

Investigation of Key Barriers Regarding Adoption and Implementation of Augmented Reality in Industrial Organizations – A Delphi Study

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Abstract

Augmented Reality (AR) holds significant potential for enhancing processes in industrial organizations, but its widespread adoption is hindered by many barriers and concerns. By conducting a Delphi study, 19 industry experts using AR solutions identified relevant barriers to adoption and implementation of AR and ranked them according to their relative importance. Organizational factors like “Functional benefits of AR”, “Organizational fit of AR” and “Costs” were ranked as the most important barriers. As one of the first studies to provide a comprehensive view on relevant barriers from an organizational decision maker’s perspective, our results helps both researchers and practitioners to understand and address them, promoting the successful adoption and implementation of AR technology in industry.

Keywords: Augmented Reality, Industry, Barriers, Adoption, Delphi Study

1. Introduction

In modern industrial organizations, processes are typically very complex, requiring an ever-growing number of steps, where errors are costly. Furthermore, industrial systems are increasingly digitized and connected via the Internet, enabling, for example, the provision of real-time sensor data (Masood & Egger, 2019; Schuir & Teuteberg, 2021). To help manage this increasing complexity, companies following the Industry 4.0 paradigm are looking to adopt digital technologies such as Augmented Reality (AR) to improve their processes in a sustainable way. AR offers an effective new information delivery model for how data is gathered and displayed - data formerly confined to paper or to 2D displays can be transferred directly to the real world (Hein & Rauschnabel, 2016). By overlaying virtual data onto real objects or environments within industrial organizations, AR enables users to seamlessly integrate physical and digital information. In industrial organizations, AR may be used to supply

employees with context-specific real-time information for knowledge-intensive tasks. A non-exhaustive list of potential use cases includes using AR in maintenance, assembly, or commissioning processes. Other potential industrial uses include indoor navigation for warehouses and production facilities, remote assistance, or training applications (Jetter et al., 2018). The potential benefits of adopting AR systems for industrial applications are numerous. Research found they are decreasing operating times and error rate, offer greater production flexibility, and increase both employee process compliance and safety (Souza Cardoso et al., 2020). For example, Volvo has implemented AR-based process guidance and training systems to mitigate the impact of increasing product complexity on product quality as well as productivity, efficiency and safety of its workers (Volvo Group, 2023).

Considering all these potential advantages, it seems obvious that AR would have become a quasi-standard in all industrial organizations (Schein & Rauschnabel, 2022). However, the adoption of AR technology is still in the beginning and most concurrent industrial AR projects are proof-of-concept prototypes or limited to small-scale implementations (Jetter et al., 2018; Palmarini et al., 2018). According to a survey by Capgemini (2018) two thirds of German industrial organizations adopting AR are still in the pilot phase with small-scale implementations. Reports like that show that large-scale adoptions are still rare.

To gain a deeper understanding of this issue, certain studies have identified barriers to the adoption and implementation of AR in industrial contexts (e.g. Masood & Egger, 2019). However, existing research mainly focused on technological aspects, e.g. improvements in terms of hardware performance and visualization of visual information. Organizational and environmental barriers are mentioned, but only to a limited degree. Furthermore, these studies usually assume the perspective of the employee as end user or the developer of AR solutions (e.g. Schuir & Teuteberg, 2021). While the employees' perspectives are undoubtedly important and can provide insights into bar-

riers like AR system usability and performance, focusing on decision makers is crucial because they hold the authority to greenlight or block AR adoption projects. Understanding their concerns, priorities, and decision making criteria is essential for addressing and overcoming the barriers that may hinder the successful implementation of new technologies like AR in industrial organizations. To the best of our knowledge, no study has yet provided a comprehensive overview of barriers to the adoption and implementation of AR from the organizational decision makers' perspective. Additionally, there is little valid information from business practice on the actual relevance of these barriers to industrial organizations. To address this research gap, we want to explore the following research question (RQ): *“What are barriers regarding the adaption and implementation of AR in industrial contexts as perceived by industrial decision makers and what is the relative importance of these barriers?”*

First, we reviewed previous research to develop a list of potentially relevant barriers based on the Technology-Organization-Environment (TOE) framework. Using this list, we conducted an exploratory Delphi study. We synthesized the knowledge and opinions of 19 (at the end of the study, with 22 at the beginning) domain experts with diverse experiences within industrial contexts. We identified 32 relevant barriers, of which the top 13 were ranked by their relative importance by the experts. The results of our study help advance the understanding of these barriers in industrial contexts by providing insights from the field. In addition, our findings help industry practitioners to make better decisions regarding AR-related projects by providing them with structured information on these barriers.

