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A state of the art and scoping review of embodied information behavior in shared, co-present extended reality experiences

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Abstract

We present a state of the art and scoping review of the literature to examine embodied information behaviors, as reflected in shared gaze interactions, within co-present extended reality experiences. Recent proliferation of consumer-grade head-mounted XR displays, situated at multiple points along the Reality-Virtuality Continuum, has increased their application in social, collaborative, and analytical scenarios that utilize data and information at multiple scales. Shared gaze represents a modality for synchronous interaction in these scenarios, yet there is a lack of understanding of the implementation of shared eye gaze within co-present extended reality contexts. We use gaze behaviors as a proxy to examine embodied information behaviors. This review examines the application of eye tracking technology to facilitate interaction in multiuser XR by sharing a user's gaze, identifies salient themes within existing research since 2013 in this context, and identifies patterns within these themes relevant to embodied information behavior in XR. We review a corpus of 50 research papers that investigate the application of shared gaze and gaze tracking in XR generated using the SALSA framework and searches in multiple databases. The publications were reviewed for study characteristics, technology types, use scenarios, and task types. We construct a state-of-the field and highlight opportunities for innovation and challenges for future research directions.

Introduction

The release of the Oculus DK1 in 2013 was a catalyst for renewed interest in extended reality (XR) technology. Commercial availability of head mounted displays (HMD) and GPU-enabled personal computing increased access to XR and opened the door to new use scenarios, heralding the start of an era of ubiquitous XR experiences along the Reality-Virtuality continuum [1]. Extended reality technology is utilized to access information in both real world and virtual contexts. Use scenarios and applications range from education and healthcare, to training and just-in-time tasks, to fantastical game and story environments.

Shared XR experiences that exist along the Reality-Virtuality Continuum all utilize some aspect of immersion and presence which alter the perception of sensorimotor abilities and embodiment through the establishment of a body ownership illusion and interactive capabilities [2]. Presence, which is the experience of a sense of being there or being real in a virtual environment, is extended to include interactions with other users, which is known as co-presence. Co-presences is the user's experience of a sense of being together within a shared, virtual environment. Copresence and interaction in multiuser or shared spaces is guided by implicit social expectations of other users, the objects within the space, and the space itself [3], [4]. The expectations and behaviors that guide a user's interaction with other users and with the virtual space and objects can be examined as information behaviors. Information behaviors include all behavior as it relates to information seeking or use [5]. Embodied information behaviors specifically consider information behaviors from the perspective of human embodiment. Embodiment includes the structure and characteristics of the body as an entity in the world, as well as the use of information generated through engaging with the senses [6], [7]. We structure this state-of-the-art review using embodiment as the guiding concept throughout our analysis [8].

Shared gaze is a communicatory mechanism in collaborative environments that involves the conveyance of a user's eye gaze behaviors to other user(s). Given the current predominance of the use of head worn displays, which primarily engage the visual sense, eye gaze behaviors can function as one type of proxy for embodied information behaviors in XR. Here we narrow the focus of this review to XR experiences in which gaze sharing is a component. This review investigates how shared gaze is conceptualized in contemporary research, 2013 to 2021, that incorporates co-presence in XR by addressing the following research questions: What XR, eye tracking and input/output technologies are utilized in this research literature? What types of research study designs are implemented, and what are their outcomes? What is the role of shared gaze in these study designs? Within these studies, what tasks and use cases utilize shared gaze? This points to topical areas in XR research incorporating eye gaze that are actively being explored, and areas that are in need of further exploration.

Embodied Information Behaviors & Shared Gaze

Information behaviors include all human behaviors as they relate to information seeking and use [5]. It is a prominent area, often identified as a subfield, within Library and Information Science (LIS). Literature from this field focuses on recounting foundational theories, definitions, or models. Existing modeling approaches in this area do not develop and improve upon theory, rather these models are complementary and nested [9]. Information behavior models and theory utilize a broad perspective to provide overviews based on generalized behaviors and identify gaps in research rather than exploring causative factors or characterizations of information behaviors [9], [10]. While LIS research tends to underutilize research in allied or cognate fields [9], information behavior research is deeply related to and benefits from inclusion of interdisciplinary perspectives [11]. The inclusion of the body and nonconscious processing into information behavior modeling is necessary to develop a complete and holistic understanding [12] given that bodily interactions with the world shape cognitive and behavioral processes [13].

Embodied information behavior is how humans seek and use information in a manner that is shaped by our physical embodiment or corporeality. The engagement with information includes all interactions that rely upon perceptual, cognitive, and physical embodied processes. Lueg [6] emphasizes that any experience that is resultant of embodied interaction is specific to the individual and deeply tied to the corporeality and shape of our bodies. The body is the main tool for intelligent use of the environment [14], whether that environment is real or virtual. Cognition occurs across the user and the system [15] and is thusly shaped by individual differences and aspects of the environment and system [6], [16]. Just as human perception and action is situated within context and environment, information exists within the contexts of human perception, cognition, and interaction [7], [17]. [12] emphasizes the value of and need for information behaviors to be examined as both embodied and embedded in its context.

Embodied information is the corporeal manifestation of information, both perceived and known, and is one of the fundamental forms of information identified by [17]. Bates [17] identifies three subtypes of embodied information as experienced, enacted, and communicatory. Embodied information is not solely composed of what is experienced through conscious awareness [17], rather it includes all sensory and nonconscious processing. This includes tacit knowledge, know-how, intuitive knowledge, and so on. Information is communicated between individuals through multiple senses and modalities, including traditional communication, like verbal and gestural methods, or nonconscious methods, like vision, facial expression, and body language [18]. Nonverbal and nonconscious communication cues are crucial aspects of effective collaboration in extended reality contexts [19] and are the focus of large areas of research, including natural user interface (NUI) design. Developing an understanding grounded in a human centered perspective enables information technologies, including extended reality technologies, to function as an extension of the user.

