

**A FRAMEWORK FOR DESIGNING AND ANALYZING MULTIMODAL LEARNING  
ANALYTICS SYSTEMS**



# **A Framework for Designing and Analyzing Multimodal Learning Analytics Systems**

Thesis for Doctoral Degree (Ph.D)

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The thesis will be defended in public at Niagara, Auditorium C

Tuesday, 24 September, 09:00 - 12:00

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# Studies in Computer Science number 26

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ISBN 978-91-7877-520-0 (print)

ISBN 978-91-7877-521-7 (pdf)

DOI 10.24834/isbn.9789178775217

Print: Media-Tryck, Lund university, 2022



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HAMZA OUHAICHI

**A FRAMEWORK FOR DESIGNING AND  
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ANALYTICS SYSTEMS**

Malmö university, 2024  
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# ABSTRACT

The integration of technology in education offers transformative potential, especially with the advent of data-driven approaches that can personalize learning, support educators, and provide valuable insights into the learning process. Multimodal learning analytics (MMLA) holds remarkable promise within this context. By capturing and analyzing data from multiple sources—including video, audio, and digital interactions—MMLA systems offer a holistic view of learning experiences and the ability to tailor interventions in real time. This application has profound implications for understanding and enhancing learning experiences. However, the design of such sophisticated systems poses a significant challenge. Without conventional and field-tested frameworks, MMLA system development often remains self-driven and tailored to specific contexts, limiting both these systems' broader adoption and full utilization. This thesis proposes a structured framework for designing MMLA systems across diverse educational contexts to address this fundamental challenge. The development of the framework followed a multifaceted methodology. In addition, action design research involving empirical studies, literature reviews, and expert interviews was employed to establish a set of foundational design considerations. The framework was then applied and refined within real-world educational settings. These included applications in the context of a globally distributed classroom and language acquisition environments. This practical application led to refinements that enhanced the framework's adaptability and user-centric design. This thesis makes three key contributions: (1) a set of design considerations for MMLA systems, (2) a framework offering a structured guide for the design of MMLA systems, and (3) a conceptual system demonstrating the framework's principles. The implications of this work are significant for researchers and stakeholders in MMLA, providing a foundation for future MMLA system development and ensuring more systematic and conventional design practices. This structured approach paves the way for broader adoption and integration of MMLA, ultimately enhancing educational outcomes and fostering personalized learning environments.

## LIST OF PUBLICATIONS

- Paper 1. **Ouhaichi, H.**, Spikol, D. and Vogel, B.: Rethinking MMLA: Design Considerations for Multimodal Learning Analytics Systems. In Proceedings of the Tenth ACM Conference on Learning @ Scale (L@S '23). 354–359. ACM, 2023 doi: 10.1145/3573051.3596186
- Paper 2. **Ouhaichi, H.**, Vogel, B. and Spikol, D.: Exploring design considerations for multimodal learning analytics systems: an interview study. In Frontiers in Education (Vol. 9, p. 1356537). Frontiers Media SA, 2024. doi: 10.3389/feduc.2024.1356537
- Paper 3. **Ouhaichi, H.**, Spikol, D. and Vogel, B.: Guiding the Integration of Multimodal Learning Analytics in the Glocal Classroom: A Case Study Applying MAMDA. In Proceedings of the 16th International Conference on Computer Supported Education (CSEDU). 478-485. SciTePress, 2024 doi: 10.5220/0012690900003693
- Paper 4. **Ouhaichi, H.**, Spikol, D. and Vogel, B.: Learning Swedish with AI: Exploring Multimodal Learning Analytics in Spoken Language Acquisition. In 14th International Conference on Methodologies and Intelligent Systems for Technology Enhanced Learning (MIS4TEL'24). p-p. SpringerLink, 2024
- Paper 5. **Ouhaichi, H.**, Spikol, D. and Vogel, B.: Analytics in Glocal Classrooms: Integrating Multimodal Learning Analytics in a Smart Learning Environment. In 24th IEEE International Conference on Advanced Learning Technologies (ICALT24). p-p. IEEE, 2024
- Paper 6. **Ouhaichi, H.**, Spikol, D., Vogel, B.: A Systematic Review Of Multimodal Learning Analytics Design Models And Frameworks. In 16th annual International Conference on Education and New Learning Technologies (EDULEARN24). 5304-5314. IATED, 2024 doi: 10.21125/edulearn.2024.1299

## **Personal Contributions**

For all the publications listed, the first author was the main contributor to the research planning, execution, and manuscript writing processes. The co-authors provided valuable input in the conceptualization stages and contributed to the supervision and editing processes. All co-authors reviewed and edited drafts of the publications, ensuring the integrity and quality of the work presented.

# ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my main supervisor, Professor Daniel Spikol, for his unwavering support, guidance, and availability throughout my research journey. His insightful feedback and encouragement have been instrumental in the completion of this work. I am also immensely grateful to my co-supervisor, Professor Bahtijar Vogel, Head of the Department of Computer Science and Media Technology. His continual support and consistent assurance of availability, even during vacations, have been invaluable. Both Professor Spikol and Professor Vogel have not only been excellent mentors but also genuinely fun colleagues and friends, making the research process a memorable life experience. Special thanks to Prof. Arianit Kurti for reviewing both my licentiate thesis and this thesis, and for providing valuable feedback that greatly improved the quality of my work. I would also like to thank Prof. Bo Peterson, my former co-supervisor, for his guidance and support during the early stages of my research. Additionally, I am grateful to Prof. Åse Jevinger for her continued support even after leaving her duties in research education. I extend my appreciation to my former manager, Henriette Lucander, for supporting my professional development through constructive dialogue and engaging discussions.

To my fellow Ph.D. students, Alberto Alvarez and Sergei Dytckov, thank you for leading the way and being present during the challenging times of the COVID pandemic when the office was nearly empty. I am also grateful to Sara Caramaschi, Michael Belfrage, Gent Ymeri, Ali Soleimani, and all the others for their unwavering support and camaraderie. My colleagues have also been a tremendous source of support and inspiration. Johan Holmberg, thank you for the great teaching experience we shared and for many co-hosted dinners, parties, hikes, and beautiful moments. Sussi Lundborg, your assistance throughout the

Ph.D. process was invaluable. Kristina Allder, your meticulous organization made teaching with you a learning experience. Mats Syde, I am grateful for your mentorship in teaching. Fisseha Mekuria, thank you for your invaluable fatherly advice and wisdom. Jeanette Eriksson, I appreciate your initiation of pedagogical projects and for opening doors for me and others to contribute, as well as the delicious fika in your meetings. Steve Dahlskog, your interesting and fun seminars, and boundless energy have been truly motivating. Reza Malekian, despite being the busiest person I know, your quick email responses and genuine interest in my progress never went unnoticed. Solveig-Karin Erdal, thank you for those constructive breakfast meetings and for being a source of useful tips about nearly everything at the university. Lena Rolén, your consistent support is greatly appreciated. Farid Naisan, thank you for the consistent cheerful attitude. Charlie Kronberg, your continuous support with orders and administrative tasks was always appreciated.

To everyone who has contributed to my journey, both mentioned and unmentioned, thank you for your support, encouragement, and friendship. This thesis would not have been possible without you.



اللهم أرني الحق حقاً وارزقني اتباعه ، وأرني الباطل باطلا وارزقني اجتنابه

إلى أمي، سكينه اخوي و أبي، عبد الله أوحيشي

# INTRODUCTION

Education is a fundamental duty that human society owes to itself, an intrinsic part of our existence that transcends economic or vocational purposes. It is impossible to envision life without learning, as it is an integral thread woven into the fabric of human existence. Just as Descartes declared, “I doubt, therefore I am,” we might also assert, “I doubt, therefore I learn.” This reveals that learning is not merely an act but a fundamental human imperative, making education an indispensable cornerstone of our lives [1]. As individuals, we spend a significant portion of our lives within the walls of schools, universities, and other educational institutions. This commitment is mirrored by society’s immense efforts and resources dedicated to the education system, encompassing schools, academia, research, and training programs. It is through education that we gain the ability to understand ourselves and the world around us, fostering a sense of curiosity and lifelong learning. Education cultivates critical thinking, empathy, and cultural understanding, thereby enabling us to become more aware, responsible, and engaged members of society [2]. It is not merely a process of acquiring knowledge but a continuous journey of personal and communal growth.