2. Theoretical background

2.1 Augmented Reality

AR refers to technology that is used to enhance the user's perception of the physical environment with virtual elements in real-time. These virtual elements may range from basic text-based annotations up to realistic 3D elements. In contrast to Virtual Reality (VR), AR does not separate a user from the reality, but augments real-world environments with additional information (Azuma, 1997). The hardware used to provide the user with additional information can be broadly categorized into three main types: wearable devices like head-mounted displays (HMDs), handheld mobile devices like smartphones or tablets or static devices like projectors and computer screens. (Carmigniani et al., 2011). Differences between the technologies are only briefly mentioned in this study.

2.1 Technology adoption and implementation

A variety of different theoretical models have been developed in information systems (IS) research to understand the adoption of a new technology. Some models examine technology adoption by end users at the individual level, such as the Technology Acceptance Model (Venkatesh et al., 2003). Other models such as Tornatzky and Fleischer's (1990) Technology-Organization-Environment framework (TOE) examine the organization as unit of analysis at the company level (for an in-depth review of these adaption models, refer to Oliveira and Martins (2011)).

To examine the adoption and implementation process of AR from the organizational decision maker's perspective, the TOE was chosen as a research model. This framework characterizes factors and challenges that influence this process into three independent constructs – technological context, organizational context and environmental context (Tornatzky et al., 1990). The technological context describes technical and functional characteristics of an innovative technology like its complexity or its integration with already existing technology within the organization. The organizational context represents characteristics and resources of the organization that may facilitate or inhibit adoption of a technology. Examples for this are organization structure, business processes and strategy or cultural aspects. The environmental context refers to external factors that may influence the organization, for example industry competitors and the regulatory environment (Oliveira & Martins, 2011).

In previous research, the TOE framework has already been applied in numerous studies to explain the adoption of innovative technologies at the company level, e.g. the adoption of Industry 4.0 technologies like the Internet of Things (Senna et al., 2022) or adoption of AR in E-Commerce (Chandra & Kumar, 2018). Therefore it is regarded as a suitable choice for the investigation of barriers regarding the adaption and implementation of AR in industrial organizations.

2.2 Barriers to adoption and implementation of AR in industrial organizations

To answer the mentioned research question, we first reviewed previous research. With only limited literature available that examines barriers for the adoption and implementation of AR from an organizational perspective (e.g. Masood & Egger, 2019), we also reviewed studies that research the employee's perspective as end user of AR. Certain studies from the user perspective mention some barriers at the organizational level, even if they're not the focus of the respective publication (e.g. Hein & Rauschnabel (2016) or

Schuir & Teuteberg (2021)). An overview of identified barriers to AR adoption and implementation structured according to the TOE framework is presented below. The complete list of all identified barriers is presented in the appendix.

Despite the increasing maturity of AR solutions, many of the barriers identified in previous research are part of the technological context (Masood & Egger, 2019). Existing research has shown that the level of technical maturity of AR solutions still needs to be improved. On the hardware side, further improvements in factors like computing power, tracking and latency of displaying AR content are seen as necessary before they can meet the requirements of industrial organizations. On the software side, lacking capabilities of AR applications in terms of context-dependent provision of information or unfitting design of the user interface are frequently mentioned (Danielsson et al., 2020; Masood & Egger, 2020). Closely related are factors referring to the ergonomics and handling of AR solutions, i.e. unintuitive input modalities that are not compatible with industrial work processes or the weight and limited battery life of AR hardware (Bottani & Vignali, 2019; Souza Cardoso et al., 2020). Furthermore, the development and deployment of AR solutions requires specific knowledge about AR as well as about the processes within the organization, which is only available to some extent in industrial organizations (Danielsson et al., 2020). In addition, the technical implementation of AR systems into the existing IT infrastructure is seen as a major barrier (Schein & Rauschnabel, 2022; Schuir & Teuteberg, 2021). Industrial AR applications require a proper management of complex data, which especially smaller or medium-sized organizations need to develop first (Palmarini et al., 2018; Souza Cardoso et al., 2020). Furthermore, information security and privacy concerns might arise from both user and organizational perspective when AR solutions are deployed in industrial environments (Langfinger et al., 2017).