Eye gaze behaviors are often utilized in extended reality contexts due to the supplementation or replacement of sensory input by XR technologies. The current dominance of HMD devices across the Reality-Virtuality Continuum reinforces the notion that XR is a predominantly visual medium. Gaze is increasingly utilized as an input in XR experiences (e.g. deictic gestures or indicators [3]) or as an output (e.g. gaze representation and sharing). Eye gaze behaviors provide valuable insight into behavioral contextualization, visual attention, and communicatory intent both explicit and implicit [3], [18], [20]. Shared gaze, which involves the communication of a user's eye gaze to other user(s), represents a modality for synchronous interaction in multiuser XR experiences that can be utilized to establish a basis for collaborative work and joint attention. Joint attention requires the understanding of common referential practices and objects within the space to enable negotiation and coordinate effort within a collaborative task [3]. Collaboration in XR contexts is a complex, iterative process that includes interaction with the other users, system, and technology [21].

Shared gaze is particularly important when working with other people, a focus of the field of computer supported cooperative work (CSCW) [22], [23]. Existing research on shared gaze primarily focuses on desktop and personal computer use, yet applications to immersive technologies are gaining more attention [24]. Immersive technologies and environments provide opportunities for users to engage and interact with information in an embodied manner. Many research studies within this area are focused on enabling shared gaze by comparing different methods to convey gaze cues [23], [25]. This research is enabled through a focus on establishing effective mechanisms and algorithms [26]. Analyzing information gathered from wearable devices, such as eye trackers and HMDs, enables the evaluation of shared gaze from a user centered perspective rather than a computational view. Shared gaze and eye tracking is increasingly studied to enhance remote collaboration, however existing research includes a large variance in approaches that haven't been integrated to develop a complete understanding [27]. To our knowledge, no existing review focuses on the application of shared gaze and eye tracking in extended reality contexts. Given the prominence of vision as the primary mode of interaction in extended reality, within this review, we focus on eye gaze behaviors as a proxy for embodied information behaviors and shared gaze as a communicatory representation of eye gaze in XR contexts.

Methods

To assess the landscape of research and use scenarios for shared gaze in XR, we conduct a scoping and state-of-the-art review utilizing the SALSA framework [28]. SALSA provides a reproducible methodology for categorization and analysis of sources for scoping and narrative reviews that articulate the current state of the art for a technology. It's four steps and our respective methods and outcomes are presented in table 1.

SALSA Steps	Method	Outcomes
Method	Search query development	Search query
Outcomes	PRISMA-S [29]	Possible papers for inclusion
Preliminary searches	QualSyst [30]	Selected papers for inclusion
Search query development	Tabular and narrative analysis	Findings

Table 1: SALA framework steps corresponding to review methodology steps and outcomes.

Our search methodology utilizes the Preferred Reporting Items for Systematic Reviews and MetaAnalyses (PRISMA - S) extension for reporting literature searches in Systematic reviews [29], [31]. PRISMA-S provides a four-part structure for evaluating studies for inclusion in the review process: Identification, Screening, Eligibility, and Inclusion. Our search and appraisal processes (which correspond to SALSA's 4 steps in table 1) are conducted within the PRISMA-S process as detailed in figure 1.

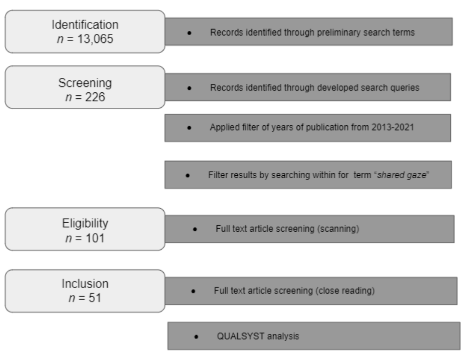

Figure 1: Flow diagram of search and review process to identify the text corpus

Multiple web database searches were conducted on November 2, 2021, using a set of primary keywords in combination with limitations by year and a filter term (See figure 2). To cover a broad range of perspectives, preliminary searches were conducted in six databases: EBSCO, ScienceDirect, Scopus, Web of Science, IEEE Xplore, and ACM Digital Library. Upon results of preliminary searches, two of the databases (EBSCO and ScienceDirect) were removed from the set of information sources because their indexing of literature sources fell primarily out of scope for the final filter search term in our query methodology. Ultimately, four of the databases were selected for searches: Scopus, Web of Science, IEEE Xplore and ACM Digital Library.

Preliminary Searches

Our primary, secondary, and tertiary queries were quite broad; therefore, we began our review process by conducting a set of preliminary searches with each of the queries in combination. This combination of queries enabled us to determine suitable search queries. A total of 13,065 papers were retrieved as a result of each of the searches in the four databases.

Searches

While our interest is in the intersection of embodied information behaviors and XR, the specific terms were either too broad or not associated specifically within the body of literature. We therefore applied the following search process:

1. We searched combinations of the search terms: VR, virtual reality, AR, Augmented Reality, MR, Mixed Reality, XR, Extended Reality, Multiuser, Multiple Users, Multiplayer, Collabor- (with * wild card for all forms of terms pertaining to collaboration), Eye Tracking, Gaze, Eye Gaze, Gaze Tracking. These were combined with OR and AND logical operators.
2. We limit the results from these searches by year: 2013 to 2021.
3. We limit the results from these searches by a filter term: shared gaze.