The advent of digital transformation has brought profound changes across all sectors, and education is no exception. The integration of digital technologies into educational systems has influenced how we teach and learn. Traditional classrooms are being increasingly supplemented or replaced by digital platforms that offer flexible and accessible learning experiences. Online courses, digital textbooks, and interactive learning tools have become commonplace, providing learners with unprecedented access to educational resources [3]. This transformation has significant potential for enhancing the reach and efficiency of education and enables innovative pedagogical approaches that can adapt to diverse learning styles and needs [4]. Within this context, learning analytics has emerged as a powerful tool inspired by the principles of data analytics and business intelligence. Learning analytics [5] involves the collection, analysis, and interpretation of data about learners and their contexts with the aim of

understanding and optimizing learning and the environments in which it occurs. By leveraging large datasets, learning analytics can provide insights into student performance, identify at-risk students, and inform instructional strategies. It offers educators a data-driven approach to enhancing teaching and learning outcomes, making education more responsive and adaptive.

A particularly promising development in this field is multimodal learning analytics (MMLA) [6]. Unlike traditional learning analytics, which may rely solely on log data that represent the interaction of the learner with a computer, MMLA integrates multiple data sources to create a more comprehensive picture of the learning experience. This includes data from digital interactions, physiological sensors, video and audio recordings, and other sources. The multimodal nature of MMLA reflects the complex, multifaceted nature of learning itself, which cannot be fully captured by any single type of data [7]. The concept of multimodality in MMLA is crucial. It recognizes that learning is a dynamic process influenced by various factors—from cognitive and emotional states to social interactions and environmental contexts. This approach aligns with the streetlight effect [8], a phenomenon in which people search for something only where it is easiest to look. In traditional learning analytics, this might mean focusing on easily quantifiable data while neglecting richer, more complex sources of information. MMLA seeks to illuminate the full spectrum of the learning experience by integrating diverse data types.

In life and learning, multimodality is inherent. Just as people use multiple senses to perceive and understand their surroundings, learners engage in various modes of interaction and expression [7]. For example, a student might listen to a lecture, participate in group discussions, take notes, and complete hands-on projects—all within a single learning session. Each of these activities can be traced digitally into different types of data that, when combined, offer an overview of the learning process. Thus, MMLA stands out in educational innovation, promising to support how we understand and practice learning [9]. By capturing and analyzing the various ways in which students interact with their learning environments, MMLA provides a holistic view that can inform learning interventions, support teachers, and enhance educational outcomes.

## **Motivation**

The promise of MMLA [9] lies in its ability to capture and analyze a broader range of learner behaviors and interactions compared with traditional learning analytics. The study conducted by Blikstein in 2013 [6], introduced the concept of MMLA, highlighting its potential in integrating diverse data sources to provide

a more comprehensive understanding of the learning process. This pioneering study underscored the limitations of traditional analytics in capturing the full spectrum of learning activities, proposing MMLA as a way to encompass both digital and physical interactions within learning environments. Further exploring the promise and challenges of MMLA, Cukurova, Giannakos, and Martinez-Maldonado [9] presented a detailed overview of its potential benefits, methodological challenges, and ethical considerations. They emphasized that MMLA can enhance our understanding of learning processes by integrating data from various modalities, such as eye tracking, gesture analysis, and physiological sensors. This holistic approach can reveal deeper insights into learner engagement, emotions, and cognitive processes, ultimately contributing to a better understanding of educational experiences. Ochoa and Worsley [8] further consolidated the state of MMLA research by identifying key trends, methods, and applications. Their review highlights the flexibility of MMLA in addressing diverse educational challenges, from assessing affective states to predicting learning outcomes. By synthesizing findings from numerous studies, they demonstrated that MMLA can offer valuable insights across various educational contexts, making it a promising tool for researchers and practitioners.

Specific applications of MMLA have been shown to be effective in different educational settings. For instance, D’Mello and Graesser [10] explored the use of analytics to assess learners’ affective states, such as boredom, confusion, and engagement. In a 2015 study [11], Bosch demonstrated how MMLA can predict learning outcomes in soft skills. Both studies emphasized the use of learners’ physiological, behavioral, and verbal data. This approach allows educators to understand how emotional states influence learning and tailor interventions accordingly. This predictive capability is crucial for identifying at-risk students and implementing timely support measures. Additionally, several studies [12], [13], [14] have focused on the application of MMLA in collaborative learning settings, highlighting its potential to provide insights into group dynamics and interaction patterns. By understanding how students collaborate and communicate, educators can design more effective activities and improve learning outcomes.