Regarding the organizational context, it is often not apparent for decision makers whether adopting AR solutions will lead to functional benefits, i.e. an increase in performance or productivity (Jetter et al., 2018; Schuir & Teuteberg, 2021). In addition, the adoption of a new technology like AR involves substantial costs for the organization, which must be carefully considered in relation to the potential benefits. (Hein & Rauschnabel, 2016; Souza Cardoso et al., 2020). Furthermore, for many decision makers it is difficult to assess whether the use of AR solutions is a suitable choice considering the organization's structure, requirements and business strategy (Hein & Rauschnabel, 2016; Jetter et al., 2018). This can in-

volve hesitation to change long-established work processes and existing IT systems by industrial decision makers (Masood & Egger, 2019). Closely related to these barriers is research on acceptance of AR. Acceptance problems like limited previous interactions and a lack of trust into AR technologies are barriers that occur on both the organizational decision maker and the worker level (Schuir & Teuteberg, 2021).

Considering the environmental context, barriers outside of the organization were also identified in the literature. Examples are the lack of standardization of AR solutions and legal uncertainty regarding their use in industrial environments, which are considered as major barriers for industrial organizations (Danielsson et al., 2020; Schuir & Teuteberg, 2021).

3. Research design

We choose a ranking-type Delphi study as our research approach to collect information from experts regarding the adaption and implementation of AR in industrial organizations (Schmidt, 1997). Delphi studies are designed to gather the opinion of a panel of experts through an iterative process of controlled feedback (Schmidt, 1997). The Delphi method is appropriate when "the problem does not lend itself to precise analytical techniques, but can benefit from subjective judgments on a collective basis" (Mahajan et al., 1976), which is why this method was considered to be a suitable choice.

The study was conducted in several rounds. In the first round, expert interviews were conducted to gather further information on the barriers, i.e. in terms of accuracy or completeness of the list. The goal of the following ranking rounds was to assess the relevance of the identified barriers for industry organizations. The Delphi study is concluded when a reasonable level of panel consensus or another predefined stopping criterion is reached (Paré et al., 2013; Schmidt, 1997).

3.1 Panel selection

We recruited a diverse panel of industry practitioners, academic researchers, software developers and consultants with considerable experience regarding AR in industrial contexts to make use of a wide range of knowledge.

Our selection criteria for the Delphi panel required experts to have a minimum of two years of experience with AR in an industrial context. In addition, they had to be actively involved with at least one implementation of AR in an industrial context. The position of the experts in their respective organization must be related to decision making. Alternatively, they may be a consultant, software developer or academic

researcher closely involved in at least 3 AR-related industry projects. Overall, we made sure to invite experts representing a variety of AR use cases and the use of different types of AR technologies (e.g. HMDs, mobile devices, projectors) as well as different industry sectors and organizations of all sizes.

We found 46 experts who met our selection criteria through industry workshops on AR, business networking platforms, and the authors' network of professional contacts. 22 of these experts agreed to join the panel and participated in the first round. On average, our panel experts have 6.8 years of AR experience in industrial organizations, exceeding the minimum criteria we required by far. The expert panel consists of 50% (11 people) decision makers from industry, including 2 CEOs and some department heads. It includes 5 academic researchers who are involved in AR research projects together with industrial partners. In addition, there are 4 consultants with their own companies and two software developers involved. Experts from small, medium, and large organizations are represented.

4. Results

In round 1, semi-structured interviews were conducted with each expert on barriers to AR in industrial organizations. The accumulated interviews were transcribed by the researchers. To synthesize and analyze the findings, Strauss and Corbin's (2015) method was used, utilizing open and axial coding to identify relevant barriers. To achieve consistent coding, the interview transcripts were independently coded line-by-line by two researchers using phrases from the transcripts describing potential barriers. Conflicting results in this process were discussed by the authors to reach a consensus. This open coding process resulted in a list of 74 codes and 379 phrases. The substantial information provided in the transcripts served as the foundation for the subsequent axial coding. The open codes were merged by the two researchers into broader axial categories, resulting in a list of 32 unranked barriers regarding AR in industrial contexts. These barriers are listed in the appendix.

In round 2, we provided the experts with a randomized list of the 32 unranked barriers from round 1 on an excel sheet, along with a description of each barrier. To obtain a more manageable list for the subsequent ranking, a majority voting by panelists was used (Schmidt, 1997). We asked each expert to select – not rank – the most relevant barriers (at least 10, at most 20) regarding the adoption and implementation of AR in industrial organizations. Subsequently, we reviewed each expert's selection and kept only barriers voted as relevant by at least 50% of the expert panel (Singh et

al., 2009). This resulted in a compact list of 13 barriers considered most relevant.

