Bringing Adaptive On-the-Move AR to Outdoor Environments

Helen Stefanidi
eleni.stefanidi@plus.ac.at
University of Salzburg
Salzburg, Austria

Markus Tatzgern
markus.tatzgern@fh-salzburg.ac.at
Salzburg University of Applied Sciences
Puch, Austria

Alina Itzlinger
alina.itzlinger@plus.ac.at
University of Salzburg
Salzburg, Austria

Alexander Meschtscherjakov
alexander.meschtscherjakov@plus.ac.at
University of Salzburg
Salzburg, Austria

Abstract

A growing body of research has focused on the integration of Augmented Reality (AR) into everyday tasks. The recent advancements in Artificial Intelligence (AI) introduced the possibility of adaptive and context-aware AR, tailoring virtual content to be personalized and align with users' context and environment. Designing AI-driven AR applications for dynamic situations leads to both opportunities, such as a seamless personalized experience, and challenges, such as hardware limitations and security concerns. As part of our research, we have conducted a participatory design fiction workshop, an outdoor field study and an autoethnographic study around the use of AR for everyday activities while on-the-move, in-the-wild. We have also conducted a systematic literature review of the current state-of-the-art of the contexts and applications that have been explored for AR users while on-the-move outdoors. In this position paper, we reflect on challenges, opportunities, and open questions that we envision discussing in the workshop.

CCS Concepts

• **Human-centered computing → Mixed / augmented reality**.

Keywords

augmented reality, artificial intelligence

ACM Reference Format:

Helen Stefanidi, Markus Tatzgern, Alina Itzlinger, and Alexander Meschtscherjakov. 2025. Bringing Adaptive On-the-Move AR to Outdoor Environments. In *Proceedings of ACM CHI conference on Human Factors in Computing Systems (CHI 2025 Workshop).* ACM, New York, NY, USA, 3 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 Research Experience

Our research thus far focuses on investigating the potential and use of AR Head-Mounted Displays (HMD) in dynamic everyday contexts while people are on-the-move outdoors. In such scenarios, we aim to identify meaningful approaches for seamlessly integrating AR technologies in daily activities. Key points of interest include the presentation and interaction with AR data visualizations, as well as exploring the social impact of using AR HMDs in public for both users and 'non-users' (i.e., surrounding individuals or interaction partners not wearing an HMD).

A systematic literature review regarding AR for people being on-the-move outdoors [17] revealed that the majority of the contexts that prior research has investigated concern navigation, content interaction and/or visualization and safety. Nonetheless, only one paper from our corpus examined the use of AI and context-sensitivity while AR users are in motion [16]. In this review, we also present design recommendations for utilizing AR in various on-the-move use cases as well as presents visions for future research in this context. Indicatively, to enhance spatial awareness in AR users, we propose highlighting key physical objects within an environment and subtly incorporating additional information, such as distance and direction, to aid navigation and identification of points of interest (POI). We also propose that AR research should move out of the lab and into real-world environments. In particular, we envision for future work to explore on-the-move AR in real-world outdoor settings, going beyond simulations and controlled lab studies to develop more practical and effective solutions. Moreover, we highlight the need for transparent and responsible design, as AI is reshaping the use of AR by enabling real-time, context-sensitive applications. However, it also raises trust, acceptance, and ethical concerns, including potential dark patterns, privacy risks, and social implications.

Overall, we believe AI pushes the boundaries for context-sensitive, personalized and adaptive AR, especially in dynamic, on-the-move settings. This entails the optimization of current methods and the identification of significant user and software requirements when implemented in outdoor, mobile environments. Nevertheless, the social and ethical implications of conducting such studies outside controlled laboratory settings, in real-world scenarios, warrant thorough examination.

2 Employed Methodology

So far, our research has followed a mixed-methods approach employing various quantitative and qualitative methods from different methodologies (i.e., user-centered design, participatory design, design fiction, ethnography). Indicatively, we have conducted participatory design fiction workshops to explore and envision design possibilities for people being on-the-move with AR technologies.

