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Review Article

Interaction Strategies in Augmented Reality-Situated Visualization for Decision Support: A Systematic Literature Review

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ABSTRACT

This systematic literature review (SLR) investigates interaction strategies in augmented reality (AR)-situated visualizations that support decision-making tasks. Despite its growing relevance, a gap remains in understanding how users interact with these systems to perform decision-related tasks. This review aims to examine how various interaction modalities contribute to effective user engagement in decision-making contexts. A total of 23 peer-reviewed studies, published between 2016 and 2024, were analyzed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological rigor and conceptual alignment. The review focuses on device types, manipulation methods, and interaction modalities. Findings indicate that head-mounted displays (HMDs) are commonly used in immersive settings, while hand-held devices (HHDs) are preferred for their portability and affordability. Touchscreen interaction dominates among HHDs, enabling direct manipulation, while gesture and voice commands are more prominent in HMD-based systems. A conceptual mapping aligns these modalities with manipulation methods such as selection, navigation, and filtering based on Brehmer and Munzner's typology. This review also highlights key challenges, including limited collaborative support, usability concerns, and underrepresentation of domains such as industrial training and public events. This work provides a structured foundation for designing AR-situated visualization systems that better support decision-making across diverse application contexts.

Keywords: Augmented reality, decision-making, situated visualization, user interaction

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INTRODUCTION

Decision-making is a complex cognitive process integral to human behavior, influencing actions across diverse environments and contexts (Darioshi & Lahav, 2021). It involves selecting an option from a set of alternatives, each assessed against specific criteria to achieve a defined goal. Wang and Ruhe (2007) highlights that effective decision-making requires individuals to be well-informed and possess relevant information for evaluating various options. Research into user decision-making processes and the quality of decisions has been a focal point across multiple fields (Ceschi et al., 2017; Carneiro et al., 2019; Stanitsa et al., 2022). Technological advancements have revolutionized how people access, analyze, and utilize information, reshaping decision-making landscapes and influencing cognitive processes and human behavior (Osiurak et al., 2018; Bonicalzi et al., 2023; Shanmugasundaram & Tamilarasu, 2023). In the context of context-aware interactive systems, especially those delivering real-time or location-specific data, effective decision-making depends not only on access to relevant information but also on how that information is presented and interacted with. The way information is presented and interacted with within a user interface (UI) can significantly influence users' decision-making processes (Starke & Baber, 2018; Peng, 2024). However, the increasing volume of available information has led to the challenge of information overload, which can interfere with decision-making by increasing cognitive load (Roetzel, 2019).

With the rise of emerging technologies such as AR, users now engage with information in immersive and spatially anchored formats that reshape decision behaviors. AR refers to a technology that overlays virtual content onto the real world in real time, aligning digital elements with the user's physical environment to support enhanced perception and interaction (Azuma, 1997). A key application of AR in visualization is through the situated visualization approach, which has become prominent in recent information visualization research (Bressa et al., 2022). Situated visualization integrates virtual data within the physical context of a site, thereby enhancing users' understanding of and interaction with their surroundings (White & Feiner, 2009). The defining feature of this approach is contextual relevance, where data is embedded within the environment to support real-world decision-making (Thomas et al., 2018).

In decision-making scenarios, AR-situated visualizations offer immersive and interactive experiences. By blending virtual objects with real-world environments, AR delivers relevant, contextual information, fostering informed decisions and improving overall decision-making processes (Chen et al., 2024). These benefits have been demonstrated across multiple domains, including agriculture (Zheng & Campbell, 2019), smart home environments (Zheng et al., 2022), shopping environments (Xu et al., 2022; Han et al., 2023), and healthcare (Tanbeer & Sykes, 2024). In AR-situated visualization, decision-making involves users interacting with spatially embedded information to assess options, compare alternatives, and make informed choices within real-world environments.

Despite its advantages, designing effective AR-situated visualizations for decision-making presents challenges. These include ensuring contextual relevance without overwhelming users with excess information, addressing the varying technical skills and visual capabilities of users (Martins et al., 2023) and creating seamless, intuitive integration into real-world environments (Zhu et al., 2024). Marques et al. (2019) explored the use of AR and situated visualization in decision support systems (DSS), highlighting benefits like improved efficiency, better contextual understanding, and interdisciplinary research opportunities. Martins et al. (2022) refined this framework, focusing on dimensions like space, time, and community, but noted limited empirical validation. Zhu et al. (2024) proposed innovative interaction techniques, including eye-based, hand-based, and spatially aware inputs, to improve usability and engagement in public AR-situated visualization settings. Zheng et al. (2024) further advanced the field by introducing a taxonomy for AR data visualization based on semantic data-reality relationships, demonstrating AR's ability to enhance efficiency, reduce cognitive load, and provide context-aware decision support.

While extensive research has explored the role of AR in decision-making, gaps remain in understanding how AR-situated visualizations can be effectively designed to support these processes. This study addresses this gap by analyzing how AR facilitates decision-making through the presentation of situated information. The study focuses on interaction strategies that enable users to engage effectively with AR-situated visualization data, emphasizing gesture-based controls, touch interfaces, and context-aware interactions.

To ensure a structured and unbiased examination of existing literature, this study adopts an SLR approach. A SLR is a research methodology used to systematically collect, identify, and critically analyze existing studies such as journal articles, conference proceedings, books, and dissertations with the aim of summarizing current knowledge on a specific topic and identifying gaps for future research (Carrera-Rivera et al., 2022). This study examines the interconnection of AR-situated visualization, interaction design, and decision-making processes across various fields. The research aims to provide concrete, applicable findings to enhance AR-situated visualization development and application. The review's core objective is to analyze decision-making task performance using AR-situated visualizations. The study's direction was shaped by specific research questions and their underlying reasoning, detailed in Table 1.

This review is important for advancing the design of AR-situated visualization systems and fostering innovation in decision-making applications for many fields.

Table 1
Research questions and corresponding rationales for conducting the SLR study

No.	Research question	Rationale
RQ1	How does AR-situated visualization support and enhance decision-making processes across various domains?	To uncover the potential of AR-situated visualizations by identifying the application areas and decision categories they impact, and demonstrate how they enhance decision-making across diverse fields
RQ2	What are the predominant AR device technologies examined in research on AR-situated visualization to support decision-making processes?	To highlight the technological advancements driving AR-situated visualization research by identifying the predominant AR devices and their critical roles in enabling effective and efficient decision-making processes
RQ3	How do users interact with AR-situated visualizations to support decision-making processes?	To advance the understanding of user engagement with AR-situated visualizations in facilitating information interpretation and decision-making

Note. SLR = Systematic literature review; RQ = Research question; AR = Augmented reality

MATERIALS AND METHODS

The methodology adheres to the PRISMA framework (Moher et al., 2010) and incorporates an adapted version of the flow diagram from Siean and Vatavu (2021), shown in Figure 1.