In round 3 the 13 top barriers from round 2 were sent in randomized order to each expert. They ranked these 13 barriers in order of relevance and briefly explained their reasoning. The degree of consensus among the experts was measured by Kendall's coefficient of concordance (W) (Schmidt, 1997). 21 experts participated in the first iteration of ranking in round 3, yielding a W of 0.22 thus indicating weak consensus. As suggested by authors like Paré et al. (2013) we continued to iterate in round 3 until reaching at least one of the following three stopping criteria: (1) $W > 0.7$ = strong consensus, or (2) three ranking iterations have been conducted, or (3) the level of consensus has plateaued in two consecutive iterations.

For subsequent ranking iterations, we provided each expert with the following information as controlled feedback: (i) the ranking given for each barrier by the respective expert during the previous ranking iteration, (ii) the average rank of each barrier as voted by the entire expert panel and (iii) the percentage of experts who ranked each barrier within the top 50%. As a fourth piece of controlled feedback (IV), we supplied the experts with a summary of the comments made for each barrier in the previous iteration (Schmidt, 1997). Similar to authors like Singh et al. (2009) we believe that providing additional information would aid experts in reviewing their own rankings against the group rankings and adjusting their own rankings where it made sense to them. 19 experts participated in the second iteration of round 3, resulting in an increased W of 0.36. Considering this increase, we decided to conduct a third iteration of round 3, where 19 experts participated, and W increased to 0.61, indicating moderate consensus. Such improvements of almost 50% between iterations may seem surprising, but are quite common in the literature (Paré et al., 2013). By providing controlled feedback, the experts were able to reconsider their own assessment in relation to that of the panel, thus achieving group consensus.

The question now was whether another iteration should be conducted to achieve an even higher level of consensus. To make such a decision, it is necessary to weigh the trade-off between feasibility in terms of the experts' time required against the potential benefits (Schmidt, 1997). We felt that a certain degree of fatigue had developed among our participants. Their motivation appeared to be declining because we had to send more and more study reminders. Having reached one of the stopping criteria described above, we decided to stop after three ranking iterations. Considering the high heterogeneity of the panel of experts, we

believe that a reasonable level of consensus has been achieved and that the expert's ranking is valid.

Table 1 shows the results of three ranking iterations on the relevance of the barriers. Out of the 13 ranked barriers, 6 are part of the organizational context and 7 are part of the technological context. No environmental barriers are part of the most relevant barriers as ranked by the experts.

Table 1: Results of round 2 and 3

Barrier	Ite. 1 avr.	Ite. 2 avr.	Ite. 3 avr.	Final Rank
Functional benefits of AR	6.20	4.68	2.37	1
Organizational fit of AR solutions	4.05	2.79	2.47	2
Costs	5.55	5.00	4.32	3
Complexity of AR solution development	5.25	4.95	4.58	4
Maturity of AR hardware	5.85	6.00	5.21	5
Integration into existing IT systems	5.20	5.89	6.53	6
Acceptance of new digital technologies	8.20	7.58	7.63	7
High data complexity	7.45	7.79	8.05	8
Data security	8.10	8.11	8.26	9
Operation of AR in industrial environments	7.75	8.32	9.16	10
Maturity of AR applications (Software)	7.90	9.16	10.26	11
Hesitation to change long-established work processes and systems	9.20	10.05	10.84	12
Trust	10.30	10.68	11.32	13
Kendall's W	0.22	0.36	0.61	
Kendall's W > 0.7 → strong consensus among panelists 0.5 ≤ Kendall's W ≤ 0.7 → moderate consensus among panelists Kendall's W < 0.5 → weak consensus among panelists				

5. Discussion

The findings of the Delphi study regarding the 13 ranked barriers are discussed below in relation to previous research and categorized according to the TOE framework.

5.1 Identification and ranking of barriers

5.1.1. Organizational Context "Functional benefits of AR" was ranked as the most important barrier with an average rank of 2.37. With the words of one of our panelists, *"When I consider using AR in an industrial context, I find that the benefits are not immediately apparent, it is difficult to try to put it into objective number."* Many of the experts agreed with that statement, explaining that they had to persuade other stakeholders within the organization of the functional benefits of AR. In the literature, there are many benefits associated with the use of AR in industrial organizations for

certain use cases (Schuir & Teuteberg, 2021). The experts supported the notion from the literature that untrained employees benefit from the use of AR, but that it is not evident whether skilled employees actually benefit from the use of AR in many situations (Masood & Egger, 2020). This implies that it is a major challenge for decision makers to assess these potential benefits.

"Organizational fit of AR" was ranked as the second most important barrier with an average rank of 2.47. The experts postulated the need to carefully consider for which work processes AR is appropriate. According to both the experts and literature, decision makers need to ensure a fit between AR technology and the organization, which requires a deep understanding of both AR technology and the organization (Masood & Egger, 2019). It is obvious to the experts that existing processes would have to be modified to some degree to incorporate AR. However, the experts indicated that they've experienced or observed inadequate AR pilot projects that do not fit the requirements and structure of the organization, resulting in AR not being established beyond these experiments.