MMLA holds significant promise for educational research, particularly in complementing traditional qualitative methods. Educational research has traditionally relied heavily on qualitative approaches, such as interviews, observations, and case studies, to gain insights into learning processes and outcomes [9]. Although these methods are invaluable, they often lack the ability to capture the real-time, dynamic interactions that occur in learning environments. MMLA offers a quantitative and objective complement to these approaches by providing continuous data collection on various aspects of

learning. This integration of qualitative and quantitative data can lead to richer, more nuanced understandings of educational phenomena, ultimately advancing research practices in education. For teachers and educators [15], MMLA can serve as a powerful tool for enhancing instructional practices. By providing real-time feedback on student engagement, comprehension, and emotional states, MMLA enables educators to adjust their teaching strategies to better meet the needs of their students. This data-driven approach allows for more personalized and responsive instruction, fostering a more supportive and effective learning environment. Students also benefit from MMLA [16], particularly in the context of self-regulated learning. By gaining insights into their own learning behaviors and patterns, students can develop greater self-awareness and take more control over their learning processes. Furthermore, MMLA can help identify areas where students may need additional support or practice, thereby guiding them toward more effective study strategies and enhancing their overall learning experiences. In terms of data-driven learning design and decision-making, MMLA provides invaluable insights that can inform curriculum development, instructional design, and policy decisions. By understanding how different instructional approaches impact learning outcomes, educators and administrators can make more informed decisions regarding curriculum design and resource allocation. MMLA can also identify best practices and innovative teaching methods that can be scaled and implemented across educational institutions, ultimately improving the quality of education.

The promise of MMLA extends across various dimensions of education, offering benefits for research, teaching, learning, and decision making. Its focus on capturing and analyzing multimodal data provides a comprehensive understanding of the learning process, paving the way for data-driven educational practices.

## **Problem Statement**

Despite its potential, MMLA faces considerable challenges in terms of design [9]. The potential of MMLA to capture and analyze a broad range of learner behaviors and interactions has been well documented; however, the complexity of designing MMLA systems cannot be overstated. The design aspects of an artifact are crucial because they directly impact its adoption and usage. Without thoughtful design, the implementation and use of MMLA systems become even more challenging [17], leading to issues in terms of their reliability and overall effectiveness.

One of the primary obstacles in the design of MMLA systems is the lack of conventional design practices [18]. This absence not only complicates the design

process but also undermines the reliability of the systems. As highlighted in the “Motivation” section, although MMLA holds significant potential, the lack of conventional design practices means that systems are often built in a single-use manner that is narrowed and specific to research goals and learning scenarios. This disjointed approach can lead to inconsistent results and reliability issues, making it difficult for these systems to be implemented and adopted within educational contexts. Furthermore, there is a lack of research that directly addresses the design aspects of MMLA. Existing research often focuses on the use of MMLA to support learning design, such as designing learning activities [19], rather than on the design of the MMLA systems themselves. This misalignment means that although we understand how MMLA can be used to enhance learning, we need guidelines on how to design these systems from the ground up. The need for direct research into MMLA system design is critical to bridging this gap and providing a foundation for future developments in the field. Moreover, existing knowledge about the design of MMLA systems is highly fragmented. Researchers and practitioners have developed various methods and tools independently, leading to a diverse but disjointed body of knowledge [17]. This fragmentation makes it difficult to consolidate best practices and create unified design guidelines. The multitude of factors that must be taken into account—ranging from technical specifications and data integration to ethical considerations and user experience—further complicates the design process. Each of these factors plays a vital role in the overall functionality of MMLA systems, and balancing them requires a structured approach, which is currently lacking in the literature.

Moreover, the sheer number of considerations in play can be overwhelming. Designers must navigate a complex field that includes technological constraints, data privacy issues, ethical considerations, and the need for user-friendly interfaces [9]. Each of these elements must be planned and integrated to create a cohesive and functional system. The absence of a standardized design approach means that each new MMLA system must address these challenges anew, often leading to reinventing the wheel and further contributing to the fragmentation of knowledge in the field.

## **Research Questions**

The design of MMLA systems presents a complex challenge due to the multitude of factors that impact this process. The objective of this thesis is to address this complexity and facilitate the design process of MMLA systems for researchers and practitioners. This objective aims to provide a structured approach to the

design of MMLA systems for various educational contexts. To achieve this objective, this research is guided by the following research questions:

- *RQ1: What are the factors that impact the design process of MMLA systems?*

This question focuses on identifying the elements that need to be taken into account when designing MMLA systems. By pinpointing these elements, the research aims to provide a broad checklist that can guide researchers and practitioners throughout the design process.