CHI 2025 Workshop, Yokohama, Japan

ACM ISBN 978-x-xxxx-xxxx-x/YYYY/MM
https://doi.org/10.1145/nnnnnnn.nnnnnnn

It provided inspiration for the outdoor on-the-move setting that we explored the use of an AR HMD in an uncontrolled field study. Through interviews, the participants of this in-the-wild AR study were asked among others about their perceptions of using this technology in an everyday, urban scenario while also having to interact with other surrounding people [Publication Under Review]. Furthermore, we have conducted an autoethnographic study revolving around the use of AR in an everyday outdoor activity. This preliminary study will be part of a bigger autoethnographic study where we as experts will reflect on conducting outdoor in-the-wild AR studies for everyday activities while on-the-move.

3 Reflections

Based on our current research experience and relevant prior work in this domain, we outline some key opportunities, challenges and present some open questions.

3.1 Opportunities

Over the past few years, the use of AR applications in mobile contexts is prominent, addressing areas such as navigation [21], safety [18], POIs [4], and accessibility [15]. Research has highlighted several benefits of AR visualizations in daily life, such as improved spatial awareness through visual cues and markers [16], remote collaboration via virtual scene navigation [7], and real-time information about hazards [20]. Although various studies have addressed context-awareness in AR [5, 8, 12, 16], there remains a gap in evaluating context-aware solutions in outdoor on-the-move environments. To ensure AR content is ubiquitous and always accessible, even in such dynamic settings, we should consider AI not only for optimal virtual content presentation [9] but also how to design interactions that adapt to the user's context.

In addition, research needs to transition from single-function AR applications to a more versatile, pervasive AR experiences that can cater to multiple purposes [8]. For instance, an AR application that can provide navigation to a new city as well as within the isles of a supermarket or an application that supports both physical an virtual social interaction (e.g., cross-reality interaction). Such AR interfaces, might require more context-sources and complex user modeling, but will pave the way for adaptive AR solutions in dynamic, on-the-move and even social settings.

Another opportunity for future research in using AR and AI outdoors is to analyze user performance in diverse, real-world settings. This involves leveraging existing machine learning (ML) models (e.g., StarGAN [3], ARShadowGAN [13]) to understand how users interact with AR interfaces in dynamic, uncontrolled environments. By examining instances where users themselves trigger (activate) AR applications in diverse outdoor scenarios, researchers can gain insights into user preferences and performance[14]. This will ultimately enhance the ecological validity and applicability of AR systems in everyday life.

3.2 Challenges

Context is particularly important when designing AR visualizations, as the applications using this technology are inherently context-based due to the spatial registration of AR content [8]. Especially for people on-the-move the effectiveness and meaningfulness of these visualizations depends on their integration into the specific situation and people's needs. Design considerations should include the user's location, movement, and tasks, as real-world environments are dynamic and ever-changing and AR systems need to be able to adapt to these context changes. When people are on-the-move, they inherently experience an additional cognitive load. Without proper context-awareness, AR visualizations could distract users or provide misinformation, potentially leading to accidents [16]. Thus, the user's context should be a primary factor in determining suitable visualizations [11]. However, the current adaptation in context-aware interfaces utilizing AI is limited in scope, typically detecting only a narrow set of contextual factors (i.e., fatigue [1]) and relying on predefined design principles for specific scenarios [6, 8]. This could be particularly problematic when researching AR in dynamic on-the-move contexts in-the-wild.

Another challenge is the narrow focus of current ML models (e.g., gaze models), which are generally tailored for specific tasks. This would prove even more difficult in outdoor settings due to the dynamic and frequent context changes. It is essential to expand research efforts to evaluate these models in a broader range of environments and scenarios [10]. While field and in-the-wild studies are crucial for evaluating the validity and applicability of research findings, testing them in an uncontrolled environment remains challenging.