"Costs" was ranked as third most important barrier, with an average rank of 4.32. Significant initial investments in hardware and specialized applications, as well as ongoing maintenance costs have to be considered in comparison to potential benefits. Predictably, this barrier has been ranked quite high by the experts, as cost is especially significant to decision makers when it comes to adopting a unproven technology such as AR in any organization (Hein & Rauschnabel, 2016).

"Acceptance of new digital technologies" was ranked 7th with an average value of 7.63. Both experts and research highlight the need to address skepticism of both employees and decision makers within the company as a major barrier (Schuir & Teuteberg, 2021). While the literature on AR adoption mostly focuses on the employee perspective, our interview results suggest that employees and decision makers influence each other within the organization. Consequently, this barrier is also quite relevant for decision makers, it is obvious that decision makers should accept AR to ensure a successful adoption, too.

"Long-established processes within the organization" ranked 12th with an average value of 10.84, is closely related to the barrier mentioned before. Some of the experts argued from personal experiences that they, at least initially, didn't want to change established processes and systems to adapt them to a new technology like AR. They feared that the change could lead to disadvantages rather than benefits. Similar findings are reported in the literature (e.g. Masood & Egger, 2019).

The barrier “Trust” was ranked 13th with an average value of 11,32. Until now, this barrier has received little attention in the literature on AR in industry and is essentially only mentioned as a antecedent to acceptance (e.g. Hein & Rauschnabel, 2016; Quandt et al., 2018). The experts argue that decision makers must consider whether they can trust AR solutions to consistently deliver the promised functionality and operate reliably for industrial use cases. And trust will have to be earned, as there is still only limited empirical data on the long-term use of AR technology in industrial organizations.

5.1.2. Technological context “Complexity of AR solution development” was ranked 4th with an average value of 4.58. In the literature, this barrier is regarded as one of the most important obstacles to the adoption of AR in industry. The development of AR solutions necessitates specialized skills and knowledge that are typically not readily available within industrial organizations and thus need to be sourced from external service providers (Danielsson et al., 2020; Hönemann et al., 2023). The experts consider current AR authoring tools, which are designed to mitigate this complexity and help domain experts within the organization to independently create AR applications, as too difficult to use and yet limited in their potential application areas.

“Maturity of AR hardware” was ranked 5th with an average value of 5.21 and is most frequently cited as a significant barrier to AR adoption. Research shows that AR hardware currently available still needs to be improved to meet the expectations and requirements of industrial organizations, i.e. in terms of computing power and tracking (Danielsson et al., 2020; Souza Cardoso et al., 2020). The experts acknowledge that the hardware currently available on the market is mature to a certain degree, otherwise it would not be sold. However, it often fails to meet the expectations and requirements of industrial contexts, which is why they ranked this factor as the most important technological barrier.

“Integration into existing IT systems” was ranked 6th with an average value of 6,53. The experts believe that this barrier could become a bottleneck for organizations with limited IT expertise, as AR solutions require proper integration with various IT systems both inside and outside the organization to function properly. While extensively addressed in the literature (e.g. Danielsson et al., 2020; Schuir & Teuteberg, 2021), some experts were initially unaware of the significance of this barrier at the start of their AR projects, leading to challenges during the implementation process.

Closely related to the previous factor is the barrier “High data complexity”, which was ranked 8th with an

average value of 8.03. While this barrier has received only limited attention in the literature (e.g. Palmarini et al., 2018), the experts suggest that organizations looking to adopt AR not only have to ensure a proper integration of the AR solutions with the existing IT infrastructure. Data management must also meet a certain level, such as ensuring data quality and actuality, for AR to be able to provide reliable information for work processes. According to the experts, data complexity is a latent obstacle that is often not recognized until after initial AR testing, which can significantly delay or prevent the adoption of AR.

“Data security” was ranked 9th with an average ranking of 8.26. The experts highlighted the constant activation of sensors like cameras and microphones as a significant barrier for AR systems. Both experts and literature suggest the necessity of reliable data protection mechanisms to facilitate the adoption of AR within industrial organizations (Palmarini et al., 2018). Some experts expressed the need for a mechanism that would allow AR solutions to access only the specific data needed at the time of use to ensure that the data being processed is secure, remains on the device, and that trade secrets, such as sensitive CAD models used in the visualization process, are not at risk.