- *RQ2: How can the design process of MMLA systems be organized and facilitated for researchers and practitioners?*

The second question aims to develop an organized approach that can be followed to systematically design MMLA systems. This approach will outline the stages of design—from initial conceptualization to evaluation and refinements. By providing a clear and practical framework, this research seeks to streamline the design process and ensure consistency and reliability across different MMLA systems.

## **Objectives and Scope**

The potential of MMLA is substantial [8]. By integrating diverse data sources, MMLA offers a holistic view of the learning process, enabling data-driven insights that can enhance educational practices. The potential of MMLA in supporting education lies in its ability to provide nuanced understandings of learner behavior, engagement, and performance, thereby supporting tailored interventions and improving learning outcomes. However, the realization of this promise is hindered by several critical issues [20]. The foremost among them is the lack of conventional design practices for MMLA systems. Current designs are often custom-made and developed for specific contexts without broader applicability or scalability [18]. This fragmentation of knowledge about MMLA design practices means that many systems are subject to reliability issues and are difficult to replicate across different educational settings [19]. Additionally, the multitude of factors involved in the design of MMLA systems—ranging from data integration to ethical considerations—further complicates the development process.

Consequently, a significant gap exists between the promise of MMLA and its actual impact on education [17]. The primary objective of this thesis is to contribute to filling this gap by focusing on the design problems of MMLA

systems. Specifically, the aim is to develop an approach that supports and facilitates the design of MMLA systems for researchers and practitioners across various educational settings. This involves synthesizing the available fragmented knowledge and creating a systematic strategy that guides the design process. By achieving this objective, the thesis aims to provide a foundation for the development of MMLA systems. To accomplish this, the research employs action design research (ADR) [21], a methodology that combines action research with design science to develop and refine practical solutions iteratively. ADR is particularly suitable for this study because it allows for the iterative development of solutions in real-world settings, ensuring that the resulting framework is theoretically sound and practically applicable [22]. Through cycles of design, application, evaluation, and refinement, the research aims to produce a comprehensive design framework that addresses the complexities of MMLA system development.

This thesis focuses on the design and process of creating MMLA systems. The primary aim is to develop an approach that facilitates and supports the design of these systems. However, this thesis does not extend to examining the impact of MMLA systems on learning outcomes or student engagement. Although these are important aspects of educational technology, they fall outside the primary focus of the thesis on design processes and considerations. Similarly, the broader promises and potential benefits of MMLA, such as improved educational outcomes or enhanced student experiences, are not the main concerns of this research. Instead, the thesis concentrates on the practical aspects of designing MMLA systems. Although a conceptual MMLA system has been developed as a proof of concept, this thesis does not provide an extensive evaluation of its implementation or long-term usage in educational settings. The focus remains on the design framework and considerations rather than the operational aspects of MMLA systems. Furthermore, although the findings proposed in this thesis are based on specific case studies and expert insights, there may be limitations in their generalizability to all educational contexts or technological environments.

## **Thesis Outline**

MMLA can potentially transform educational experiences by offering insights from diverse data sources, such as student interactions, videos, and learning tools. However, a critical challenge lies in the need for conventional design practices. This gap was identified through previous foundational research [9], which highlighted the predominantly specialized, single-use nature of existing MMLA systems, which are often developed by researchers themselves. Recognizing this



gap, our research adopted a systematic exploration to bridge this gap and address the need for practices that facilitate MMLA design processes.

This thesis begins with the development of a knowledge base. The first study focuses on exploring design considerations for MMLA systems, synthesizing existing literature to establish an initial set of considerations. Building on these findings, the second paper incorporates insights from semi-structured interviews with MMLA experts, leading to an expanded set of design considerations and the proposal of an initial MMLA design framework. This framework is intended to provide a structured approach for guiding the development of MMLA systems. The subsequent papers shift toward the practical application and evaluation of the proposed framework. Papers 3, 4, and 5 examine the framework's applicability in real-world educational settings, such as the Glocal Classroom and language acquisition environments. These practical applications provide essential feedback, leading to iterative refinements of the framework. Finally, the sixth paper conducts a comparative analysis using systematic literature review (SLR) methodologies to benchmark the proposed framework against existing models. This analysis helps ensure that the framework is aligned with the latest advancements in the field of MMLA, thereby guiding targeted refinements.