For each data source, we conducted four search queries, one for each of the immersive technology terms: VR, AR, MR XR. All searches were conducted in Title, Author, and Keyword metadata. A total number of 226 papers were retrieved as a result of each of the filtered queries. A sample of our search queries is included in figure 2 below. For a complete list of search queries, see appendix A.

Figure 2: Example query from database

We limited our search to papers published since 2013, which marks the release of the Oculus Rift DK1 and the subsequent revitalization of interest and use of XR technology. However, we must acknowledge the existence of significant early work in eye gaze within VR in the preceding decades, for example, the 1993 paper by Benford and Fahlen on spatial models of interaction in large scale virtual environments. We confirm this limitation and display the year distribution of our sample in the table below (figure 3).

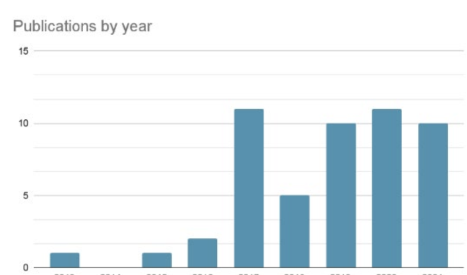

Figure 3. Publication year of the fifty publications reviewed

Appraisal

Of the 226 papers retrieved, 101 were excluded during deduplication. Journal or conference papers in English were selected for review. Poster, news articles, short reports, extended abstracts, and book chapters were excluded. Manual screening for inclusion criteria resulted in removal of an additional 25 papers that were retrieved by the queries due to metadata keywords, yet the papers themselves were off topic and for example, did not include information about gaze or shared gaze in XR. In addition to these criteria, papers were screened for quality using the QualSyst [30] in line with the methodology presented in [32], [33]. QualSyst is comprised of a set of 14 criteria. For a full list of criteria, see appendix B. Two reviewers evaluated each study independently and disagreements were resolved by a third reviewer. We utilize a 0.55 threshold as per [30] and excluded 2 papers. Further exclusion occurred through a close reading, which identified several papers that met the quality criteria yet did not directly involve eye tracking and shared gaze in XR. The overall appraisal process results in a total of 50 papers in 36 of distinct journals and conference proceedings.

Our selected papers were drawn from three types of venues: journals, conferences, and symposia. These venues were sorted based on their topics and applications, which were: interaction, learning, graphics, robotics, eye tracking, AR, VR, and AI (See figure 4). Drawing papers from a wide range of venues and topics provides a robust perspective into current, extended reality technology use with eye tracking and shared gaze.

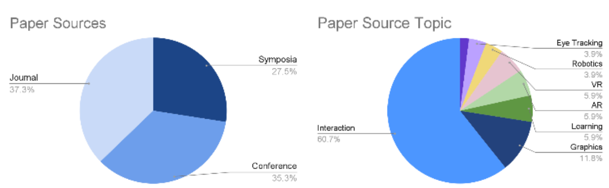

Figure 4. Publication venue of the fifty publications reviewed. (Left: venue type, right: venue topic)

Synthesis and Analysis

After completing the PRISMA process (Identification, Screening, Eligibility, and Inclusion) to review the literature, we identified a total of 50 papers for the purpose of this study. The data synthesis and analysis process is developed according to [28] and informed by the research question. The synthesis method for scoping reviews and state of the art reviews consists of both tabular and narrative analysis [28]. The goal of this process is to identify and extract information as it relates to the communication of gaze in co-present extended reality contexts, as well as fundamental information regarding study characteristics and approaches.

After evaluating the quality of the included publications (described in the appraisal section above), we conducted a close reading of the selected papers. The studies included in the corpus were heterogeneous in terms of domain and study type, and therefore reported on diverse types of information. Analysis of the text corpus to identify tasks, use cases, and conceptualizations of shared gaze and gaze tracking in shared, co-present XR experiences yielded a series of categories that allowed the extraction of consistent types of information across the corpus. We aggregate information about shared gaze implementation and study characteristics and present the findings in tabular form.

Synthesis: Findings from the Literature

We present our findings along five dimensions: types of XR technologies employed, eye tracking technology to record or employ gaze in XR experiences, research approaches, the method of how shared gaze is utilized, and research study characteristics.

Extended Reality Technology

Shared gaze studies utilized commodity technologies, including virtual reality, augmented reality, 360 displays, and custom display systems. The selected studies utilized 29 different extended reality technologies. Of those technologies, 11 were virtual reality headsets, 5 were augmented reality devices, 6 were custom systems. The most commonly utilized technologies were the Microsoft HoloLens (28%, n=14), HTC VIVE (24%, n=12), Oculus Rift (16%, n=8), and screen based VREs (14%, n=7). Most studies included multiple technologies, some of which combined multiple XR types (ex. AR & VR), and some utilized multiple technologies of the same types (ex. VR & VR).