“Operation of AR”, was ranked 10th with an average rank of 9,16. Both experts and literature argue that input modalities for AR are still in development and user input may not be registered correctly, which can lead to user errors and frustration (Jetter et al., 2018). Certain input modalities, such as hand gestures may not be compatible with many work processes in industry, which can impede their proper use.

“Maturity of AR applications (Software)” was ranked 11th with a value of 10.26. This rather low ranking is in contrast to the literature (e.g. Danielsson et al., 2020; Jetter et al., 2018; Masood & Egger, 2020) and the interviews conducted, both of which considered this barrier to be of much higher importance. It is obvious that the capabilities of the AR application are the key to its implementation. Industrial organizations require AR applications that can display contextual information effectively and in a visually appealing way, as well as provide an easy-to-use graphical interface. According to experts, the majority of existing applications require further development to meet the requirements and expectations of industrial organizations.

5.1.3. Environmental context The experts did not rank any of the identified barriers from the environmental context as highly relevant. It must be emphasized that while these barriers are not part of the Top 13, this does not mean that they are not important to decision makers. There are different opinions in the

literature, for example Masood and Egger (2019) argue that factors such as external support have no influence. In contrast, authors like Senna et al. (2022) argue that factors such as a lack of standardization or legal uncertainty have a significant role in the adoption of new technologies in industrial organizations. It is likely that the experts in this study did not consider some of these factors to be as important because they have already gained experience with AR.

5.2 Implications and limitations

Our study contributes to research on the adoption and implementation of AR in industrial organizations by examining the decision makers' perspective. This point has been neglected so far in comparison to the employees' perspective. The perspective of decision makers is more important because they inherently have a major influence on the adoption of new technologies in the organization, and they may evaluate these barriers differently or, in some cases, perceive different barriers than employees. Our study expands upon the knowledge of barriers previously identified in the literature and enhances our understanding of their relative importance through the interviews and ranking process of the Delphi study. In the literature, technological aspects have already been extensively covered as they form the basis for the capabilities of AR solutions and therefore enable their potential use. However, the experts consider organizational barriers to be more relevant, as these are ultimately the deciding factors for the actual adoption and implementation of AR in industrial organizations. Consequently, there is a need for research into organizational barriers in the context of industrial organizations and especially from the decision makers perspective, which are currently not being adequately met. For example, the experts suggested the development of a taxonomy of task types, application areas, and groups of people for which the use of AR in industrial organizations offers functional benefits. Furthermore, it is necessary to investigate which processes and structures in industrial companies should be changed in what manner to facilitate the adoption of AR. Such changes can have far-reaching consequences for organizations and have not yet been studied in a structured way in the literature. In addition, it is necessary to conduct further research on the environmental context; specifically, to establish which of these barriers are actually significant for the adoption of AR in industrial organizations.

For practitioners, the validated list provides useful information about 32 barriers that are relevant to the adoption and implementation of AR in industrial organizations. The ranked list of 13 relevant barriers offers a compact overview of the most important criteria

according to our expert panel. Decision makers being involved with AR technology can use this information to identify relevant problem areas in their own company at an early stage and address them in a systematic manner. In particular, organizations must consider whether AR solutions are appropriate for specific processes and, if so, which AR solutions are best suited. For proper utilization, the implementation of AR must be customized to the company, while concurrently adjusting the company's processes and structures to accommodate AR usage. AR solution providers can use this list to gain a better understanding of the requirements of decision makers in industrial organizations. They should introduce specific support offerings for implementation of AR in industrial organizations, i.e., assistance in preparing organizational data and existing IT systems for use with AR solutions. Moreover, some of these barriers need to be addressed by a consortium of researchers, policymakers, industrial organizations, and AR solution providers to develop guidelines and standards for the emerging AR technology.

Some limitations of this study must be noted. The results of the Delphi study rely on the input of finally 19 non-randomly chosen experts, thus limiting the sample size, and restricting the generalizability of the findings. By not reaching a Kendall's $W > 0.7$ it is important to emphasize that we did not select participants based on their likely responses in order to maximize the level of consensus. Our expert panel was deliberately chosen to be diverse in order to reflect a complex technology such as AR in industrial organizations. As a result, we believe that the level of consensus achieved also mirrors the diverse nature of experts that participated in the study.

6. Conclusion

To enhance the understanding of barriers regarding adoption and implementation of AR in industrial organizations as perceived by organizational decision makers, we conducted a Delphi study. The study yielded a structured list of 32 barriers, of which 13 were ranked by the experts according to their relative importance for industrial organizations. Our findings serve as a research agenda for future investigations into these barriers. We contribute to research and practice by providing a structured overview of the barriers industrial organizations need to consider, emphasizing the fact that besides technological factors, the organizational context also need to be considered.