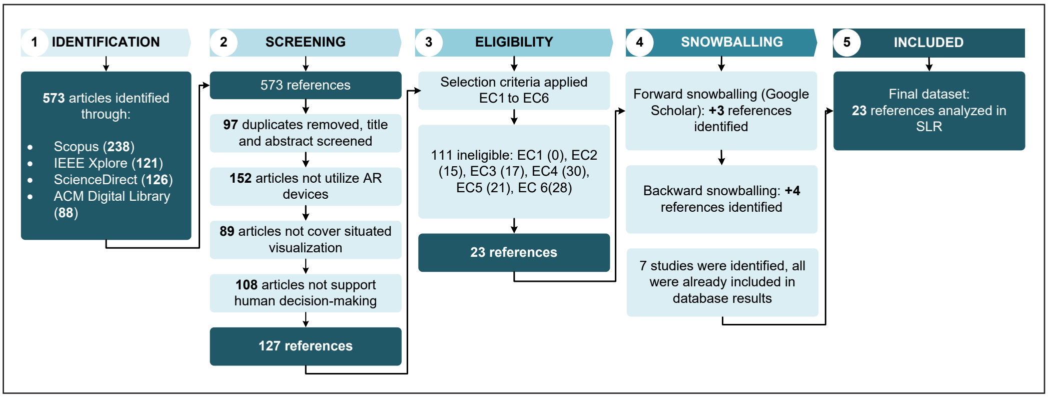

Figure 1. PRISMA-based flow diagram of the study (adapted from Siean & Vatavu, 2021)
Note. PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-Analyses; IEEE = Institute of Electrical and Electronics Engineers; ACM = Association for Computing Machinery; AR = Augmented reality; EC = Eligibility criteria; SLR = Systematic literature review

Identification

The SLR employed a meticulous search methodology to locate pertinent research examining the impact of AR-situated visualization on decision-making processes. Multiple prestigious scholarly databases were utilized:

- ScienceDirect,
- Scopus

- ACM Digital Library
- IEEE Xplore

These repositories were chosen due to their comprehensive coverage of AR, human-computer interaction (HCI), and decision-making scholarship.

To ensure both breadth and precision in identifying relevant literature, a staged Boolean search strategy was employed. The initial search queries were constructed using three core concept blocks: (1) AR, (2) situated visualization, and (3) decision-making. This approach aimed to capture a comprehensive set of studies that address the foundational aspects of AR-based DSS. Based on preliminary screening and the review's evolving focus on user interaction, a fourth concept block (4), interaction techniques, was later introduced to refine the search results.

A structured approach was used to craft precise yet inclusive search queries, combining relevant keywords with Boolean operators. Keywords included terms such as "Augmented Reality", "Situated Visualization", and "Decision-Making", along with related phrases like "User Interaction" and "AR Devices". Boolean operators were applied strategically to refine and optimize the search results, with the query structure summarized in Table 2.

Table 2
Boolean search string used to retrieve relevant studies on AR-situated visualization, decision-making, and user interaction for the SLR

Boolean operators
("Augmented Reality" OR "AR") AND ("Situated Visualization" OR "In-situ Visualization OR Visualization") AND ("Decision-Making" OR "Decision Support OR "Decision Task") AND ("User Interaction" OR "Interaction Technique")

Note. AR = Augmented reality; SLR = Systematic literature review

Screening

The database search yielded 573 references, from which 97 duplicate entries were removed, resulting in 476 distinct titles for abstract evaluation. Each abstract underwent thorough analysis to assess its alignment with the research focus on AR-situated visualization and decision-making processes.

The screening procedure eliminated references according to specific criteria:

- 152 papers were discarded due to their absence of AR technology implementation. Though some examined visualization or decision-making in various settings, they fell outside the review's parameters due to a lack of AR components.
- 89 publications were removed for not incorporating situated visualization elements. These works concentrated mainly on standard visualization techniques or AR applications that did not encompass situated visualization principles.

- 108 articles were excluded because they lacked an investigation into decision-making aspects. Despite featuring AR and situated visualization components, these studies did not address the core research objective of exploring the impact of AR-situated visualization on decision-making processes.

Following this comprehensive screening approach, 127 references qualified as suitable and progressed to the eligibility stage.

Eligibility

In the eligibility stage, a comprehensive review was conducted on the complete content of 127 references that had passed the screening phase. This stage employed six specific eligibility criteria (EC), detailed in Table 3, to further narrow down the selection and maintain alignment with the research goals. These carefully crafted criteria served to identify studies of sufficient quality and relevance. Each publication underwent a thorough assessment against these requirements to determine whether it qualified for inclusion. Articles were removed from consideration if they:

- Had publication dates earlier than 2016,
- Were not published in English,
- Examined technologies excluding AR,
- Omitted situated visualization components,
- Did not include decision-making elements, or
- Did not present a concrete system or application.

Publications that satisfied all six criteria were selected for further analysis, while those failing any criterion were eliminated. This meticulous evaluation process yielded a final

Table 3
Eligibility criteria (EC) for selecting studies included in the SLR, detailing both the inclusion and exclusion conditions

No.	Criterion	Inclusion	Exclusion
EC1	Language	Articles written in English	Articles written in non-English
EC2	Timeline	Published between 2016 and 2024	Published before 2016
EC3	Technology deployment	Utilize AR technology for deployment	Does not utilize AR technology
EC4	Articles related to studies	Focus on situated visualization studies	Focus on non-situated visualization studies
EC5	User tasks support	Studies that support decision-making tasks	Studies that do not support decision-making tasks
EC6	Implementation of the system/application	Present an implemented system, prototype, or application of the proposed AR approach	Theoretical or conceptual studies without implementation

Note. SLR = Systematic literature review; AR = Augmented reality collection of 16 references that specifically matched the study's intended focus, ensuring the maintenance of relevance and uniformity throughout the review process.

Snowballing

A database search was conducted as the primary method, complemented by snowballing techniques to enhance the completeness of the study selection. The snowballing process involved both backward and forward chaining, identifying four studies through backward chaining and three through forward chaining, based on 83 Google Scholar citations. However, all seven studies were already present in the database results, contributing no additional unique articles. This step confirmed the completeness of the initial database search. The final dataset comprised 23 peer-reviewed publications spanning from 2016 to August 2024. The selection process is illustrated in Figure 1.

Data Extraction and Synthesis

The systematic integration of findings from 23 selected studies involved a comprehensive data extraction and synthesis methodology to address the research questions. The extracted information encompassed:

- Basic study identifiers: authors, year of publication, and work title.
- Publication source and publisher information.
- Categories of AR equipment, including portable devices and wearable displays.
- Types of decision-oriented activities.
- User interaction strategies.
- Study constraints and limitations noted by researchers.

The synthesis methodology incorporated dual analytical approaches:

- Quantitative analysis: Identified patterns in AR technology adoption, fields of application, and interaction methodologies, establishing a broad research context.
- Qualitative analysis: Uncovered common themes and challenges across studies.

The results were organized and displayed through structured tables and visual representations to maintain clarity and alignment with the research objective.

Data analysis and classification aligned with specific research questions and their underlying purposes:

- RQ1: Explored domains of application and decision support categories influenced by AR-situated visualizations.
- RQ2: Analyzed technical implementations and AR device classifications in immersive settings.
- RQ3: Investigated user interaction approaches using the taxonomy of interaction techniques for immersive AR proposed by Hertel et al. (2021). This framework

structured the analysis of interaction techniques, mapping them to the multi-level typology of abstract visualization tasks by Brehmer and Munzner (2013). These tasks included *selecting*, *navigating*, *arranging*, *changing*, *filtering*, and *aggregating*, providing a comprehensive perspective on user engagement.