Category	Subcategory	#	Sources
AR Handheld	Smartphone AR	1	[34]
AR HMD	HoloLens	14	[26], [34]–[44]
	Magic Leap	4	[45]–[48]
	Epson Moverio BT-200	1	[49]
	custom - Empathic Glasses	1	[43]
VR HMD	BinaryVR	1	[50]
	HTC Vive	12	[40]–[43], [51]–[57]
	Vive Pro Eye	2	[37], [45]
	Vive Pro	4	[25], [46], [48], [58]
	Oculus Rift	7	[53], [59]–[64]
	Oculus Quest	3	[53], [59], [65]
	Oculus Go	1	[66]
	NVIS nVisor SX111	1	[67]
	Dell Windows MR	1	[68]

	Desktop VRE	1	[69]
	FOVE VR HMD	1	[70]
Display	3 screen pseudo-CAVE	1	[71]
	Non immersive screen based VRE	7	[27], [61], [69], [72]–[75]
	Projection based VRE	2	[76], [77]
	Gloma 350	1	[51]
	Camera based VR	3	[54], [73], [78]
Custom system	The Octave - fully immersive display	1	[79]
	OmniGlobeVR	1	[51]
	OmniGlobe 360	1	[51]
	REFLCT, a head mounted projective display	1	[80]
	withyou, projection-based octave display	1	[76]
	CollaboVR	1	[64]
360 Camera	Richo Theta V1	2	[37], [51]
	360-degree video	1	[71]

Table 2. Extended reality technologies utilized within our corpus

Each display system uses different modes and mechanisms of interactions to generate a desired system output. Within the variety of XR systems identified within our corpus, we examined and determined the most commonly utilized user input and the related system outputs. The five most common types of user inputs included: eye gaze (64%, n=32), head position (28%, n=14), controller (28%, n=14), gesture (26%, n=13), and voice (18%, n=9). The most commonly used input was eye gaze, identified as an input in 64% of reviewed papers. The eye gaze category included the following terms: eye gaze, gaze ray, gaze patterns, gaze awareness, and gaze dwell. Gesturing was another common input method, including nonspecific gestures and hand gestures. A variety of other input methods were less used, such as facial expression, full-body tracking, and heart rate.

Input	#	%	Sources
Eye gaze	32	64	[25], [27], [34]–[39], [41]–[46], [48]–[50], [55]-[57], [62], [63], [65], [66], [69]–[73], [76], [78], [80]–[83]
Controller	14	28	[34], [35], [37], [40], [46], [52], [56]–[58], [65], [67], [70], [75], [81]
Head position	14	28	[39], [41]–[43], [48], [52], [55], [57], [60], [62], [69], [73], [78], [86]
Gesture	13	26	[35], [40], [42], [45]–[48], [50], [51], [53], [69], [74], [84]
Voice	9	18	[27], [39], [44], [51], [54], [60], [62], [79], [84]
Movement	7	14	[50], [59], [67], [71], [76], [77], [79]
Facial expression	5	10	[41], [49], [64], [68], [79]
Heart rate	2	4	[41], [49]
Text communication	2	4	[27], [57]

Table 3. Summary of user input mechanisms

The selected studies utilized 15 different types of system outputs. The five most common system outputs included: gaze visualization (64%, n=32), avatar representation (24%, n= 12), use of or as controller (16%, n=8), placement of annotations (10%, n=5), and display of facial expression (10%, n=5). A variety of other output methods were less commonly used, including changing viewpoints, communicating emotional states, speech recognition, and termination of the ray cast. A complete list of user inputs and system outputs is included in the tables below.

Output	#	%	Sources
Gaze Visualization	32	64	[25], [27], [36]–[44], [46], [48], [49], [53]–[56], [58], [60], [62], [66], [67], [69], [71]–[75], [78], [85], [86]
Avatar representation	12	24	[37], [43], [45], [48], [50], [59], [62], [63], [76], [83], [84], [86]
Controller	8	16	[34], [35], [39], [42], [46], [57], [70], [80]
Place annotations	5	10	[35], [54], [56], [65], [84]
Facial Expression	5	10	[49], [51], [71], [79], [83]
Gestures	4	8	[46], [51], [71], [79]
Voice Command	3	6	[27], [44], [74]
Change viewpoint	3	6	[34], [35], [65]
Render objects visible	2	4	[34], [57]
Body Tracking	2	4	[27], [77]
Emotion Communication	2	4	[41], [86]
Speech Recognition	1	2	[79]
Termination of Ray	1	2	[47]
Virtual Sound	1	2	[52]
Heart Rate Visualization	1	2	[41]

Table 4. Summary of system output mechanisms

Eye Tracking Technology

To enable shared gaze, eye tracking technologies are employed and integrated into the extended reality experiences. Eye-tracking devices are used to detect an individual's gaze direction and movements [81], [82]. Eye gaze behaviors are often characterized in terms of fixations and saccades (movement of eye gaze). Despite the few characteristics of eye gaze behaviors, there is a wide range of eye-tracking devices and approaches. These device types include eye tracking built into a head mounted display, external eye tracking glasses (Tobii pro), eye tracking bar devices, and Vuforia trackers. This review identified 16 different eye-tracking technologies. Of the 16 devices, 5 were eye trackers separate from the HMD and 5 were eye tracking enabled HMDs. The most used were Tobii eye trackers (22%, n = 11), HTC VIVE Pro/Pro Eye (26%, n = 13), and Microsoft HoloLens (24%, n=12). Other approaches used tools like the Pupil Labs (14%, n = 7) and aGlass eye tracker (8%, n = 4), yet some studies collected only approximate gaze through head position (12%, n=6) or used custom systems (6%, n= 3). Table 3 represents all of the eye tracking devices identified in this review.