This thesis is structured to address the gaps identified in the design of MMLA systems. It begins with a "Background" section, wherein we delve into related work, examine the current trends in MMLA research, and articulate the critical gaps this thesis aims to address. Then, the "Methodology" section offers a detailed overview of the methods employed in each of our studies, emphasizing their interconnectedness and how they contribute to the overall research goals. We outline our approach within the ADR methodology and utilize interviews, field studies, prototyping, and literature reviews. We then provide a summary of the papers included in this research. We answer the research questions in the "Results" section, wherein we explain the nature of the answers in an abstract way. In the "Contributions" section, we present the tangible outcomes of our research, including the identification of design considerations, the development and refinement of the MMLA design framework (MDF), and the development of the MBOX system. These results form the core contributions of this thesis. The "Conclusion" section summarizes our main findings and emphasizes the contribution of this thesis to the field of MMLA. Finally, we conclude by highlighting the potential impact of the MDF and the MBOX system on educational practices and student outcomes.

## BACKGROUND

MMLA is a growing field within educational technology that leverages diverse data sources to gain a deeper understanding of the learning process [6]. Unlike traditional learning analytics, which typically rely on single data modalities, such as clickstream data or assessment scores, MMLA integrates data from various sources, including audio, video, physiological signals, and even social interactions. This multimodal approach offers a more holistic and nuanced view of learner behavior, engagement, and performance [20]. The roots of MMLA can be traced back to traditional learning analytics [21], which emerged with the rise of digital learning environments. However, the limitations of relying on single-modal data became increasingly apparent as researchers sought to capture the complexities of human learning. This led to the evolution of MMLA, driven by advancements in data collection technologies and machine learning algorithms.

The emergence of MMLA was further fueled by the need for more comprehensive learner models that could account for the diverse ways in which individuals learn and interact with educational content [20]. MMLA systems utilize a range of technologies, such as sensors, wearables, eye-tracking devices, microphones, and cameras, to capture a wide array of learner behaviors and physiological responses. These data are then processed using machine learning algorithms, natural language processing, and/or computer vision techniques to extract meaningful insights. The outputs are presented through interactive dashboards and graphical representations, providing educators and stakeholders with actionable information [7]. The significance of MMLA lies in its potential to support educational practices by offering educators and learners more adaptive and data-driven insights [22]. In addition, MMLA systems can help identify at-risk learners, tailor instructional strategies to individual needs, and foster a deeper understanding of the factors that influence learning outcomes [23]. With the increasing prevalence of digital learning environments, MMLA is positioned to play a pivotal role in shaping the future of education [9]. However, despite its potential benefits, MMLA research does not show evidence of causing an impact

on education [17]. Moreover, MMLA faces significant challenges in its design and implementation [19], such as the need for standardized practices, as well as in terms of the complexities of integrating diverse data sources, thereby underscoring the need for comprehensive frameworks that guide MMLA's design and implementation.

## **Related work**

This thesis project is inspired by previous foundational research that explored the field of MMLA, serving as the groundwork for recognizing the need and importance of developing tools and strategies for designing MMLA systems. This initial investigation, as detailed in the licentiate thesis [24], focused on understanding the necessary components for achieving a flexible and effective MMLA system design. The study highlighted the varied needs inherent in educational settings utilizing multimodal data (MBOX) [25], emphasizing the importance of systems capable of adapting to different learning environments and contexts. A key aspect of this foundational research was the emphasis on flexibility and adaptability in MMLA systems. It underscored the importance of designing systems that can adjust to unique educational settings, ensuring that they meet specific requirements effectively. Furthermore, the research proposed an integrative approach to MMLA system design, suggesting that these systems should seamlessly combine various data modalities—such as audio, video, and textual inputs—to provide a comprehensive understanding of the learning process.

### **Research Trends in MMLA**

Recent studies in the field of MMLA have identified several trends and gaps. According to our mapping study [26], MMLA researchers often take on multiple roles, including designing and implementing new MMLA systems. A researcher might simultaneously be an academic responsible for teaching a course, a designer and developer of MMLA systems, a tester, a user, and the person responsible for its implementation. This multifaceted role blurs the lines between the various stages of system development and use, leading to potential conflicts of interest and biases in the research process [27]. The overlap of these roles can result in the conflation of the development, application, and evaluation processes, which complicates the establishment of clear, objective design practices and guidelines.

