Wearable, Everyday AI+Augmented Reality: Perceptual Mediation, Harms, and Governance

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1 INTRODUCTION

Smartphones are the predominant technology by which we communicate, engage with society and consume digital content. Approximately 88% of the EU population and 90% of children in Europe and Asia, have access to a smartphone, and these devices shape our perception, acting as an ever-present lens into digital and augmented worlds (1). But once a smartphone is in your pocket, the power this lens holds over the user is greatly diminished as they no longer perceive or interact with visual digital content but instead are limited to haptic or audio content. Furthermore, the sensing capability of the device (cameras and microphones) and any associated multimodal AI agents and models is severely restricted, e.g. allowing GPS tracking permissions means the device can locate where the user is but crucially is no longer able to perceive and capture the user's surrounding environment and reality. And though smartphone addiction is a concern (2, 3), this offers a natural limit and barrier for how this technology can mediate attention, activities, perception, and the extent to which it is aware of a user's surroundings at any given moment.

Wearable technologies, however, by design reduce and/or remove such limits, providing an everyday/all-day wearable and fashionable form factor (e.g. smart glasses (4, 5)) that circumvents the barriers imposed by the user's pocket, instead placing the device between the user's eyes/ears and their surrounding reality (6). This switch enables these devices to continually surveil the wearer's actions and environment (aurally and visually through cameras and microphone arrays), process and interpret that data (through multimodal local and cloud AI models), and act upon it in how they mediate our aural and visual perception of the real world (through visual and auditory augmented reality, heads-up smart glasses, projective displays and more), all in discreet form factors e.g. stylised as a pair of glasses (6). And such wearable technologies are seeing surging commercial interest with companies such as Meta (7) (RayBan Display), Google (8), and Samsung (9) (Android XR) releasing, or soon expected to release, AI-enabled smart glasses to consumers.

For users, this combination of continuous sensing and oversight, AI comprehension, display modalities, and form factor, promises a transformative experience and increase in technical capabilities. Such devices offer the prospect of AI-driven insights interleaved into user's everyday lives, e.g. augmenting memory, intelligence, cognition and perception, and personalization of how we perceive ourselves, others, and our surrounding world (10), empowering users, communities, business, governments, and others to alter, augment, diminish or otherwise mediate our perception of reality (11). In doing so, the expectation is the sheer utility, and eventual necessity, of this technology will force adoption, with users being no more able to opt out from using such devices in the future as they can opt out of owning smartphones today (12). But

alongside the envisioned benefits of these devices, there are clear, inherent potential harms which have yet to be addressed (4, 13). For example, if we consider those who control these devices, their underlying software/hardware platforms, and the predominant applications and ecosystems that emerge, there are clear motivations around: instrumenting individuals to better understand their likes, dislikes, behaviours and attitudes (14); aggregating this data as a form of *worldscraping*; and then ultimately leveraging this to inform or influence those very same behaviours and attitudes, both individually and collectively. Such a position of power could be utilised for persuasion and coercion, deceptive and manipulative design, information disorder, censorship, and more (15, 16). Moreover, the necessary technical capabilities to achieve this will already be present in these devices, i.e. the same technology needed to enable real-time text comprehension assistance could also be used for enacting information disorder and censorship (6, 15).

The question then is: what recommendations, regulations, laws, and rights should govern the development and use of a technology that largely does not yet exist but has such potential, given that failure to act before widespread adoption may render meaningful regulation and protections slow and difficult to enact (10). Our motivation for addressing this now is in examining how companies are pursuing this technology, e.g. with Meta, Google, Microsoft, Apple, Bytedance, and more, all investing significantly in AI, wearables and immersive technologies, anticipating their eventual convergence and the influence they will potentially exert on users, alongside the significant economic value and data collection systems to be obtained. And these companies pursue this from a regulatory perspective that is arguably not aligned with the principles of the EU. For example, companies at UnitedXR 2025 openly questioned the restrictions imposed by EU law around privacy and data processing whilst suggesting that existing measures for protecting bystanders from these devices remain sufficient (17), despite contrary scientific evidence (18) and public sentiment (19, 20).

In this agenda-setting paper, we offer insight into concerns around everyday AI-enhanced wearable augmented reality (AR) from the perspective of Human-Computer Interaction (HCI, a field of computing science that evaluates, interrogates, and anticipates the capabilities, usage, and human impact of technology), highlighting some key topics and provocative works both we, and others within HCI, have contributed around the scope of perceptual tensions and vulnerabilities/harms. In particular, we focus on less widely covered considerations around the concept of *perceptual mediation*, where the wearable device leverages visual and auditory displays and AI inputs to mediate the user's perception of reality. Informed by this, we then discuss our on-going work on what we termed *perceptual rights*, and the approach we are exploring to formalise our framework through cross/multi-disciplinary expert-led consensus around actionable recommendations, regulations and prospective rights that could inform governance of these technologies, and ensure we anticipate and mitigate the harms exposed by wearable AI/AR prior to their realisation.