Technology Type	Technology	#	%	Sources
Eye Trackers	Tobii Eye Tracker	11	22%	[27], [35], [38], [43], [57], [61], [64], [72], [74], [75], [78]
	Pupil Labs eye-tracker	7	14%	[38], [41]–[43], [49], [71], [73]
	aGlass Eye Tracker	4	8%	[44], [53], [55], [56]
	Advanced realtime tracking (ART) system	1	2%	[77]
	Ergoneers Dikablis gaze tracker	1	2%	[67]
Eye Tracking Enabled HMDs	HTC Vive Pro & Pro Eye	13	26%	[25], [37], [41]–[43], [45], [46], [48], [54]–[58]
	Microsoft HoloLens	12	24%	[26], [34]–[37], [39]–[44], [47]
	Magic Leap	3	6%	[46]–[48]
	FOVE VR	2	4%	[50], [70]
	BinaryVR HMD	1	2%	[50]
Other Approaches	Gaze estimation from head position	6	12%	[52], [59], [60], [62], [63], [65]
	Custom system	3	6%	[51], [76], [80]
	OptiTrack Marker balls	2	4%	[67], [71]
	Webcam & gaze recognition software	1	2%	[68]
	artificially generated, standard eye gaze data	1	2%	[66]
	Unspecified	1	2%	[79]

Table 5. Eye tracking devices and technologies.

The methods used to track eye gaze differ from the types of devices and technology utilized to execute eye gaze tracking. Standard techniques for tracking eye gaze utilize reflections in the eye using an infrared light, which enables effective gaze detection in different environmental lighting conditions [82]. This information is utilized and visualized in various ways, each with their own advantages and disadvantages. This review identified 11 eye tracking methods that were utilized within our corpus, as represented in table 4. Within the identified eye tracking methods, 28% used field of view (FOV) (n = 14), 28% used region of interest, ROI (n = 14), 16% fixation (n = 8), and 12% ray cast line (n = 6). Other methods that were less prevalent in our sample include frustum, heatmap, and depth map. A list of eye tracking methods we identified is included in table 4.

Eye Tracking Approach	#	%	Sources
FOV	14	28%	[35], [39], [40], [48], [51], [57], [59], [60], [63], [68], [70], [78], [79]
Region of Interest	14	28%	[27], [34], [36], [46], [52], [54], [61], [66], [69], [74]– [76], [80]
Fixations	8	16%	[26], [41], [44], [50], [55], [58], [72], [73]
Ray cast line	6	12%	[41]– [43], [45], [65], [77]
Point of focus	5	10%	[25], [26], [38], [56], [62]
Frustrum	4	8%	[41]– [43], [45]
Saccades	3	6%	[37], [49], [53]
Heatmap	3	6%	[47], [66], [71]
Facial expressions	1	2%	[49]
Gaze direction	1	2%	[67]
Depth map	1	2%	[64]

Table 6. Summary of eye tracking approaches

Research Approaches

Due to the variety of research questions that explore shared gaze in XR, we identified and sorted the aims from the research questions to understand the larger goals that motivate this area of research. Many studies include multiple research aims and fall into multiple categories. Four research aims were prominent in the selected studies: improving remote collaboration (62%, n=31), evaluating UX (46%, n=23), presenting their system (32%, n=16), and evaluating components of a system (26%, n=13). Six papers included aims beyond these categories, which included review methodology (n=4), metric development (n=1), and developing a training system (n=1).

Research Aims	#	%	Sources
Improve remote collaboration	31	62%	[25]–[27], [34], [37]–[40], [42], [43], [45]–[49], [51], [52], [55], [56], [60]–[63], [68], [71], [75]–[79]
Evaluate UX	23	46%	[26], [27], [34], [38], [43], [45], [46], [51], [53], [54], [57], [61], [65], [67]–[70], [72]–[76], [80]
Present their system	16	32%	[35], [37], [42], [44], [48]–[51], [56], [60], [64], [71], [74], [77], [80]
Evaluate components of a system	13	26%	[36], [40], [45], [52], [53], [58], [60], [66], [67], [69], [76], [79]
Review methodology	3	6%	[47], [50], [58]
Metric development	1	2%	[65]
Develop a training system	1	2%	[59]

Table 7. Research aims identified from research questions

We classified the methods utilized within the selected studies. The two main types of methods employed were experimental designs and prototype-based designs. Experimental methods represented 62% of the sample and within this category, we identified four types: within-subject (28%, n=14), within-group (18%, n=9), mixed methods (28%, n=14), and between groups (2%, n=1). Within-subject experimental designs were the most prominent method within our sample. Prototype based methods represented 38% of the total sample and within this category, we identified six types. Of those, the most used were user experience presentation (14%, n=7), evaluation (8%, n=4), and within subject (8%, n=4).

Method	Type	#	Sources
Experiment	Within subject	14	[25], [26], [38], [40], [46], [53]–[55], [59], [67], [68], [71], [73], [78]
	Mixed	7	[34], [57], [61]–[63], [74], [75]
	Within group	9	[27], [39], [47], [52], [58], [60], [69], [70], [72]
	Between Groups	1	[65]
Prototype	User Experience Presentation	7	[35], [36], [41], [42], [49], [76], [79]
	Evaluation	4	[44], [50], [64], [66]
	User Survey	1	[37]
	Within group	2	[51], [77]
	Within Subject	4	[43], [45], [48], [56]
	Between Subjects	1	[80]

Table 8. Summary of research methods utilized

Shared Gaze Utilization

We evaluated how and to what end shared gaze was utilized within our sample. Eight types of shared gaze were identified in the text corpus that enable communication between users. These were: shared gaze awareness (44%, n=22), copresence (30%, n=15), focus & attention (28%, n=14), gaze direction (18%, n=9), avatar gaze (14%, n=7), behavior awareness (14%, n=7), target identification (12%, n=6), and interactional gaze (6%, n=3). Of these, shared gaze awareness was the most predominant form of communication. Shared gaze awareness differs from shared gaze in that it includes a user's perception of another user's gaze.

