined the relation between the dynamics of visual processing (ambient/focal attention) and lecture-related information. These were our hypotheses: (1) self-reported levels of cognitive load, concentration, and interaction difficulty would all be related to test scores; (2) high scorers students would pay more visual attention to the teacher and presentation than low scorers students; (3) the presence of students' and one's own face would divert attention; and (4) the degree of focal attention would predict greater lecture-related knowledge.

A total of 24 second-year psychology students (M age = 21, SD = 4.6, 15 females) took part in the study. We split participants into low score (11 students with fewer than 50% good answers) and high score (13 students with more than 50% good responses) groups based on a post-lecture knowledge exam. Before statistical analyses, four Areas-of-Interest (AOI) were defined: over the presentation displayed during the class, the teacher, each student’s own face (self) and the rest of the students (see Figure 4).

5.2 Main results

The results showed that during online lectures, students who retained more information looked at the instructor longer than those who did not. Students who recalled more from the lecture paid less attention to their fellow classmates than those who remembered less. According to the findings, seeing other students while paying attention to the teacher causes more disruption than advantage. Additionally, students with lower task scores paid more visual attention to their own image than students with higher test scores did (see Figure 5).

Further, for those who remembered more from the lecture, fixation duration - a sign of visual processing depth was shown to be longer. By including measures of ambient/focal attention in the dynamics of visual information acquisition, we expand this line of analysis. showing that students' focal attention was positively correlated with their knowledge test score.

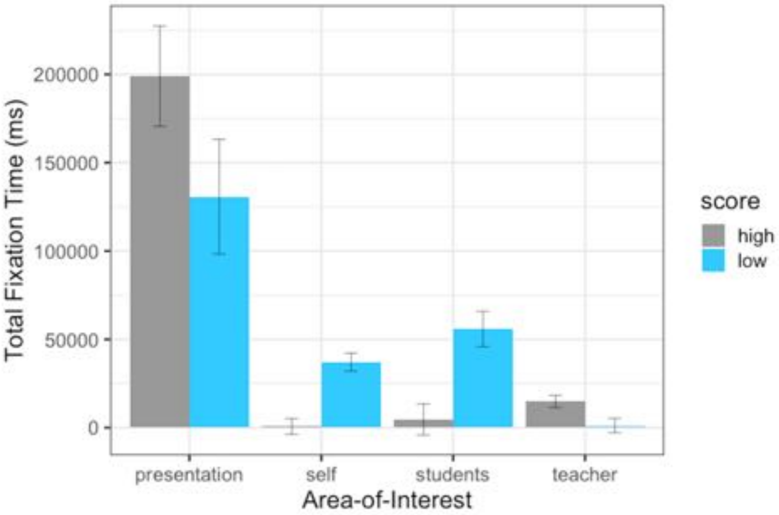


Figure 5: Total fixation time Dwell time of looking at each AOI (presentation vs. self vs. students vs. teacher) in high score and low score group.

5.3 Conclusions and future studies

This study's objective was to assess the efficacy of information assimilation during online lectures by recording the distribution of visual attention in a natural, ecological setting. We monitored students' visual attentiveness during online lectures using a computer webcam that enabled participants to behave naturally.

My results supported Wang's (2017, 2020) findings by the fact that students with higher test scores seem to value the visual contact with a teacher. However, it is important to note that we did not compare this effect to the situation where the teacher's face was not present in real-time online lectures. To determine the impact of missing the teacher's face, it is important to compare the research situation with the absence of the teacher's face in subsequent trials.

According to the findings, seeing other students while paying attention to the teacher causes more disruption than advantage. The virtual learning community may benefit from seeing friends' faces and being able to watch their reactions (Vygotsky 1978; Harasim et al.1995; Wilson, 2001), but our findings do not support this theory. Investigating the lecture's various scenarios is worthwhile. In our study, the student's task was to pay attention to the lecture and, if necessary, to ask questions. More collaborative tasks could potentially modify attention allocation and have a different effect on information acquisition, taking into account the significance of involvement in online learning (Davies and Graff 2005; Vonderwell and Zachariah 2005; Hrastinski 2008).

Perhaps more intriguingly, students with lower task scores paid more visual attention to their self-image than students with better test scores. It is compatible with theories of self-focused attention that suggest that one's self-image interferes with attention when learning (Spurr & Stopa 2002; Ingram 1990; Liao and Masters 2002). Further, our research supports Yang et al (2013) observation that students who remember more of the lecture material fixate on presentations for longer periods of time. By including measures of ambient/focal attention in the dynamics of visual information processing, we expanded this line of analysis. In our study, the knowledge test score was positively correlated with students' focal attention.

Future online evaluation systems may incorporate eye tracking techniques to more thoroughly study the cognitive process during e-learning (Tsai 2012). However, the present study is the first to use online eye tracking to track the distribution of visual attention during real-time synchronous learning.

6. Comparison of webcam and remote eye tracker - validation

Wisiecka, K., Krejtz, K., Krejtz, I. & Duchowski, A. (2022). Dynamics of visual attention during online lectures - evidence from webcam eye tracking. In T. Bastiaens (Ed.), Proceedings of EdMedia + Innovate Learning (pp. 1220-1230). New York City, NY, United States: Association for the Advancement of Computing in Education (AACE). Retrieved July 8, 2022. ISBN 978-1-939797-65-0. from [https://www.learntechlib.org/primary/p/221437/.](https://www.learntechlib.org/primary/p/221437/)

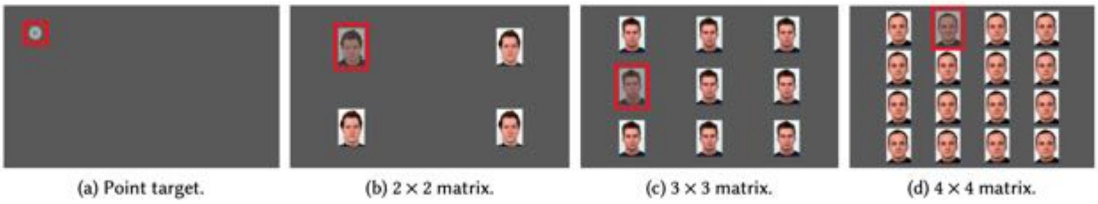

(a) Point target. (b) 2 × 2 matrix. (c) 3 × 3 matrix. (d) 4 × 4 matrix.

Figure 6: Areas Of Interest on displayed (a) point target, and face target with (b)–(d) various-sized matrices.

A promising technique for capturing eye movements in unrestricted, ecological situations is webcam-based eye tracking. This technology is becoming more and more popular within the eye tracking community because of its relatively inexpensive costs and quick data collecting. Web-based eye tracking raises questions concerning its validity and accuracy, as with any novel technology, yet there is little research on this subject. The present study fills this gap by comparing the accuracy, precision, and validity of webcam-based eye tracking to a commonly used stationary, remote eye tracker.

6.1 Hypotheses and design of the study

In this study, two tasks - a point detection task and an emotional visual search task called the Face-In-the-Crowd (FIC) task (Gilboa-Schechtman et al. 1999) - are used to compare the validity of online webcam eye tracking to a remote video eye tracker. The FIC broadens the comparison of eye movements by contrasting location-based (such as fixations) and process-based eye tracking metrics (such as dynamics of ambient/focal attention), see Figure 6.

I predicted that the webcam eye tracker would produce more measurement error than the other two eye tracking settings for the point detection challenge. We anticipated that using web-based software in conjunction with the remote eye tracker would produce results with accuracy comparable to the remote condition. We predicted that for the FIC task, we would see comparable effects across all recording conditions: (1) the time to first fixation would be faster for a happy face than a sad one; and (2) the degree of focal attention would be related to crowd density.

6.2 Main results and conclusions

We tested the webcam eye tracking in theoretical-based and precision tasks. In point detection and visual search tasks, we examined the measurement accuracy and validity of webcam (RealEye), remote (the GP3) eye tracking, and an integrated technique (combining remote eye tracker software with a webcam recording). The accuracy and precision error of webcam recording were lower than those of the other two conditions, as was expected. In spite of the lower precision in the webcam recording, our theory-based hypotheses were supported in all recording conditions. The results of visual search were comparable in the webcam, remote and integrated condition, indicating happiness-oriented visual attention and similar dynamics of visual attention. As a consequence, we supported earlier findings that webcam eye tracking can be utilized in cognitive and behavioral studies (Semmelmann and Weigelt 2018) .

The contribution of the paper is threefold. First of all, compared to past research, the measurement error of webcam eye tracker in our study was quite small (Burton et al. 2014). The development of the hardware and camera platform is related to the increase in precision and accuracy.

Second, to the best of our knowledge, this is the first study to look into the dynamics of visual attention as observed by webcam eye tracker. As focal attention suggests deeper attentional processing, the current results may be helpful for the development of real-time alerting systems of focal processing (Krejtz et al. 2016). Numerous sectors, such as computer-supported learning or assistive technology, may benefit from such applications (Skovsgaard et al. 2011) .

Third, we suggested combining remote eye tracker software with a webcam. When compared to the remote condition, the integrated condition's effects were similar but more accurate in terms of measurement precision. It is important to emphasize that the fixation filters were the same as those used for webcam recording. High velocity thresholds and noise reduction are features of the default filters, which are perhaps more effective with webcam cameras. However, our goal was to demonstrate that even with variations in sampling rate and fixation period, combining the GP3 eye tracker with RealEye software may make preparation and analyzes simple and quick, resulting in similar results.

Finally, taking into account the in-lab experimental setup, the present findings should be reproduced outside the lab in more ecological settings. The accuracy of the webcam may be improved by controlled variables such as head position in the current investigation.

7. General conclusions

The project was focused on investigating visual attention during collaboration and communication in different shared workspaces. First, I monitored visual attention to broaden understanding of how in-person collaboration on a large display can help users focus their visual attention on the most important areas. Second, as in-person collaboration occurred to direct attention to important parts of the interface, I tested the use of gaze visualization in remote settings to enhance the quality of collaboration among people with different attentional focus. Third, I examined the communication restriction effect during online lectures suggesting how to design online learning environments to promote better information acquisition and focal attention.

Understanding the attentional mechanism underpinning the efficiency of in-person and remote collaboration is the project's key contribution. In-person collaboration enables users to concentrate their visual attention on the most crucial data required for the best selections. Designers of attentive user interfaces (Vertegaal 2002, 2003) for interactive systems for remote collaboration may benefit from understanding this attentional mechanism.

Furthermore, it is necessary to expand our understanding of attentional focus during distant collaboration to develop solutions improving information flow especially at the non-verbal level (Kreijns et al. 2003). In the field of online and augmented collaboration systems, establishing joint attention is a crucial issue (Schnier et al. 2011; Vertegaal 1999). The present findings could serve as the foundation for gaze-based solutions that improve computer-supported collaboration for users with different individual traits.

The project evaluated also the influence of reduced contact with a teacher and distractions during presentation on the screen on knowledge assimilation efficacy during online lectures. I showed that the level of information assimilation is correlated with the dynamics of visual attention registered by a webcam eye tracker. Our research can be applied to the creation of real-time alerting systems for educators. To assist in changing the present level of students' concentration, it may be helpful to monitor the level of focused attention during the online lesson.

8. References

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9. Articles with co-authors' statements

Supporting Complex Decision-Making. Evidence from an Eye Tracking Study on In-Person and Remote Collaboration

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(a) In-person collaboration (b) Remote collaboration (c) Single user

Fig. 1. Study participants collaborating on the system interface resolving a natural resource management task (Reindeer Task, [Moxnes 2014]) in (a) in-person collaboration, (b) remote collaboration, and (c) single user condition. Each participant is wearing a mobile eye tracking device.

This paper examines the attentional mechanism of in-person collaboration by means of System Dynamics-based simulations using an eye tracking experiment. Three experimental conditions were tested: in-person collaboration, remote collaboration, and single user. We hypothesized that collaboration focuses users' attention on key information facilitating decision-making. Collaborating participants dwelt longer on key elements of the simulation than single users. Moreover, in-person collaboration and single users yielded a strategy of decision-making similar to an optimal strategy. Finally, in-person collaboration was less cognitively demanding and of higher quality. The contribution of this paper is a deeper understanding of how in-person collaboration on a large display can help users focus their visual attention on the most important areas. With this novel understanding, we believe collaborative systems

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designers will be better equipped to design more effective attention-guiding mechanisms in remote collaboration systems. The present work has the potential to advance the study of collaborative, interactive technologies.

CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**; **Collaborative interaction**; **Empirical studies in interaction design**.

Additional Key Words and Phrases: System Dynamics simulation, visual attention, collaboration, eye tracking, natural resource management

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1 INTRODUCTION

As well-informed decision-making on natural resources, e.g., food, water, and construction material is getting more critical, employing natural-resource models and simulations to support knowledge workers in making decisions are becoming vital tools for good governance. Understanding and enhancing computer-supported collaboration is one of the most pressing needs of our society, where people are increasingly forced to solve complex tasks via remote collaboration. Olson and Olson [2000] predicted that remote collaboration in the new millennium would be empowered with high internet bandwidth and large displays. These advances in technology, which are currently in common use, were considered as technical requirements for remote collaborations "to come closer to some aspects of the face-to-face work" [Olson and Olson 2000, p.143]. Literature has demonstrated that large interactive surfaces improve performance and user satisfaction in various tasks involving collaborative decision-making, such as model design or data analysis [Butscher et al. 2018]. Recently, Mateescu et al. [2021] investigated collaboration on large interactive surfaces. Their findings suggest a "relatively clear advantage of the use of" large interactive surfaces over classic forms of collaboration, in particular over single-user environments (e.g. laptops). Mateescu et al. [2021] found positive effects of large interactive surfaces for knowledge gains and task-related outcomes. Collaborative decision-making requires mutual understanding of the task [Patel et al. 2012], which can be facilitated by focusing attention on key elements of the task. To our best knowledge, visual attention processes during in-person and remote collaborative decision-making have not previously been tested on large displays using the means of eye tracking.

In the present eye tracking study, participants were randomly assigned to three experimental conditions: in-person collaboration, remote collaboration, and single-user (Figure 1). Their main task, in all conditions, was to make several decisions when interacting with a System Dynamics-based simulation of reindeer rangeland management. The reindeer rangeland management task is representative of a large class of dynamic decision-making issues in natural resource management, such as deforestation and forest degradation, biodiversity loss, ecosystem degradation, reduction in soil quality, and fall in available water quantity [Tietenberg and Lewis 2019]. System Dynamics is a model-based approach to dynamic decision-making and policy analysis [Sterman 2000], often used to understand the parameters involved, their interactions, and how decisions on even a single parameter can affect complex system dynamics. The System Dynamics-based (SD-based) simulations are intended to help in this complex decision-making by visually presenting the parameters of the system and the effects of single decisions. Related research [Guy et al. 2013; Moxnes 1998b; Sterman and Sweeney 2007] shows that decision-makers tend to underestimate what it takes to restore depleting natural resources and that they rely on wait-and-see strategies, with, at times, disastrous long-term consequences.

Effective decision-makers need to focus their attention on key information of an SD-based simulation user interface [Bentzen et al. 2011; Milkman et al. 2009]. In the present study, we investigated visual attention distribution over key elements of the interactive simulation task by recording participants' eye movements during the task. In general, we hypothesized that collaboration would facilitate focusing participants' visual attention on the most important information presented on the large display, and thus more likely to lead to better decisions. We present our detailed hypotheses after a brief review of relevant literature.

2 BACKGROUND

Collaboration has a strong potential to tackle problems posed in decision-making since it may facilitate emergent strategies [Cohen 1994] and novel problem perception and descriptions [Schwartz 1995; Shirouzu et al. 2002]. It is often described as a process of constructive problem exploration to find solutions that transcend each partner's individual point of view [Wood 1991]. However, just working in a group does not necessarily guarantee success. Often, there can be difficulties in group work leading to time wasted, discouragement, and, in the end, lack of progress [Barron 2003]. The success of problem-solving varies significantly among groups, even when group members have comparable knowledge levels [Hogan et al. 1999; Webb et al. 2002]. It is critically important to better understand visual attention mechanisms underlying collaboration on complex decision-making tasks in order to design effective tools and methods supporting remote collaboration.

2.1 Visual Attention during Collaboration

During collaboration, people share focus on an object, indicating to each other their course of attention. Individuals can either indicate things physically (deictic gestures), verbally (describing the object of interest), or by using their body position and orientation. Partners in social interaction also need to demonstrate awareness that they are working on something in common via non-verbal signals, such as gaze direction [Tomasello 1995]. Mutual gaze and gaze-following represent processes involving two individuals. Their actions lead to joint visual attention that is created by following and directing another person's gaze to a new target making a referential triangle [Pfeiffer et al. 2013]. This process is considered an important aspect of the understanding of other minds and building shared reality during collaboration [Echterhoff et al. 2009].

While there are many methods to study communication during interaction, such as head [Cognolato et al. 2018; Müller et al. 2018; Yu and Smith 2017] and gesture analysis [Gullberg and Holmqvist 1999; Kendon 1988], we chose to use mobile eye tracking to examine gaze patterns. Eye tracking enabled us to register participants' attention allocation during task performance as a measure of shared visual workspace [Fussell et al. 2000]. Eye tracking is considered to be an effective tool to study gaze behavior during interaction and cooperation [Pietinen et al. 2008a]. For example, gaze behavior measured with mobile eye tracking was used as an index of turn-taking during in-person dyadic [Jokinen et al. 2009, 2010] and triadic interaction [Holler and Kendrick 2015]. In another study, Gergle and Clark [2011] showed in a dyadic mobile eye tracking experiment that when pairs have shared visual reference they rely less on language in their communication. However, when their visual attention was not coordinated, specific referential forms such as deictic references can be used to direct their attention to the referent object during collaboration. Wang and Shi [2019] showed that awareness of a partner's gaze direction changes gaze behavior. Their results indicate that an interaction partner's gaze is more likely to lie on the referred object when the subject knows the helper can see his/her eyes. Awareness of the partner's gaze direction enhances joint attention and quality of performance, which has been demonstrated in eye tracking studies on in-person collaboration [Schneider et al. 2018].

In computer-supported collaboration, non-verbal communication such as gaze cueing to shared reference is often lost, especially in remote settings. In remote collaboration, visual attention has been taken into account both in early and recent works [Otsuki et al. 2017; Shiro et al. 2018; Vertegaal 1999]. Eye tracking studies examined methods of facilitating joint attention e.g. by gaze display [Bednarik et al. 2011; D'Angelo and Gergle 2018; Kütt et al. 2019; Maurer et al. 2017; Velichkovsky 1995; Yao et al. 2018]. For instance, Velichkovsky [1995] used projection of eye fixations, which increased the efficiency of problem solving by experts and novices. However, it is still difficult to find such solutions in off-the-shelf systems. Eye tracking has also been used to uncover cognitive processing within visualization evaluation studies [Goldberg and Helfman 2011]. By combining eye movement data and interaction logs, Blascheck et al. [2018] studied how non-expert users "discover the functionality of an interactive visualization". Visual attention of two or more collaborators has also been taken into account in the design of large vertical and horizontal user interfaces during in-person collaboration on large displays [Kontogiorgos et al. 2018; Serim et al. 2018; van der Meulen et al. 2016]. Large displays enable simultaneous use by multiple users, providing at the same time high visibility to all the parties, and support joint work [Pietinen et al. 2008b; van der Meulen et al. 2016].

2.2 Computer-Supported Collaboration Tools

An extended body of literature points out that computer-supported collaboration tools have proven their capacity to facilitate collaboration by supporting workspace awareness, an "up-to-the-moment understanding of another person's interaction with a shared workspace" [Gutwin et al. 1996]. Lopez and Guerrero [2017] underlined the importance of the system providing information about partners' momentary actions during collaboration [Dourish and Bellotti 1992]. Similarly Heer and Agrawala [2007] underlined the role of workspace awareness and sense-making during computer-supported social interaction. They presented design considerations for collaborative visual analytics to improve workspace awareness. In line with this, Burch and Schmauder [2018] proposed several collaborative interaction techniques, e.g. the highlighting of user interface elements selected by other users for providing additional context for collaborative problem-solving on large high-resolution displays.

A large display could be used by single or multiple users as they have enough space to freely walk around and explore an individual sub-area of the display. Indeed, Kim and Snow [2013] showed that collaboration on a large shared display influences task efficiency, depending on how individuals effectively cooperate with others in the display context and with multiple inputs. Both asynchronous access and multiple input leads users to take on both separate and cooperative roles in task performance. Consequently, peer interaction increases attention on work practices and verbal communication in collaborating groups. Moreover, elements of non-traditional interaction techniques might support group collaboration, e.g. in collaborative learning situations [Schneider et al. 2016]. With such interaction techniques, e.g. sharing physical objects or space, students can intuitively explore complex systems, and collaborative groups find it easier to establish common ground for work [Falcao and Price 2011; Schneider et al. 2012; Valdes et al. 2012].

Along the same lines of thought, Arias et al. [2000] presented a large display prototype aiming to create "shared understanding" through discussion and negotiation, that ironically shifted attention away from the computer toward the interpersonal relationship and understanding between working partners. In an empirical study Liu et al. [2016] demonstrated that wall-sized displays encouraged collaborative manipulation, reduced physical navigation and fatigue, and improved collaboration efficiency. Gorkovenko et al. [2018] showed that collaborative data exploration on a large, high-resolution display in comparison to a tablet-size display evoked less cognitive demands on users. However, large displays are not only beneficial for interaction with the system. Jakobsen and Hornbæk [2013] showed in two experiments that for making screen size beneficial it is important to take into consideration the interaction of display size, information space, and scale ratio.

We postulate that decision-supporting systems like SD-based simulation presented on large displays, foster awareness of the problem and focus collaborating partners' attention on the most important information necessary to solve the collaborative task. Focusing visual attention on key elements of a simulation task during the decision-making process may be treated as a cognitive mechanism standing behind workspace awareness during computer-supported collaboration. In our study, we extend previous works through the inclusion of remote collaboration on large displays. Using a shared large display during in-person collaboration allowed for direct comparisons of attention mechanism during in-person and remote collaboration.

3 THE PRESENT STUDY

Our study examined visual mechanisms of collaboration during complex decision-making. This research was conceived in the context of an important societal challenge: sustainability in natural resource management. More specifically, we researched the management of natural resources that are threatened by over-exploitation and collapse. For our natural resource management simulation, we chose a reindeer rangeland management task. This task's structure is representative of a wide range of natural resource management tasks, including, for example, mitigation of climate change, and builds on benchmarking data from previous experiments [Derwisch et al. 2011; Moxnes 2004]. While most SD-based simulation tasks were designed for and tested on single users, a few studies have discussed the potential of multiplayer SD-based simulations [Happach and Schoenberg 2017]. In our work, we try to fill the gap by examining collaborative decision-making on large displays with the use of an eye tracking method. We investigate the visual attention process during collaborative decision-making on large interactive displays. By monitoring eye movements during collaboration we uncover a cognitive mechanism underpinning workspace awareness during computer-supported collaboration. The new contribution of this study is a deeper understanding of how in-person collaboration on large displays can help users focus their visual attention on the most important areas [Bentzen et al. 2011]. With this novel understanding, we believe system designers will be better informed when designing attentive user interfaces [Vertegaal 2002, 2003] with potential for remote collaboration.