RESULTS AND DISCUSSION

This section presents the results from the 23 reviewed articles, summarized in Table 4. The articles published between 2016 and August 2024 explore AR-situated visualization as an innovative solution to support and enhance decision-making experiences.

Overview of Application Areas and Decision Categories (RQ1)

The existing research reveals various implementations of AR-situated visualization for facilitating decision-making, as shown in Figure 2. The retail sector emerges as the primary domain, representing 35% of studies, with eight investigations centered on improving the shopping experience. Agricultural applications, healthcare, domestic spaces, and maintenance each contribute two studies to the literature. Several other fields have single-study representations, encompassing transportation safety, street navigation, classroom environments, business operations, entomology, sports, and aquaculture.

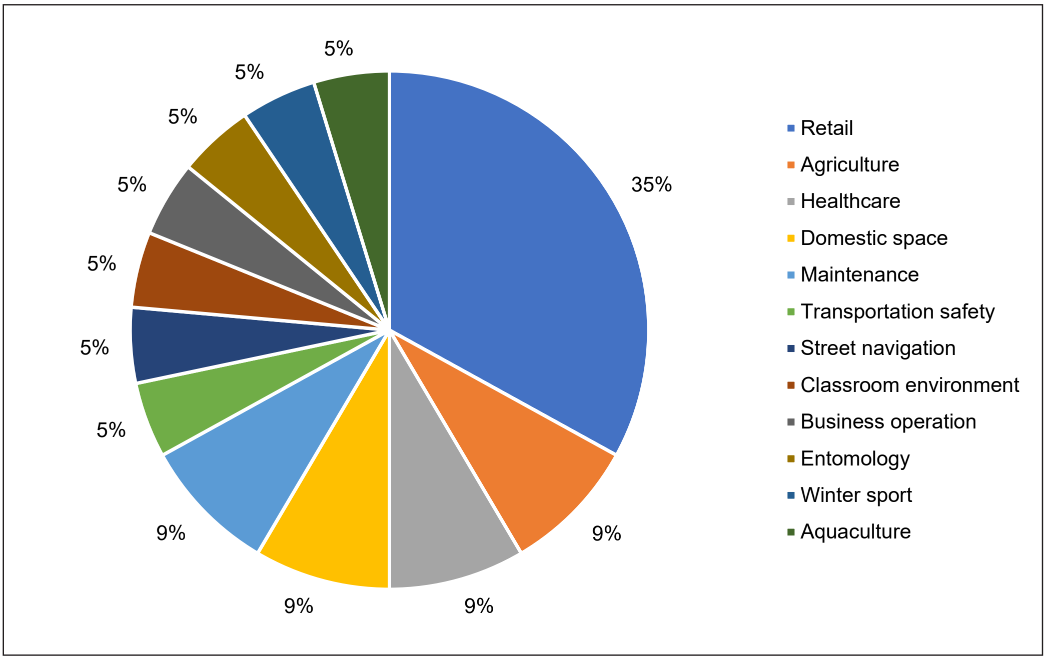

Figure 2. Distribution of application areas identified in studies utilizing augmented reality-based situated visualization from 2016 to August 2024

Table 4
Overview of the studies included in the SLR, summarizing key information such as article title, authorship, publication year, source, publisher, and AR application

No.	Title	Reference	Source	Publisher/Database	AR application/system
1	MiVitals-*Mi*xed Reality Interface for *Vitals* Monitoring: A HoloLens based prototype for healthcare practices	Tanbeer and Sykes (2024)	Computational and Structural Biotechnology Journal	Elsevier/ ScienceDirect	MiVitals
2	BerryScope: AR strawberry picking aid	Tamura et al. (2023)	Proceedings of the 2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct	IEEE	BerryScope
3	PMM: A smart shopping guider based on mobile AR	Han et al. (2023)	Proceedings of the 16th International Symposium on Visual Information Communication and Interaction	ACM	PMM
4	BeeAR: Augmented reality beeline navigation for spatial knowledge acquisition	Mazurkiewicz et al. (2023)	Proceedings of the ACM on Human-Computer Interaction	ACM	BeeAR
5	Using smart glasses to support situated decision making in aquaculture	Xi et al. (2023)	Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems	ACM	Pondside Visualization System
6	BikeAR: Understanding cyclists' crossing decision-making at uncontrolled intersections using augmented reality	Matviienko et al. (2022)	Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems	ACM	BikeAR
7	STARE: Augmented reality data visualization for explainable decision support in smart environments	Zheng et al. (2022)	IEEE Access	IEEE	STARE
8	ARShopping: In-store shopping decision support through augmented reality and immersive visualization	Xu et al. (2022)	Proceedings of the 2022 IEEE Visualization Conference	IEEE	ARShopping

Table 4 *(continue)*

No.	Title	Reference	Source	Publisher/Database	AR application/system
9	Informed ShoppAR - visualizing privacy information in augmented reality	Kaiser et al. (2022)	Proceedings of Mensch und Computer 2022	ACM	Informed ShoppAR
10	Augmented situated visualization methods towards electromagnetic compatibility testing	Guarese et al. (2021)	Computers and Graphics (Pergamon)	Elsevier	ASV
11	VacuumCleanAR: Augmented reality-based self-explanatory physical artifacts	Ludwig et al. (2020)	Proceeding of the 2020 Conference on Mensch und Computer	ACM	VacuumCleanAR
12	Augmented situated visualization for spatial and context-aware decision-making	Guarese et al. (2020)	Proceedings of the 2020 International Conference on Advanced Visual Interfaces	ACM	ASV
13	Occupational therapy meets design: An augmented reality tool for assistive home modifications	Aoyama and Aflatoony (2021)	Proceedings of the 2nd Australian Computer-Human Interaction Conference	ACM	Home-modification AR
14	Location-based augmented reality in-situ visualization applied for agricultural fieldwork navigation	Zheng and Campbell (2019)	Adjunct Proceedings of the 2019 IEEE International Symposium on Mixed and Augmented Reality	IEEE	Location-based AR in-situ visualization and fieldwork navigation system
15	Augmented-reality-enhanced product comparison in physical retailing	Márquez and Ziegler (2019)	Proceedings of the 2019 Conference on Mensch und Computer	ACM	AR-based shopping assistant
16	Let's get in touch - Decision making about enterprise architecture using 3D visualization in augmented reality	Rehring et al. (2019)	Proceedings of the Annual Hawaii International Conference on System Sciences	IEEE	AR EAM
17	gAR-age: A feedback-enabled blended ecosystem for vehicle health monitoring	Shah et al. (2018)	Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications	ACM	gAR-age

Table 4 *(continue)*

No.	Title	Reference	Source	Publisher/Database	AR application/system
18	PHARA: An augmented reality grocery store assistant	Gutiérrez et al. (2018)	Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services	ACM	PHARA
19	AR Furniture: Integrating augmented reality technology to enhance interior design using marker and markerless tracking	Viyanon et al. (2017)	Proceedings of the 2nd International Conference on Intelligent Information Processing	ACM	AR Furniture
20	MelissAR: Towards augmented visual analytics of honey bee behaviour	Engelke et al. (2016)	Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems	ACM	MelissAR
21	A health industry perspective on augmented reality as a communication tool in elderly fall prevention	Lo Bianco et al. (2016)	A Health Industry Perspective on Augmented Reality as A Communication Tool in Elderly Fall Prevention	ACM	Augment
22	Design and evaluation of a wearable AR system for sharing personalized content on ski resort maps	Fedosov et al. (2016)	Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia	ACM	SkiAR
23	Situated Analytics: Demonstrating immersive analytical tools with augmented reality	ElSayed et al. (2016)	Journal of Visual Languages and Computing	Elsevier/ ScienceDirect	Situated Analytics

Note. SLR = Systematic literature review; AR = Augmented reality; IEEE = Institute of Electrical and Electronics Engineers; ACM = Association for Computing Machinery; CHI = Computer-human interaction; PMM = Product Magic Mirror; STARE = Semantic Augmented Reality; ASV = Augmented Situated Visualization; EAM = Enterprise architecture management; PHARA = Personal health augmented reality assistant

The studies are further organized into specific decision support categories, as summarized in Table 5, illustrating the context in which AR-situated visualization enhances decision-making across various domains.