Furthermore, the effectiveness of AR interfaces is often compromised by information overload, visual clutter, and distractions, which negatively impact situational awareness, cognitive load, and overall performance [19]. This is critical in outdoor environments, where information is dynamic and social interactions can occur unexpectedly. In social contexts, poorly designed AR can obstruct facial expressions, hindering communication and raising issues of social isolation and privacy [6]. Additionally, the continuous use of multiple cameras for tracking and scene understanding introduces privacy and ethical challenges, especially with omnidirectional video [2]. This necessitates careful consideration of future hardware and software solutions when AR is used outdoors [17], such as masking sensitive regions or detecting events that should not be recorded, to protect user privacy and address ethical concerns effectively.

3.3 Open Questions

- **Question 1:** How can AI be used to facilitate adaptive and context-sensitive AR while people are in motion outdoors? What opportunities and additional challenges arise?
- **Question 2:** What are the ethical and societal impacts of combining AR and AI in public?
- **Question 3:** How can we achieve real-time human-AI interaction in AR in-the-wild outdoors? What challenges arise?

3.4 Acknowledgments

This research was funded in whole by the Austrian Science Fund (FWF) 10.55776/DFH12.

References

[1] Wan-Jung Chang, Liang-Bi Chen, and Yu-Zung Chiou. 2018. Design and Implementation of a Drowsiness-Fatigue-Detection System Based on Wearable Smart

Glasses to Increase Road Safety. *IEEE Transactions on Consumer Electronics* 64, 4 (Nov 2018), 461–469. doi:10.1109/TCE.2018.2872162

[2] Hyunsung Cho, Matthew L. Komar, and David Lindlbauer. 2023. RealityReplay. *Proceedings of the ACM on Interactive Mobile Wearable and Ubiquitous Technologies* (2023). doi:10.1145/3610888

[3] Yunjey Choi, Minje Choi, Munyoung Kim, Jung-Woo Ha, Sunghun Kim, and Jaegul Choo. 2018. StarGAN: Unified Generative Adversarial Networks for Multi-domain Image-to-Image Translation. In *2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition*. 8789–8797. doi:10.1109/CVPR.2018.00916

[4] Rafia Rahman Chowdhury and Aseef Iqbal. 2022. LocatAR - An Augmented Reality Application for Local Points of Interest Identification. In *Proceedings of the 2nd International Conference on Computing Advancements (ICCA '22)*. Association for Computing Machinery, New York, NY, USA, 302–308. doi:10.1145/3542954.3542998

[5] Shakiba Davari and Doug A. Bowman. 2024. Towards Context-Aware Adaptation in Extended Reality: A Design Space for XR Interfaces and an Adaptive Placement Strategy. *arXiv.org* (2024). doi:10.48550/arxiv.2411.02607

[6] Shakiba Davari, Daniel Stover, Alexander Giovannelli, Cory Ilo, and Doug A. Bowman. 2024. Towards Intelligent Augmented Reality (iAR): A Taxonomy of Context, an Architecture for iAR, and an Empirical Study. *arXiv.org* (2024). doi:10.48550/arxiv.2411.02684

[7] Steffen Gauglitz, Benjamin Nuernberger, Matthew Turk, and Tobias Höllerer. 2014. In Touch with the Remote World: Remote Collaboration with Augmented Reality Drawings and Virtual Navigation. In *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology (VRST '14)*. Association for Computing Machinery, New York, NY, USA, 197–205. doi:10.1145/2671015.2671016 event-place: Edinburgh, Scotland.

[8] Jens Grubert, Jens Grubert, Tobias Langlotz, Tobias Langlotz, Stefanie Zollmann, Stefanie Zollmann, Holger Regenbrecht, and Holger Regenbrecht. 2017. Towards Pervasive Augmented Reality: Context-Awareness in Augmented Reality. *IEEE Transactions on Visualization and Computer Graphics* (2017). doi:10.1109/tvcg.2016.2543720

[9] Violet Yinuo Han, Hyunsung Cho, Kiyosu Maeda, Alexandra Ion, and David Lindlbauer. 2023. BlendMR: A Computational Method to Create Ambient Mixed Reality Interfaces. *Proc. ACM Hum. Comput. Interact.* (2023). doi:10.1145/3626472

[10] Teresa Hirzle, Florian Müller, Fiona Draxler, Martin Schmitz, Pascal Knierim, and Kasper Hornbæk. 2023. When XR and AI Meet - A Scoping Review on Extended Reality and Artificial Intelligence. *International Conference on Human Factors in Computing Systems* (2023). doi:10.1145/3544548.3581072

[11] J. Lee, F. Jin, Y. Kim, and D. Lindlbauer. 2022. User Preference for Navigation Instructions in Mixed Reality. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Piscataway, NJ, USA, 802–811. doi:10.1109/VR51125.2022.00102 Journal Abbreviation: 2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR).