3.1 Hypotheses and Variables

The present study verifies four main hypotheses in relation to the three experimental conditions: in-person collaboration, remote collaboration, and single user condition (the between-subjects independent variable). First, that making a collaborative decision is highly cognitively demanding and can be manifested in the characteristics of eye movement fixations [Duchowski et al. 2020; Krejtz et al. 2020]. The *eye-mind assumption* suggests a close relationship between the average length of fixation duration and depth of cognitive processing [Just and Carpenter 1976]. Based on this assumption, we expected (hypothesis 1) to observe a longer average fixation duration reflecting deeper information processing while looking at the decision-related areas, compared to simulation control areas [Krejtz et al. 2016]. The within-subjects independent variable related to this hypothesis was areas-of-interest, which had two levels: simulation control vs. decision-making regions (see Figure 4b).

Second, we expected that collaboration would trigger the visual attention of partners to the most important visual information presented in simulation control areas, which in turn could influence system understanding and the decision-making strategy. We expected in this case to observe an attention bias toward the graph presenting the dynamics of lichen density (hypothesis 2). The attentional bias would manifest in a longer viewing time (dwell time as a dependent variable) while looking at the lichen density graph in comparison to other system dynamics visualizations. The within-subjects independent variable related to this hypothesis differentiated between simulation control graphs: lichen density vs. lichen growth vs. herd size graph (see Figure 4b).

Third, we aimed to examine how the process of collaborative decision-making and distribution of visual attention was affected by the distance between partners (in-person vs. remote collaboration condition). We anticipated that collaboration would lead to more effective task-solving than the single user condition. Related research [Guy et al. 2013; Moxnes 1998a,b; Sterman 2008; Sterman and Sweeney 2007] shows that decision-makers tend to underestimate what it takes to restore depleting natural resources and that they rely on wait-and-see strategies, with, at times, disastrous long-term consequences. That was reconfirmed in recent work [Gary and Wood 2016; Moxnes 2014; Nyam et al. 2020; Perissi et al. 2017], for which a detailed review would fall out of the scope of the present paper. Our task was a simplified structure of a natural resource system where users could easily draw wrong conclusions about resource management. Specifically, we hypothesized that in-person collaboration would promote a strategy of decision-making similar to the optimal strategy derived from a dynamic model simulation which can be observed at the behavioral level in participants' decisions recorded with system logs (hypothesis 3). The first independent within-subjects variable related to this hypothesis was the decisions made during the simulation task (16 decisions). The second independent variable differentiated between optimal and experimental decisions.

Finally, we assessed the subjective quality of collaboration, task workload, and usability as a self-reported dependent variable, expecting to observe differences favoring in-person decision-making. This prediction was a natural consequence of task solving strategies presented in the preceding hypotheses, which presumed that deeper information processing during problem solving, focusing attention on key information for problem understanding and more optimal decisions, would lead to a higher subjective satisfaction from collaboration (hypothesis 4). Previous research found a link between complex problem solving and motivation, satisfaction, and attitudes towards collaboration [Albay 2019; Geister et al. 2006].

4 METHOD

To meet the study aims and verify the hypotheses we conducted a mixed-design eye tracking experiment in which participants were randomly assigned to one of the three experimental conditions: single user, in-person collaboration, or remote collaboration. This study design allows for the triangulation of the data from three different sources: self-report questionnaires, behavioral decisions captured with the simulation system logs, and attentional captured with the eye tracking devices. A similar mixed-method approach has been used previously to study collaboration, for example by Mayer et al. [2018]. Next, we present details of the study method, including participants' descriptions and sampling, experimental procedure and task, study materials, and equipment.

4.1 Participants

A total of 71 students volunteered to participate in the experiment in exchange for student activity credit points (30 Females, $M_{age} = 26.52$, $SD_{age} = 5.12$). Participants were recruited via an advertisement on a university recruitment system and social-media closed groups. Most participants ($n = 58$) were psychology students.

Participants were randomly assigned to one of three experimental conditions: single user (17 individuals), in-person collaboration (13 pairs), and remote collaboration (14 pairs). Since some reviews suggest that sex may influence team work [Bear and Woolley 2011], the collaborating pairs were of the same sex. Participants declared that their vision was normal or corrected to normal. The characteristics of the participants in each experimental condition are presented

Table 1. Demographic characteristics of participants in each experimental condition. None of the differences for variables listed in the Table were statistically significant ($p > 0.05$). In the Table the three first rows represent numbers (n) of participants in each experimental condition. The numbers presented in the following rows represent means and standard deviation for each sample characteristic in each experimental condition (M stands for mean value and *(SD)* for standard deviation value. The questions about prior experience with systems supporting complex decisions, in-person collaboration, remote collaboration, in-person games, remote games, and ICT devices usage were measured on the Likert-type scales (from 1-never to 5-everyday). The last column provides the results of statistical tests of difference between experimental conditions on respective dependent variables (chi-square tests or one-way between-subjects ANOVA tests were used accordingly to the dependent variable)

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Variable	in-person collaboration	remote collaboration	single user	difference test
Number (n)	26 (13 pairs)	28 (14 pairs)	17	
Gender	18 females	16 females	7 females	$\chi^2(2) = 3.32, p = 0.19$
Handedness	3 left	2 left	0 left	$\chi^2(2) = 2.09, p = 0.35$
Age (years)	26.88(5.61)	27.14(4.55)	24.94(4.55)	$F(2, 54) = 1.14, p = 0.33$
Prior experience with:	$M(SD)$	$M(SD)$	$M(SD)$	difference test
Decisions systems	2.58(1.79)	1.82(1.54)	1.76(1.48)	$F(2, 54) = 1.44, p = 0.25$
ICT devices	2.65(0.65)	2.95(0.64)	2.75(0.53)	$F(2, 54) = 1.53, p = 0.23$
In-person collab.	3.81(1.39)	4.11(1.06)	4.18(1.19)	$F(2, 54) = 0.47, p = 0.63$
Remote collab.	4.04(1.25)	4.00(1.25)	3.76(1.25)	$F(2, 53) = 0.24, p = 0.79$
In-person games	2.73(1.25)	2.46(1.20)	2.12(1.11)	$F(2, 54) = 1.06, p = 0.35$
Remote games	2.37(1.19)	2.57(1.26)	2.00(1.00)	$F(2, 54) = 1.23, p = 0.30$

in Table 1. Power analysis was conducted with the use of *G*Power* software [El Maniani et al. 2016; Erdfelder et al. 1996]. The results showed that a sample of 75 participants would yield 0.95 power to detect effect sizes of 0.1 with the mixed-design ANOVA procedure.

4.2 Procedure

The flow of the experimental procedure is presented in Figure 2. Prior to testing, all participants signed an informed consent form. Participants were informed that they could resign from taking part in the experiment at any stage of the study. Then they filled out the pre-study online questionnaire. Next, the experimenter placed a mobile eye tracker on the participant's head and set three cameras (world camera and two eye cameras) adapting the device to the participants' eyes. Each person was informed how the eye tracker worked and was asked if cameras were occluding their vision. After a brief talk, during which the participants got accustomed to the eye tracker, they individually passed through a single marker calibration. The experimenter, at a distance of two meters and using a single circle marker, showed five calibration points around her head. Participants were asked to follow with their eyes the central point of the circle. After calibration, participants received instructions on how to maintain a stable position approximately one meter away from the large display and were instructed on how to proceed with the simulation task (Figure 2). Participants completed the task in an office environment either individually (single-user condition) or in pairs (in-person and remote collaboration conditions). Working in pairs, participants cooperated in one room on one interactive large display (in-person collaboration condition) or in two rooms on separate large displays (remote collaboration condition).

Participants could talk to each other and discuss their decisions during the entire task. In the remote condition, communication took place via Skype, where participants could talk and see each other in the window located in the upper right corner of the simulation user interface (Figure 1). All conversations were recorded using Pupil Labs Capture software.

After completion of the task, participants filled out post-study online questionnaires and were thanked for their participation. The entire procedure lasted about 30 minutes. The experimental procedure was approved by Ethical Committee No. 15/2020 of the first author's institution prior to the data collection.

4.3 Pre-study Questionnaire

The pre-study questionnaire was completed by all participants prior to the simulation task. It consisted of 10 questions. The questionnaire was prepared with the use of the Qualtrix online questionnaire system. The first four questions were about basic demographic information (age, gender, handedness, sight problems). There were also six questions about participants' prior experience with systems supporting context decision: how often they use ICT devices (laptop, mobile phone, tablet, smartwatch, computer, smartphone), how often they collaborate in-person and remotely, and how often they play games in-person and remotely. Participants answered the six questions on a five-point Likert-type scale from 1 'never' to 5 'everyday'. Descriptive statistics of the pre-study questionnaire are presented in Table 1. Using one-way ANOVA, we tested differences among experimental conditions for ICT usage, prior experience, and average

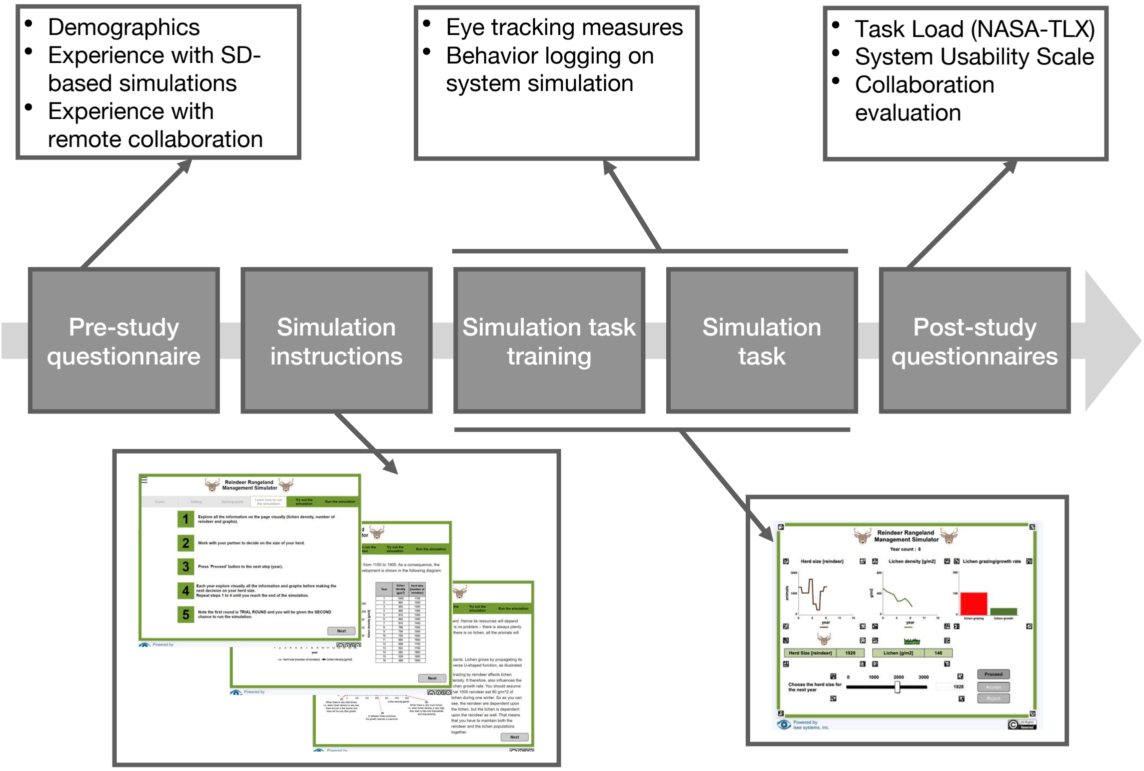
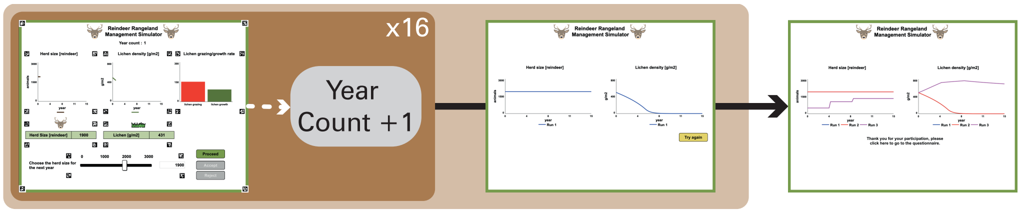
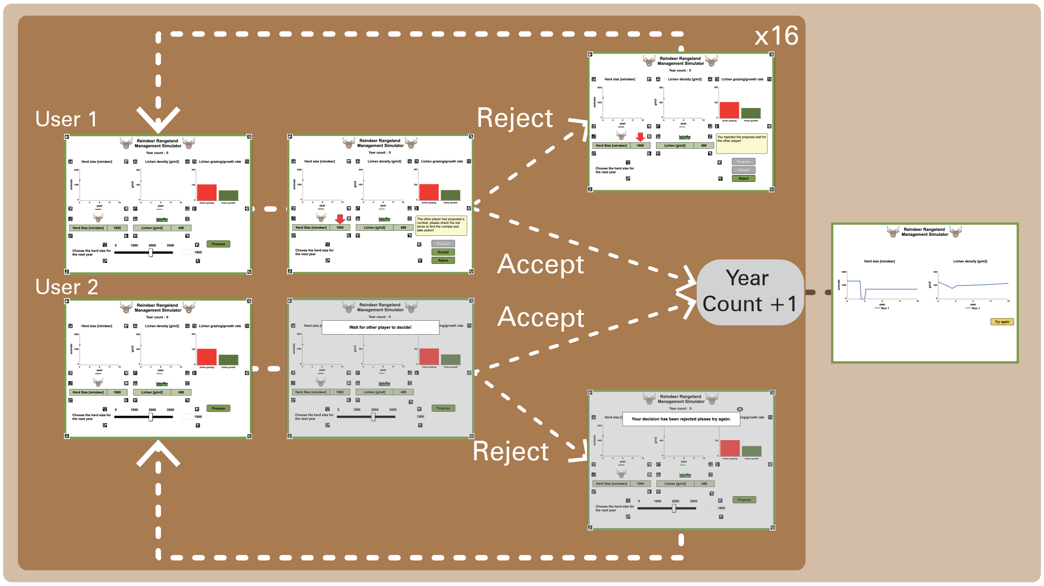


Fig. 2. Experimental procedure scheme. On the timeline (from left to right) we see steps followed by participants during the experiment. Above the timeline, the Figure presents the key measures used in subsequent steps of the experiment. Below the timeline, we present the exemplary user interface visible to the participants in the subsequent steps.



(a) Simulation task workflow used in a single-user experimental condition.



(b) Simulation task workflow used in remote and in-person collaboration experimental conditions.

Fig. 3. Simulation task workflow in all experimental conditions (single user, in-person collaboration, and remote collaboration). The user interface displays data such as herd size, lichen density, and lichen grazing rate. This data is presented in two ways: as a graph over time and as a numerical display. There are two input areas at the bottom of the user interface; one for users to enter their decisions on reindeer herd size and the other for users to interact with collaboration partner in the collaboration condition. The participants could enter the number of reindeer using either a slider or numeric input. Once they proposed their decision using the propose button, they were directed to a waiting page where they had to wait for the other collaboration partner to decide on the proposed number. The collaboration partner was notified that a number for the reindeer herd had been proposed. They could either accept or reject the proposed number using consensus buttons. If they were in agreement, they clicked the accept button, which advanced the simulation by one year. The reject button was used if the collaboration partner did not agree, whereby the partner who had proposed the number was notified and they had to agree upon a new number for the reindeer herd. Participants made sixteen decisions in the simulation task as described above.

age. There were no significant differences between the experimental conditions. This suggests that participants' samples were similar in terms of the measured demographics across all three experimental conditions. The average pre-study questionnaire completion time was four minutes. All participants completed the questionnaires.

4.4 Experimental Task

For the experimental task we used an SD-based simulation task developed by Moxnes [2004]. Participants played the role of sole owners of a reindeer herd. This task's structure is representative of a wide range of natural resource management tasks and provides ample bench-marking data from previous experiments [Derwisch et al. 2011; Moxnes 2004].

Time is a key dimension in natural resource management simulations, including understanding of historic data and planning for future decision-making. In the simulation task participants were required to take over reindeer rangeland in an over-utilized state and decide on the herd size for each of 16 consecutive years (16 decisions). Their goal was to reach the maximum sustainable herd size within as few years as possible. Unlike climate change, in which most people have some knowledge and perhaps considerable interest, people usually do not have deep knowledge about reindeer rangeland management and thus focus more on the information provided in the experimental setting than on their own prior knowledge. Thus, prior to the simulation, participants were provided with detailed information about the rules of the rangeland simulation, i.e., the lichen grazing rate of the reindeer, the description of lichen growth rate, the historic record on reindeer herd size, and lichen density levels (Figure 2). After the detailed instructions, they started with two training runs of the simulation task prior to the main simulation task from which the data was analyzed (Figure 2).

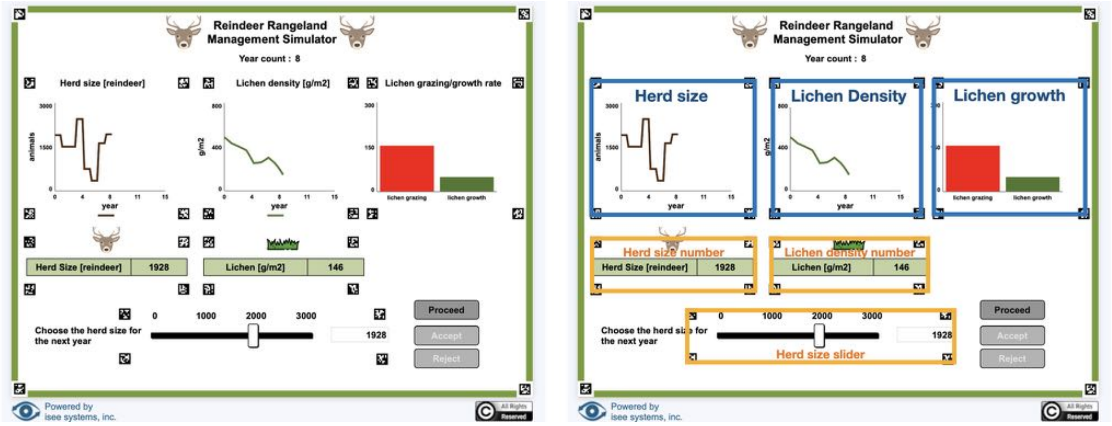
Determination of the size of the reindeer herd is performed using a touch interface as shown in Figure 4a. Participants make decisions for each year by checking the analytical information displayed on the user interface (herd size, lichen density, and lichen growth) and select the herd size for the following year using the slider located at the bottom of the user interface.

Performing an optimal simulation requires an understanding of the convex growth function of lichen density [Kopainsky and Sawicka 2011]. Thus, in a simulation achieving a maximum sustainable herd size, participants needed to first reduce the herd size dramatically so that the natural resource (lichen) could recover and reach maximum annual regeneration rates.

The simulation task workflow (Figure 3) was similar in all the experimental conditions, with small adjustments required by the collaboration conditions. In the single-user condition (Figure 3a), each participant decided on the reindeer herd size for each year. In the in-person and remote collaboration conditions one of the two users set the reindeer herd size for each year using the same interface as in the single-user condition (Figure 3b). However, both users needed to agree on the herd size decision. Therefore, when one participant in the collaboration pair proposed the size of the reindeer herd, the other was asked to accept or reject this proposal. If accepted, the task moved to the next year. If rejected, the decision on herd size had to be retaken until an agreement was achieved.

We built the lichen-reindeer simulation model and its interactive user interface using the Stella Architect software [isee systems inc. 2020]. This software supports web-based, remote collaboration, online data storage and analysis, and touch input. The software offers a drag-and-drop user interface builder. The simulation task was performed on a multitouch 55-inch 4K UHD Google Jamboard large display with 1920 × 1080 resolution on the floor stand controlled by a standard laptop computer. The Google Jambord large display was used as a secondary display thus its native resolution was scaled to the laptop's maximum resolution. Participants interacted with the Google Jamboard using passive styluses (Figure 1). In the in-person condition, participants worked on the same large display, similar to a single user condition. In the remote condition, participants completed the task on two Google Jamboard large displays located in separate rooms.

4.5 Eye Tracking Equipment



Herd Size [reindeer] 1928

Lichen [g/m2] 146

Choose the herd size for the next year 1928

(a) Simulation user interface

(b) Simulation user interface with marked AOIs

Fig. 4. Simulation task user interface. Figure 4a presents an exemplary screenshot with important information on the history and current status of the simulation (lichen density, reindeer size, and lichen growth graphs) and controls (buttons and slider) for current decision-making. The fiducial markers (squares with black and white patterns) were embedded in the interface to define Areas of Interest (AOIs) for eye tracking data analysis. Figure 4b presents the same user interface with color-marked Areas-Of-Interest. The AOIs marked with a blue color relate to simulation control. AOIs marked with orange relate to decision-making (see Section 5). The AOIs marked in color on Figure 4b were not visible to the participants.

During the simulation task, participants' eye movements were recorded using mobile PupilLabs Core eye trackers (120Hz sampling rate). This is a non-invasive device that allows free gaze communication, does not obstruct the vision and does not cause discomfort to the participants during the cooperation due to its design [Schindler and Lilienthal 2017]. PupilLabs mobile eye trackers have been used before in dual eye tracking studies [Shvarts et al. 2018]. Recorded gaze data quality was above 0.80 confidence level (1.00 is the maximum). Gaze data were pre-processed and exported using the PupilLabs Player software. The fixation detection threshold was set to 80ms. The Apriltag visual fiducial markers [Olson 2011] were used to define Areas-of-Interests (AOIs) on the key elements of the simulation user interface (Figure 4b). These are necessary to link eye-movement measures to selected parts of the interface [Hessels et al. 2016]. The user interface contained two types of visual information (see Figure 4b) defining two types of Areas-of-Interest (AOIs). The first type was related to simulation control. These were the three graphs for herd size, lichen density, and lichen growth, presenting momentary outcomes of the simulation (Figure 4b, AOIs marked with blue color). The second type was related to decision-making processes. These were the three AOIs presenting actual herd size, lichen density, and the herd size choice slider (Figure 4b, AOIs marked with orange color). We averaged eye movement-based dependent variables across these types of AOIs. Average fixation duration and dwell time (total viewing time) for simulation control AOIs and decision-making types of AOIs were considered as the main dependent measures of visual attention distribution during the simulation task.

4.6 Post-study Questionnaires

After the simulation task participants completed post-study questionnaires prepared with the use of the Qualtrics online questionnaire system. We used the following scales to assess their subjective perception of three aspects of collaboration during the experimental task (task load, usability, and collaboration quality). These questionnaires have frequently been used in previous HCI research [Duchowski et al. 2020].