Purchasing decision support is particularly well explored. As shown in Table 5, eight papers highlight AR-situated visualization's ability to address challenges such as limited access to detailed product information (Márquez & Ziegler, 2019; Xu et al., 2022; Han et al., 2023), limited access to product privacy information (Kaiser et al., 2022), difficulties in visualizing items in real-world settings (Viyanon et al., 2017), and challenges in product comparison (ElSayed et al., 2016; Márquez & Ziegler, 2019; Xu et al., 2022). AR-situated visualization effectively addresses these issues by overlaying product descriptions, attributes, and user reviews directly onto the physical or virtual environment. It helps consumers visualize how items would function in real-world settings, reducing uncertainty and enabling more confident purchasing decisions (Márquez & Ziegler, 2019; Xu et al.,

Table 5
Decision support categories and corresponding application contexts in AR-situated visualization studies, along with the number of studies and references reviewed

Decision support category	Number of studies	Application context	List of studies
Purchasing decision	8	Groceries	ElSayed et al. (2016); Gutiérrez et al. (2018); Han et al. (2023); Xu et al. (2022)
		Electronic devices	Ludwig et al. (2020); Márquez and Ziegler (2019); Kaiser et al. (2022)
		Home furniture	Viyanon et al. (2017)
Monitoring decision	5	Pond aeration	Xi et al. (2023)
		EMC	Guarese et al. (2021)
		Automotive maintenance	Shah et al. (2018)
		Patient monitoring	Tanbeer and Sykes (2024)
		Honeybee monitoring	Engelke et al. (2016)
Route navigation decision	3	Cycling	Matviienko et al. (2022)
		Skiing and snowboarding	Fedosov et al. (2016)
		Street navigation	Mazurkiewicz et al. (2023)
Home improvement decision	3	Home-modification	Lo Bianco et al. (2016); Aoyama and Aflatoony (2021)
		Smart home	Zheng et al. (2022)
Agricultural management decision	2	Strawberry farm	Tamura et al. (2023)
		Crops farm	Zheng and Campbell (2019)
Seating decision	1	Seat-choosing	Guarese et al. (2020)
Management decision	1	EAM	Rehring et al. (2019)

Note. AR = Augmented reality; EMC = Electromagnetic compatibility; EAM = Enterprise architecture management

2022). Additionally, it supports side-by-side comparisons of similar products (ElSayed et al., 2016; Márquez & Ziegler, 2019; Xu et al., 2022).

Five studies examined AR-situated visualization for monitoring, improving real-time data collection, visualization, and actionable insights. The technology integrates data within physical spaces to address scattered information systems and cognitive load. Applications range from holographic patient monitoring (Tanbeer & Sykes, 2024) to vehicle maintenance diagnostics (Shah et al., 2018) and electromagnetic compatibility testing (Guarese et al., 2021). Specialized applications include beehive monitoring (Engelke et al., 2016) and aquatic system assessment (Xi et al., 2023). Navigation-focused studies reveal AR's impact on safety enhancement, spatial awareness, and team coordination, featuring applications like AR-enhanced cycling navigation (Matviienko et al., 2022), marker-based routing (Mazurkiewicz et al., 2023), and collaborative navigation systems (Fedosov et al., 2016). Agricultural applications incorporate soil analysis and crop management (Zheng & Campbell, 2019), while precision farming utilizes AR for harvest optimization (Tamura et al., 2023). In home modification situations, AR-situated visualization facilitates occupational therapists in evaluating assistive devices through three-dimensional (3D) modelling in actual settings (Lo Bianco et al., 2016; Aoyama & Aflatoony, 2021). Smart home applications integrate IoT data with physical objects, managing information overload (Zheng et al., 2022). The AR-situated visualization helps users choose better seating by showing environmental information right in the place where they are making those choices (Guarese et al., 2020) and also aids in enterprise architecture management (EAM) by providing easier-to-understand 3D images of information technology (IT) infrastructure (Rehring et al., 2019).

AR-situated visualization demonstrates significant potential across various fields and decision contexts. Technology addresses information accessibility issues, cognitive demands, and spatial integration challenges by providing contextualized decision support. However, scalability remains problematic, with many solutions being confined to specific domains or controlled environments, thereby limiting their broader application. Future developments should emphasize expandable designs and practical implementation studies, focusing on scalability, group interactions, and practical application challenges to maximize the transformative impact of AR.

Predominant Display Device Technologies for AR Situated Visualization in Decision Making (RQ2)

This review categorizes and discusses devices based explicitly on those demonstrated in user testing and evaluation studies. Table 6 presents the specific devices utilized in each research study.

The literature review highlights HMDs and HHDs as the primary input and output devices to deploy AR applications and prototypes that assess AR-situated visualization

Table 6
Predominant device technologies used in AR-situated visualization to support the decision-making process, categorized by input/output device types, number of studies, and cited sources

Device technology	Input/output device	Numbers	Studies
HMD	MR Headset	10	Márquez and Ziegler (2019); Rehring et al. (2019); Guarese et al. (2020, 2021); Ludwig et al. (2020); Matviienko et al. (2022); Zheng et al. (2022); Mazurkiewicz et al. (2023); Tamura et al. (2023); Tanbeer and Sykes (2024)
	Smart glasses	1	Xi et al. (2023)
	VR Headset	1	Zheng and Campbell (2019)
	Smartphone-based HMD (head-worn mount)	1	Fedosov et al. (2016)
HHD	Smartphone	5	Viyanon et al. (2017); Gutiérrez et al. (2018); Shah et al. (2018); Kaiser et al. (2022); Xu et al. (2022)
	Tablet	7	ElSayed et al. (2016); Engelke et al. (2016); Lo Bianco et al. (2016); Viyanon et al. (2017); Zheng and Campbell (2019); Aoyama and Aflatoony (2021); Han et al. (2023)
Wearable devices	Smartwatch (input only)	1	Fedosov et al. (2016)

Note. AR = Augmented reality; HMD = Head-mounted displays; HHD = Hand-held devices; MR = Mixed reality; VR = Virtual reality

approaches in decision-making support. HMDs are devices that are worn on the head and allow virtual content to be displayed directly in the user's field of view (FOV). In contrast, HHDs are portable mobile devices operated manually by users, employing video-see-through technology through rear-facing cameras to seamlessly integrate virtual content with the real-world environment in AR applications (Leins et al., 2024).