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6. Appendix – Consolidated list of the 32 identified barriers

TOE View	Barrier and ranking	Description	Source
O	Functional benefits of AR (#1)	Using AR does not provide any functional benefits to the organization, e.g., it does not increase performance or productivity nor results in a reduced error rate. Supplying information could also be done without AR, for example, by using text, images, or video.	Schuir & Teuteberg, 2021
O	Organizational fit of AR (#2)	It is difficult to determine whether the use of AR solutions fits the organization's needs, given its existing structure and capabilities. It may be necessary to fulfil certain prerequisites within the organization before incorporating AR solutions. This requires a complete understanding of the organization's processes and use cases, and the ability to customize the AR solution accordingly. Sometimes this may entail adjusting existing processes and structures within the organization more than is necessary or appropriate for the implementation of AR. This goes against the fundamental purpose of AR solutions, which is to provide support and assistance.	Masood & Egger, 2019
O	Costs (#3)	Adoption and implementation of AR solutions entail substantial costs, e.g. a significant initial investment in hardware and applications. There must be resources accessible for buying or enhancing specialized AR solutions.	Hein & Rauschnabel, 2016
O	Acceptance of new digital technologies (#7)	Augmented Reality is only a futuristic vision or a gimmick; the use of this technology is not necessary for processes in industrial organizations. Certain decision makers or employees, e.g. those with little technology experience, low flexibility, or older age, tend to be skeptical about the use of AR. They must be convinced of the benefits of AR applications for their respective jobs.	Schuir & Teuteberg, 2021
O	Hesitation to change long-established processes and systems (#12)	Adopting new technologies like AR requires changing long-established work processes or altering/replacing legacy systems. This issue may cause resistance or hesitation within the organization.	Masood & Egger, 2019
O	Trust (#13)	Adoption and use of AR within the organization requires trust into this new technology, something that cannot be established from the outset due to a lack of experience. AR solutions still need to establish this trust by demonstrating functionality, reliability and usefulness when employed in an industrial context. Furthermore, providers and developers of AR applications and hardware need to be trustworthy, i.e. in terms of competence, predictability, and benevolence.	Quandt et al., 2018
O	Cognitive load	Using AR in industrial contexts may result in a high cognitive load for employees. This is caused, for example, by interference and distraction through virtual elements, the need for a frequent change of focus between real life and virtual information.	Jetter et al., 2018
O	Dependency on AR	The implementation of AR solutions may lead to a dependency of employees. By relying on AR, employees are at risk of losing work-related competences and might not be able to perform their work tasks without the support of AR.	Schein & Rauschnabel, 2022
O	Lack of knowledge and expertise about AR	Decision makers in industrial companies may lack awareness, knowledge and/or technical know-how about Augmented Reality technology.	Hein & Rauschnabel, 2016
O	Lack of management support	There is no (sufficient) allocation of resources for AR-related development projects and evaluations within the organization due to a lack of (long-term) management support, as a return on investment is uncertain.	Masood & Egger, 2019
O	Lock-In	The implementation of AR solutions may lead to economic dependency (lock-in) of the organization on specific AR application or hardware providers. Switching AR solutions is considerably more difficult than migrating other systems, e.g. CRM systems.	Masood & Egger, 2020
O	Occupational safety	The use of AR may involve a potential risk to the health of employees and/or the physical safety of machines and equipment. For each use case, a risk assessment required by the Occupational Health and Safety Law is necessary. The threats identified during the risk assessment have to be mitigated by taking appropriate measures, which can cause additional burdens for the employees.	Quandt et al., 2018
O	User reaction to occlusion	AR solutions are capable of providing immersive experiences that directly affect users' perceptions and actions in the physical world. In industrial contexts this implies various risks, e.g. unintentional occlusion of reality through virtual elements, unintended misinformation or potential for manipulation or malicious deception.	Palmarini et al., 2018
O	Social consequences	Using AR in work processes disrupts interaction between employees and has a negative impact on quality of interpersonal factors like communication, which may reduce their productivity.	Schein & Rauschnabel, 2022
O	Necessary training	Introducing AR applications and hardware for use in work processes within the organization requires specialized training, given that employees are usually not as familiar with AR as they are with PCs and smartphones. Generic introductions integrated into AR applications and AR hardware cannot cover all possible process requirements; specialized trainings are necessary in industrial contexts.	Masood & Egger, 2019