(1) The NASA Task Load Index (NASA-TLX) is a six-item scale that measures a participant's reported level of task workload [Hart and Staveland 1988]. This is a subjective, multidimensional assessment tool rating perceived workload in assessing a task or a system. The range of responses was from 0 (very low) to 21 (very high). The sample item: *How hard did you have to work to accomplish your level of performance?* The reliability of the scale was satisfactory (Cronbach's $\alpha = 0.75$) [Tavakol and Dennick 2011].
(2) The System Usability Scale (SUS) is a ten-item attitude Likert scale with responses ranging from 1 (strongly disagree), to 5 (strongly agree), giving an overview of subjective assessments of usability [Brooke 1996, 2013]. The sample item:*I would imagine that most people would learn to use this system very quickly.* Following [Hart and Staveland 1988] we subtracted 1 from each value of the item and multiplied it by 5. The overall score was the mean of all items. The reliability of the scale equaled 0.79 Cronbach's α.
(3) The Collaboration Assessment Scale (CAS) measures self-reported levels of collaboration quality from 1 (very bad), to 5 (very good) and the degree of being in control or being overwhelmed from 1 (not at all) to 5 (a lot). The CAS was completed only by participants in the collaboration conditions. The sample item: *Did you feel overloaded by the collaborator?* The reliability of the scale equaled 0.72 Cronbach's α. The average post-study questionnaires completion time was 6 minutes. All participants completed the questionnaires.

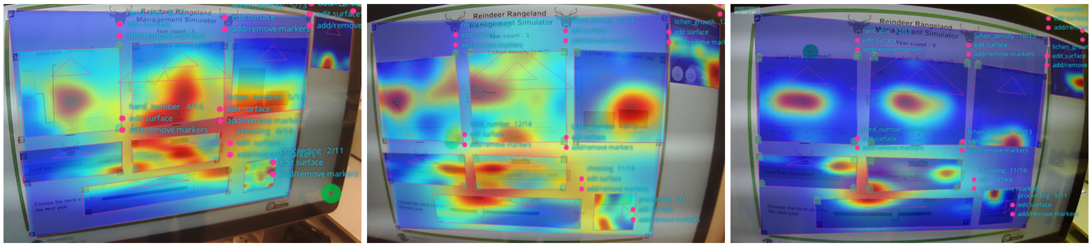
5 RESULTS

The Results Section is divided into three parts: (a) depth of information processing (hypothesis 1), visual attention distribution (hypothesis 2), (b) simulation outcome analyses (hypothesis 3), and (c) subjective assessments of task workload, system usability, and collaboration quality (hypothesis 4). All the statistical analyses were performed in the R language for statistical computing [R Core Team 2020]. R language for statistical analysis has become an "industry standard" in the realm of data science [Weston and Yee 2017] and it covers all statistical procedures needed for hypothesis testing in the present study. To test the hypotheses, we decided to use analysis of variance (ANOVA) as a statistical test because it allows for obtaining statistical significance for means comparison between three experimental conditions in the present study, and also because it is a well-established standard statistical procedure for such comparisons [Field et al. 2012]. Any statistically significant effects obtained in the analyses were followed by *post-hoc* comparisons with HSD Tukey correction for multiple comparisons. The raw data used in the described analyses are available in the OSF repository (https://osf.io/bymak/).

Prior to the hypotheses testing, we examined differences between experimental conditions for demographic variables listed in Table 1. All comparisons were statistically insignificant ($p > 0.05$), therefore we did not include these demographic variables as covariates while testing the hypotheses (see Table 1 for the results of the statistical tests results of comparisons between experimental conditions on each demographic variable.)

5.1 Distribution of Attention and Visual Information Processing

According to hypothesis 1 we expected that collaboration would increase the focus of attention to key information presented on the user interface. Understanding the mechanics of the simulation model and finding an optimal outcome requires focusing attention on the simulation control AOIs.



(a) In-person collaboration (b) Remote collaboration (c) Single user

Fig. 5. Exemplary heatmaps presenting attention distribution in three experimental conditions: single user, in-person collaboration, and remote collaboration. The heatmaps were prepared and normalized in Pupil Player software [Kassner et al. 2014]. Heat maps provide an overview on the visual attention distribution over the screen and separate different levels of observation intensity. The longer the gaze on a certain region, the warmer the color is used to represent it [Špakov and Miniotas 2007]. Color codes represent the amount of time spent gazing on each AOI. *Note*: The heatmaps are projected onto images from the eye tracker's front camera when looking at the SD-based simulation in different experimental conditions.

In order to test our hypotheses related to differences in attention distribution, we conducted a series of mixed-design analyses of variance (ANOVAs) with experimental condition as the between-subjects independent variable and areas-of-interest as the within-subjects independent variable. The analyses were conducted for average fixation duration (cognitive processing measure) and dwell time (attention distribution measure) as dependent variables. Details of the analyses are presented in the following Subsections.

5.1.1 Depth of Information Processing: Simulation Control vs. Decision-Making Areas-of-Interest. We tested the first hypothesis that decision-making evokes deeper cognitive processing than simulation control. We ran a two-way (2×3) mixed design ANOVA, with AOI type as the within-subjects dependent variable and experimental condition as the between-subjects independent variable, and average fixation duration as the dependent variable. In line with the hypothesis, the analysis revealed a significant main effect of an AOI type, ($F(1,34)=5.96,\ p=0.020,\ \eta^2=0.037$). Average fixation duration was significantly longer while looking at decision-making AOI type ($M=149ms,\ SE=51.9$) than simulation control AOIs type ($M=143ms,\ SE=51.9$).

5.1.2 Distribution of Attention over Simulation Control Areas-of-Interest. To verify if in-person and remote collaboration, in comparison to single user condition, facilitated a more thorough exploration of Areas-of-Interest containing important information for controlling the simulation, we examined attention distribution over the three AOIs related to simulation control: the graphs presenting herd size, lichen density, and lichen growth (Figure 4b). Figure 5 presents exemplary differences in attention distribution over AOIs in the experimental conditions.

Two-way mixed-design (3×3) analysis of variance (ANOVA) was carried out with AOIs related to simulation control graphs (lichen density vs. lichen growth vs. herd size) as within-subjects independent variable and experimental condition as between-subjects the independent variable, and dwell time (attention distribution measure) as the dependent variable.

The ANOVA for attention distribution (dwell time) on AOIs related to the simulation control graphs revealed a main effect of experimental condition ($F(2,32)=5.80,\ p=0.007,\ \eta^2=0.136$). As expected, participants collaborating in-person spent significantly more time examining the simulation control graphs ($M=36668ms,\ SE=4576$) than participants in the single user condition ($M=16425ms,\ SE=4246$). Also participants collaborating remotely tended to spend significantly

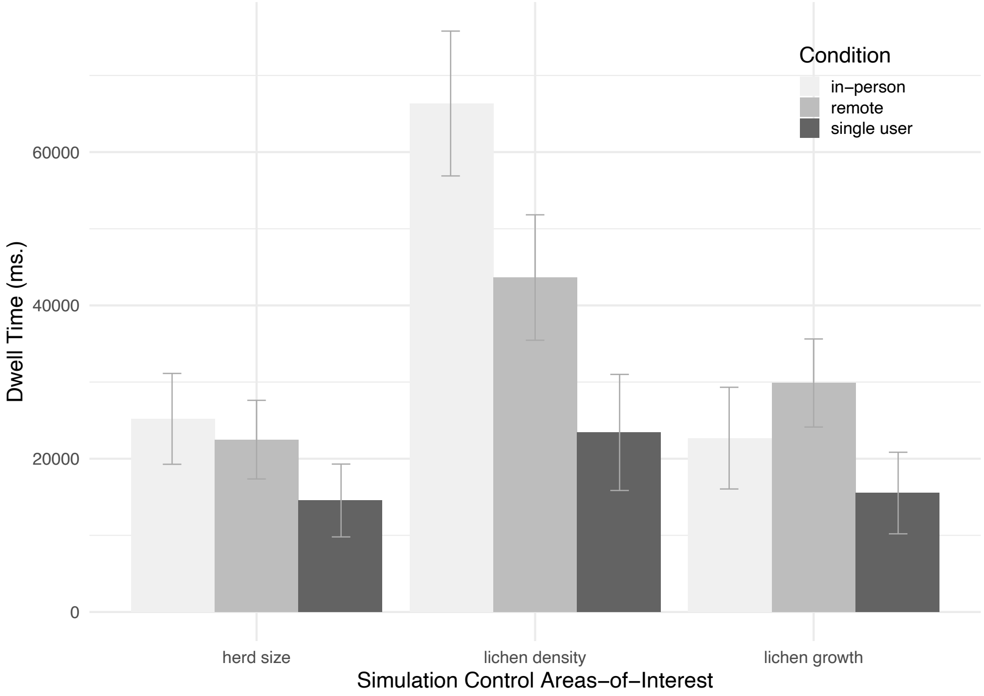


Fig. 6. Differences in distribution of attention (dwell time) over Areas-of-Interest (herd size, lichen density, and lichen growth graphs) related to control of the simulation task between experimental conditions (in-person collaboration, remote collaboration, and single user condition). *Note*: the height of bars represents estimated means of dwell time and error bars represent ±1 *SE*.

($t(32)=2.43,\ p=0.05$) more time examining the simulation control graphs ($M=3592ms,\ SE=4348$) than participants in the single user condition. The difference between remote and in-person collaboration was not significant.

There was also a significant main effect of AOI, ($F(2,64)=13.73,\ p<0.001,\ \eta^2=0.195$). In line with expectations, the longest dwell time was recorded for the lichen density graph ($M=43060ms,\ SE=3836$) when compared to the attention paid to the lichen growth graph ($M=21287ms,\ SE=3836$; $t(64)=4.331,\ p<0.001$) and the herd size graph ($M=19338ms,\ SE=3836$; $t(64)=4.719,\ p<0.001$).

The main effects were quantified by a significant interaction of AOI and condition ($F(4,64)=2.68,\ p=0.039,\ \eta^2=0.086$), see Figure 6 for a comparison of means in dwell time on different AOIs between experimental conditions as well as Figure 5 for heatmaps of eye movements presenting the attention distribution over different AOIs in different experimental conditions. *Post-hoc* comparisons showed that in-person collaboration triggered significantly ($t(91.7)=4.47,\ p<0.001$) longer dwell time on the lichen density graph ($M=64933ms,\ SE=7254$) in comparison to the single user condition ($M=22019ms,\ SE=6196$). The difference between in-person and remote collaboration conditions was marginally significant ($t(91.7)=2.29,\ p=0.062$), and remote collaboration triggered marginally longer dwell times on the lichen density graph ($M=42229ms,\ SE=6532$; $t(91.7)=2.27,\ p=0.063$) than for the single user condition.

Next, we calculated *post-hoc* comparisons for the differences in attention distribution among simulation control graphs. In the single user condition no significant differences in attention distribution on different elements of simulation control were found, suggesting more equal attention distribution in comparison to both collaboration conditions (Figure 6).

In line with the second hypothesis, the collaboration conditions induced more attention to the lichen density graph, which is the most an important part of the simulation control visualizations. In the in-person condition, participants focused their attention significantly more on the lichen density graph than on the herd size graph ($M = 23793ms,\ SE = 7254;\ t(64) = 4.22,\ p < 0.001$) and on the lichen growth graph ($M = 21278ms,\ SE = 7254;\ t(64) = 4.48,\ p < 0.001$). Similarly, in remote collaboration, participants spent significantly more time inspecting the lichen density graph than the herd size graph ($t(64) = 2.51,\ p = 0.039$), but the difference in dwell time between lichen growth graph and herd size graph was not significant.

5.2 Simulation Outcome

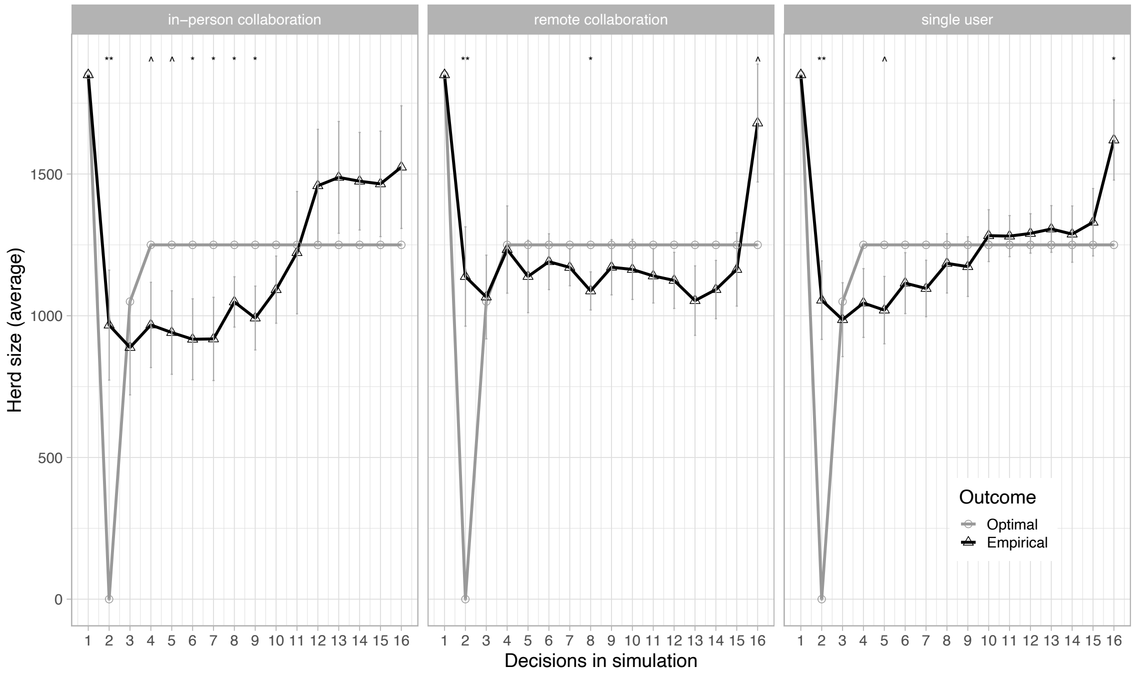


Fig. 7. Participants' decisions of herd size during the simulation task (black line) compared to an optimal outcome (gray line) for each experimental condition. The gray lines represent the optimal herd size derived from the model. Each graph represents the results of a separate analysis of variance comparing herd size obtained in certain experimental condition compared to the optimal herd size outcome. *Note*: Error bars represent ±1 *SE*. Significant differences between empirical and optimal outcomes are annotated above the lines ($\hat{}\ p < 0.1$, $^{*}\ p < 0.05$, $^{**}\ p < 0.01$).

The third hypothesis predicted that in-person collaboration would promote a strategy of decision-making similar to the optimal strategy derived from the model. The optimal solution is not intuitive and requires understanding by users that, at the outset of the task, the rangeland is overutilized and that, for lichen density to recover, the number of reindeer (herd size) needs to be reduced drastically for a short period of time (see the gray line in Figure 7). The simulation outcome is indicated by lichen density in each simulation step, after each decision taken by participants regarding herd size. The optimal lichen density outcome is visible in the gray line on Figure 8. In order to test the third hypothesis regarding decisions taken by participants in each experimental condition we conducted three mixed-design

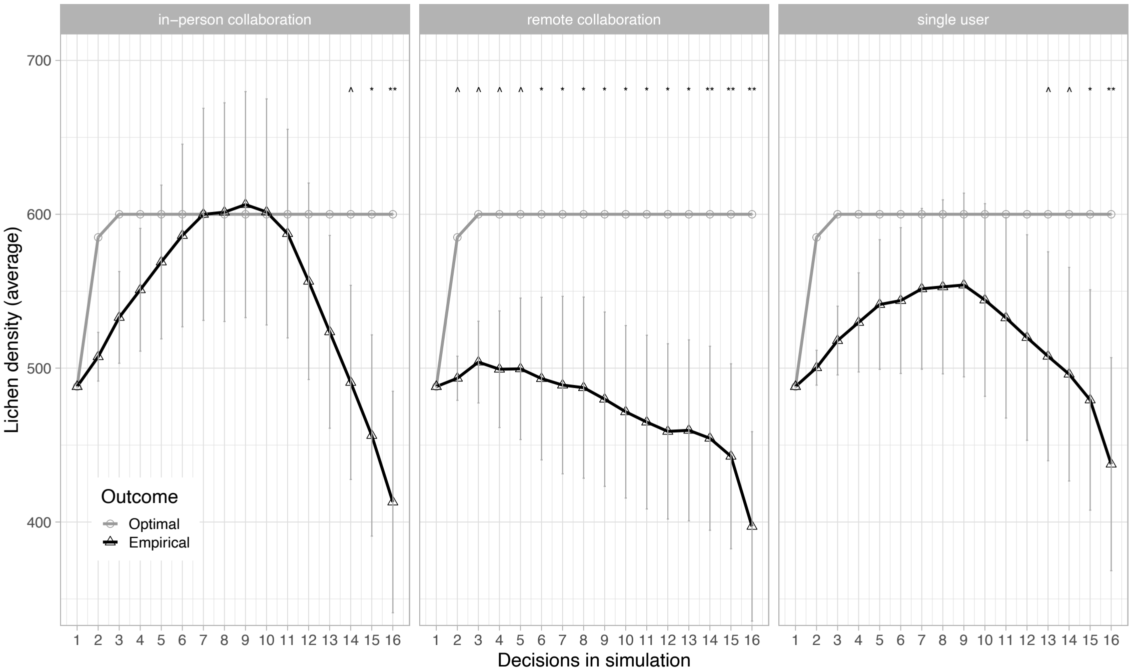


Fig. 8. Outcome of the simulation task represented in changes of lichen density (black lines) compared to an optimal outcome (gray line) for each experimental condition. The gray lines represent the optimal lichen density derived from the model. Each graph represents the results of a separate analysis of variance comparing lichen density in certain experimental conditions compared to the optimal lichen density. *Note*: Error bars represent ±1 *SE*. Significant differences between the empirical and optimal outcome are annotated above the lines with ($^{\wedge}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$).

($2\times$ 16) analyses of variance (ANOVAs) with herd size as the dependent variable, separately for each experimental condition. Sixteen decisions (steps of simulations) in the simulation task were entered as the within-subjects factor and the type of outcome (empirical vs. optimal) as the between-subjects factor.

In general, the empirical herd size did not differ from the optimal outcome ($M_{herd} = 1197$), neither in in-person collaboration ($F(1,12) < 1,\ M_{herd} = 1201,\ SE_{herd} = 68.20$), nor in the remote collaboration ($F(1,13) < 1$), ($M = 1216\ SE =$ 34.40) and single-user condition ($F(1,16) < 1,\ M_{herd} = 1245,\ SE_{herd} = 64.50$).

The interaction effects between outcome type and consecutive decisions were statistically significant in all three conditions: for in-person collaboration ($F(15,180) = 5.27,\ p < 0.001,\ \eta^2 = 0.152$), remote collaboration condition ($F(15,195) = 7.80,\ p < 0.001,\ \eta^2 = 0.337$), and single user condition ($F(3.59,57.5) = 13.08,\ p < 0.001,\ \eta^2 = 0.265$). Each interaction effect was followed by pairwise comparisons of empirical and optimal herd sizes in each year (step of simulation) with HSD Tukey correction. For detailed comparisons see the interaction effects on Figure 7.

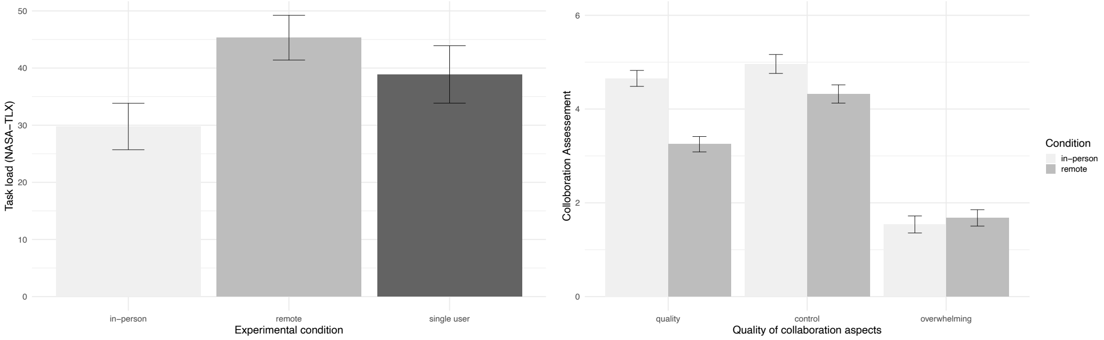
Next, we compared the average empirical lichen density (obtained as a result of participants' decisions) to the optimal outcome derived from the model. For each experimental condition, we conducted a mixed-design (2×16) analysis of variance (ANOVA) for lichen density as the dependent variable. 16 decisions were entered as a within-subjects factor and the type of outcome (empirical vs. optimal) as a between-subjects factor.

The analyses revealed that the empirical outcome did not differ significantly from the optimal one, neither in the single-user condition ($F(1,16) < 2.39,\ p = 0.141,\ M_{lichen} = 518.57,\ SE_{lichen} = 18.55$) nor in the in-person collaboration condition ($F(1,12) < 1,\ M_{lichen} = 541.94,\ SE_{lichen} = 20.47$). However, the difference was statistically significant in remote collaboration condition ($F(1,13) = 6.92,\ p = 0.021,\ \eta^2 = 0.265$), where participants' decisions led to significantly lower lichen density ($M = 473.93\ SE = 17.25$) than the optimum ($M = 592.06$).

The interaction effect between outcome type and consecutive decisions was significant for in-person collaboration ($F(15,180) = 3.88,\ p < 0.001,\ \eta^2 = 0.071$), remote collaboration ($F(15,195) = 3.50,\ p < 0.001,\ \eta^2 = 0.042$), but not for the single user condition ($F < 1$). Both of the significant interaction effects were followed by pairwise comparisons of empirical to the optimal outcome in each step of the simulation with HSD Tukey correction for multiple comparisons. Figure 8 presents estimated means with the significance of each comparison.

5.3 Subjective Assessments: Task Workload, Usability, and Collaboration Quality

In this Section, we present subjective assessments of participants' reactions to the simulation task related to the fourth hypothesis. In a series of between-subjects one-way ANOVAs, we compared differences between experimental conditions in self-reported task workload, collaboration quality, and system usability. Collaboration quality was examined only in the collaboration conditions (in-person and remote).



(a) Task workload

(b) Collaboration assessment

Fig. 9. Subjective assessment of (a) task workload and (b) collaboration quality measured with three scales (quality, being in control, and feeling overwhelmed). Note: The error bars represent ±1 *SE*.

System Usability Evaluation. The analysis for system usability did not indicate significant differences among the three experimental conditions, ($F(2,68) = 1.48,\ p = 0.20$). System usability, on average, was similar in all experimental conditions (in-person: $M = 80.6,\ SE = 3.56$, remote: $M = 76.2,\ SE = 3.43$, and single user: $M = 70.9,\ SE = 4.40$).

Task Workload. We start by examining differences in participants' perceived task workload measured with NASA-TLX questionnaire. A one-way between-subjects ANOVA revealed a significant effect of experimental condition ($F(2,68) = 3.77,\ p = 0.03,\ \eta^2 = 0.1$), see Figure 9a. The *post-hoc* comparisons suggest a higher reported task load among participants working in the remote condition ($M = 45.1,\ SE = 3.92$) compared to the in-person condition ($M = 29.7,\ SE = 4.07$) and the single user condition ($M = 38.8,\ SE = 5.03$). The difference between single user and in-person condition in perceived task workload was not significant ($t(154) = 1.41,\ p = 0.34$).

Collaboration Quality. The collaboration assessment was conducted for remote and in-person collaboration experimental conditions. To check the differences between these conditions, three one-way ANOVAs were conducted separately for three dependent variables: quality of collaboration, feeling of being in control, and feeling of being overwhelmed.