Shared Gaze Utilization	#	%	Sources
Shared Gaze Awareness	22	44%	[27], [34], [35], [39], [41], [43]–[47], [50], [51], [54], [55], [60], [65], [67], [69], [71], [72], [74], [77]
Copresence	15	30%	[37], [40], [42], [43], [52]–[54], [56], [57], [61], [63], [67], [68], [74], [76]
Focus and Attention	14	28%	[34], [37], [41], [46], [47], [49], [54], [56], [57], [59], [62], [66], [71], [75]
Gaze Direction	9	18%	[38], [40], [42], [44], [47], [48], [58], [73], [78]
Avatar gaze	7	14%	[61], [62], [67], [68], [79], [80], [83]
Behavior awareness	7	14%	[35], [36], [40], [42], [52], [63], [66]
Target Identification	6	12%	[25], [26], [38], [44], [48], [69]
Interactional Gaze	3	6%	[35], [70], [79]

Table 9. Approaches to utilizing shared gaze

Research Study Characteristics

Within the text corpus, gaze sharing was implemented in a variety of applications and use cases for XR systems. The most frequently mentioned use cases were collaboration and communication (n=49), teaching and learning (n=11), gaming (n = 10), and HCI & HCC (n=7). Almost every study was included in some aspect of collaboration & communication. This category was broken down into six subcategories, the most common were general collaboration & communication (60%, n=30), non-verbal cue communication (18%, n=9), and teleconferencing (10%, n=5). Other potential use cases included manufacturing & industrial assembly, health, wellbeing & therapy, and architectural modeling. A complete list of use cases is included in table 8 below.

Use cases	Sub – use cases	#	%	Sources
Collaboration & Communication	All Collaboration & Communication	30	60%	[25]–[27], [34], [36], [37], [39]–[41], [43], [45], [46], [48], [50]–[52], [56], [57], [61]–[63], [65], [68], [69], [71], [75]–[77], [80], [83]
	Non-verbal cues	9	18%	[40], [46], [48], [56], [61]–[63], [65], [75]
	Teleconferencing & meetings	5	10%	[57], [61], [75], [77], [83]
	Avatar visualization	3	6%	[61], [68], [80]
	Wide-area awareness	1	2%	[25]
	Collaborative writing	1	2%	[27]
Gaming	All Gaming	8	16%	[27], [44], [51], [53], [57], [72], [77], [80]
	Social VR gaming	1	2%	[53]
	Board & card games	1	2%	[72]
Teaching, Training, & Learning		11	22%	[43], [47], [55], [58], [59], [62], [65], [66], [78]–[80]
HCC & HCI		7	14%	[38], [41], [43], [44], [47], [50], [70]
Manufacturing & Industrial Assembly		4	8%	[36], [54], [55], [73]
Empathic Computing		3	6%	[42], [49], [71]
Manufacturing & Industrial Assembly		3	6%	[54], [55], [73]
Music, Dance & Entertainment		3	6%	[45], [60], [67]
Large Machine Maintenance & Control Room		2	4%	[45], [57]
Health, Wellbeing & Therapy		2	4%	[74], [76]
Policing		1	2%	[38]
Architectural modeling		1	2%	[35]

Table 10. Summary of use cases identified

Within the variety of potential use cases we identified, there is a wide range of tasks that were completed or examined. Overall, we identified 14 types of tasks, all of which focus on different aspects of collaboration or completing collaborative tasks. The most frequently observed tasks were task completion (28%, n=14), identification tasks (22%, n=11), managing collaborative work (20%, n=10), task tracking (18%, n=9), and navigation and orientation tasks (18%, n=9). The full list of observed tasks is listed in table 9 below.

Task type	#	%	Sources
Task completion	14	28%	[25], [26], [34]–[36], [43], [54]–[56], [66], [67], [75], [78]
Identification task	11	22%	[26], [37], [40], [43], [44], [48], [67], [69], [70], [73], [77]
Manage collaborative work	10	20%	[27], [37], [39], [41], [45], [47], [52], [60], [68], [79]
Task tracking	9	18%	[37], [38], [41], [53], [57], [62], [65], [71], [73]
Navigation & Orientation	9	18%	[35], [38], [45], [46], [48], [55], [66], [70], [73]
Interaction	7	14%	[27], [42], [44], [49], [58], [61], [83]
Guidance & Training	5	10%	[46], [51], [54], [59], [65]
Conversation simulation	5	10%	[50], [52], [63], [80], [83]
Gaming	5	10%	[25], [53], [57], [74], [80]
Assessment	4	8%	[60], [68], [69], [72]
Exploration	2	4%	[57], [62]
Monitoring	2	4%	[43], [46]
Emotion communication	2	4%	[43], [71]
Recall	1	2%	[73]

Table 11. Summary of task types identified

We compiled the most commonly identified research findings from the selected studies. Of the many results, five main results occurred more often and throughout the whole corpus: improved collaboration/performance, improved co-presence, improvement with inclusion of non-verbal cues, reduced cognitive load, and avatar representation improvement. The most frequent result being improved collaboration/performance (74%, n=37) from the use of eye gaze in various use scenarios of collaboration in XR. The second most common result was improved co-presence from use of eye gaze (42%, n=21). Some studies combined hand, body, and face gestures in their study in addition to eye gaze and saw improvement in performance (26%, n=13). Some studies recorded avatar representation was improved through the use of shared gaze (14%, n=7). Lastly, studies reported reduced cognitive load from the use of eye gaze in their studies (8%, n=4). Some studies had a combination of two (n=14) or three (n=9) of the categories, but none had four or all four categories in their results. For an alternative view of these findings presented in a matrix format, see appendix C.