[12] David Lindlbauer, David Lindlbauer, David Lindlbauer, Anna Maria Feit, Anna Maria Feit, Otmar Hilliges, and Otmar Hilliges. 2019. Context-Aware Online Adaptation of Mixed Reality Interfaces. *ACM Symposium on User Interface Software and Technology* (2019). doi:10.1145/3332165.3347945

[13] Daquan Liu, Chengjiang Long, Hongpan Zhang, Hanning Yu, Xinzhi Dong, and Chunxia Xiao. 2020. ARShadowGAN: Shadow Generative Adversarial Network for Augmented Reality in Single Light Scenes. In *2020 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*. 8136–8145. doi:10.1109/CVPR42600.2020.00816

[14] Feiyu Lu, Leonardo Pavanatto, Shakiba Davari, Lei Zhang, Lee Lisle, and Doug A. Bowman. 2024. "where Did My Apps Go?" Supporting Scalable and Transition-Aware Access to Everyday Applications in Head-Worn Augmented Reality. *IEEE Transactions on Visualization and Computer Graphics* (2024). doi:10.1109/tvcg.2024.3493115

[15] Sebastião Rocha and Arminda Lopes. 2020. Navigation Based Application with Augmented Reality and Accessibility. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–9. doi:10.1145/3334480.3383004

[16] Arne Seeliger, Raphael P. Weibel, and Stefan Feuerriegel. 2022. Context-Adaptive Visual Cues for Safe Navigation in Augmented Reality Using Machine Learning. *International Journal of Human–Computer Interaction* 40 (Sept. 2022), 1–21. doi:10.1080/10447318.2022.2122114

[17] Helen Stefanidi, Markus Tatzgern, and Alexander Meschtscherjakov. 2024. Augmented Reality on the Move: A Systematic Literature Review for Vulnerable Road Users. *Proc. ACM Hum.-Comput. Interact.* 8, MHCI, Article 245 (Sept. 2024), 30 pages. doi:10.1145/3676490

[18] U. Gruenefeld, T. C. Stratmann, J. Jung, H. Lee, J. Choi, A. Nanda, and W. Heuten. 2018. Guiding Smombies: Augmenting Peripheral Vision with Low-Cost Glasses to Shift the Attention of Smartphone Users. In *2018 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. IEEE, Piscataway, NJ, USA, 127–131. doi:10.1109/ISMAR-Adjunct.2018.00050 Journal Abbreviation: 2018 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct).

[19] D.W.F. van Krevelen and R. Poelman. 2010. A Survey of Augmented Reality Technologies, Applications and Limitations. *International Journal of Virtual Reality* 9, 2 (Jan. 2010), 1–20. doi:10.20870/IJVR.2010.9.2.2767

[20] Tamara von Sawitzky, Thomas Grauschopf, and Andreas Riener. 2022. Hazard Notifications for Cyclists: Comparison of Awareness Message Modalities in a Mixed Reality Study. In *27th International Conference on Intelligent User Interfaces (IUI '22)*. Association for Computing Machinery, New York, NY, USA, 310–322. doi:10.1145/3490099.3511127 event-place: Helsinki, Finland.

[21] Yiyi Zhang and Tatsuo Nakajima. 2022. Exploring 3D Landmark-Based Map Interface in AR Navigation System for City Exploration. In *Proceedings of the 20th International Conference on Mobile and Ubiquitous Multimedia (MUM '21)*. Association for Computing Machinery, New York, NY, USA, 220–222. doi:10.1145/3490632.3497858