The ANOVA for the quality of collaboration revealed that participants in the in-person condition rated the quality of pair-work significantly higher ($M = 4.64,\ SE = 0.18$) than participants in the remote condition ($M = 3.24,\ SE = 0.18$), $F(1, 52) = 21.4,\ p < 0.001,\ \eta^2 = 0.04$, (Figure 9b).

The ANOVA for the feeling of being in control suggested that participants felt significantly more in control while working in-person ($M = 4.95,\ SE = 0.18$) compared to working in the remote condition ($M = 4.31,\ SE = 0.18$), ($F(1, 52) = 5.22,\ p = 0.03,\ \eta^2 = 0.09$). Finally, there were no significant differences between the in-person and remote conditions for a feeling of being overwhelmed, ($t(154) = 0.55,\ p = 0.586$). In general, participants reported low levels of feeling overwhelmed during in-person ($M = 1.53,\ SE = 0.18$) and remote collaboration ($M = 1.67,\ SE = 0.18$).

6 DISCUSSION

In this article, we presented the results of an eye tracking experiment revealing the attentional mechanism underlying effectiveness and quality of in-person and remote collaboration during SD-based complex decision-making task solving. The experiment participants, all new to reindeer rangeland management, were given instructions on how to recover and grow lichen density and run the simulation task. During task performance, their eye movements were recorded. We hypothesized that collaboration would help to focus their visual attention on crucial information related to simulation control (hypothesis 1 and hypothesis 2). Consequently, we expected that collaboration would facilitate a more optimal outcome of the simulation task (hypothesis 3). The effectiveness of collaboration was traced via participants' decision outcomes and the self-reported quality of collaboration (hypothesis 4). In general, the triangulated results of eye movements, behavior, and self-report analyses supported our hypotheses.

6.1 In-Person Collaboration Fosters Attention to Key Task Information

To test the hypotheses about attentional bias to key information and provide insight into decision-making, we analyzed visual attention distribution and depth of processing over simulation control and decision-making areas of interest. Participants in all three experimental conditions had significantly longer average fixation duration on decision-making AOIs than on simulation control AOIs. Referring to Just's and Carpenter's "*eye-mind assumption*" [1976] this may suggest that decision-making was more cognitively demanding than reading simulation control graphs. In line with the second hypothesis, when analyzing simulation control graphs, participants in both collaboration conditions focused longer on the lichen density graph than on the other two graphs (Figure 6). That was especially salient in the in-person collaboration condition, where participants focused more on the lichen density graph than in the other two experimental conditions. The lichen density graph was a critical piece of information for understanding the principles underlying the simulation task. In the single-user condition, participants' attention was evenly distributed across the simulation control graphs.

6.2 Closer to Optimal Decision-Making Strategy in In-Person Collaboration and Single-User Conditions

Previous System Dynamics research [Derwisch et al. 2011; Moxnes 2004] has shown that people have persistent difficulties with performing the reindeer rangeland management task. The task is formulated such that the sole owner of a reindeer herd (decision-maker) takes over the associated rangeland (pasture covered by lichen) in an overgrazed situation. The optimal solution to the task requires understanding that for lichen density to recover and grow to its maximum sustainable yield (which, in turn, allows for the maximum sustainable reindeer herd size), one needs to substantially reduce the number of reindeer in the first years and then gradually adjust the herd size up to the maximum sustainable number.

Overall, participants' decisions on herd size led to the outcome (lichen density) that was similar to the optimal task solution. Notably, participants in the in-person and single user conditions seemed to follow a slightly different strategy than participants in the remote condition. In the first years, in-person and single user participants reduced the reindeer herd size to below 1000 animals. This allowed lichen density to recover and grow closer to maximum sustainable levels. With this strategy, they followed the principles underlying an optimal solution more closely than participants in the remote condition who, at the beginning of the simulation, did not reduce herd size enough for lichen density to recover. In the last years, participants seemed to show some end-of-game behavior where they increased herd size again well above the maximum sustainable levels. This, in turn, led to the depletion of lichen density towards the end of the simulation. Similar performance improvements have been observed in studies with targeted instructional support for single users [Kopainsky and Alessi 2015; Kopainsky and Sawicka 2011], and we thus generalize that similar performance patterns can also be expected for other SD-based complex decision-making tasks.

6.3 Higher Self-Reported Collaboration Quality and Lower Task Load in the In-Person Condition

Even though all participants similarly rated system usability, participants in the in-person collaboration and single user condition reported less workload than people working remotely. Participants collaborating in person also reported a higher quality of collaboration and felt more in control of the simulation than participants during remote collaboration. Based on the results, we postulate that a better understanding of the task, reflected in attention bias toward the most important information and optimal outcome of own decisions, resulted in higher satisfaction from collaboration. However, future studies may want to add explicit measures of the model understanding level achieved during interactive simulation tasks [Happach and Schoenberg 2017].

6.4 The Role of In-person Contact

Taken together, our findings lead us to conclude that collaboration in remote and in-person conditions facilitated the focus of users' attention on the information most important for understanding the simulation more than in the single-user condition. The findings align with the definition of collaboration as a construction of shared understanding through interaction with others, and commitment to problem-solving [Roschelle and Teasley 1995]. Importantly, an in-person collaboration facilitated even stronger attention focus on key information than remote collaboration.

Also, users' decisions and their outcomes were most similar to the optimal when participants collaborated in person. The in-person collaboration tested in our research thus seems to have improved understanding when compared to alternatives (without any instructional support) for single users [Moxnes 1998b, 2004]. The in-person collaboration yielded a lower task workload than remote collaboration. Presumably, this was why our participants valued in-person collaboration more than remote.

Remote collaboration is sometimes evaluated as more confusing, less satisfactory [Thompson and Coovert 2003], and less productive [Straus and McGrath 1994], which may result in lower participation satisfaction [Lipponen et al. 2003] than in-person collaboration. Limited access to non-verbal signals of communication in remote collaboration, such as gaze communication [Pfeiffer et al. 2013], or mimicking others' non-verbal behavior and postures [Shockley et al. 2003], may be responsible for the level of shared understanding and commitment in task-solving. Remote collaboration settings seem to lack several coordination behaviors between partners exhibited by, e.g., drawing both partners' attention to the same visual elements by pointing, gesturing, or gazing [Clark and Krych 2004]. Therefore, examining solutions enabling non-verbal communication in an online workspace is needed. For instance, Ashdown and Robinson [2005] have created a system called the Escritoire, allowing participants to gesture to each other in ample visual space to enhance their remote communication. To enhance the effectiveness of remote collaboration, interface designers may also guide users' attention to the most important elements of the collaboration interface using subtle graphical gaze cues (color, blinking) [Frischen et al. 2007; Lu et al. 2012] thereby activating the bottom-up mechanisms of visual attention [Posner 2004], and as a result, curtail haphazard attention distribution. Future work may focus on testing practical guidelines for designers of collaborative interfaces.

6.5 Conclusion and Outlook

Our research offers quantitative results demonstrating that collaboration may lead to a more successful SD-based simulation strategy, especially during in-person collaboration. We investigated the process of achieving an improved understanding of the simulation by registering visual attention distribution. The results of our research demonstrated that during in-person and remote collaboration, the visual attention of collaboration partners focused on key elements of a simulation task more than in the single user condition and that in-person collaboration yielded less cognitive workload and was perceived as of higher quality than remote collaboration.

The main contribution of this study is understanding of the attentional mechanism underlying the effectiveness of in-person collaboration on a large interactive display. In-person collaboration helps users to focus their visual attention on the most important information necessary for optimal decisions. Understanding this attentional mechanism may serve designers of attentive user interfaces [Vertegaal 2002, 2003] for remote collaboration interactive systems.

That is, based on our findings and using eye tracking technology, future remote collaboration systems may be able to detect and guide remote user's visual attention to decision-related areas. By using visual or even eyes-free, vibrotactile notifications to present attention cues to the remote user, improved effectiveness and efficiency of distributed decision-making can be expected. Inspired by eyes-free, vibrotactile notification principles, such as OmniVib [Alvina et al. 2015], ultra-low-cost prototypes, such as DragTapVib [Fang et al. 2022], can reliably provide dragging, tapping, and vibrating sensations to their users.

Complex Dynamic Systems are characterized by three factors: feedback processes, non-linearities, and accumulations [Sterman 2000]. Most people, including experts, have difficulty in understanding and managing these factors [Brehmer 1992; Funke 1991; Jensen 2005; Moxnes 2004; Sterman 1989; Sterman and Sweeney 2007]. One of the main purposes of System Dynamics is to improve the design of computer simulations, as tools, to improve decision-making, problem-solving, and management. Existing SD research has mainly focused on task performance and less on understanding and its determinants [Kopainsky and Alessi 2015].

In the present study we examined collaboration on large interactive displays. That work may be extended to very popular small screens e.g., tablets or smartphones, where workspace awareness over small screen may be harder to achieve. Recent research prototypes offering dynamic bindings among multiple tablets or smartphones, e.g. RAMPARTS project [Wozniak et al. 2016] have shown how workspace awareness benefits from such bindings. Moreover, studies of visual application sharing mechanisms among large interactive displays and small screens, e.g. CamCutter project [Hagiwara et al. 2019], have demonstrated effective ways to integrate large and personal displays into a shared workspace. Employing application sharing principles like CamCutter [Hagiwara et al. 2019], visually pulling down results displayed on an interactive surface to participants personal devices, such as phones and tablets, can be a way to make insights outlast the process itself. The present work may also be extended by adding additional technologies which may increase workspace awareness, like haptic or tangible input devices [Fjeld et al. 2007; Patten et al. 2001]. Another direction worth exploring is the role of awareness in collaborative workspaces combining physical and VR environments [Kudo et al. 2021].

To extend the understanding of visual attention processes as a mechanism underlying effective and satisfactory collaboration supported by computer systems e.g., SD-based simulations, future studies may aim at evaluating the role of joint attention in complex task understanding and optimal outcome achievement. Joint attention can be detected by tracking the gaze of interaction partners as they focus their attention on the same objects or events within a specific time frame [Andrist et al. 2015; Schneider and Pea 2013]. Following previous studies [Stahl et al. 2014; Webb et al. 2002], one may claim that joint attention may substantially improve the effectiveness and satisfaction of collaboration. In the future, advancing the understanding of visual attention distribution may play an important role for System Dynamics and eye tracking research. Broadening our knowledge base about cognitive processes in using various interfaces is needed. Therefore, appropriate visual and analytical methods to explore and analyze time-oriented data [Aigner et al. 2011], and eye-movement analysis is needed.

Future studies may focus on corroborating the current results with different collaborative tasks, e.g., joint text writing, mathematical and algorithmic problems solving, or software coding. Future studies may also address other collaboration settings, e.g., desktop computers with relatively small screens, as well as collaboration using mobile devices.

Our findings provide insights for designing collaborative ICT-based systems, e.g., computer-supported collaboration or remote teamwork, which may lead to novel technological solutions. Our findings can scale to collaborative problem-solving over large displays in related domains, such as natural resource planning, smart grid design, and logistics simulation. More generally, our results may also be applicable to collaborative learning and social discussion. and can help to inform the future design of collaborative technologies for groups, organizations, communities, and networks.

7 AUTHORS' STATEMENT REGARDING PRIOR WORK

This article entirely presents original work that has not been, entirely or in parts, published elsewhere.

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- conception of study design
- statistical analyses
- article preparation
- writing revision after reviews

Katarzyna Wisiecka was the lead author of the paper and was primarily responsible for its creation. Katarzyna Wisiecka contributed to the following tasks:
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Computers in Human Behavior

Supporting Computer-Supported Collaboration with GazeVisualization among Self-Focused Individuals

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Abstract:	Successful and satisfactory collaboration requires joint attention of collaborating partners and their mutual focus on an object. However, computer-mediated collaboration settings may restrict access to gaze communication. Restricted nonverbal communication channels may, in turn, boost self-focused individuals to neglect their partner's perspective and make joint attention inaccessible for collaborating partners. We investigate to which extent visualization of collaborators' gaze may foster joint attention during Computer-Supported Collaboration among individuals with high and low self-focus. We conducted an eye-tracking experiment in which we presented the users' eye movements to the partner while solving logical problems in both remote and co-located settings. The results show that gaze visualization fosters joint attention and enhances collaboration effectiveness measured by task accuracy among self-focused individuals. We postulate introducing visualization of gaze communication to remote computer-mediated systems for yielding a partner-oriented perspective during long-distance collaboration.
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Supporting Computer-Supported Collaboration with Gaze Visualization among Self-Focused Individuals

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Abstract

Successful and satisfactory collaboration requires joint attention of collaborating partnersand their mutual focus on an object. However, computer-mediated collaboration settingsmay restrict access to gaze communication. Restricted nonverbal communication channelsmay, in turn, boost self-focused individuals to neglect their partner's perspective and makejoint attention inaccessible for collaborating partners. We investigate to which extent visu-alization of collaborators' gaze may foster joint attention during Computer-Supported Col-laboration among individuals with high and low self-focus. We conducted an eye-trackingexperiment in which we presented the users' eye movements to the partner while solvinglogical problems in both remote and co-located settings. The results show that gaze visu-alization fosters joint attention and enhances collaboration effectiveness measured by taskaccuracy among self-focused individuals. We postulate introducing visualization of gazecommunication to remote computer-mediated systems for yielding a partner-oriented per-spective during long-distance collaboration.

Keywords: computer-supported cooperative work, computer-mediated communication, gaze visualization, self-focused attention, joint attention

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Supporting Computer-Supported Collaboration with GazeVisualization among Self-Focused Individuals

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Abstract

Successful and satisfactory collaboration requires joint attention of collaborating partners and their mutual focus on an object. However, computer-mediated collaboration settings may restrict access to gaze communication. Restricted nonverbal communication channels may, in turn, boost self-focused individuals to neglect their partner's perspective and make joint attention inaccessible for collaborating partners. We investigate to which extent visualization of collaborators' gaze may foster joint attention during Computer-Supported Collaboration among individuals with high and low self-focus. We conducted an eye-tracking experiment in which we presented the users' eye movements to the partner while solving logical problems in both remote and co-located settings. The results show that gaze visualization fosters joint attention and enhances collaboration effectiveness measured by task accuracy among self-focused individuals. We postulate introducing visualization of gaze communication to remote computer-mediated systems for yielding a partner-oriented perspective during long-distance collaboration.

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1. Introduction

Nowadays, Computer-Supported Collaboration without direct Face-to-Face (F2F) contact with collaboration partners is becoming part of our everyday life. Several meta-analyses showed that collaboration with technical support can effectively promote retention and problem-solving Li and Ma (2010). However, there is a lack of information about the psychophysiological nature of collaboration in F2F compared to remote conditions, especially concerning the use of technology and its influence on information processing. The existing solutions often lack understanding of attentional processes that are imperceptible or even unconscious during collaboration. It can easily lead to social inequality in coping with the change of cultivating collaboration on a technological basis. The outset to struggle with inconsistencies of existing systems is to understand the cognitive processes during Computer-Supported Collaboration and different needs resulting from remote communication settings or individual differences.

In the F2F, non-verbal communication, such as mutual gaze and gaze cueing, are crucial in creating joint attention between partners. It enhances collaboration performance by

January 30, 2023

observing and following the partner's eye direction to shared reference Pfeiffer et al. (2013); Schneider et al. (2018). The knowledge of gaze communication during Computer-Supported Collaboration compared to F2F collaboration is scarce. Computer-Supported Collaboration decreases non-verbal communication Hadwin et al. (2018); therefore, conveying the gaze direction of interaction partners during Computer-Supported Collaboration may enhance the quality of their collaboration. Gaze visualization can improve communication during remote Computer-Supported Collaboration. However, researchers have not yet fully explored different gaze visualization techniques or individual differences that can affect real-time gaze communication D'Angelo and Gergle (2018). In detail, the attentional focus is a tendency to direct attention to either internal or external stimuli Astle and Scerif (2009); Posner and Petersen (1990). People with high attentional focus on internal stimuli (self-focus attention, Ingram (1990)) may benefit from gaze visualizations because they tend to be more distracted during collaboration due to their self-contained attention.

This paper examines gaze visualization as an external cue directing the attention of collaboration partners to facilitate joint attention and collaboration. Our goal was to enhance the quality of remote collaboration among participants differing in attentional focus. In the present study, participants solved collaborative problem-solving tasks with and without gaze visualization in co-located and remote settings in pairs with an equal self-focused attention level. To our knowledge, this is the first study evaluating attentional individual differences in remote communication.

In this paper, we show that in comparison to settings without gaze visualization, adding a partner's gaze visualization led to improved accuracy in collaborative problem-solving tasks and increased joint attention. Especially participants who participated remotely and have a high level of self-focused attention benefited the most from gaze visualizations. We believe that our findings provided support that gaze visualizations may be a solution that helps people with higher self-focused attention to direct their attention to crucial information during remote collaboration. Broadening the knowledge of attentional focus during remote collaboration is needed to elaborate solutions to facilitate information exchange also at the non-verbal level Kreijns et al. (2003). Establishing joint attention is an important issue in the field of online and augmented collaboration systems Schnier et al. (2011); Vertegaal (1999). Our results may be used as a basis for gaze-based solutions enhancing Computer-Supported Collaboration for people with different individual characteristics.

2. Related Work

We situate our work at the intersection of computer-supported cooperative work (CSCW) and psychology. For this, we first review the intersection itself, thus, the importance of joint attention during collaboration. Next, we highlight work fostering joint attention using eye-tracking and how gaze cueing was used to control attention. Finally, we bring in the psychology perspective to show how collaboration is affected by self-focused attention, which needs to be considered in a system design.

2.1. Importance of Joint Attention During Collaboration

Research on Computer-Supported Collaboration underlines the value of shared visual workspace and references during collaboration Fussell et al. (2000); Gergle and Clark (2011). Wang and Shi (2019) showed that participants' gaze was more likely to lie on the referred object when they knew that the communication partner could see his/her eyes. The mutual recognition of the partner's gaze direction leads to joint attention, which is created by following and directing another person's gaze to a new target, making a referential triangle between partners of collaboration and the object Pfeiffer et al. (2013). Therefore, shared visual workspace may be achieved by collaborators' gaze following, e.g., editing another user's document with her/his visual supervision Serim et al. (2018); Schlösser (2018).

There is a wealth of literature showing that joint attention is among the strongest predictors of an effective collaboration Tomasello (1995); Barron (2003); Eilan et al. (2005); Siposova and Carpenter (2019); Mundy and Newell (2007). Social neuroscience has demonstrated that human beings have an intrinsic motivation to engage in joint attention, the occurrence of which recruits reward-related neurocircuitry Schilbach et al. (2010). Also, the process in which we engage attention on the same target may lead to enhanced cognitive processing while solving the problems together. For example, Gregory and Jackson (2017) showed that joint attention enhances visual working memory. In her studies, she compared gaze versus nonsocial cueing effects on working memory. Experiments revealed that a nonsocial cue and a low-level motion cue - both shown to orient attention reliably - did not reliably modulate working memory, indicating that social cues are more effective.

2.2. Eye-tracking Studies on Computer-Supported Collaboration

Evidence from eye-tracking studies provide further support by suggesting that information about participants' gaze direction enhances Computer-Supported Collaboration's quality Soller et al. (2005); Velichkovsky (1995); Ishii and Kobayashi (1992). The eye-tracking provides objective and quantitative information of the individual's visual and attentional processes Duchowski (2002). Thus, fixations and saccades are recorded to ascertain the participants' attentional patterns over a given stimulus. Eye-tracking provides information about the attentional patterns of two or more collaborators, indicating the role of gaze-based solutions in enhancing Computer-Supported Collaboration. For example, Brennan et al. (2008) demonstrated that sharing a partner's gaze during searching tasks decreased search time compared to a condition without gaze visualization. In another study, Zhang et al. (2017) showed that gaze visualization during geographical map searching accelerated finding crucial information in a co-located collaboration.

There are also observable effects of the gaze display in pair-programming D'Angelo and Begel (2017); Bednarik et al. (2011); Cheng et al. (2022). For example, students' gaze patterns were different when the gaze of a programming expert was shown during a programming lecture compared to a condition without a gaze display. When the gaze display of an expert was available, students' gaze behavior showed less variation, and thus, their attention patterns were more alike Bednarik et al. (2011). D'Angelo and Begel (2017) used gaze visualization for remote pair programmers, which showed where in the code their partner was looking and changed color when they were looking at the same locations. Results reveal that partners spend more time looking at the same code areas simultaneously when using the visualization. In addition to using more implicit references than explicit references, pairs responded to references more quickly and effectively. So far, gaze visualization during Computer-Supported Collaboration was also positively related to performance Velichkovsky (1995), coordination Serim et al. (2018), and searching behavior Zhang et al. (2017); Siirtola et al. (2019). However, there is a lack of studies investigating how gaze visualizations may reduce difficulties resulting from individual differences in attentional focus.

2.3. Gaze-cueing in Control of Visual Attention

Visual attention is guided by two types of cues: exogenous and endogenous Posner (1980). During endogenous control, attention is likely motivated by our intentions and motivations Velichkovsky et al. (2005)). During exogenous control, attention is likely guided by stimuli characteristics, e.g., color, size, movement Krejtz et al. (2012). For example, Bailey et al. (2012) showed that motion in the periphery cued attention to important parts of the visual field. In another study, Krejtz et al. (2016) showed that audio description added to a visual material modified people's patterns of visual attention resulting in better memorizing. By analogy, we argue that gaze visualizations may serve as exogenous cues that enable collaborators to focus on a task.

The reciprocity of social interaction influences how gaze cues are perceived Bayliss et al. (2013); Schilbach et al. (2013). Cueing attention to where one's gaze was directed encourages better performance at these locations; the 'gaze-cueing effect' Driver et al. (1999). Synchronization of gaze-cueing led to joint attention, and better collaboration outcomes in F2F communication Pfeiffer et al. (2013). The gaze-cueing synchronization is investigated, e.g., in computer-mediated collaborative learning. For example, Shvarts and Abrahamson (2019) indicated the emergence of synchrony between student's and tutor's eye movements and coordination between student's action and tutor's perception. They were simultaneously aware of the geometric patterns on the screen and anticipating the student's current activities. In this way, the instructor guided the actual performance of the student.

Using gaze visualization in remote collaboration reveals promising results; however, effective gaze-cueing is possible to achieve if both/all participants can inhibit their own perspective (self-focused attention inhibition) Samson et al. (2005). We believe that self-focused attention inhibition is limited in remote collaboration, and it may lower capacity to join attention with partner. Thus, we tested if gaze visualization during Computer-Supported Collaboration enhances the gaze-cueing among individuals differing in self-focused attention.

2.4. Self-Focused Attention

Self-focused attention is defined as an awareness of self-referent, internally generated information Ingram (1990). It is highly related to many clinical disorders e.g. depression Smith and Greenberg (1981); Pyszczynski et al. (1989), social anxiety Woody and Rodriguez (2000); Spurr and Stopa (2002), or eating disorders Zucker et al. (2015). High self-focused attention is related to impaired endogenous control of attention Kaplan and Berman (2010) and impaired ability to direct attention to something that is of no particular (internal) interest to the individual Morecraft et al. (1993). It detracts attention from the current task and, as a result, may impair the ability to solve it effectively Spurr and Stopa (2002).