2 PERCEPTUAL AND COGNITIVE VULNERABILITIES

Works in HCI have increasingly started to interrogate augmented cognition (21, 22, 23), perceptual vulnerabilities (24, 25), manipulation (26, 27, 28), inter-reality (29) and societal risks (30, 4, 31), ethics and responsible practice (32, 33, 34) and more, going beyond more grounded and near-term considerations around e.g. privacy risks posed by AR+AI (6). We draw upon these in discussing a handful of example topics as provocations to consider when addressing prospective regulation of this technology.

2.1 Social Identity and Appearance

For individuals, the capacity to augment how we, and others, are perceived (35, 36). could risk provoking a range of psychologically damaging reactions as users feel a pressure to conform their appearance to perpetuated ideals (37). And for malicious actors, this capability could enable new forms of abuse. Beyond

'identity hacks' such as identity theft (34), it is easy to envision a convergence of AR sensing and cheap/deep fake technology (38) to, for example, sexualise (39) or otherwise appropriate the identity of others for socially unacceptable reasons (e.g. blackface filters (40)). Lemley *et al.* considered the legality of this ability to augment our personal sensescape and the sensescapes of others, asking: "What if people use this... to make [you] appear ridiculous... without your knowledge or consent? Or what if they want to make you appear naked" (41). But as O'Hagan et al discussed, even when used with consent there exists the potential for sexualised use cases to facilitate unhealthy sexual relationships where partners become a "haptic proxy" and are reduced to placeholders for the fantasies re-enacted by the other person, or even be mislead as to how they are being augmented, e.g. believing they are being augmented in a way they have requested but in actuality are being portrayed as a child during sex (42).

2.2 Maladaptive Use of Augmented Cognition

The combination of AR and AI offers the prospect of real-time AI support around memory, intelligence, cognition, social interactions, and more. E.g., Meta's "Persistent Assistant" AI (43) autonomously infers about the user's goals and analyses the environment to provide AR-rendered guidance on objects of interest. Whilst in "Memoro" (44), participants interacted with an autonomous "query-less" AI assistant that provided auditory information about their current context, and preferred the passive query-less version over an approach requiring active user input. AI such as Visual Language Models (VLMs) could be used to understand our activities, environments, intent and needs and react to them autonomously - in effect providing new and greater levels of cognitive offloading than any previous technology. Given the increasing capability and automation of AI agents more than 50 authors from academia and industry came together to publish a position paper on "The Ethics of Advanced AI Assistants" (45). The paper covers a range of topics however, there is no mention of potential positive or negative effects (or ethical concerns) regarding human memory, cognition or everyday living.

In contrast, in the HCI domain, we have begun to consider what *responsible* cognitive tools and support - or cognitive integration (46) - might be. E.g., for memory augmentation, the possibility of AI providing perfect recall/support across semantic, procedural, episodic, spatial and prospective memory risks potential maladaptive use, such as over-reliance that degrades human memory and even biological brain matter (21), as well as overt manipulation and interference with how memory is encoded, experienced, and retrieved (22). Research is already showing how generative AI can imperceptibly alter a person's memory of events (47, 48) or the presentation of information online (16, 49, 50). And critically, the proper consolidation of memory requires time and repetition (51), and if technology has supportive or disruptive effects on consolidation it may occur over long time periods. Meaning by the time research has grappled with how to responsibly augment such capabilities, these harms may already have occurred to long-term users.

2.3 Pervasive Advertising and Personalization

Unlike digital or print advertising, AR ads are not confined to screens or physical objects, but can be augmented anywhere within a user's perceived environment (52). As such pervasive advertising's potential is far greater with AR as any "surface", including building facades, vehicles, people, food, and even the sky (53, 54, 55, 56), are available to be monetised. It is highly likely AR platforms will leverage this given advertising is central to their underlying platform economics (57). In practice, platforms may subsidise the cost of their technology (and associated inference costs) with AR adverts, operating under similar models as used in social media today, where applications attract interaction and engagement and then sell access to this audience to advertisers (58). This is already reflected in industry, with Google having obtained patents for "pay per gaze" and "pay per emotion" systems, adapting current "pay-per-click" models to AR (53).