HMDs were employed in 13 of the reviewed studies, as shown in Table 6. Among these, MR headsets, particularly the Microsoft HoloLens, were the most frequently utilized, appearing in 10 out of 23 studies, as shown in Table 6. These headsets are favored for their advanced spatial tracking features and mapping capabilities (Guarese et al., 2020, 2021; Mazurkiewicz et al., 2023; Tamura et al., 2023), their hands-free operation with natural interaction that allows users to maintain a head-up experience (Rehring et al., 2019; Zheng et al., 2022; Mazurkiewicz et al., 2023), and their high-quality visualization and display performance (Mazurkiewicz et al., 2023; Tanbeer & Sykes, 2024). In addition to mixed reality (MR) headsets, smart glasses were employed by Xi et al. (2023) in pond water management, highlighting practical considerations for aquaculture tasks, including ruggedization support, lightweight design, computing power, camera capability, and developer-friendly operating systems. Zheng and Campbell (2019) adopted a virtual reality

(VR) headset (HTC VIVE Focus), which provides a wide 110-degree FOV beneficial for viewing wide agricultural fields. However, due to the absence of a built-in Global Positioning System (GPS), smartphone GPS was used for location tracking. Lastly, Fedosov et al. (2016) implemented a head-worn AR system using a smartphone mounted in a head-worn holder that acted as a video see-through display, accompanied by a smartwatch serving as the input device.

In contrast to HMDs, HHDs, which include smartphones and tablets, were employed in 11 studies. Gutiérrez et al. (2018) and Xu et al. (2022) emphasized smartphones' widespread availability and user familiarity, positioning them as the most accessible AR platform. Han et al. (2023) noted HMDs' impracticality and expense in consumer applications like AR shopping, reinforcing HHDs such as tablets as more viable alternatives. These studies underscore HHDs' utility and cost-efficiency, particularly where mobility, affordability, and user-friendliness are crucial. HHDs are also particularly valuable in fieldwork and collaborative scenarios due to their portability. Engelke et al. (2016) developed a tablet-based AR system for bee monitoring, facilitating mobile data access for beekeepers and researchers. Similarly, Aoyama and Aflatoony (2021) demonstrated how HHDs such as tablets facilitate collaborative decision-making by allowing users to explore 3D models from multiple angles within their real environment. The personal health augmented reality assistant (PHARA) system's architectural flexibility demonstrates AR systems' adaptability across devices and scalability potential, from HHDs to HMDs (Gutiérrez et al., 2018). Moreover, Aoyama and Aflatoony (2021) observed that the larger screen size of tablets enhances both interaction and visualization capabilities in AR environments.

Notably, some studies employed devices that fall into more than one category of input/output technology. For example, Zheng and Campbell (2019) utilized a VR headset (classified under HMDs) and a tablet (classified under HHDs) for device comparison. Meanwhile, Fedosov et al. (2016) implemented a smartphone-based head-worn device (classified under HMDs) alongside a smartwatch (classified as a wearable device) for user input. Additionally, Viyanon et al. (2017) does not specify which device was used during user testing; the categorization is based on the stated compatibility of their AR application with both a smartphone and a tablet. Although such studies appear under multiple device categories, each was counted only once in the total number of reviewed studies (N = 23), ensuring accurate representation without duplication.

As shown in Figure 3, research trends in AR decision-making from 2016 to 2024 show that the use of HMDs has generally increased since 2019, while HHD usage had significant increases in 2016, 2018, and 2022, suggesting they are good for mobile and cost-effective applications. The Y-axis in the figure indicates the number of studies published and included in the review that employed either HMDs or HHDs in AR-situated visualization research.

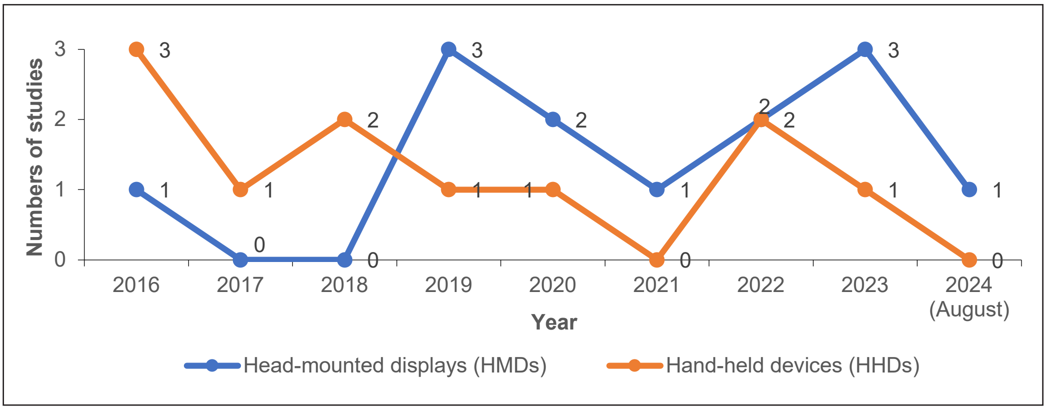

Figure 3. Temporal distribution of augmented reality device usage in reviewed studies from 2016 to August 2024, comparing HMDs and HHDs

The literature review highlights that both HMDs and HHDs offer distinct advantages in AR-situated visualization research. HMDs, such as the Microsoft HoloLens, are particularly effective in scenarios requiring deep immersion, enhanced spatial cognition, and complex interactive features, making them suitable for hands-free applications that demand heightened spatial awareness. Conversely, HHDs like smartphones and tablets provide flexible, cost-effective solutions that are well-suited to dynamic environments with limited resources. Technological advancements have further enhanced the feasibility of HHDs for wider audiences. As noted by Ludwig et al. (2020), while HMDs are advantageous for capturing user attention, smartphones offer greater accessibility. Therefore, the selection between HMDs and HHDs should be guided by the specific constraints and requirements of the decision-making context.

How Do Users Interact with AR Situated Visualization to Support the Decision-Making Process? (RQ3)

This section presents the findings from the literature review on how users interact with AR-situated visualizations during decision-making processes, with a specific focus on HMDs and HHDs. A summary of these findings appears in Table 7, organized using an adapted version of Hertel et al.'s (2021) taxonomy. The analysis categorizes the results based on the input devices, modalities, and interaction methods used, accompanied by corresponding literature citations.

Interaction Through HMDs

Among the 23 studies analyzed, ten employed MR headsets. Six studies (Márquez & Ziegler, 2019; Zheng & Campbell, 2019; Guarese et al., 2020, 2021; Tanbeer & Sykes, 2024) found that users interacted with AR visualizations using hand gestures such as

Table 7
Summary of studies examining how users interact with AR-situated visualization in decision-making contexts, categorized by input device, modality, and interaction techniques, adapted based on the taxonomy of interaction by Hertel et al. (2021)

	Input Device	Modality	Interaction techniques	List of studies
User interaction	MR/VR headset /smart glasses	Gestures	Hand	Márquez and Ziegler (2019); Rehring et al. (2019); Guarese et al. (2020, 2021); Zheng et al. (2022); Tanbeer and Sykes (2024)
		Voice	Voice command	Rehring et al. (2019); Zheng and Campbell (2019); Zheng et al. (2022); Xi et al. (2023); Tanbeer and Sykes (2024)
		Gaze	Head	Márquez and Ziegler (2019); Zheng and Campbell (2019); Ludwig et al. (2020); Guarese et al. (2021)
	Tablet	Tactile interaction	Touch Screen	ElSayed et al. (2016); Engelke et al. (2016); Lo Bianco et al. (2016); Viyanon et al. (2017); Zheng and Campbell (2019); Aoyama and Aflatoony (2021); Han et al. (2023)
	Smartphone			Viyanon et al. (2017); Gutiérrez et al. (2018); Shah et al. (2018); Kaiser et al. (2022); Xu et al. (2022)
	Smartwatch			Fedosov et al. (2016)
	Smart glasses		Touchpad	Xi et al. (2023)
	Clicker device		Clicker	Ludwig et al. (2020)