Self-focused attention refers to the bi-directionality of human social consciousness Duval and Wicklund (1972), which is focused on the self or the external environment. The degree to which self-focused attention will be disruptive during collaboration depends on the effectiveness of attention control processes Mor and Winquist (2002). The ability to inhibit the tendency to focus attention on self depends on switching from involuntary control (directing visual attention to self-focus related stimulus) to more directed, endogenous control (directing visual attention to task-related stimulus). Directed attention is forcing oneself to focus attention on something that is of no particular (internal) interest to oneself Morecraft et al. (1993) and is linked with endogenous control. On the other hand, involuntary attention is related more to our internal state and self-focused needs manifesting endogenous control. It is reflected by automatic behavior, e.g., directing visual attention to the stimulus, which is more related to our state of mind.

The control of attention among high self-focused individuals is additionally hindered, during remote collaboration, by the distance between collaborators and the lack of non-verbal communication. Adding gaze visualizations as exogenous cues during remote and co-located collaboration may focus on another person's perspective and enhance collaboration work quality. To the best of our knowledge, previous research did not consider differences in attentional focus as a factor potentially influencing gaze communication in the computer environment.

3. The Present Study

Our experiment investigated the role of gaze visualization projection on complex problem-solving tasks and the quality of Computer-Supported Collaboration in co-located and remote collaboration. Further, we controlled for individual differences in attentional focus that may influence gaze communication in the computer environment.

In general, we expect that projection of gaze visualization will enhance effectiveness during problem-solving measured by task accuracy (H1). Further, we expect gaze visualization to enhance joint attention measured by mutual gaze fixations (H2). Finally, we assume that the relation between accuracy and joint attention will be moderated by the level of self-focused attention (H3).

To address these hypotheses, we designed a 2 × 2 × 2 laboratory experiment in which participants in pairs solved Bongard Problems while their eye movements were recorded. The within-subjects independent variable VISUALIZATION is related to the presence of gaze visualization; participants solved half of the problems with gaze visualization and the other half of problems without gaze visualization (VISUALIZATION: control vs. gaze visualization). The within-subjects independent variable SETTING is related to the setting of collaboration; participants solved half of the problems in remote setting and the other half of problems in co-located setting (SETTING: co-located vs. remote), see Figure 2. We divided participants into low and high self-focused attention groups based on the Self-Consciousness Scale (SCS-R)

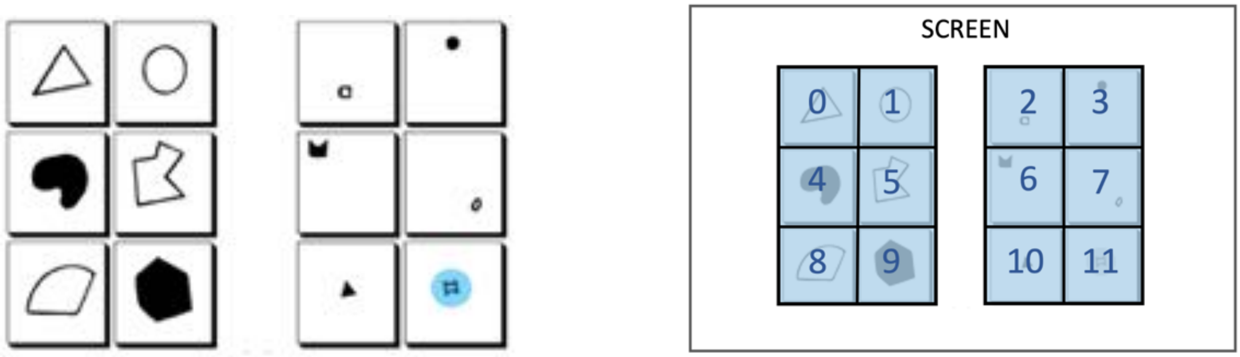
Scheier (1985) in a pre-screening step, resulting in a between-subjects independent variable Self-Focused Attention (low vs. high).

3.1. Apparatus

Participants collaborated on the Bongard Problems in an office environment with natural conversational settings. The experiment was run on three identical Windows PCs connected with Ethernet LAN for fast synchronization of the tasks and gaze visualization. They were equipped with one 23.8-inch monitor ($1600 \times 900px$ resolution), one Pupil Labs Core eye tracker with a sampling rate of 120 Hz, a computer mouse, and a keyboard. The Pupil Labs light-weight mobile eye trackers are not obstructive for participants allowing free communication Kassner et al. (2014).

3.1.1. Gaze Visualization

During the collaboration, the gaze position of each participant was tracked using a head-mounted Pupil Labs eye tracker (see Figure 2). To ensure the accuracy of gaze visualization, we used a standard 5-point calibration performed prior to the experimental task. 14 ArUco style markers attached around the screen (see Figure 1) helped in the automatic, real-time estimation of gaze position on the computer screen. When participants were not looking at the screen, their gaze visualization was not shown to their partners. As both screens showed the same content, this allowed us to visualize the gaze for the partner by streaming the gaze to the partner's PC via a local network, ensuring a latency lower than 5 ms. The visualization of the partner's current gaze location was shown to his partner as a cyan circle at 50% transparency with a diameter of 33mm (100px), see Figure 1b. Our gaze visualization is inspired by Zhang et al. Zhang et al. (2017).



(a) An example of the Bongard's Problem

(b) Areas of Interest

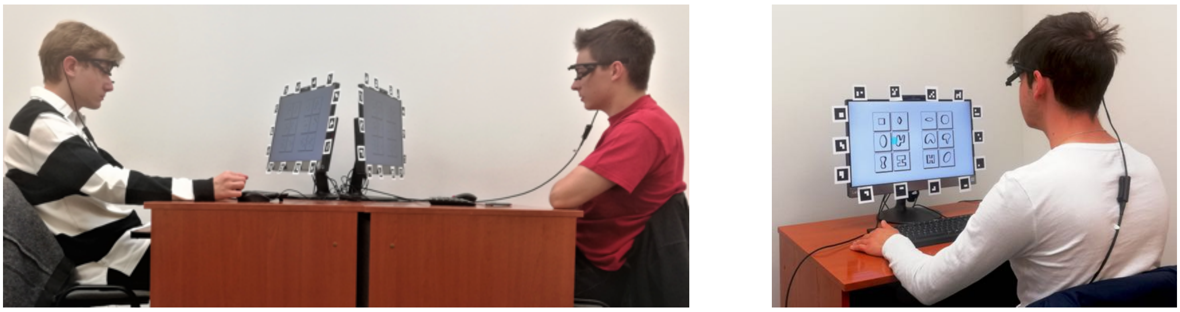
Figure 1: a) An example of the Bongard's Problem with a Gaze Visualization point (cyan circle). The correct answer: figures on the images on the left are big. b) Areas of Interests (AOIs). Each AOI corresponds to one image.

3.2. Task – The Bongard Problems

The goal of the Bongard Problems Bongard (1968) is to find a common pattern or rule among six images presented on the left, which does not work for the six images on the right, see Figure 1a. The task requires cognitive penetration in visual processing Vetter and Newen (2014). Collaborators were asked to make a unified decision on the task solution. In our version of the task, when the common pattern was discovered, one of the collaborators pressed a spacebar and the next slide appeared with a space provided to type in the answer. The difficulty of the problems was counterbalanced across experimental conditions (see Bongard, 1968 for difficulty description Bongard (1968)). In each condition, participants started with 2 easy problems, which were treated as training and they were not included in the analysis. The order of the other problems was random in each condition.

3.3. Procedure

After welcoming the two participants, we introduced them to the study and answered any open questions they might have. Before the experiment started, participants signed an informed consent form and we informed them that they can resign any time from taking part in the study. Each pair solved 32 Bongard Problems during the experiment, 16 in each of the two Setting (co-located vs. remote).



(a) Co-located Setting

(b) Remote Setting

Figure 2: Participants solve the problems in a co-located setting (left); remote setting (right). Each participant is wearing an eye tracking device

In the remote setting, participants worked in separate offices. They were able to talk to each other using a microphone and speakers; however, they did not see each other. In the co-located setting, participants collaborated in the same office sitting behind separate desks facing each other, see Figure 2a. Both of them saw the task on their computer screen directed to their side. Participants were able to talk and see each other. Since the computer screens were synchronized, the content displayed on the computer screens was the same in both setting conditions. In each setting, half of the problems was solved with gaze visualization and the other half without gaze visualization, creating another independent within-subjects variable: Visualization. There was no time limit for the task completion.

After each collaboration conditions participants completed the following paper measures of task workload and collaboration quality: raw NASA Task Load Index (NASA-TLX) Hart (2006) and a Collaboration Assessment Scale (CAS).

We counterbalanced the order of the blocks (remote/co-located *times* with/without gaze visualization) across groups so that each condition appeared (first, second, third, and fourth) equally often.

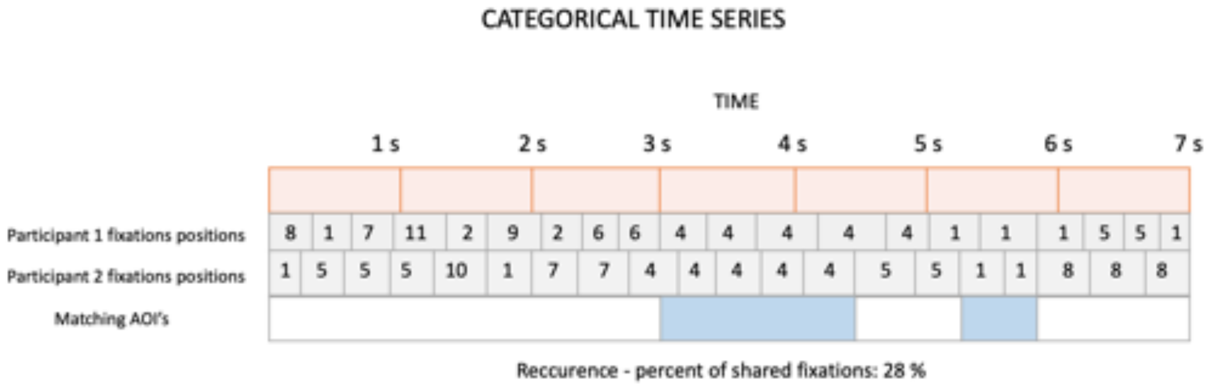


Figure 3: A dyad eye-movement scarf plot illustrating joint attention calculation for a 7-sec segment. The table shows two time series of fixations' positions on particular AOIs of two participants. Each number in the grey table refers to one fixation on a particular AOI. The size of the grey square refers to the fixation duration. When fixations of two collaborators were on the same AOI at the same time, we understood this as joint attention, depicted as a blue area in the table.

3.4. Measurements

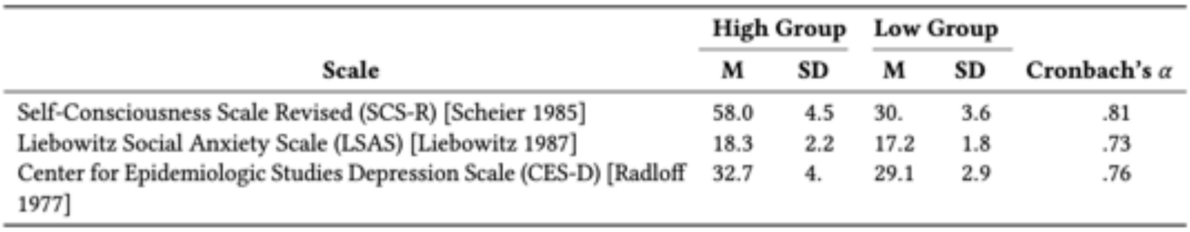
To measure the joint attention, we, first, defined 12 Areas-of-Interest (AOI) around each image displayed on the screen to identify the position of fixations and assigned them to a particular AOI, see Figure 1b. Fixations are eye movements that stabilize our focus on an object of interest. They can be understood as relative stops between two consecutive saccades, fast eye movements that reposition the fovea to fixate on a new object Duchowski and Duchowski (2017). According to the literature, the typical duration of fixation is between 150 and 300 ms; however, shorter and longer fixations have been observed Rayner (1998). In our study, data were pre-processed using Pupil Labs Player software. The fixation detection threshold was set to 80ms (minimum fixation duration). Recorded gaze data quality was above the 0.70 confidence level (1.00 is the maximum).

Second, joint attention was assessed by calculating the percentage of fixations placed simultaneously over the same area of interest while solving the Bongard Problems. The calculations were based on Richardson and Dale (2005) categorical time series analyses. Categorical time series are time-sequenced data in which the values at each time point are categories rather than measurements McGee and Harris (2005). In this case, each AOI was a separate category. The categorical time series data inform us in which order participants were viewing the figures (AOIs) in each Bongard Problem. Data sets of each pair were merged by timestamps. On the Figure 3, we can see a scarf plot with the example of one pair fixations' alignment in the 7-sec segment. Based on Richardson and Dale (2005) whenever gaze of the 1st and 2nd participant fixated the same AOI at the same time the recurrence occurred, which we treated as the indicator of joint attention. This allowed us to calculate the percentage of joint attention, indicating to what extend collaborating pairs were looking at the same AOIs at the same time. The percentage of joint attention was calculated for each pair. If participants were looking at the same time outside the AOIs (e.g., they were looking at blank spaces or off-screen) it was not counted as joint attention.

Four pairs were excluded from analyses of joint attention degree due to missing eye tracking data.

3.5. Participants

Twenty four male participants (age: $M = 20.86$, $SD = 1.7$) took part in the experiment. Only participants without diagnosed clinical disorders were selected to the study. Depending on their Self-Consciousness Scale Revised (SCS-R) score (Scheier (1985)), we divided them into two Self-Focused Attention groups: a *high* self-focused attention group and *low* self-focused attention group. We randomly paired up each participant with a person with a similar level of self-focused attention. Groups high and low differed only in terms of self-focused attention degree, they did not differ on CES-D and LSAS scores ($p > 0.05$). The detailed descriptive statistics for groups low and high on self-focused attention are presented in tab:stats. Participants did not know each other. Participation in the study was voluntary; however, students could receive extra credit points for student activity. The experimental procedure was approved by local Ethical Committee.



	High Group		**Low Group**		
Scale	**M**	**SD**	**M**	**SD**	**Cronbach's α**
Self-Consciousness Scale Revised (SCS-R) [Scheier 1985]	58.0	4.5	30.	3.6	.81
Liebowitz Social Anxiety Scale (LSAS) [Liebowitz 1987]	18.3	2.2	17.2	1.8	.73
Center for Epidemiologic Studies Depression Scale (CES-D) [Radloff 1977]	32.7	4.	29.1	2.9	.76

Figure 4: The pre-screening results of the participants of self-focused attention, depression, and social anxiety scales in the two Self-Focused Attention groups.

4. Results

For the analyses, we computed used the R software using Linear Mixed Models (LMMs) with repeated data estimated with Residual Maximum Likelihood method. Pair ID was treated in the models as a random factor. Models also included three fixed factors: Self-Focused Attention (low vs. high) as between-subjects factor and Visualization (control vs. visualization) with Setting (co-located vs. remote) as within-subjects factors. Since there was no time limit for the task performance, Completion Time was added to the models as a covariate. Effects of LMMs were calculated with the analysis of variance (ANOVA) with type III sum of squares correction.

4.1. Accuracy

To understand the influence of Visualization, Setting and Self-Focused Attention on task performance, we compared the percentage of correct answers among pairs with high and low self-focused attention in each condition. As expected, results of Linear Mixed

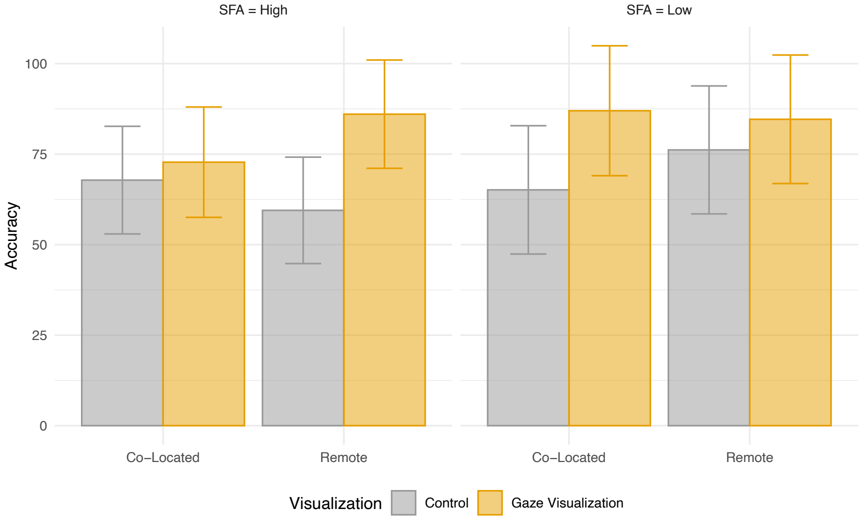


Figure 5: Accuracy percentage in each SETTING (remote vs. co-located) and VISUALIZATION (gaze visualization vs. control) for SELF-FOCUSED ATTENTION (SFA). The error bars represent Standard Errors.

Models analysis revealed a significant main effect of VISUALIZATION, $F(1, 73) = 34.50$, $p < 0.001$. Contrast analysis supported the first hypothesis, participants in the gaze visualization condition solved more problems ($M = 82.6\%$, $SE = 5.48$) than participants in the control condition without gaze visualization ($M = 67.1\%$, $SE = 5.49$), $t(73) = 5.87$, $p < 0.001$.

The analysis revealed a significant three-way interaction between SETTING, VISUALIZATION and SELF-FOCUSED ATTENTION, $F(1, 73) = 11.02$, $p < 0.01$, see Figure 5. To understand the interaction, contrast comparisons were performed. Low self-focused participants had higher accuracy in the co-located setting with gaze visualization ($M = 87.0\%$, $SE = 9.03$) than in the control condition without gaze visualization ($M = 65.1\%$, $SE = 8.90$), $t(73) = 4.28$, $p < 0.001$. In remote setting, low SFA participants performed similarly when gaze visualization was present ($M = 84.6\%$, $SE = 8.91$) and when there was no gaze visualization ($M = 76.2\%$, $SE = 8.87$), $t(73) = 1.66$, $p = 0.09$.

Whereas high self-focused participants performed similarly with gaze visualization ($M = 72.8\%$, $SE = 7.67$) and without it ($M = 67.8\%$, $SE = 7.47$) during co-located collaboration, $t(73) = 0.89$, $p = 0.37$. In the remote setting, the high SFA pairs performed significantly better with gaze visualization ($M = 86.0\%$, $SE = 7.52$) than control condition without gaze visualization ($M = 59.5\%$, $SE = 7.38$), $t(73) = 4.61$, $p < 0.001$.

The other main or interaction effects were not significant.

4.2. Joint Attention

Next, we verified the effect of VISUALIZATION, SETTING, and SELF-FOCUSED ATTENTION on joint attention. We conducted an analogous LMM analysis with the percentage of joint attention as a dependent variable.

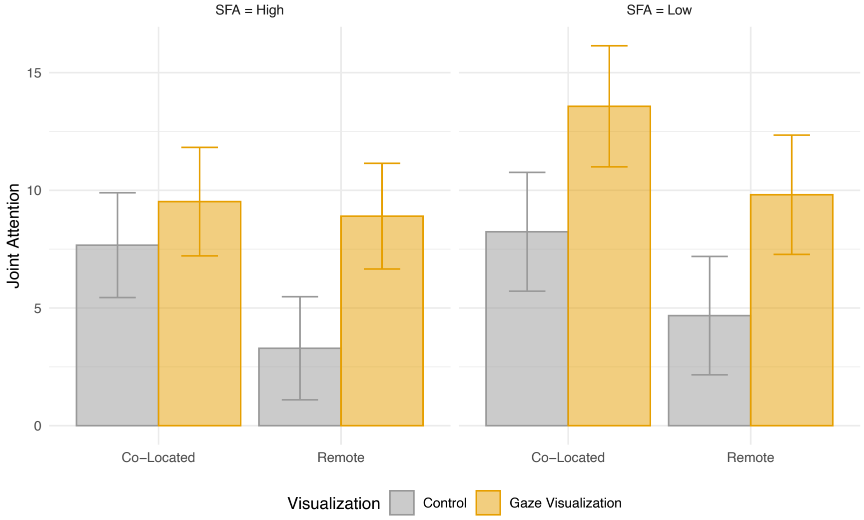
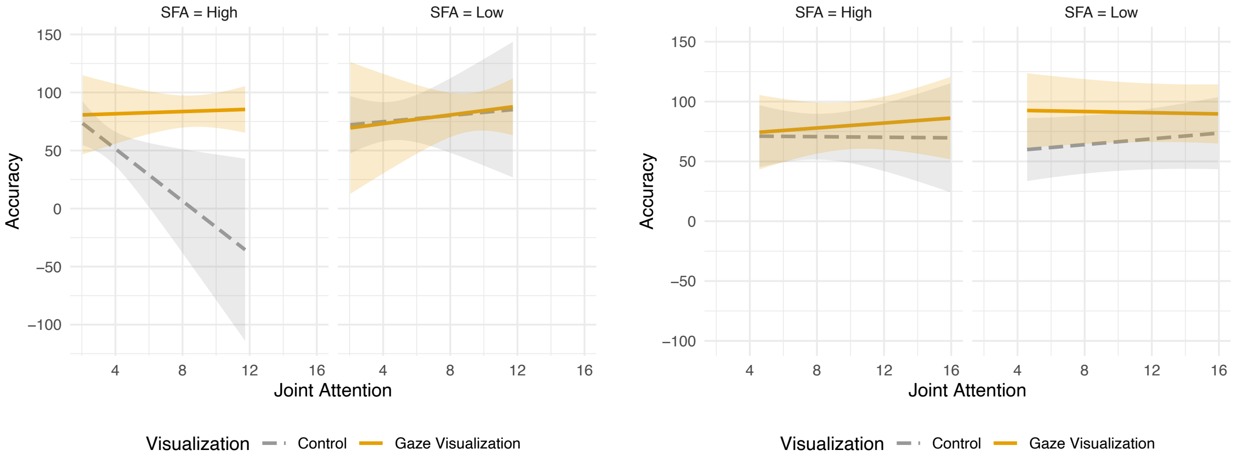


Figure 6: Joint Attention percentage in each SETTING (remote vs. co-located) and VISUALIZATION (visualization vs. control) for the two level of SELF-FOCUSED ATTENTION. The error bars represent Standard Errors.

The analysis indicated a significant main effect of VISUALIZATION, $F(1, 73) = 83.27$, $p < 0.001$. Contrast analysis supported our second hypothesis, collaborating pairs had higher degree of joint attention with gaze visualization ($M = 10.45\%$, $SE = 0.76$) than without gaze visualization ($M = 5.97\%$, $SD = 0.77$), $t(73) = -9.12$, $p < 0.001$. The main effect of SETTING was also significant ($F(1, 79) = 27.18$, $p < 0.001$). The degree of joint attention was higher in co-located setting ($M = 9.75\%$, $SE = 0.80$) than in remote setting ($M = 6.67\%$, $SE = 0.77$), $t(79) = 5.12$, $p < 0.001$.