Results	#	%	Sources
Improved collaboration/ performance	37	74%	[25], [27], [34]–[45], [48], [50], [53], [56]–[60], [63], [65], [66], [69], [70], [72]–[75], [77], [78], [83]–[85]
Improved co-presence	20	40%	[27], [37], [46]–[48], [50]–[52], [54], [62], [67], [71], [72], [76], [77], [79], [80], [83], [84], [86]
Improvement with inclusion of non-verbal cues	12	24%	[42], [43], [45], [46], [48], [49], [52], [55], [67], [69], [76], [86]
Avatar representation improvement	7	14%	[43], [45], [53], [66], [69], [71], [83]
Reduced cognitive load	4	8%	[37], [46], [52], [85]

Table 12. Main research findings featured across the entire corpus

Discussion

This review elucidates a state-of-the-field of an aspect of embodied information behavior – shared gaze – within shared, co-present experiences across multiple extended reality technologies along the Reality-Virtuality Continuum. To reveal how shared gaze is conceptualized in contemporary research (2013 to 2021) that incorporates co-presence in XR, this review analyzes the technology, research approaches, and applications in which shared gaze and gaze tracking are being applied in shared XR experiences. Developing an understanding along these dimensions provides insight into specific topical areas within this research that are actively being explored or are in need of further exploration.

This review focuses on studies that utilized eye tracking technologies to capture gaze behaviors. Both looking and observing another person's gaze are embodied information behaviors as they are mechanisms of information seeking that rely on an individual's embodiment. The process and behavior of looking, rather than the information perceived, is embodied and shaped by the morphology and sensory capabilities of the user's body [6]. Like all other information behaviors, looking is situated within the environment it takes place in and environmental cues, like associated social behaviors that relate to that context [87]. A familiar setting, like a classroom, is likely to evoke different information behaviors than unfamiliar or novel settings, like data driven or fantastical environments. The process of utilizing information behaviors and extracting information relies on nonconscious processes and tacit knowledge [10] that is necessary to consider when evaluating the larger behavior of looking.

In real world contexts, detecting other peoples' eye gaze is not limited to observing another person's eyes or pupils, rather it relies on the integration of eye gaze direction, head positioning, and body orientation [88], [89]. The perception of other's eye gaze in XR is more challenging as it relies on mediating gaze via digital avatars with varied levels of fidelity. These methods often convey incomplete information about one's inner state in co-present XR experiences. Gaze information can be supplemented with deictic references, like pointing gestures or phrases, to coordinate attention and collaboration [90]. Virtual contexts create constraints for these behaviors through sensory limitations caused by the technology used or design elements, like avatar representation. Shared, social gaze implementation can be understood and evaluated from the influences of human behavior, design, and technology [91].

Considering the research aims or motivations of the reviewed studies, which focused on enabling remote collaboration and evaluating user experience with a system, as well as the research methodologies employed, which prominently featured within subjects study designs, we can surmise that the research focused on small scale studies that included few participants. One limitation of applications of shared gaze is that it is often constrained to experiences that only include two people [27]. Research studies that employ shared gaze investigate these interactions and perceptions from a smaller scale, either individual or interpersonal. This method of investigation can provide insight into how shared gaze affects and reflects a user's inner state and is likely to include aspects of embodiment.

The utilization of shared gaze was found to commonly augment or enable communication through the generation of shared gaze awareness, guided attentional allocation, and increased co-presence. An unexpected finding in the corpus is the large number of studies that examined the perception of shared gaze, as opposed to the mechanisms for enabling the sharing of gaze. Use cases included applications of shared gaze in a wide range of domains, such as health, construction, and entertainment. An equally wide range of tasks is represented within these domains that utilize shared gaze to support collaborative work and task completion. Future research indicated in the corpus includes perceptual studies to understand how shared gaze awareness is utilized to improve collaboration or to generate joint attention. An opportunity to expand future research is to investigate how to scale gaze-based interactions in multi-user XR contexts beyond dyads or triads. Do the design considerations for dyads or small groups scale to crowds, or do these require distinct approaches?