Note. AR = Augmented reality; MR = Mixed reality; VR = Virtual reality

pointing, tapping on buttons or symbols, and air-tapping (Guarese et al., 2020, 2021; Ludwig et al., 2020). Other ways to interact included zooming, sliding, moving, rotating, panning, and resizing (Rehring et al., 2019; Guarese et al., 2021; Tanbeer & Sykes, 2024). Gesture-based interactions reduced task completion time and supported natural manipulation of in-situ AR visualizations. One notable example is the "touch lens" interaction developed by Guarese et al. (2021), which implements a magnifying glass concept through direct touch. It allows users to access detailed information by simply hovering or tapping over specific data points, which helps minimize hand movement and cognitive load. This interaction is especially beneficial in time-critical decision-making scenarios.

In addition to gesture-based interactions, five studies (Rehring et al., 2019; Zheng & Campbell, 2019; Zheng et al., 2022; Xi et al., 2023; Tanbeer & Sykes, 2024) showed that voice commands can enhance AR interaction by enabling hands-free use. This reduces cognitive load and improves decision-making speed. In applied settings such as healthcare and enterprise management, users relied on voice input to perform tasks like expanding holographic panels, activating visual content, or changing data views. Common voice commands included "show user analysis" and "rotate left" (Rehring et al., 2019), along with "reset" to return to the original view and "change view" to adjust perspective (Tanbeer & Sykes, 2024). However, real-world environmental challenges such as wind interference and accent variability limited the practical use of voice interaction in Xi et al. (2023), resulting in recognition issues. Despite successful performance in controlled lab conditions, the system failed to interpret spoken commands reliably in the field, leading all participants to abandon voice input in favor of the more consistent touchpad-based tactile interaction.

Four studies examined how AR-situated visualization supports decision-making by investigating gaze modality, particularly head gaze, as an interaction technique. Guarese et al. (2021), Ludwig et al. (2020), Márquez and Ziegler (2019), and Zheng and Campbell (2019) demonstrate that head gaze serves as a hands-free alternative to gesture inputs, allowing for natural interaction with virtual elements through head movement. Head gaze minimizes cognitive burden by matching natural human behaviors and improves effectiveness in product comparison, comprehension, real-time data retrieval, and field operations. However, the studies reveal limitations in head gaze precision and efficiency. Hardware restrictions, such as a limited field of view, diminish interaction effectiveness, particularly in extensive area tasks like agricultural visualization, as observed by Zheng and Campbell (2019). Ludwig et al. (2020) introduced a hybrid interaction combining head movement for orientation with a clicker for selection to overcome usability issues with the HoloLens' "air tap" gesture. Initially, participants struggled with coordination and the limited field of view, but gradually adapted by moving around to view virtual content from different angles. This behavior suggests that spatial exploration can help offset hardware limitations and enhance engagement with AR-situated visualizations during decision-making.

Interaction Through HHDs

Out of the 23 studies examined, 11 specifically investigated AR visualization on HHDs, including tablets and smartphones. Mobile applications were the dominant platform for HHD-based AR. However, one study adopted a web-based AR approach to avoid installation requirements, which raised potential challenges related to internet connectivity in physical settings (Xu et al., 2022). In HHD-based AR applications, users interact with AR content via touchscreens, enabling control of virtual objects through actions such as tapping, swiping, rotating, and dragging. Various functions, such as object selection, deselection, and accessing information, were supported through buttons or icons displayed on the interface (ElSayed et al., 2016; Engelke et al., 2016; Xu et al., 2022; Han et al., 2023).

However, more complex interactions like rotation or drag-and-drop were found to be challenging without clear guidance (Aoyama & Aflatoony, 2021). The heavy reliance on tapping as the primary input method limited interaction flexibility, affecting interface fluidity and the sense of naturalness (Engelke et al., 2016). Moreover, navigation and task performance were hindered by ambiguous or poorly labelled interface components (Viyanon et al., 2017). While tablets offer a larger display, users generally prefer smartphones due to their convenience and ease of handling. Tablets were associated with ergonomic and usability issues during prolonged use (ElSayed et al., 2016). These findings highlight several areas for improvement: diversifying interaction methods, enhancing interface navigation through clearer labelling, and optimizing the user experience for specific device types.

Multimodal Interaction

The literature review highlights the role of multimodal interaction in enhancing AR visualization applications within decision-making contexts. Several studies demonstrated how combining different input modalities can improve flexibility, usability, and adaptability in task execution. For instance, Rehring et al. (2019) and Tanbeer and Sykes (2024) explored gesture and voice commands in HMD-based systems, while Ludwig et al. (2020) combined head gaze with tactile input through a clicker. Similarly, Zheng et al. (2022) developed a system incorporating image analysis and object recognition with voice commands and hand gestures to facilitate IoT data annotation.

Multimodal interaction provides several advantages. Studies reported that users could switch between modalities based on personal preferences or contextual demands (Rehring et al., 2019; Tanbeer & Sykes, 2024). For users with physical limitations, voice commands served as a practical alternative to hand gestures (Rehring et al., 2019). The ability to select appropriate interaction methods according to situational needs contributed to greater system usability (Ludwig et al., 2020; Tanbeer & Sykes, 2024). In tasks requiring simultaneous actions or divided attention, such as in industrial or field-based settings, combining voice commands with gaze-based input proved effective (Zheng & Campbell, 2019; Zheng et al., 2022).

However, despite these benefits, multimodal systems introduced new challenges. Users often faced steep learning curves when mastering gesture and voice command combinations, and device management complexity was frequently noted, particularly when using HoloLens (Zheng & Campbell, 2019; Ludwig et al., 2020). Reported issues included physical discomfort, limited field of view, and the need for frequent repositioning of the device (Rehring et al., 2019). These findings highlight the trade-offs between interaction flexibility and physical ergonomics. Addressing these limitations remains essential for real-world decision-making applications, and future research should prioritize the development of more intuitive and ergonomically optimized AR devices.

While both HMDs and HHDs enable rich interactive AR experiences, the interaction challenges within AR-situated visualization systems persist. Some studies have proposed reducing user input demands altogether by enhancing passive or minimal-interaction designs. Fedosov et al. (2016), Matviienko et al. (2022), and Mazurkiewicz et al. (2023) explored the use of persistent visual cues and movement-based guidance to support spatial awareness and real-time decision-making in situations with limited interaction. These designs were especially relevant in time-critical environments such as skiing and cycling, where safety and rapid response were prioritized. Visual overlays guided user attention and navigation while reducing cognitive and physical input load. Although such streamlined approaches demonstrated potential for supporting decisions in fast-paced tasks, their applicability to more complex or multi-step decision scenarios remains underexplored.