The interaction between VISUALIZATION, SETTING and SELF-FOCUSED ATTENTION was also significant, $F(1, 73) = 4.05$, $p = 0.04$, see Figure 6. To understand the interaction, contrast comparisons were performed. Low self-focused participants had higher degree of joint attention in co-located setting with gaze visualization ($M = 13.57\%$, $SE = 1.30$) than without gaze visualization ($M = 8.24\%$, $SE = 1.27$), $t(73) = 5.61$, $p < 0.001$. Similarly in remote setting, when gaze visualization was present the low SFA participants had higher degree of joint attention ($M = 9.81\%$, $SE = 1.27$) than without gaze visualization ($M = 4.68\%$, $SE = 1.26$), $t(73) = 5.42$, $p < 0.001$.

High self-focused participants however, in co-located collaboration achieved similar degree of joint attention without gaze visualization ($M = 7.67\%$, $SE = 1.12$) and with gaze visualization ($M = 9.52\%$, $SE = 1.16$), $t(73) = 1.78$, $p = 0.08$. On the other hand, in the remote setting, the high SFA pairs had significantly ($t(73) = 5.23$, $p < 0.001$) higher degree of joint attention with gaze visualization ($M = 8.90\%$, $SE = 1.13$) than without gaze visualization ($M = 3.29\%$, $SE = 1.10$). The other main or interaction effects were not significant.



(a) Co-located Setting

(b) Remote Setting

Figure 7: The relation between Accuracy and Joint Attention in each co-located and remote collaboration setting in control and visualization conditions for low and high SELF-FOCUSED ATTENTION (SFA) groups.

4.3. Relationship Between Joint Attention and Accuracy

To examine the relationship between task accuracy and joint attention and how it depends on SFA and gaze visualization, we run LMMs separately for the remote and co-located setting. JOINT ATTENTION, SELF-FOCUSED ATTENTION and VISUALIZATION were treated in these models as fixed factors and COMPLETION TIME as a covariate.

In the analysis for remote collaboration setting, the three-way interaction was significant, suggesting that the relationship between accuracy and joint attention was moderated by self-focused attention and visualization, $\beta = -12.60$, $SE = 5.86$, $t(20) = 2.15$, $p = 0.04$. The model trends showed that for high self-focused participants, the slope of the relation between the joint attention and accuracy was significantly negative in the control condition ($\beta = -11.25$, $SE = 4.81$, $t(8) = -2.34$, $p = 0.04$). Whereas in the condition with gaze visualization, the relationship tend to be positive ($\beta = 0.48$, $SE = 2.46$), yet it did not reach statistical significant level ($t(8) = 0.20$, $p = 0.85$). Contrast analysis showed that the difference of joint attention trends between control and visualization condition was statistically significant ($\beta = -11.74$, $SE = 3.63$, $t(25) = -3.23$, $p < 0.01$).

Analogous trends for low self-focused individuals were not significant ($p = 0.91$), see Figure 7. The analysis for the co-located collaboration setting did not revealed significant effects involving the relationship between joint attention and accuracy ($p > 0.25$). Therefore, we found a partial support for our third hypothesis. In line with the hypothesis, self-focused attention moderated the relation between accuracy and joint attention, but only in the remote condition.

4.4. Subjective Assessments: Task Workload and Collaboration Quality

In a series of within-subjects three-way ANOVAs, we compared whether VISUALIZATION and SETTING caused differences in perception of task workload or collaboration quality among participants with high and low SFA level. In the case of task workload, we observed no significant main effects of VISUALIZATION and SETTING ($F(1, 22) = 0.08$, $p = 0.77$, $n^2 < 0.01$; $F(1, 22) = 1.04$, $p = 0.31$, $n^2 < 0.01$; respectively) and no significant interaction ($F(1, 22) = 1.89$, $p = 0.18$, $n^2 < 0.01$). No significant differences between condition with and without gaze visualization may suggest that gaze visualization did not produce additional cognitive load to our participants. Results for collaboration quality were similar, there was no significant main effect of VISUALIZATION ($F(1, 22) = 0.04$, $p = 0.85$, $n^2 < 0.01$) and SETTING ($F(1, 22) = 1.70$, $p = 0.21$, $n^2 < 0.01$) or significant interaction ($F(1, 22) = 0.23$, $p = 0.64$, $n^2 < 0.01$).

5. Discussion

Our study examined the efficiency of gaze visualization in promoting collaboration during co-located and remote collaboration depending on individual differences in self-focused attention. We used gaze visualization during remote and co-located Computer-Supported Collaboration and verified its effectiveness in enhancing joint attention and performance. In general, the results provided support for our main hypotheses; however, the effect of gaze visualization was dependent on collaboration setting and group. In general, adding a partner's gaze visualization resulted in higher accuracy of solved Bongard Problems and higher joint attention when compared to conditions without gaze visualization. Gaze visualizations were especially beneficial for participants identified as having high self-focused attention who collaborated in the remote setting.

Our findings support previous research about gaze visualization effectiveness in co-located search tasks Zhang et al. (2017), as well as remote collaborative learning Yao et al. (2018); Spakov et al. (2019), collaborative writing Kütt et al. (2019), group gaming Maurer et al. (2017) and pair programming D'Angelo and Gergle (2018). Nevertheless, none of these studies compared, in within-subjects study design, the co-located to remote collaboration setting, with and without gaze visualization. The mixed design enable us to observe that despite the importance of direct contact during co-located collaboration, the accuracy of solved problems in this setting appeared to be also enhanced by gaze visualization. However, the effectiveness of gaze visualization in each setting was differentiated by self-focused attention level. Low self-focused individuals benefit from gaze visualization more in co-located setting, whereas high self-focused in remote setting. The difference between groups in co-located setting might be related to higher ability to absorb social cues, both off-screen and on-screen among low self-focused than among high self-focused individuals. Contrary, in the remote setting, without F2F social cues, the performance of high self-focused individuals decreased and gaze visualization improved their performance more than among low self-focused group.

5.1. Self-focused Attention and Joint Attention

While the Computer-Supported Collaboration literature is replete with research and knowledge, it is remarkable that there has been almost no consideration of key findings from a field of individual differences. Taylor (2004) admittedly showed that cognitive style and sex affect computer-mediated knowledge management systems usage in sharing knowledge;

however, his study did not consider real-time collaboration. Our study investigated the role of individual differences in attentional focus as a factor potentially explaining the variance in co-located and remote real-time Computer-Supported Collaboration during problem-solving and modifying the relation between joint attention and task performance.

According to the literature, joint attention is positively associated with performance in Computer-Supported Collaboration Serim et al. (2018). Our study demonstrated that high self-focused attention may moderate this relationship. In remote collaboration for high self-focused individuals, higher joint attention was related to lowered accuracy. Supporting previous findings, self-focused attention may decrease the partner's oriented perspective Smith and Greenberg (1981). Our results extend these findings by showing that during remote collaboration, gazing at the same targets at the same time is not enough to enhance collaboration among high self-focused participants. However, gaze visualization enhanced the awareness of the other person's focus of attention resulting in higher accuracy and joint attention among high self-focused individuals in the remote setting. Therefore, the awareness of where the partner is looking increased by gaze visualization seems to be a key to enhancing collaboration quality in high self-focused individuals.

Self-focused attention is an important factor in models of social phobia, and social anxiety Wells et al. (1995). High self-focused attention interferes with performance and prevents from observing external information Spurr and Stopa (2002). Low self-focused attention individuals in the co-located setting benefit more from gaze visualization than high self-focused attention since collaboration partner is not a source of anxiety. As far as we know, this is the first experiment that showed that individuals differing in attentional focus perform differently in co-located and remote collaboration settings, with and without gaze visualization.

6. Conclusion

The present study provide insights into enhanced gaze communication by requiring participants to follow the partner's attentional cues during collaboration. Here, the partner's gaze visualization facilitated joint attention and switching from self-focused attention to focusing on another person's point of view. Therefore, gaze visualization intends to enhance the partner's perspective in collaborative task solving leading to a better performance.

The contribution of the present study is twofold. First, we examined the efficiency of gaze visualization in enhancing joint attention during remote and co-located collaboration. Second, to our best knowledge, this is the first study in which individual differences in attentional focus and their impact on collaboration were examined during remote collaboration.

We indicate that individuals with specific attentional tendencies during computer-mediated collaborative work can benefit from gaze visualization. We postulate that gaze communication may be enhanced in remote collaboration or enriched in existing online platforms dedicated to group work. The solution based on the perception of eye direction may play an important role in remote collaboration and eye-tracking research development in the next few years, considering individuals' specific needs.

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I declare that I contributed to the following tasks:

- conception of study design & planning
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- article preparation

Katarzyna Wisiecka was the lead author of the paper and was primarily responsible for its creation. Katarzyna Wisiecka contributed to the following tasks:
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Dynamics of visual attention during online lectures - evidence from webcam eye tracking

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Abstract: During the pandemic, online learning had replaced the role of traditional in-class learning. While there are declarative studies examining advantages and disadvantages of online classes, there is a lack of evidence of the effect of online learning on objective, physiological indicators. Little is known about attentional mechanisms related to acquisition of information during online classes. The aim of this study was to examine the effectiveness of information assimilation during online lectures by recording visual attention distribution in natural, ecological learning settings. During online lectures, we monitored students' eye movements via a computer webcam. After the lectures, students (n = 24) completed a knowledge test and reported their level of concentration and cognitive load during the lecture. The results showed that students who recalled more information from the lectures looked longer at the presentation and the lecturer, than on their image and other students, compared to students who remembered less from the lecture. Fixation duration, which is an indicator of visual processing depth, was longer for those who memorized more from the lecture. Further, the knowledge test score was positively correlated with students' focal attention and its dynamics. Finally, the level of concentration and cognitive load during the lecture was positively related to the assimilation of class content. The results can be used in designing interfaces to help students focus on relevant information, or real-time recommender systems informing teachers about the level of student concentration.

Introduction

The spread of COVID-19 incurred the closure of educational institutions around the world. It has verified the readiness of universities to deal with a crisis that requires use of advanced technologies, including hardware and software, to enable effective distant learning. This situation has accelerated the development of online systems so that the learning process is not disrupted (Kumar 2019). While declarative studies conducted among students and lecturers indicate a positive attitude and evaluation of remote learning (Mukhtar, Javed, Arooj, & Sethi 2020) there is a lack of evidence of the effect of online learning on objective indicators of visual attention in terms of spatial distribution and depth of information processing. In addition, it is not known how social cues such as the faces of other students at a presentation affect information processing. Referring to Vygotsky's (1978) concept of shared social cognition, Wilson (2001) described participants in online communities as "having a shared sense of belonging, trust, expectation of learning, commitment to participate and to contribute to the community". Although many online learning researchers emphasize the ability to create virtual learning communities (Harasim, Hiltz, Teles, & Turoff 1995), others point to issues such as lack of attention and active participation (Mason & Hart 1997), the lack of place, synchrony, and anonymity that depress certain components of a community (Hine 2000).

Research highlights the role of eye contact between teacher and students during natural classroom settings (Haataja, Salonen, Laine et al. 2021) as well as the cognitive overload caused by looking at a computer screen during the learning process (Mierlo, Jarodzka, Kirschner, Kirschner 2012). There is still a need to explore the visual attention dynamics during synchronous online classes. There is a lack of information about the mechanism of visual attention in an online environment, comparing it to naturally found processes between teacher and students in the classroom. Second, the influence of distractors on the screen such as their own and other students' faces displayed next to the presentation need to be further examined. Third, we need to investigate how the distractors and instructors modify dynamics of visual attention, changing attention from ambient to focal.

The aim of this study is to verify the effectiveness of information assimilation in an online environment, where eye contact is reduced, and students are exposed to greater external distraction than in the classroom (Hollis & Was 2016). For this purpose, we recorded the distribution of visual attention of students during an online lecture and related it to the retention level of the material presented in an online class. Further, we correlated their knowledge with dynamic characteristics of their visual attention, namely the level of ambient/focal attention.

Related Works

Registering visual attention provides information about attentional processes in education, both in traditional and online learning. Eye tracking allows to delve deeper into the cognitive processing that occurs during the integration of textual and pictorial content, assuming that individuals respond to and analyze visual information while fixated (Just & Carpenter, 1980; Hyönä 2010). Fixations are eye movements that help us maintain our focus on a particular object. Saccades are quick eye movements that relocate the fovea to fixate on a new object, while fixations can be interpreted as relative stops between two consecutive saccades (Duchowski 2017). Different eye movement patterns result from reading and scene perception. Fixations last on average about 200-300 milliseconds while reading; however, when examining a scene, fixations can last anywhere from under 100 to over 500 milliseconds, with an average of 300 milliseconds (Rayner 1998). Fixation counts and fixation duration are used as measures of information processing and cognitive effort. Longer fixation durations on stimuli, for example, indicate increased processing difficulty. Scene aspects that are more significant to the task attract more attention (greater number of and longer fixations) than scene elements that are less important (Christiansen, Loftus, Hoffman & Loftus 1991).

Eye tracking is a useful tool for studying learning processes (Holmqvist et al. 2011). The reason for this is that we absorb most of the information through our eyes, both when we learn and when we perform professional work. Jarodzka et al. (2017) introduced three research areas of educational science that have successfully used eye tracking. To begin with, eye tracking has been utilized to improve the instructional design of computer-based learning and testing settings, which frequently employ hyper- or multimedia. Second, in visual domains such as chess or health applications (e.g., scanning chest or dental X-rays), eye tracking has offered information on competence and its development (Castner 2019, 2020). Third, using eye movement modeling examples, eye tracking has lately been employed to enhance visual expertise during the learning process.

In six empirical studies Jarodzka et al. (2021) presented examples of how to capture visual perception in the complexity of a classroom lesson. These examples provide new opportunities for research outside laboratory scenarios: some use video recordings from real classes, while others analyze actual classrooms. This shift toward more realistic scenarios allows us to investigate visual perception in classrooms from new perspectives, including those of teachers, students, and their relationships. As a result, well-established theoretical notions like students' participation during actual lessons, teachers' professional vision while teaching, and the development of joint attention between teachers and students in a lesson can be illuminated in new ways.

Traditional Learning and Visual Attention

Yang et al. (2013) studied in a real classroom, the visual attention of university students, experts, and novices to the topic of earth science, during a lecture accompanied with a power point presentation. In general, earth-science students paid more attention to the text areas than non-earth-science students, but there were minimal differences in the image areas. Examination of fixation densities and saccade routes revealed that earth-science students were better at interpreting and integrating information than non-earth-science students.

Reciprocal eye contact is an important element of human interaction, but its significance in classroom engagement has been largely ignored, owing to methodological concerns. Multi-person mobile eye-tracking, a unique tool in educational science, allows to collect data on the fleeting processes of nonverbal connection. Using this research technique during three mathematics sessions, Haataja, Salonen, Laine et al. (2021) studied the role of teacher-student eye contact in interpersonal classroom interaction. The frequency and duration of teachers and students' gazes at each other were found to be affected by teacher communication and agency. During high teacher communion and low agency, students tend to look at their teachers more, but there were also qualitative and quantitative differences between the teachers and their classes suggesting that eye contact development is situational and influenced by both momentary interpersonal changes and the quality of teacher-student interactions.

Online Learning and Visual Attention

The amount of online instructional content, particularly in the form of video lectures, is rapidly developing. Kizilcec et al. (2014) investigated how adding the instructor's face to video training affects information retention, visual attention, and affect using eye tracking and memory tests. Face-to-face instruction was significantly favored by participants, who admitted it was more instructive. They spent roughly 41% of their time looking at the face, and every 3.7 seconds shifted between the face and the slide. There was no significant change in short- and medium-term recall ability. The use of the face in video training was related to positive affective reaction of students.

The impact of teacher presence on learning, visual attention, and perceived learning in mathematics instructional videos of different subject difficulty was investigated also by Wang et al. (2017). Thirty-six participants watched two 10-minute arithmetic films (simple and difficult topics) with or without instructors present. The findings suggest that instructors attracted most of visual attention, especially when learners were watching a video on a simple topic. The presence of an instructor had a beneficial impact on participants' perceptions of learning and satisfaction for both topics, as well as a reduction in self-reported mental effort for difficult topics. In the second study, Wang et al. (2020) indicated that for difficult topics, instructor's presence improved transfer performance, reduced cognitive load, increased positive judgment of learning, and enhanced satisfaction and situational interest. The instructor attracted a considerable amount of overt visual attention in both videos. The visual attention allocated to the instructor positively predicted participants' satisfaction level for both topics.

Kruger et al. (2014) evaluated the visual attention distribution between subtitles and other sources of information during watching the lecture and linked it to academic comprehension and cognitive load using eye tracking, self-report questionnaires and EEG. Regarding attention distribution, subtitle language, and comprehension, it was observed that the language of the subtitles or their presence/absence had no significant impact on students' performance.

Dynamics of Visual Processing

The analyses of eye movements may be based on fixation allocation (e.g., Grindinger et al. 2010) or on the process (sequence) (e.g., de Bruin et al. 2013). In the process of acquiring information, it is crucial to register not only distribution of attention, but to capture the time-ordered path (sequence) of visual attention. For example, Krejtz et al. (2014) used the metric of entropy to observe the students' strategy of the learning material visual inspection. When individuals were given control over the visual simulation and the learning process, they maintained visually switching between different parts of the content in an organized manner.

The process of visual processing is a dynamic interplay between fixations and saccades. Their characteristics reflect two modes of attentional processing: ambient and focal, with the latter generally more serial rather than parallel in visual search. During visual acquisition of information, attention switches from parallel (ambient attention) to serial processing (focal attention) (Velichkovsky et al. 2005). The more focal attention the deeper information processing and control of attention occur (Pannasch et al., 2011). In the present study, we used the measure of ambient/focal attention to verify the relationship between dynamics of visual processing and acquiring information during online classes.

To calculate the dynamic of visual processing, we used the *K* coefficient (Krejtz et al. 2016). Velichkovsky et al. (2005) originally suggested characterization of fixations as ambient or focal based on their durations and the amplitude of successive saccades. Krejtz et al. (2012) used an ambient/focal attention coefficient, defined as the relation between the current fixation duration and the subsequent saccade amplitude. The ambient/focal attention coefficient permits statistical comparison between individuals and between groups. Values of *K* that are close to zero indicate relative similarity between fixation durations and saccade amplitudes (in terms of their distance from their respective means). Positive values of *K* show that relatively long fixations were followed by short saccade amplitudes, indicating focal processing. Analogously, negative values of *K* refer to the situation when relatively short fixations were followed by relatively long saccades, suggesting ambient processing. For details pertaining to its computation, see (Krejtz et al. 2012; Krejtz et al. 2016; Krejtz et al. 2017).

Present Study

Despite the current advancement of online learning and growing number of technological solutions, the mechanism of visual attention during real-time synchronous online learning is almost unknown. The empirical background in this area is very scarce in terms of importance of the areas on the learner's screen. It is still not clear how the presence of the teacher's, friends', or their own faces next to the presentation influences the students' attention during online lectures - does it help to build a sense of shared cognition or distract the learner's attention? The registration of visual attention may provide a unique source of information about the focus of a student's visual attention during the class revealing what students perceive as important, which parts of the online platform help them to maintain concentration allowing to identify which attention indices are related to successful learning.

In the present study, our aim was to capture the mechanism behind absorbing information taking into consideration social context during online classes. First, we compared the distribution of visual attention between presentation, teacher, and other students and one's own face (self) registered by a webcam. Second, we compared visual attention distribution in the groups with low and high scores from the post-lecture knowledge test. Third, we verified the relationship between lecture-related knowledge and dynamics of visual processing (ambient/focal attention) during the lecture. Our hypotheses were as follows: (1) self-reported level of cognitive load, concentration and interaction difficulty would be related to the test score; (2) slides presentation and teacher would draw more visual attention among high score students compared to low score students; (2) the presence of students' and own face would disrupt attention; (4) the level of focal attention would predict higher lecture-related knowledge.

Method

Participants

24 students (*M* age = 21, *SD* = 4.6, 15 females) of the 2nd year of Psychology participated in the study. Before logging in to the online lecture, each volunteer read the informed consent informing about confidentiality of data and the possibility to withdraw from the study any time, without any reason or consequences. Each participant received an individual code which was stored in the database but not linked to personal data. Based on a post-lecture knowledge test, we divided participants into low score (11 students with less than 50% good responses) and high score (13 students with more than 50% good responses) groups.

Procedure

The experiment was conducted during three 15-min online lectures about eye tracking methods during which students' visual attention was tracked by a webcam connected to RealEye eye tracking software (Wisiecka et al. 2022). Students received an invitation to take part in the study before the start of the lecture. Those willing to participate received a link to the webcam platform. After logging on to the platform, students read the terms and conditions of the experiment and the RealEye privacy policy, which informs that the platform does not record the image of the tested person (only eye movements), nor does it collect personal data. After giving their consent, participants were informed that they could behave naturally sitting in front of the computer screen, as in any other online lecture, bearing in mind that their visual attention will be registered by the computer camera. Participants then went through a calibration procedure and joined the lecture.

When students, participating in the study, logged into the lecture via the RealEye platform, had returned to class, the teacher continued with the lecture for 15 min. on average. The student's task was to listen to the lecture and ask questions if needed. After class, students were directed to the Qualtrics platform to answer six questions about the content of the class and to self-report about difficulties experienced during the lecture in three areas: level of concentration, cognitive load, and interaction quality. The system automatically sent the participant ID, not linked to personal information, to the Qualtrics platform. At no stage could the lecturer or experimenter link the answers to any specific student. The experimental procedure was approved by Ethical Committee No. 85/2021 of the first author's institution prior to the data collection.

Software

The class was conducted using the Google Meet Platform. To record real-time eye movements of students during the online class we used RealEye software. RealEye is an online system that uses a regular webcam and web browser to record gaze position. The eye tracker uses the client machine to perform face landmarks and gaze detection. The web browser runs an eye tracking engine written in JavaScript. The software is based on WebGazer (Papoutsaki et al. 2016), improved and customized using TensorFlow.js with a face landmark model (Apache License 2.0). Webcam access (via JavaScript Media Devices API) sets camera resolution to 640×480 at minimum 30 fps and up to 60 fps if the webcam supports it. RealEye uses an algorithm similar to the I-VT (Velocity-Threshold Identification) fixation filter, assuming data with a sampling rate over 20 Hz, with minimum fixation duration set to 100 ms by default. A median filter (set to 21 by default) is used for noise reduction. RealEye software provides an online platform for preparation and running of the study. It supports analyzing the data online by real-time gaze/fixation estimation on specific Areas Of Interest (AOIs). In this study we used default settings of fixation calculation.

Results

Before statistical analyses, four Areas-of-Interest (AOI) were defined: over the presentation displayed during the class, the teacher, each student's own face (self) and the rest of the students. The positions of the AOIs were slightly different in terms of layout for each participant but of the same size. Statistical analyses were performed using the R language for statistical computation (version 4.1.1) using the afex, dplyr, sjPlot, tidyverse and emmeans packages (R Core Team 2017).

Self-reported Measures of Concentration, Cognitive Load, and Interaction Difficulty

First, we examined the relationship between lecture-related knowledge and self-reported measures of concentration, cognitive load, and interaction difficulty (hypothesis 1). Multiple linear regression with test score as dependent variable and self-reported measures as predictors was statistically significant ($R^2 = .24$, $F(3,89) = 9.36$, $p < .001$). As predicted, concentration is positively related to test score ($\beta = .12$, $p = .01$, see Figure 1-left), whereas cognitive load is negative ($\beta = -.30$, $p < .01$, see Figure 1-right). Self-reported interaction difficulty during the class did not significantly predict the accuracy ($\beta = .09$, $p = .1$) (see Figure 1).