T	Complexity of AR solution development (#4)	Developing or customizing AR solutions for use within industrial organizations is nontrivial and/or must be carried out at high cost by external service providers. External AR developers often do not fully understand the processes and use cases within the organization. AR authoring tools for use by industry domain experts may fail to adequately address the requirements in industrial contexts and can only be used for specific use cases.	Danielsson et al., 2020
T	Maturity of AR hardware (#5)	AR hardware currently available on the market is still in need of development or adjustment to meet the expectations and requirements of the business (e.g. computing power of the hardware, accuracy, and latency of displaying AR content in the real world, battery life or weight of the hardware, field of view etc.).	Danielsson et al., 2020
T	Integration into existing IT systems (#6)	A seamless integration of AR solutions into already existing systems and processes of the organization's IT landscape is not easily possible. This applies to both internal processes as well as collaborating with AR developers or customers of the organization.	Schuir & Teuteberg, 2021
T	High data complexity (#8)	AR systems require a variety of data from different sources. There are many different types and structures of data. This data must be linked together, which requires complex data management. It is also not trivial to prepare already existing data adequately for the use of AR.	Palmarini et al., 2018
T	Data security (#9)	Technical protection of AR system data against unauthorized access (e.g. protection of company secrets) is not guaranteed. It is ambiguous by which measures, if any, organization data is protected by the application or hardware providers. The constantly active sensor technology (camera, audio, Lidar, etc.) makes AR systems a particularly attractive target for malicious actors.	Quandt et al., 2018
T	Operation of AR in industrial environments (#10)	Operating AR solutions is often not intuitive and/or not explained adequately. User input is often not registered correctly, and operating errors are possible. A wide range of input modalities (e.g. touch gestures, hand gestures, eye tracking, voice control) can lead to confusion. These modalities might only be partially compatible with the organization's work processes or not at all.	Bottani & Vignali, 2019
T	Maturity of AR applications (Software) (#11)	AR applications (software) currently available still require further development to meet the organization's expectations and requirements (e.g. quality of information visualization, dynamic and context-dependent provision of information, design of the user interface of the applications).	Danielsson et al., 2020
T	Data availability	It is not always possible to guarantee availability of data and thus the functionality of the AR solution, as the use of AR solutions usually requires an internet connection and/or access to corporate networks (e.g. WLAN, 5G).	Quandt et al., 2018
T	Privacy	Employee's personal data may be compromised when using AR applications.	Berkemeier et al., 2019
T	Surveillance	AR solutions often require continuously active sensor technology (e.g. camera, microphone) to collect a wide range of information, e.g. the status of the workflow and that of the employee himself. Aggregating this data may not only serve to support employees and increase productivity, but also potentially enable monitoring of work, performance, or behavior. Employees may complain about this potential surveillance.	Berkemeier et al., 2019
T	Transferability and scalability of AR solutions	In the industrial context, AR solutions are usually developed for a specific use case. Scaling AR solutions is very difficult and of great technological complexity. Transferring an AR solution to another use case or process involves a great deal of effort, even for marginal deviations.	Bottani & Vignali, 2019
T	Use conditions within industrial contexts	AR solutions may not function properly under certain conditions within industrial contexts (e.g. light, noise, hazardous substances, temperature, etc.).	Souza Cardoso et al., 2020
E	Competitive pressure	Implementing a complex technology like AR is a time-consuming and resource-intensive process. It is not guaranteed that AR will help to maintain or improve the market competitiveness of the industrial organization compared to industrial competitors. This decision may have a negative impact on the organization's market competitiveness, at least in the beginning, compared to other investment decisions.	Hein & Rauschnabel, 2016
E	External support by industry associations	Industry associations are currently not in a position to provide information and know-how concerning the adoption and implementation of AR.	Masood & Egger, 2020
E	External support from AR solution vendors	Vendors of AR solutions do not provide sufficient information and know-how regarding adoption and implementation of AR within industrial organizations. This may apply during the decision making process prior to the adoption decision, but especially during and after the implementation phase.	Masood & Egger, 2019
E	Lack of a defined legal environment	There is legal uncertainty regarding the use of AR in industry. For example, it is uncertain how legal issues like liability would be handled when using AR devices, especially when working with external business partners.	Schuir & Teuteberg, 2021
E	Lack of standardization	Until now, there is a lack of technical, cross-vendor standards in the field of AR. This is an issue for industrial organizations, e.g. compatibility problems may occur so that AR offerings from different vendors cannot be used in combination.	Danielsson et al., 2020
<p>T = Technological context; O = Organizational context; E = Environmental context Barriers that were ranked as most relevant by the experts are highlighted in bold font; their respective ranking is indicated in brackets (e.g. (#2) = barrier ranked as second most relevant by the experts)</p>			