HCI research has begun to explore the risks of pervasive advertising in AR. Mhaidli & Schaub identified pervasive advertising as one of five manipulative XR advertising techniques, describing a scenario where a company augments its brand onto other people's clothing leading passers-by to perceive widespread adoption of that brand (59). And while some have considered mitigation strategies, e.g. AR ad-blocker (60) or how to adapt existing regulations and consumer protection laws (53), the vast majority of work in this topic does not focus or address the potential risks and manipulations of pervasive advertising. Instead, research efforts are concentrated on understanding how AR can more deeply influence customer behaviour (61, 62), with de Ruyter *et al.* arguing there has been too much reliance on the novelty of AR advertisements and we have yet to harness the true potential for AR advertisement, i.e. one that closely aligns adverts to the user's context and spatial environment (63) by, for example, utilising real-time gaze tracking to learn about the significance of objects in the user's home (63). Such works point towards a potential convergence of contextualisation and personalisation in AR advertising, highlighting the risk of AR advertising not only being more pervasive in where it can be augmented but also more precise and targeted in its ability to influence users at the level of perception and decision making.

2.4 Deceptive and Manipulative Design

In being able to track and understand our pre-existing likes and attitudes (e.g. through biometric psychography (64)), actions (e.g. through body tracking, context awareness, etc (6)) and even intention to act (e.g. through EEG-based readiness potential (65)), AR headsets also offer the possibility for enhanced behavioural nudging (66, 67, 68, 69), deceptive design (28), manipulation of actions (70), and preference change (71, 72, 73). This directed behaviour change may be voluntary (enacted through persuasion, nudging, positive reinforcement) or involuntary (via coercion or imperceptible manipulation). E.g., Ruocco *et al.* examined how a supermarket shopper's attention could be redirected to manipulate purchasing decisions (27). Pandjaitan *et al.* through *AuctentionAR* suggested users' attention to real-world objects could become a quantifiable and manipulable property "to auction off" to the highest bidder (26). And Krauß *et al.* outlined how AR could be used to amplify existing deceptive designs, and enable new ones, leveraging perception, spatiality, physical/virtual barriers, and device sensing (28).

2.5 Information Disorder and Censorship

Significant also is the potential capacity to comprehend and then alter our perception of our environments and the media we consume that exist outside of the system in use. E.g., a real-world political advert such as a billboard or poster by one party could be rebutted, undermined, or obfuscated by another. LLMs have been shown to be capable of re-writing web content to, for instance, alter the perceived political bias of content (49), and it is reasonable to expect VLMs might enact similar alterations on physical and digital media perceived by AR users. Indeed, political parties might create their own metaversal media layers over reality for their supporters to experience (4), e.g. the *Trumpverse* (13). And, going beyond physical media, particular social groups and demographics could even be visually "othered" (74) based on personal characteristics to confirm and amplify bias, and political opponents could be visually and/or aurally "blocked" *Black Mirror* style (75) or otherwise censored. Going further, censorship and information disorder may even collide. E.g., Eghtebas *et al.* discussed using AR to 'beautify' the physical environment, and despite their positive intentions (e.g. to support digital regeneration), this could lead to the "removal of poverty from sight", a form of censorship of the real state of a given society or community (31).

2.6 Perceptual Illusions and Manipulations

Beyond the above examples, everyday AR will open the door to new perceptual attacks and targeted augmentation of *any perceivable visual or auditory element of reality*. E.g., *SwitchAR* demonstrated how passthrough AR devices could imperceptibly switch from real to digital twin environments, exposing the user to physical safety risks and harms if this approach were abused (25). Similarly, Tseng *et al.* leveraged Virtual-Physical Perceptual Manipulations (VPPMs) of physical movements to redirect VR users into taking harmful actions (e.g. walking into obstacles, hitting other users aligned with virtual elements) and we could imagine similar illusions or manipulations occurring given sufficiently capable devices, ultimately demonstrating the potential for direct mediation and transformation of human perception (24, 76). This raises fundamental challenges for user autonomy, informed consent, and safety, reinforcing the need for anticipatory safeguards before such capabilities become widely deployed.

3 TOWARDS PERCEPTUAL RIGHTS

Given the potential of the combined use of AR and AI to reshape perception, we think it is necessary to consider the concept of *perceptual rights* - as a parallel to similar efforts in other fields such as around neuro-rights (77), as a means of codifying and unifying the disparate recommendations and guidelines made around the metaverse and immersive technologies, and as a bridge to support policy makers, regulators and law makers to explore the applicability of existing rights, laws and regulations to the concerns raised. In prior work (4, 13, 33, 21), we have speculated on prospective rights to be considered around the *right to metaversal access*; *perceptual agency and autonomy* around control of the user's sensecape; *cognitive autonomy* tensioning the right to free-will and independence of thought against (non-)consensual manipulation through perceptual mediation; and *perceptual integrity*, tensioning the right to freedom of expression against the risks posed by augmentations embedded in the world and perceived en masse. But we are far from alone in making such recommendations as many efforts have been made to provide guidelines and recommendations around the governance of immersive technologies including:

Multilateral Bodies, Standards and Regulators Such as the WEF (78), ITU Focus Group on the Metaverse (79), Council of Europe & IEEE (80), the European Commission (81), IEEE Standards (82), the Metaverse Standards Forum (83) and more;

Industry Coalitions and NGOs Such as XRSI, Future of Privacy Forum (FPF), the EFF etc.;

Academia With papers typically either semi-systematically reviewing, or speculating on, prospective governance challenges and recommendations (84, 85, 86, 87, 88, 89) or reflecting more broadly on ethics, risks, and the applicability of existing laws (e.g. XR4Human[1]).

However, we see a number of issues with existing efforts thus far.

3.1 The Metaverse and the Combined Treatment of AR, MR, VR

Metaverse, Web 4.0, virtual/immersive worlds, digital twins, and more, are all terms commonly used to describe the scope and context within which extended reality (XR) is situated. These terms are varyingly used to refer to different subsets of the mixed reality/reality-virtuality continuum. This combined treatment of the range of possible XR experiences causes a lack of specificity regarding recommendations attempting to be generalisable across this range. Additionally, this encourages a fallback to considering virtual reality more often, given it is the more immediate, "tangible" consumer experience available currently (90).

[1] https://xr4human.eu/outputs/

3.2 Methodological, Evidentiary, and Disciplinary Grounding

Where recommendations are made, there is often only consensus among select contributors risking bias towards the views of them. Methodologically, the majority of the papers rely on semi-systematic reviewing of existing works, or employ speculative design approaches with limited participant pools. This produces a range of whitepapers and publications making varyingly different recommendations that lack integration and a methodological approach which calls into question the validity and comprehensiveness of the made recommendations. Moreover, the evidentiary basis for recommendations, and the positionality/disciplinary grounding that underpins them, is often unclear. This risks creating a fragmented and insufficiently robust foundation for governance, limiting the reliability of existing recommendations and highlighting the need for more systematic, transparent, and interdisciplinary approaches to informing policy.

3.3 Scope and Breadth of Risks

Recommendations are often tied to specific domains, applications, use cases, or user demographics. Security, privacy, interoperability are recurring and important themes, while child safety is of paramount importance, but there is a lack of breadth in understanding the wider societal impact of specific technological innovations. Consider criminal or malicious use; or how information disorder might be enacted in a world where wearable AI mediate our perception of the world. Absent a firm grounding and understanding of the breadth of vulnerabilities exposed, it becomes challenging to understand if recommendations are sufficient and comprehensive and have reached a point of *saturation* regarding covering prospective harms to individuals and society overall given mass adoption and subsequent exploitation.

3.4 The Need for Integration and Consensus

In our view, there is a need for more detailed discussion and integrative efforts that aim to:

(a) Anticipate and map the prospective risks, harms and vulnerabilities posed by the adoption of AR+AI;
(b) Systematically track the associated and emerging evidence around efficacy and exploitation;
(c) Map potential mitigations and protective measures;
(d) Achieve multi-disciplinary consensus on recommended mitigations (rights, laws, regulations and guidelines) and the strength of recommendation, agnostic of existing (inter)national policy.

In doing so, we would have a basis for transnational consideration of the fundamental principles that should govern this powerful interaction of technologies to assist and inform policy and law makers in-practice. Addressing perceptual harms in everyday AI-enhanced AR at a regulatory level requires us to first anticipate and map these prospective risks, based on cutting-edge scientific evidence of potential exploitation of this technology. This can only be done through multi-disciplinary discussion and collaboration in identifying protective measures and mitigations, in order to reach consensus on recommended rights-based, legal, regulatory, and guideline-driven responses, agnostic of existing national and international regulations and policy. For example, a Delphi protocol study (91, 92) to address points (*a* - mapping risks, *c* - mapping mitigations, *d* - consensus), looking specifically at everyday augmented reality, and arriving at expert consensus from an XR practitioner perspective across disciplines in the EMRN would provide the foundation to prevent these harms being realised. The intended output is a cohesive set of governance recommendations grounded in a replicable, open methodology to inform policy changes, e.g. initially by extending existing legislation to explicitly cover issues such as real-time perceptual mediation or mandate perceptibility of augmentations (e.g., subtle disclosure mechanisms), and longer term by formalising core perceptual rights as a natural extension of neuro-rights frameworks and integrate them into EU AI Act and Council of Europe initiatives.

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