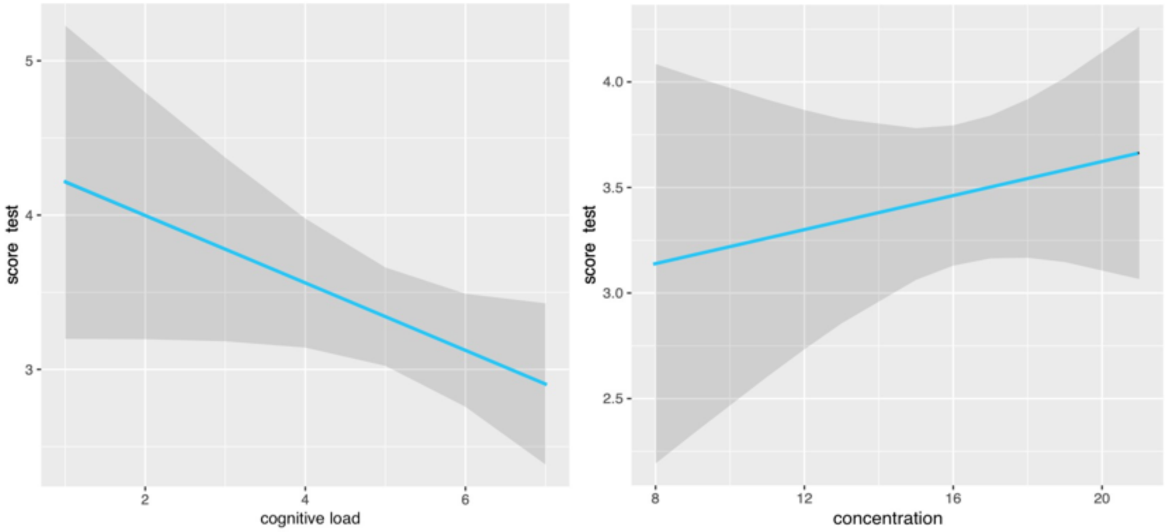
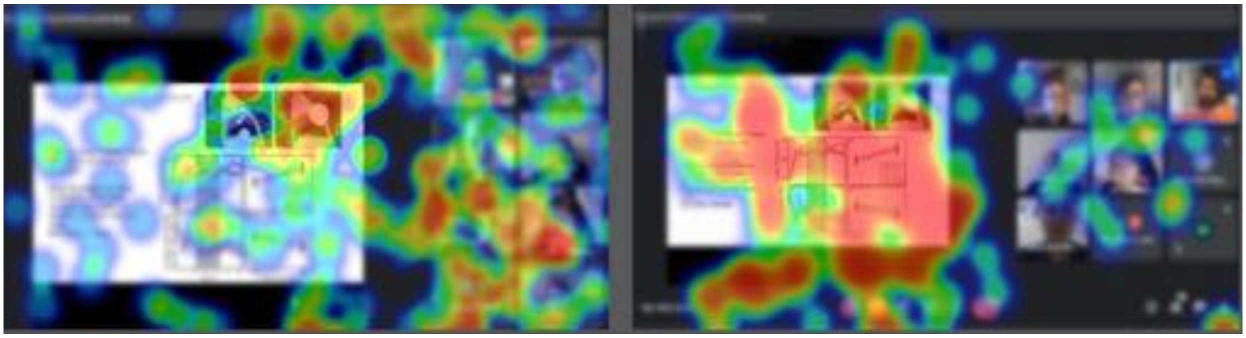


Figure 1: The linear relationship between lecture-related knowledge and cognitive load (left); and concentration (right).

Visual Attention Distribution

Next, we examined if visual attention distribution was different in the group that remembered more (high score) during the class than in the group that remembered less (low score) (hypotheses 2&3). We carried out a series of 2x4 mixed ANOVAs with a group (low score *vs.* high score) as a between-subjects factor and AOI type (presentation *vs.* teacher *vs.* students *vs.* self) as within-subjects factor. When appropriate, post-hoc tests of differences were performed using Tukey correction.

We measured visual attention using total fixation time (how long, in total, a person fixated on each AOI) and fixation duration (how long an average fixation duration lasted on each AOI) separately for presentation, teacher, students and self-image. Means for these analyses are presented in Table 1. The visualization of eye tracking data is shown at Figure 2.



a) Low score student b) High score student

Figure 2: Heatmap of (a) a low score and (b) high score students' visual attention.

Total Fixation Time

The analyses of total fixation time produced a significant two-way interaction effect between group and AOI type, $F(1,25) = 5.86$, $p = .02$, $\eta^2 = .17$. *Post hoc* comparisons suggest that the high score group, compared to the low score group, spent significantly more time looking at the teacher ($t(21) = 4.87$, $p = .02$) and significantly less time at oneself ($t(21) = 5.35$, $p < .001$), and other students ($t(21) = 3.84$, $p < .001$). The difference in terms of time of looking at the presentation was not significant ($t(21) = 1.57$, $p = .13$).

The main effect of AOI type was significant, $F(2,25) = 43.16$, $p < .001$, $\eta^2 = .592$. In general, participants looked longer at the presentation than the teacher ($t(21) = 7.27$, $p < .001$), oneself ($t(21) = 6.65$, $p < .001$), and other students ($t(21) = 6.39$, $p < .001$). The main effect of group was not significant, $F(1,21) = .01$, $p = .91$, $\eta^2 = < .001$ (see Figure 3).

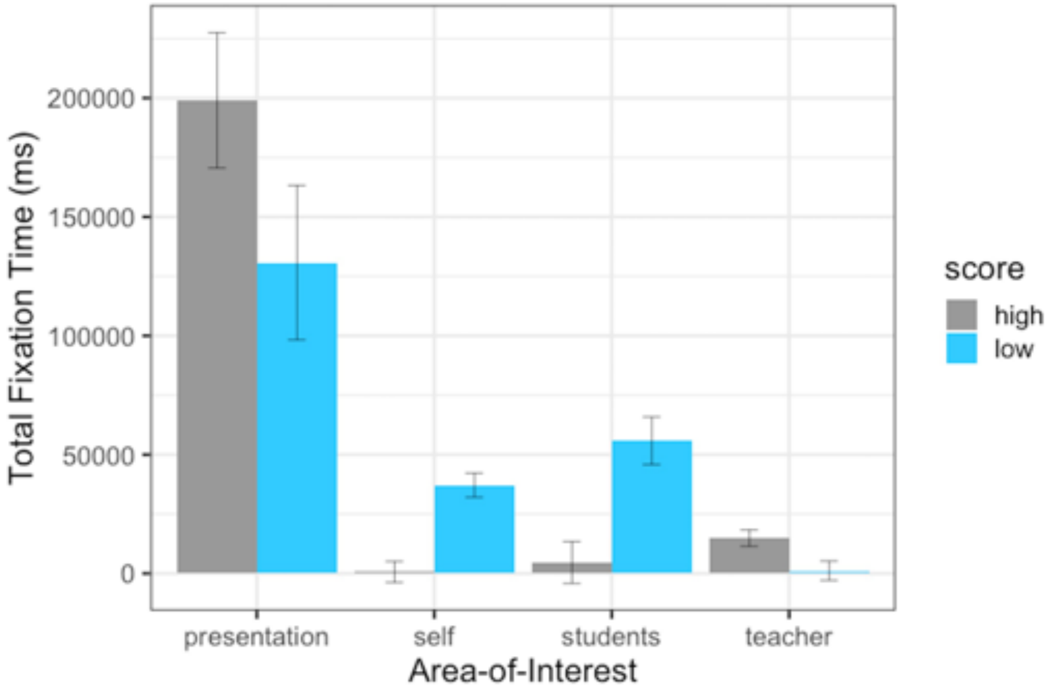


Figure 3: Total fixation time Dwell time of looking at each AOI (presentation vs. self vs. students vs. teacher) in high score and low score group.

Average Fixation Duration

To further understand these results, we repeated the two-way ANOVA with average fixation duration as a dependent variable which is an indicator of deeper visual processing. The analyses of fixation duration showed a significant two-way interaction effect between group and AOI type, $F(1,30)= 4.09$, $p = .03$, $\eta^2 = .09$. *Post hoc* comparisons suggest that high score group, compared to the low score group, had on average longer fixation duration looking at the presentation ($t(21) = 2.65$, $p = .01$), but this effect was not significant in terms of looking at the teacher, ($t_{(21)} = 1.99$, $p = .06$), self ($t(21) = .33$, $p = .74$), and other students ($t(21) = .48$, $p = .63$).

The main effect of AOI type was not significant, $F(2,30) = 2.27$, $p < .13$, $\eta^2 = .05$, as well as the main effect of group, $F(1,21) = 1.50$, $p = .23$, $\eta_p^2 = .03$ (see Figure 4). Results suggest that average fixation duration was different between groups only when looking at the area related to the assimilation of the class content.

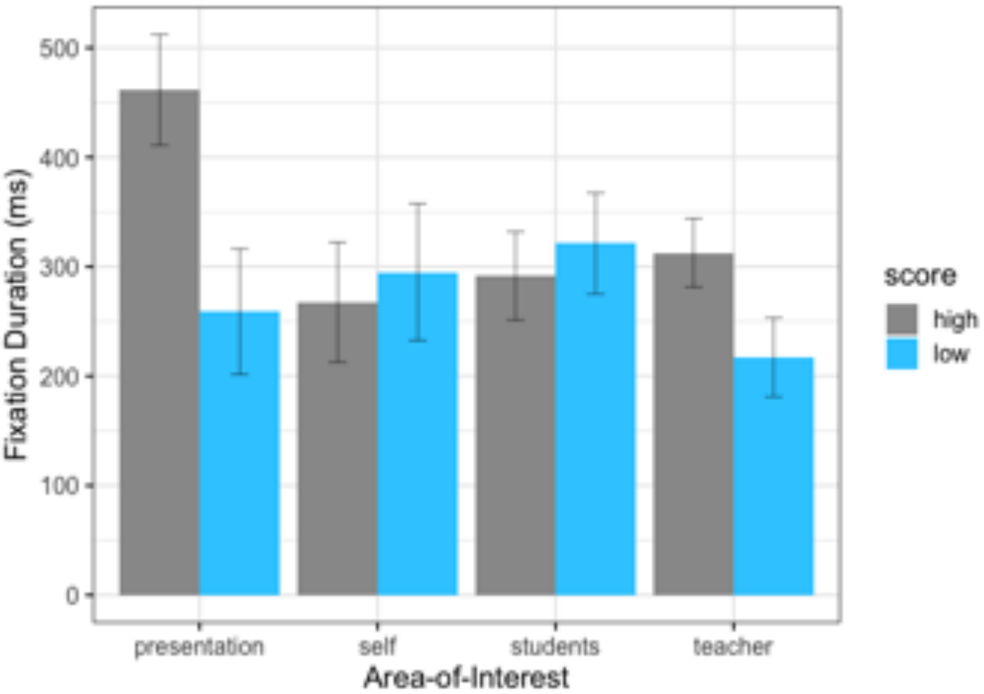


Figure 4: Average fixation duration at each AOI (presentation vs. self vs. students vs. teacher) in high score and low score group.

Table 1: Descriptive statistics for total fixation time and average fixation duration depending on AOI type and group – Mean (SE)

	Total fixation time (ms)		*Fixation Duration (ms)*	
AOI	*Low Score*	*High Score*	*Low Score*	*High Score*
Presentation	130768 (32555)	199062 (28553)	259 (57.6)	462 (50.5)
Teacher	1189 (4022)	14902 (3527)	218 (36.0)	313 (31.6)
Self	37206 (5136)	627 (4504)	295 (62.5)	268 (54.8)
Other students	55791 (9993)	4669 (8764)	321 (46.2)	292 (40.5)

Dynamics of Visual Attention

After calculating *K* coefficient for each student, simple linear regression was used to test if the level of ambient/focal attention significantly predicted test score with AOI as the moderator (hypothesis 4). The overall regression was statistically significant ($R^2 = .006$, $F(7{,}740) = 49.25$, $p < .001$). It was found that ambient/focal attention significantly predicted the test score ($\beta = .08$, $p < .001$). AOI was not a significant moderator ($\beta = .04$, $p = .33$). The interaction between K coefficient and AOI was also not significant ($\beta = .01$, $p = .73$).

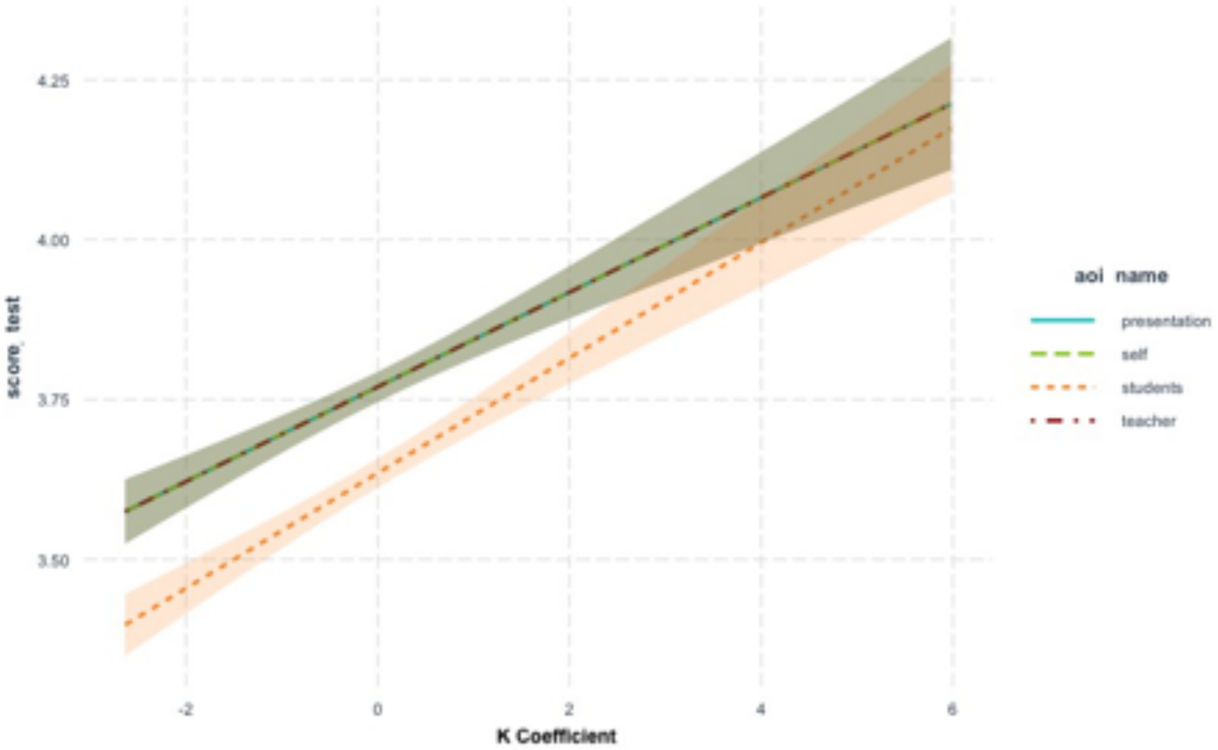


Figure 5: The linear relationship between ambient/focal attention and score test on each AOI.

Discussion

The aim of this study was to verify the effectiveness of information assimilation during online lectures by registration of visual attention distribution in natural, ecological conditions. During online lectures, we collected eye tracking measures of students' visual attention via a computer webcam. After the lectures, students completed a knowledge test concerning the content of the lecture and self-reports about their level of concentration, overload, and interaction difficulty.

The results showed that students who remembered more during the lectures looked longer at the teacher than those who remembered less. The image of the teacher appears to be important to students with higher test scores which corroborates Wang's (2017, 2020) results. It is worth mentioning however that we verified this effect in a real-time virtual environment and we did not compare it with the condition without the teacher's face. In the future studies it is worthwhile to compare the study scenario with the condition without the teacher face to verify the effect of missing the teacher's face.

Participants who remembered more from the class paid less attention to other students, than students who remembered less from the lecture. Results suggest that the images of other students while listening to the teacher provide more interference than benefit. One may conclude that the presence of friends' faces and the possibility of observing their reactions could enhance the virtual learning community (Vygotsky's 1978; Harasim, Hiltz, Teles, & Turoff 1995; Wilson 2001), however our results do not support this assumption. It is worth investigating different scenarios of the lecture. In our study the student's task was to listen to the lecture and ask questions if needed. Taking into consideration the importance of participation in online learning (Davies and Graff, 2005; Vonderwell and Zachariah, 2005; Hrastinski, 2008) more collaborative tasks could potentially change attention distribution and have a different impact on information acquisition.

What is perhaps more interesting, is that the self-image caught more visual attention of students with lower task scores than those with higher test scores. These results may be further investigated in terms of individual differences. We are not aware of previous findings in which one's self-image disrupts attention during learning; however, it is consistent with theoretical models of self-focused attention which decreases focus on task-related objects (Spurr & Stopa 2002; Ingram 1990; Liao & Masters 2002).

Fixation duration, which is an indicator of visual processing depth, was found to be longer for those who memorized more from the lecture. Our study is consistent with Yang et al. (2013) findings about longer fixation duration on presentation by students with better understanding of the class content. We further develop this path of analyses by adding metrics of ambient/focal attention in dynamics of visual information acquisition. The knowledge test score was positively correlated with students' focal attention. Eye tracking techniques have been previously suggested to be used to deeply explore the cognitive process during e-learning and be applied to future online assessment systems (Meng-Jung Tsai 2012). Yet, the present study is the first using online eye tracking to monitor visual attention distribution in real-time synchronous learning. Our findings can be used in developing real-time alerting systems for teachers. It may be valuable to observe the level of focal attention during the class to help alter the current level of students' concentration.

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I declare that I contributed to the following tasks:

- conception of study design
- article preparation

Katarzyna Wisiecka was the lead author of the paper and was primarily responsible for its creation. Katarzyna Wisiecka contributed to the following tasks:
conceptual framework and hypotheses, study design & planning,
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Comparison of Webcam and Remote Eye Tracking

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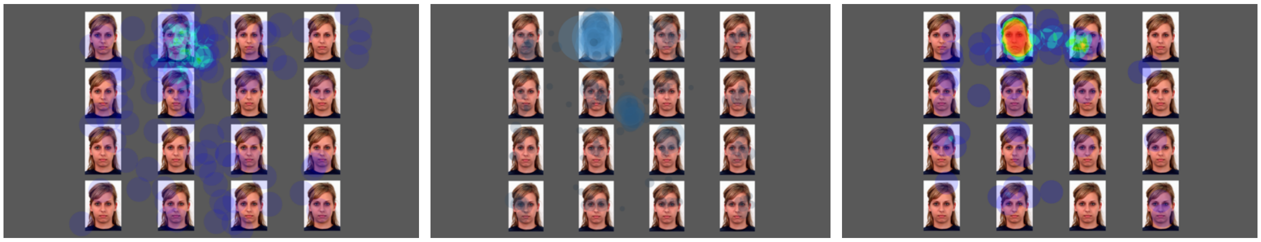

(a) RealEye. (b) Gazepoint GP3. (c) RealEye + GP3.

Figure 1: Heatmap visualization of gaze data collected by: (a) webcam, (b) remote eye tracker, and (c) integrated solution.

ABSTRACT

We compare the measurement error and validity of webcam-based eye tracking to that of a remote eye tracker as well as software integration of both. We ran a study with $n = 83$ participants, consisting of a point detection task and an emotional visual search task under three between-subjects experimental conditions (webcam-based, remote, and integrated). We analyzed location-based (e.g., fixations) and process-based eye tracking metrics (ambient-focal attention dynamics). Despite higher measurement error of webcam eye tracking, our results in all three experimental conditions were in line with theoretical expectations. For example, time to first fixation toward happy faces was significantly shorter than toward sad faces (the happiness-superiority effect). As expected, we also observed the switch from ambient to focal attention depending on complexity of the visual stimuli. We conclude that webcam-based eye tracking is a viable, low-cost alternative to remote eye tracking.

CCS CONCEPTS

• **Software and its engineering → Empirical software validation**; • **Human-centered computing → Laboratory experiments**.

KEYWORDS

webcam eye tracking, gaze detection, remote eye tracking

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1 INTRODUCTION

Webcam-based eye tracking is a promising method to record eye movements in natural, ecological settings. Relative low cost with high speed of data acquisition make this method increasingly popular within the eye tracking community. As with any novel method, web-based eye tracking raises concerns about its accuracy and validity, but research on this topic is sparse. The present paper addresses this gap by testing webcam-based eye tracking accuracy, precision and validity against a widely available remote eye tracker.

We present results from two experimental tasks supporting the claim that, despite lower accuracy and precision, webcam-based eye tracking is a highly reliable method, similar to remote eye tracking. Additionally, we contribute by validating a protocol that integrates both methods within a web-based interface. This new approach of eye tracking has potential for crossing the boundary between remote (in-lab) and webcam-based (online) empirical protocols.

2 RELATED WORK

Eye movement recording, using optical cameras without infrared light illumination, has for many years been subject to accuracy concerns which often discouraged its use. Among the greatest concerns was the possibility to discern, in real-time, the pupil from the rest of

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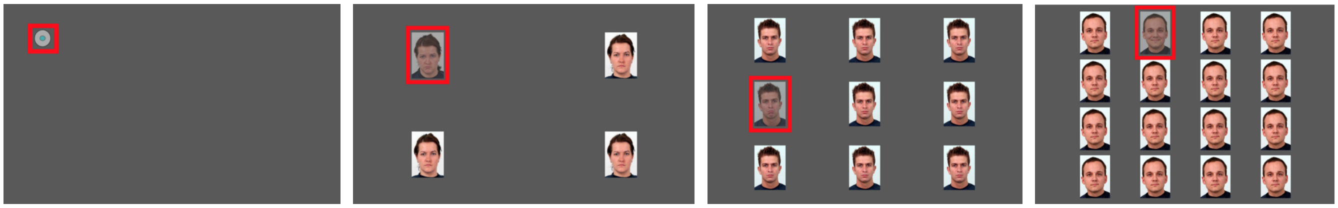


(a) Point target. (b) 2 × 2 matrix. (c) 3 × 3 matrix. (d) 4 × 4 matrix.

Figure 2: Areas Of Interest on displayed (a) point target, and face target with (b)–(d) various-sized matrices.

the iris [Sewell and Komogortsev 2010]. Currently, there is growing demand for real-time webcam-based solutions, which has led to the development of web-based eye tracking applications [Papoutsaki et al. 2017, 2016]. Deployed across the Internet, these applications rely on eye movement detection without additional infra-red light, in the visible spectrum (ambient light). Available solutions exploit such techniques as face landmark detection and machine learning to predict the users' eye positions based on relatively low resolution optical-camera input [Gudi et al. 2020; Meng and Zhao 2017].

Studies increasingly show that utilizing a webcam eye tracker can produce reliable results [Burton et al. 2014; Zheng and Usagawa 2018]. For example, Burton et al. [2014] compared results obtained using the SMI infra-red and Sticky webcam eye tracking technologies. The results of the study showed that use of the SMI infra-red eye trackers yielded an increase in accuracy over the use of the webcam along with Sticky software, particularly for small target images and images near the edges of the screen. However, webcam technology achieved nearly comparable accuracy in detecting fixations over larger images, suggesting that webcam eye tracking is a viable alternative for certain tasks.