Mapping Interaction Modalities to Manipulation Methods

This section elaborates on the categorization presented in Table 7 by mapping interaction modalities, techniques, and user actions to manipulation methods within AR-situated visualization systems. The corresponding diagram in Figure 4 illustrates these mappings, highlighting how different interaction strategies facilitate user engagement across various domains. Based on Brehmer and Munzner's (2013) multi-level typology, this study identifies six key manipulation methods: *select*, *navigate*, *arrange*, *change*, *filter*, and *aggregate*. Mapping these methods to interaction modalities is essential not only for understanding how users interact with AR-situated visualizations through touch, gesture, voice, gaze, or clicker input but also for identifying how users operate on existing visualization elements. The analysis reveals that AR-situated visualizations employ a diverse set of interaction strategies to bridge virtual information with physical contexts, ultimately supporting more efficient and context-aware decision-making. The following details each manipulation method identified in the reviewed studies, beginning with selecting.

Select

Selecting, identified in 20 studies, is a fundamental manipulation method in AR-situated visualization that supports decision-making by enabling users to focus on relevant data points or virtual objects. Among the interaction modalities, touch-based input via HHDs is most frequently used, appearing in 11 studies. These interactions typically involve tapping on 3D objects, UI buttons, or navigation elements. Hand gestures, reported in five studies, support selection through ray-guided pointing, air-tapping, or direct hologram engagement (Márquez & Ziegler, 2019; Rehring et al., 2019; Guarese et al., 2020, 2021; Tanbeer & Sykes, 2024). Voice commands, in two studies, allow hands-free selection via verbal prompts such as "Select [item name]" (Rehring et al., 2019; Tanbeer & Sykes, 2024), offering benefits in hands-occupied contexts. Gaze-driven interaction, observed in two studies, enables selection through head movement, aligning virtual focus with user intention (Márquez & Ziegler, 2019; Zheng & Campbell, 2019).

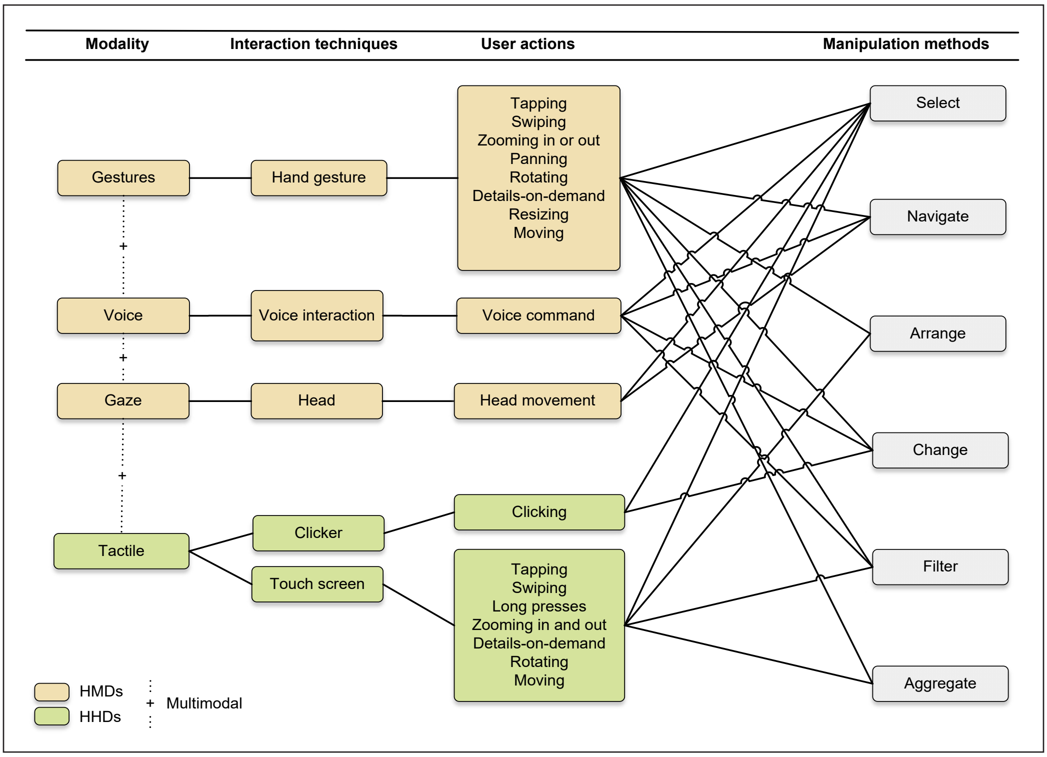

Figure 4. Mapping of interaction modalities and techniques, and user actions in augmented reality (AR)- situated visualization for decision-making tasks, linked to manipulation methods, adapted from Brehmer and Munzner's (2013) typology and Hertel et al. (2021)'s taxonomy of immersive AR interaction techniques
Note. HMDs = Head-mounted displays; HHDs = Hand-held devices

Navigate

Navigating is another core manipulation method used to change the user's viewpoint, allowing them to explore and engage with visual content from multiple perspectives. Supported by 20 studies, navigation enables users to examine objects, access layered information, and interact dynamically with their surroundings. Four studies highlight gestural inputs, such as sliding hands to move panels or zoom, pan, and rotate virtual elements (Rehring et al., 2019; Guarese et al., 2020, 2021; Tanbeer & Sykes, 2024). Three studies describe voice navigation, enabling users to switch screens or perspectives using commands like "go to [screen name]" or "rotate left" (Rehring et al., 2019; Tanbeer & Sykes, 2024), including advanced voice-focus augmentation (Zheng et al., 2022). Head-based navigation, reported in two studies, facilitates orientation and viewpoint shifts through head movement; it can also be used to select options for more information when needed (Márquez & Ziegler, 2019; Ludwig et al., 2020). Touch-based navigation, found in 11 studies, involves tapping icons or buttons to move through environments, switch modes, or manipulate virtual elements such as furniture in 3D spaces.

Arrange

Arranging, found in 11 studies, involves reorganizing visualization elements spatially to optimize layout and improve decision-making accessibility. This method can be performed manually or through system automation. Hand gestures, discussed in two studies, are used to reposition panels or 3D models (Rehring et al., 2019; Tanbeer & Sykes, 2024). Voice commands, as in Rehring et al. (2019) and Tanbeer and Sykes (2024). Arranging visualization assists with commands like "expand blood pressure" to modify panel layout (Tanbeer & Sykes, 2024). Touch screen gestures, also reported in two studies, allow users to hold, drag, rotate, position, or lock objects, which is beneficial for spatial visualization tasks such as configuring assistive technologies in home environments (Viyanon et al., 2017; Aoyama & Aflatoony, 2021). Automated arranging, reported in five studies, dynamically adapts layout based on user attention (Zheng et al., 2022), object orientation (Xu et al., 2022), or feedback (Ludwig et al., 2020; Guarese et al., 2020, 2021), enhancing contextual relevance and ease of access.

Change

Changing refers to modifying the visual encoding or spatial representation of data, identified in 10 studies as a method to adapt content during decision-making. Hand gestures enable resizing and repositioning holographic items or navigating menus in real-time (Rehring et al., 2019; Tanbeer & Sykes, 2024). Voice commands such as "change view" are used to alter perspective or representation (Tanbeer & Sykes, 2024). Touch interactions allow for toggling between data types, updating chart formats (e.g., radar views), or customizing product information (Viyanon et al., 2017; Xu et al., 2022; Han et al., 2023). Gaze-based systems, like those in Márquez & Ziegler (2019), rely on dwell-time activation to trigger visual changes. Automated systems, as in Zheng et al. (2022), highlight or reconfigure content based on focus-tracking. Changes to salient features such as colour and size (ElSayed et al., 2016; Engelke et al., 2016) also support users in comparing or interpreting key data more easily.