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Appendix A
Search Queries

Tech	Database	Query with applied filter (as interpreted by the database)
VR	ACM Digital Libraries	[[multiuser] OR [All: "multi user"] OR [All: "multiple user"] OR [All: multiplayer] OR [All: collabor*]] AND [[All: "eye tracking"] OR [All: gaze] OR [All: "eye gaze"] OR [All: "gaze tracking"]] AND [[All: "virtual reality"] OR [All: vr]] AND [All: "shared gaze"] AND [Publication Date: (01/01/2013 TO 11/30/2021)]
AR	ACM Digital Libraries	(Multiuser OR "multi user" OR "multiple user" OR multiplayer OR collabor*) AND ("eye tracking" OR gaze OR "eye gaze" OR "gaze tracking") AND ("augmented reality" OR AR) AND ("shared gaze")
MR	ACM Digital Libraries	(Multiuser OR "multi user" OR "multiple user" OR multiplayer OR collabor*) AND ("eye tracking" OR gaze OR "eye gaze" OR "gaze tracking") AND ("mixed reality" OR MR) AND ("shared gaze")
XR	ACM Digital Libraries	(Multiuser OR "multi user" OR "multiple user" OR multiplayer OR collabor*) AND ("eye tracking" OR gaze OR "eye gaze" OR "gaze tracking") AND ("extended reality" OR XR) AND ("shared gaze")
VR	IEEEXplore	(Multiuser OR multi user OR multiple user OR multiplayer OR collabor*) AND (Eye tracking OR gaze OR eye gaze OR gaze tracking) AND (virtual reality OR VR) shared gaze Filters Applied: 2013 - 2021
AR	IEEEXplore	(Multiuser OR multi user OR multiple user OR multiplayer OR collabor*) AND (Eye tracking OR gaze OR eye gaze OR gaze tracking) AND (augmented reality OR AR) shared gaze Filters Applied: 2013 - 2021
MR	IEEEXplore	(Multiuser OR multi user OR multiple user OR multiplayer OR collabor*) AND (Eye tracking OR gaze OR eye gaze OR gaze tracking) AND (mixed reality OR MR) shared gaze Filters Applied: 2013 - 2021
XR	IEEEXplore	(Multiuser OR multi user OR multiple user OR multiplayer OR collabor*) AND (Eye tracking OR gaze OR eye gaze OR gaze tracking) AND (extended reality OR XR) shared gaze Filters Applied: 2013 - 2021
VR	SCOPUS	(TITLE-ABS-KEY ((multiuser OR (multi AND user) OR (multiple AND user) OR multiplayer OR collabor*) AND ((eye AND tracking) OR gaze OR (eye AND gaze) OR (gaze AND tracking)) AND ((virtual AND reality) OR vr))) AND (shared AND gaze) AND (LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013))
AR	SCOPUS	(TITLE-ABS-KEY ((multiuser OR (multi AND user) OR (multiple AND user) OR multiplayer OR collabor*) AND ((eye AND tracking) OR gaze OR (eye AND gaze) OR (gaze AND tracking)) AND ((augmented AND reality) OR ar))) AND (shared AND gaze) AND (LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013))
MR	SCOPUS	(TITLE-ABS-KEY (((multiuser OR (multi AND user) OR (multiple AND user) OR multiplayer OR collabor*) AND ((eye AND tracking) OR gaze OR (eye AND gaze) OR (gaze AND tracking)) AND ((mixed AND reality) OR mr)))) AND (shared AND gaze) AND (LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2013))
XR	SCOPUS	(TITLE-ABS-KEY (((multiuser OR (multi AND user) OR (multiple AND user) OR multiplayer OR collabor*) AND ((eye AND tracking) OR gaze OR (eye AND gaze) OR (gaze AND tracking)) AND ((extended AND reality) OR xr)))) AND (shared AND gaze) AND (LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2013))
VR	Web of Science	(Multiuser OR multi user OR multiple user OR multiplayer OR collabor*) AND (Eye tracking OR gaze OR eye gaze OR gaze tracking) AND (virtual reality OR VR) Search within all fields: (Shared And Gaze) Publication years 2013 - 2021
AR	Web of Science	(Multiuser OR multi user OR multiple user OR multiplayer OR collabor*) AND (Eye tracking OR gaze OR eye gaze OR gaze tracking) AND (augmented reality OR AR) Search within all fields: (Shared And Gaze) Publication years 2013 - 2021

MR	Web of Science	(Multiuser OR multi user OR multiple user OR multiplayer OR collabor*) AND (Eye tracking OR gaze OR eye gaze OR gaze tracking) AND (mixed reality OR MR) Search within all fields: (Shared gaze) Publication years 2013 - 2021
XR	Web of Science	(Multiuser OR multi user OR multiple user OR multiplayer OR collabor*) AND (Eye tracking OR gaze OR eye gaze OR gaze tracking) AND (extended reality OR XR) Search within all fields: (Shared gaze) Publication years 2013 - 2021

Appendix B

QualSyst Criteria

#	Criteria
1	Question/objective sufficiently described?
2	Study design evident and appropriate?
3	Method of subject/comparison group selection or source of information/input variables described and appropriate?
4	Subject (and comparison group, if applicable) characteristics sufficiently described?
5	If interventional and random allocation was possible, was it described?
6	If interventional and blinding of investigators was possible, was it reported?
7	If interventional and blinding of subjects was possible, was it reported?
8	Outcome and (if applicable) exposure measure(s) well defined and robust to measure/misclassification bias? Means of assessment reported?
9	Sample size appropriate?
10	Analytic methods described/justified and appropriate?
11	Some estimate of variance is reported for the main results?
12	Controlled for confounding?
13	Results reported in sufficient detail?
14	Conclusion supported by the results?

See reference for additional protocol and scoring:

[30] L. M. Kmet, L. S. Cook, and R. C. Lee, Standard Quality Assessment Criteria for Evaluating Primary Research Papers from a Variety of Fields. 2004. doi: 10.7939/R37M04F16.

Appendix C

Results Matrix

See table 12, in the Research Characteristics section for additional context.

Author	Improved collaboration/ performance	Improved co-presence	Improvement with inclusion of non-verbal cues	Reduced cognitive load	Avatar representation improvement
[77]	x	x	x		
[48]	x	x	x		
[37]	x	x		x	
[64]	x	x			x
[61]	x	x			
[27]	x	x			
[72]	x	x			
[60]	x	x			
[50]	x	x			
[47]	x	x			
[69]	x		x		x
[45]	x		x		x
[43]	x		x		x
[42]	x		x		
[26]	x			x	
[53]	x				x
[66]	x				x
[75]	x				
[73]	x				
[34]	x				
[65]	x				
[25]	x				
[38]	x				
[63]	x				
[41]	x				
[40]	x				
[58]	x				
[39]	x				
[44]	x				
[57]	x				
[78]	x				
[56]	x				
[74]	x				
[36]	x				
[35]	x				
[70]	x				
[59]	x				

[46]		x	x	x	
[52]		x	x	x	
[67]		x	x		
[68]		x	x		
[76]		x	x		
[71]		x			x
[62]		x			
[79]		x			
[80]		x			
[51]		x			
[54]		x			
[49]			x		
[55]			x		