Similarly, Zheng and Usagawa [2018] used a webcam as the main device for eye tracking and achieved accuracy of 94% on a screen divided into 9 sections, reduced to 78% when the screen was divided into 25 sections (during simulation). Their study used a webcam with a low resolution of 640×480 with corresponding algorithms to suit the low-quality image. The approach was considered to be a fast eye tracking method suitable for general human-computer interaction.

2.1 Cognitive and Behavioral Studies

Validation of webcam-based eye tracking holds potential for behavioral and cognitive science research. For example, Semmelmann and Weigelt [2018] used a JavaScript-based eye tracking software library and consumer-grade webcams to record eye movements of participants in-lab and online in three tasks: fixations (detecting a point), pursuit, and free-viewing face detection. They reported roughly 200 pixel spatial accuracy. The online data showed higher variance, lower sampling rate, and increased experimental time, but no significant difference with regard to spatial accuracy during face detection compared to the in-lab setting.

Yang and Krajbich [2021] evaluated webcam eye tracking using WebGazer software. They tested the procedure with a decision-making study adjusting the code to reduce calibration/validation and improving the temporal resolution (from 100-1000 ms to 20-30 ms). Findings showed comparable results to previous in-lab findings regarding the relationship between gaze and choice with little degradation in spatial and temporal resolution.

Bott et al. [2018] examined also the relationship between a 30-minute Visual Paired Comparison (VPC) recognition memory task and cognitive composite indices sensitive to a subtle decline related to Alzheimer disease. Eye tracking data for the 30-minute VPC task was collected simultaneously by a commercial-grade eye tracker (Tobii X2-60) and a laptop-embedded camera. In a sample of typical older adults, performance on a 30-minute VPC task correlated modestly and positively with computerized and paper-pencil based cognitive composites that serve as pre-clinical Alzheimer disease cognitive indices. The strength of these relationships did not differ between camera devices.

To investigate the usability of home-based eye tracking, Greenaway et al. [2021] investigated the set-up time, number of calibration failures, and other issues faced by older adults living with and without Alzheimer's disease. They found that home-based eye tracking is feasible with set-up support such as face-meshing that helps to position of the face.

2.2 The Use of Webcam Eye Tracking

There are several development paths suitable for webcam eye tracking, such as informing/controlling gaze-based systems, and assistive technology development. For example, Skovsgaard et al. [2011] showed that a webcam tracker (the ITU Gaze Tracker) can match the performance of two commercial gaze-tracking systems (Tobii T60 and Mirametrix S1) in an interaction task. They showed that the webcam-based eye tracker can yield performance comparable to more expensive systems. The accuracy of the webcam-based gaze tracker (0.88°) was significantly better than the accuracy of the Mirametrix system (1.34°), but not significantly different from the Tobii T60 (0.67°). These results are particularly valuable to the field of control systems, where an eye tracking system using an unmodified webcam can enable severely disabled people to interact with computers without specialized equipment. For example, Juhong et al. [2018] and Wanluk et al. [2016] used eye movements recorded by webcam and customized image processing to control appliances, a wheelchair, and communications with the caregiver.

Elsewhere, Khonglah and Khosla [2015] created a low cost webcam-based eye tracker that requires no calibration as assistive technology for young children with autism in a digital communication medium. With an accuracy of 0.4° and a frame rate of 20 fps, this system was shown to be beneficial during the initial stages of applied behavioral analysis in therapeutic interventions where physical objects are uesd to teach basic skills to the individual.

3 THE PRESENT STUDY

The present study examines the validity of online webcam eye tracking via comparison to a remote video eye tracker in two tasks: a point detection task and an emotional visual search task, the Face-In-the-Crowd task (FIC), where the latter broadens the scope of eye movement comparison, contrasting location-based (e.g., fixations) and process-based eye tracking metrics (e.g., dynamics of ambient/focal attention).

3.1 Face-In-the-Crowd Task

The FIC task is widely used in psychological research to evaluate attentional biases towards emotional stimuli e.g., happy faces suggesting "the happiness superiority effect" [Gilboa-Schechtman et al. 1999]. Happy faces are less ambiguous than other faces and therefore they can be detected faster than other facial expressions [Becker et al. 2011]. In our study, we focused on detecting happy faces among neutral faces and, for comparison, sad faces among neutral faces. We checked to see if participants noticed happy faces faster than sad faces among neutral distractors differing in number and whether results were similar between the different eye movement recording conditions.

3.2 Ambient-Focal Processing

The process of visual search is a dynamic interplay between fixations and saccades. Their characteristics reflect two modes of attentional processing: *ambient* and *focal* processing, with the latter generally more serial rather than parallel in visual search. Krejtz et al. [2016] validated the $\mathcal{K}$ coefficient to capture ambient and focal eye movement patterns when they are expected during visual search tasks. $\mathcal{K} > 0$ indicates relatively long fixations followed by short saccade amplitudes, suggesting focal processing. $\mathcal{K} < 0$ is derived from relatively short fixations followed by relatively long saccades, suggesting ambient processing. For details pertaining to its computation, see Krejtz et al. [2012, 2017].

In the FIC task, we assumed that large crowds would induce a serial search reflected in more focal attention than ambient attention. In small crowds, targets would pop out triggering relatively faster localization of the target evidenced by a long saccade (large amplitude) directed to the target yielding ambient attention.

4 METHOD

We designed the present study as a 3 (RECORDING CONDITION) × 3 (CROWD SIZE) × 2 (FACE TYPE) mixed design, in-lab experiment with three between-subjects experimental conditions of data recording: remote GP3 eye tracking, RealEye webcam eye tracking, and the integrated condition: RealEye software communicating with the GP3 eye tracker.

In the point detection task, the dependent variable was the distance between eye fixation and the displayed point. In the visual search task, the analysis was conducted with the CROWD SIZE (2×2 vs. 3×3 vs. 4×4 matrix) and FACE TYPE (happy vs. sad) as the key independent within-subjects variables. The dependent variables were the time to first fixation and ambient/focal attention dynamics.

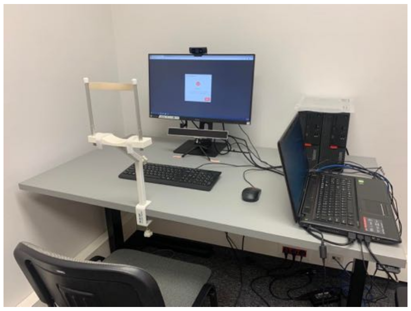


Figure 3: Experimental setting.

4.1 Hypotheses and Design

For the point detection task, we predicted that the webcam eye tracker would yield greater measurement error than the other two eye tracking conditions. We expected that the integration of web-based software with the remote eye tracker would yield similar accuracy to that of the remote condition. For the FIC task, we hypothesized that in all recording conditions we would observe similar effects: (1) time to first fixation would be shorter to a happy face than a sad one, and (2) degree of focal attention would be directly proportional to crowd density.

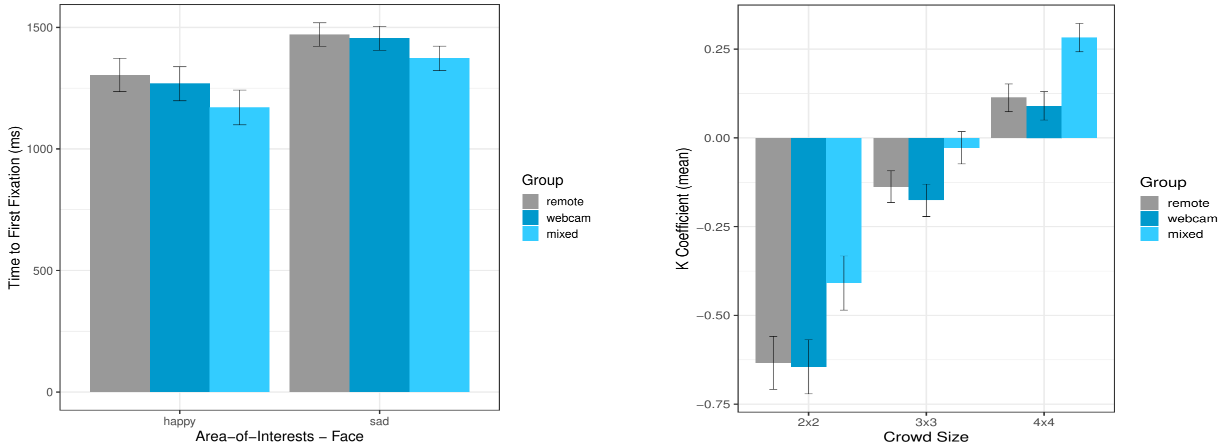
4.2 Hardware and Software

All measurements were made in a lab setting, on a 75 Hz (1900×1820 resolution) screen connected to a laptop.

4.2.1 Webcam Recording Condition. RealEye is an online software that uses a regular webcam and web browser to record gaze position. The eye tracker uses the client machine to perform face landmark and gaze detection. The web browser runs an eye tracking engine written in JavaScript. The software is based on WebGazer [Papoutsaki et al. 2016], improved and customized using TensorFlow.js with a face landmark model (Apache License 2.0). Webcam access (via JavaScript Media Devices API) sets resolution to 640×480 at minimum 30 fps and up to 60 fps if the webcam supports it.

RealEye uses an algorithm similar to the I-VT (Velocity-Threshold Identification) fixation filter, assumming data with a sampling rate of over 20 Hz, with minimum fixation duration set to 100 ms by default. A median filter (set to 21 by default) is used for noise reduction. RealEye software provides an online platform for preparation and running of the study. It supports analyzing the data online by real-time gaze/fixation estimation on specific Areas Of Interest (AOIs). In the webcam recording condition, we used RealEye to set up the experimental procedure and to collect data. A LOGITECH HD Pro C920 webcam (1920×1080 resolution) was used to record eye movements. We reduced the sampling rate to 30 Hz to gather data most representative of typical recording conditions.

4.2.2 Remote Condition. This condition was prepared in PsychoPy 3 with the ioHub eye tracker interface for connection to the GP3 eye tracker [Peirce et al. 2019]. Eye movements were recorded by



(a) Time to First Fixation.

(b) Dynamics of Ambient-Focal Attention.

Figure 4: Differences between experimental conditions in (a) time to first fixation depending on target face, and (b) dynamics of attention depending on crowd size in the FIC task ($\mathcal{K} < 0$ and $\mathcal{K} > 0$ indicate ambient and focal attention, respectively). *Note*: the height of bars represents estimated means and error bars represent -1 *SE* and +1 *SE*.

the GP3 eye tracker with sampling rate of 60 Hz. The raw eye position was pre-processed with the *gazepath* library in R, the computational language for statistical analysis [R Core Team 2017]. Eye movement events, fixations and saccades, were detected using a non-parametric speed-based approach [Mould et al. 2012]. This approach estimated velocity thresholds per individual and used the fixation duration threshold set to 80 ms. Spatio-temporally overlapping fixations were combined.

4.2.3 Integrated Condition. RealEye supports third-party eye tracking hardware (e.g., the GP3) or webcam (e.g., OpenGaze) that utilizes the OpenGaze API. Integration with the GP3 requires: (1) recommended webcam eye tracking system components; (2) recent version of the Gazepoint Control software; (3) the GP3 hardware; (4) a recent version of the RealEye OpenGaze API Adapter. The webcam is still used for facial coding and making sure participants keep their heads in the correct position. Calibration needs to be done using the eye tracker's software, e.g., Gazepoint Control. With the GP3 hardware, the OpenGaze API is provided by GazePoint Control software. Access is available via TCP/IP sockets with a socket bound to a virtual IP address, e.g., localhost.

In this condition we used the same procedure prepared for the webcam recording condition and recorded eye movements with the GP3 eye tracker running at 60 Hz. The procedure was run on the RealEye platform using the Microsoft Edge browser. The data preparation such as fixation detection was performed using the RealEye platform with default settings as described above.

4.3 Participants

A total of 83 students volunteered to participate in the in-lab experiment in exchange for student activity credit points (56 Females, $M_{age} = 24.73$, $SD_{age} = 3.22$). Participants were recruited via an announcement on the University recruitment system, social-media groups or recruited at the University campus. They were randomly assigned to one of three recording conditions: remote (27 individuals), webcam (27 individuals), and integrated recording (29 individuals). Participants declared that their vision was normal or corrected to normal.

4.4 Procedure and Experimental Tasks

After coming to the laboratory, participants were informed about the aim of the study and signed an informed consent form. They were asked to put their chin on a chin rest. The height of the setup was customized to each individual. Participants then proceeded with calibration: a standard 40-point calibration on RealEye software or a 5-point calibration in Gazepoint Control and in the integrated condition. After successful calibration, participants completed two tasks: the point detection task and the visual search task. The tasks were identical in each condition. The procedure lasted approximately 9 min.

4.4.1 Point Detection Task. Participants were asked to look and mouse click on the displayed point as fast and accurately as possible. The points were shown separately on each slide, three times at one of the nine spots on the screen, giving 27 trials. The task was self-paced, meaning that the next trial started whenever participants clicked on the previous point.

4.4.2 Face-In-the-Crowd Task. Participants were asked to find and click on the face expressing a different emotion (happy or sad) from all other neutral faces shown in the crowd matrix [Gilboa-Schechtman et al. 1999]. There were three sizes of the matrices: 2×2, 3×3 and 4×4. The target face (happy or sad one) was shown at each of the in the crowd except for the 3×3 matrix in which the middle face was always neutral. Therefore there were 8 trials for the 2×2 matrix, 16 trials for the 3×3 matrix and 32 trials for the 4×4 matrix resulting in 56 trials. To prepare the matrices, we selected six Caucasian faces from the Warsaw set of emotional

Table 1: Data in rows represent means and standard deviation in each recording condition (*M*: mean value, *SE*: standard deviation).

Time to First Fixation			
Face Type	Remote $M(SE)$	Webcam $M(SE)$	Mixed $M(SE)$
Happy	$1306ms(60)$	$1270ms(60.5)$	$1172ms(61.1)$
Sad	$1472ms(60)$	$1457ms(60.5)$	$1374(61.1)$
Main Effect of Face Type	$F(1,24) = 15.70^{**}$	$F(1,23) = 9.38^{**}$	$F(1,24) = 12.87^{**}$
Ambient/Focal Attention			
Crowd Size	Remote $M(SE)$	Webcam $M(SE)$	Mixed $M(SE)$
2×2	$-0.60(0.05)$	$-0.66(0.06)$	$-0.41(0.06)$
3×3	$-0.18(0.05)$	$-0.18(0.06)$	$-0.03(0.06)$
4×4	$0.11(0.05)$	$0.09(0.06)$	$0.28(0.06)$
Main Effect of Crowd Size	$F(1,39) = 63.18^{**}$	$F(1,32) = 70.96^{**}$	$F(1,39) = 57.79^{**}$

**statistically significant effect at $p < 0.01$

facial expression pictures (WSEFEP) [Olszanowski et al. 2015]. Half the facial expressions were female and half male. The task was self-paced, meaning that whenever participants clicked on the target face, the next trial appeared. Between each trial a fixation point was displayed for 1 second. Prior to the analyses, we defined specific AOIs around the target points and sad/happy faces (see Figure 2). This allowed us to calculate the time to first fixation on the AOI.

5 RESULTS

Results are given in two parts: (a) measurement error estimation, i.e., precision and accuracy of point detection in the self-same task and (b) validation of theoretical-based predictions in the visual search task. All statistical analyses were performed in R, the language for statistical computing [R Core Team 2017].

5.1 Measurement Error

To check the differences in measurement accuracy between RECORDING CONDITIONS, one-way ANOVAs were conducted with the distance (in pixels) between the center of the point target AOI and position of the participant's eye fixation as a dependent variable. In line with the first hypothesis, ANOVA of measurement error revealed a significant difference between conditions, $F(2,80) = 9.88,\ p < 0.01,\ \eta^2 = 0.22$. Post hoc comparisons with Tukey correction showed that the average error was significantly higher in the webcam condition ($M = 45.1,\ SE = 2.81$) than in the remote ($M=34.2,\ SE=2.75,\ t=2.78,\ p=0.02,\ \eta^2=0.11$) and the integrated conditions ($M = 27.70,\ SE = 2.81,\ t = 4.39,\ p < 0.01,\ \eta^2 = 0.26$). The difference between remote and integrated condition was not significant ($t=1.66,\ p=0.22$).

We repeated one-way ANOVA with the dispersion (in pixels) of the participant's eye fixations on each target point as a dependent variable to check the differences in measurement precision between RECORDING CONDITIONS. ANOVA of precision error revealed a significant difference between conditions, $F(2,67) = 25.60,\ p < 0.01,\ \eta^2 = 0.43$. Post hoc comparisons with Tukey correction showed that the dispersion of fixations was significantly higher in the webcam condition ($M=58.9,\ SE=2.68$) than in the remote ($M=37.9,\ SE=2.62,\ t=2.78,\ p<0.01,\ \eta^2=0.38$) and the integrated conditions ($M=33.5,\ SE=2.68,\ t=6.69,\ p<0.01,\ \eta^2=0.48$). The difference between remote and integrated condition was not significant ($t=1.18,\ p=0.47$). An example of fixation dispersion in each recording condition is shown in Figure 1.

5.2 Visual Search Task

We ran a three-way mixed-design ANOVA to test the effect of RECORDING CONDITION, FACE TYPE and CROWD SIZE, separately for time to first fixation on target AOI, and for dynamics of ambient-focal attention as dependent variables.

5.2.1 Time to First Fixation on Target Face. In line with theoretical predictions, ANOVA revealed a significant main effect of FACE TYPE, $F(1,69)=48.42,\ p<0.001,\ \eta^2=0.06$. The time to the first fixation on the target face was shorter for happy than sad faces in all three RECORDING CONDITIONS (Figure 4(a), Table 1).

The main effect of CROWD SIZE was also significant, $F(1,95) = 183.25,\ p < 0.001,\ \eta^2 = 0.42$. Search time increased significantly with crowd size (for 2×2: $M = 1007ms,\ SE = 40.3$; 3×3: $M = 1234,\ SE=40.3$; 4×4: $M=1784,\ SE=40.3$). We did not observe a significant main effect of RECORDING CONDITION, $F(2,69)=1.16,\ p=0.32$, nor did we find any significant two-way interactions, either between RECORDING CONDITION and FACE TYPE ($F<1$), or between RECORDING CONDITION and CROWD SIZE ($F(1,95)=2.18,\ p=0.10$). The three-way interaction between RECORDING CONDITION, FACE TYPE and CROWD SIZE was also not significant ($F<1$).

Results support the validity of webcam eye tracking, as well as the integrated condition in the visual search task. In all three conditions, happiness attracted attention and search complexity led to an increase in search time.

5.2.2 Ambient-Focal Attention. Analysis of the dynamics of ambient-focal attention revealed a significant main effect of FACE TYPE, $F(1,69)=23.45,\ p<0.001,\ \eta^2=0.07$. Overall, participants exhibited less ambient search for a happy face ($M=-0.12,\ SE=0.02$) than a sad face ($M=-0.22,\ SE=0.02;\ t=4.84,\ p<0.01$). These results are in line with previous findings about greater focal attention during exploration of happiness [Krejtz et al. 2018].

The main effect of CROWD SIZE was also significant, $F(1,109) = 108.95$, $p < 0.001$, $\eta^2 = 0.48$. In line with the hypothesis about dynamics of visual attention, post hoc comparisons suggested that more focal attention was observed in larger crowds in all RECORDING CONDITIONS (see Figure 4(b)).

No significant interaction was found, either between RECORDING CONDITION and FACE TYPE ($F(2,69) = 1.35$, $p = 0.26$), or between RECORDING CONDITION and CROWD SIZE ($F < 1$) or between all three factors ($F < 1$). Descriptive statistics are given in Table 1.

6 DISCUSSION & CONCLUSION

We compared measurement error and validity of webcam (RealEye) to remote (the GP3) eye tracking as well as to an integrated method in point detection and visual search tasks. We evaluated the webcam eye tracking in the precision and theory based tasks. As predicted, webcam recording showed lower accuracy and greater precision error than the other conditions. Our theory-based hypotheses however were supported in three conditions of data recording, stating that, despite lower precision in the webcam recording, effects of visual search would be similar to those in the remote and integrated conditions, suggesting happiness-oriented visual attention and similar dynamics of visual attention. Therefore, we supported previous results that webcam eye tracking can be used in cognitive and behavioral studies [Semmelmann and Weigelt 2018].

Our contribution is threefold. First, the measurement error was relatively small compared to earlier studies [Burton et al. 2014]. The improvement in precision and accuracy is related to the hardware and webcam platform development.

Second, to the best of our knowledge, this is the first study to investigate the dynamics of visual attention recorded by a webcam eye tracker. Current results may be useful for development of real-time alerting systems of focal processing, as focal attention indicates deeper attentional processing [Krejtz et al. 2016]. Such applications may be beneficial in many fields, including computer-supported learning or assitive technology [Skovsgaard et al. 2011].

Third, we proposed the integration of webcam and remote eye tracker software. Results showed similar, but stronger effects in the integrated condition compared to the remote condition. It is worth emphasizing that the same fixation filters were used as in webcam recording condition. The default filters have high velocity thresholds and noise reduction which likely works better with the webcam camera. These settings may be changed manually during data preparation in the RealEye software. Nevertheless, our aim was to show that using a the GP3 eye tracker with RealEye software may make preparation and analyses easy and fast leading to similar results even with differences in sampling rate and fixation duration.

Finally, considering the in-lab experimental setting used, findings should be replicated outside the lab in in-house conditions. Controlled factors such as head position in the present study may enhance accuracy of the webcam.

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I declare that I contributed to the following tasks:

- conception of study design
- statistical analyses
- article preparation
- writing revision after reviews

Katarzyna Wisiecka was the lead author of the paper and was primarily responsible for its creation. Katarzyna Wisiecka contributed to the following tasks:
conceptual framework and hypotheses, study design & planning,
research software programming, data collecting, statistical analyses, results interpretation, writing an initial draft, writing revision after reviews, submitting the article as a leading author. Her estimated quantitative contribution to this article is 80%.

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conceptual framework and hypotheses, study design & planning,
research software programming, data collecting, statistical analyses, results interpretation, writing an initial draft, writing revision after reviews, submitting the article as a leading author. Her estimated quantitative contribution to this article is 80%.

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Statement Of Co-Authors Of Joint Publication
for the article

Wisiecka, K., Krejtz, K., Krejtz, I., Sromek, D., Cellary, A., Lewandowska, B., Duchowski, A. (2022). Comparison of Webcam and Remote Eye Tracking. *ACM Symposium on Eye Tracking Research and Applications, ETRA'22*. https://doi.org/10.1145/3517031.3529615

I declare that I contributed to the following tasks:
- article preparation

Katarzyna Wisiecka was the lead author of the paper and was primarily responsible for its creation. Katarzyna Wisiecka contributed to the following tasks:
conceptual framework and hypotheses, study design & planning,
research software programming, data collecting, statistical analyses, results interpretation, writing an initial draft, writing revision after reviews, submitting the article as a leading author. Her estimated quantitative contribution to this article is 80%.

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