Filter

Filtering, reported in 12 studies, helps users narrow visible information by including or excluding elements based on specific attributes. This is particularly useful in selection-based or comparative decision-making tasks. Touchscreen-based filtering, reported in eight studies, allows users to tap buttons to filter by price, content, or features (ElSayed et al., 2016; Engelke et al., 2016; Fedosov et al., 2016; Gutiérrez et al., 2018; Aoyama & Aflatoony, 2021; Kaiser et al., 2022; Xu et al., 2022; Han et al., 2023). Voice commands, used in two studies, include phrases like "open lung details" or "show user analysis" (Rehring et al., 2019; Tanbeer & Sykes, 2024). Other methods involve gaze and gesture input to manage content visibility, including virtual menus anchored to the user's hand (Márquez & Ziegler, 2019; Guarese et al., 2020). Filtering enables users to focus on relevant data subsets, aiding clarity and enhancing satisfaction.

Aggregate

Aggregating, recognized in three studies, changes the granularity of visualization elements by summarizing or grouping data. For example, touchscreen interactions enable users to calculate total nutritional values by merging data from multiple products (Gutiérrez et al., 2018). AR-based summarization techniques allow collapsing detailed product attributes into broader categories, like "comfort" or "performance," or visualizing generalized overviews of individual elements (Viyanon et al., 2017; Márquez & Ziegler, 2019). This method helps users move between detailed and high-level information, supporting a more efficient understanding of complex data.

The interaction designs in AR-situated visualization enhance users' capacity to manipulate real-time information through context-sensitive and accessible interactions. These manipulation methods form the foundation of how users engage with and adjust existing visualization elements, thereby facilitating informed and situated decision-making. However, some methods (e.g., gestures or gaze) may present usability challenges, especially for non-technical users, reinforcing the importance of intuitive, multimodal interaction designs. Collectively, these manipulation methods contribute to improved accessibility, usability, and engagement in AR applications across domains such as healthcare, retail, and spatial data organization.

DISCUSSION

The findings from RQ1 reveal that AR-situated visualization plays a significant role in enhancing decision-making across diverse domains. In retail, it addresses challenges such as limited product details and comparison by embedding rich contextual information within the physical shopping environment. Beyond retail, applications in healthcare, agriculture, and navigation demonstrate the value of AR-situated visualization in supporting real-time monitoring, spatial understanding, and information clarity. Despite these advantages, several limitations persist, including cognitive overload from excessive information, technical constraints in uncontrolled environments, and ergonomic discomfort during prolonged use. These findings demonstrate the value of designing AR-situated visualization systems that are not only immersive but also adaptable and centered on user needs, thereby improving both decision accuracy and user experience.

The findings for RQ2 indicate that device selection has a critical influence on AR-situated visualization interaction design and its effectiveness in decision-making contexts. HMDs, such as Microsoft HoloLens, enable immersive experiences with features like gesture and gaze tracking, making them suitable for hands-free, spatially demanding tasks. However, their high cost, physical discomfort, and reduced outdoor usability limit their adoption in broader applications. In contrast, HHDs, including smartphones and tablets, offer greater accessibility, ease of deployment, and suitability for collaborative and mobile contexts, especially in fieldwork or consumer environments. Although they lack the immersive quality of HMDs, their affordability and familiarity make them a practical option. Therefore, device selection should be driven by the interaction needs, task complexity, and environmental constraints of the intended application.

The review for RQ3 lists numerous interaction strategies employed in AR-situated visualizations to support decision-making, each with distinct benefits and challenges. Gesture-based input, commonly used with HMDs, aligns with how users' bodies move more naturally, facilitating intuitive engagement. However, actions like air-tapping may hinder precision for novice users or in tasks requiring fine control. Voice commands offer hands-free operation, but they are sensitive to noise and accent variations, particularly in outdoor or uncontrolled settings. Tactile interaction, especially on touchscreens, offers a reliable alternative for selection and navigation but may limit expressiveness for more complex manipulation.

Consistent with Hertel et al. (2021), this review finds that gesture and voice interactions are dominant in immersive settings. However, unlike previous taxonomies, this study integrates manipulation methods to classify interaction effectiveness for real-time decision-making. Multimodal interfaces that combine gesture, touch, gaze, and voice help balance flexibility and usability, although they may increase learning demands and cognitive load. Across the reviewed studies, selecting, navigating, and filtering emerged as the most frequently supported methods for manipulation. These methods enable users to locate relevant data, explore information spatially, and refine visual content based on specific criteria, directly supporting real-time decision-making. In contrast, less frequently addressed methods, such as arranging, changing, and aggregating, highlight opportunities for further research in supporting more advanced or iterative decision processes. Addressing these underrepresented methods may help expand AR's role in complex decision-support environments.

This study did not include a meta-analysis due to the significant variability in study characteristics, such as application domains, user tasks, metric evaluations, and types of AR devices. Although certain studies demonstrated similarities, the quantity of those with closely aligned focuses, especially regarding outcome measures and experimental design, was insufficient to provide a dependable quantitative synthesis. While previous reviews provided broad overviews of situated visualization (Bressa et al., 2022) or interaction design in AR-situated visualization (Zhu et al., 2024), they did not emphasize how specific interaction modalities support distinct decision-related manipulation methods. This review offers a more decision-focused categorization, mapping interactions to concrete manipulation strategies that align with decision-making goals.

CONCLUSION

This SLR investigated how interaction strategies in AR-situated visualization support the decision-making process across domains, synthesizing findings from 23 selected studies. This review offers a structured classification of interaction modalities such as gesture, touch, voice, and tactile that directly support real-time decision-making, contributing a more decision-centered perspective to the field. It emphasizes the importance of developing AR-situated visualization systems that are not only immersive but also responsive to user needs and situational contexts. Effectiveness depends on aligning visualization and interaction design with decision complexity and cognitive demands, particularly in domains requiring timely and accurate responses.

Device selection also emerged as a critical factor influencing interaction effectiveness. Rather than favoring one platform universally, choices between head-mounted and HHDs should consider task-specific requirements, interaction precision, user mobility, and environmental conditions. Additionally, the review identifies a gap in support for advanced manipulation methods such as arranging, changing, and aggregating. These underexplored areas present valuable directions for future research, especially in complex, collaborative, or iterative decision-making scenarios where current interaction strategies may fall short.

The scope of this review was intentionally narrow to ensure conceptual clarity around decision-making support. As a result, broader AR trends involving exploratory or comparative cognitive activities, which often serve as precursors to decision-making, may not be fully captured. Future reviews would benefit from including these precursor activities and expanding domain coverage to more diverse application areas. The review also identifies areas requiring further exploration, including limited support for advanced or collaborative decision-making and the underrepresentation of domains such as education, public events, and industrial environments. Furthermore, methodological heterogeneity highlights the importance of adopting more standardized research designs to enable broader generalization and cross-study comparability. As a final remark, this review provides a focused foundation for understanding how interaction design in AR-situated visualization can enhance decision support while outlining key directions for future research in increasingly complex and dynamic environments.

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