A significant ambiguity in MMLA research is the distinction between evaluation and validation studies. Evaluation research typically occurs in controlled settings, such as laboratories, where variables can be carefully managed to assess the

system's performance [28]. In contrast, validation research is conducted in authentic educational settings, where the system's effectiveness is tested in real-world conditions. However, due to the context of educational applications, studies often describe the learning environment without clearly indicating whether it is an evaluation or validation study [19]. This lack of explicit distinction is problematic because the nature of educational settings often leads to environments that are naturally controlled. Consequently, distinguishing between controlled and authentic settings is not straightforward, which adds a layer of difficulty to the interpretation of results. The multiple roles of researchers exacerbate this issue, as they may design and implement the system, thereby influencing both the evaluation and validation processes.

One of the primary challenges in MMLA is the absence of standardized design practices, which makes it difficult to ensure the reliability and generalizability of MMLA systems across different educational contexts. Without established design guidelines and practices, researchers and developers are often required to create customized solutions for each new application, leading to inconsistencies and reliability issues [17], [20]. The absence of conventional design practices also means that best practices are not widely shared or implemented, further hindering the development of robust and effective MMLA systems. Moreover, knowledge about design practices in MMLA is highly fragmented across specific applications [26]. Each study or implementation tends to focus on a narrow aspect of MMLA, tailored to particular research goals or educational contexts. This fragmentation prevents the development of comprehensive design practices that can be broadly applied. Instead, the insights and lessons learned from individual projects are not easily accessible or generalizable, limiting the ability to build on previous work and advance the field cohesively. There is a pressing need for comprehensive guidelines that consolidate knowledge from various applications and provide clear, actionable strategies for designing and implementing MMLA systems.

## MMLA Commitments

The concept of “core commitments” plays a pivotal role in guiding effective research and system design. These core commitments, as outlined by Worsley et al. [29], serve as foundational principles that ensure that MMLA research adheres to specific methodological rigor and practical relevance. They provide a set of definitions and common ground for researchers to build upon, facilitating a consistent approach to the design and implementation of MMLA systems. A central aspect of these commitments is their focus on data collection. This involves the systematic gathering of diverse data types, thereby prioritizing comprehensive and accurate data acquisition. Ensuring that data are collected in a way that captures the multifaceted nature of learning processes is fundamental

to the effectiveness of MMLA research [30]. Furthermore, responsible analysis and inference are critical components. These principles stress the importance of using analytical methods capable of handling the complexity and variety of multimodal data, thus ensuring that the insights generated are reliable and actionable. Moreover, meaningful feedback and data dissemination are integral to these commitments [31]. This involves the processes through which the results of MMLA are shared with stakeholders, such as learners, educators, and administrators. Effective feedback mechanisms [32] enhance learning experiences by providing actionable insights that can inform instructional strategies and interventions. These commitments collectively aim to create a robust methodological framework that guides the design and implementation of MMLA systems, ensuring that they are both effective and relevant to educational needs.

Although these core commitments provide a valuable starting point, there is a need for empirical evaluation and integration of these principles into a design framework. Practical applications and real-world testing are crucial for refining these commitments and ensuring that they can meet the varied demands of different educational contexts. Empirical endeavors would evaluate their effectiveness and adaptability, highlighting any necessary adjustments to better suit practical needs [29]. Accordingly, integrating these core commitments into a unified design framework for MMLA is essential for advancing the field. Such a framework would not only standardize practices but also address the technical and pedagogical challenges inherent in MMLA system design. Given the current fragmented state of design practices, the need for comprehensive guidelines that can be broadly applied across various educational settings is pressing. By empirically testing and refining the core commitments, researchers can develop a robust framework that ensures that MMLA systems are designed with a focus on user engagement and educational alignment. The absence of such conventional practices currently hinders the reliability and scalability of MMLA systems. Therefore, addressing these gaps through the integration of core commitments into a comprehensive design framework will be beneficial for the progression of MMLA. This approach will enable the field to fulfill its promise of enhancing educational experiences and outcomes through robust, scalable, and practically sound MMLA systems.

## **Frameworks and Models in MMLA**

In the context of this research, the term “design” is associated with Ralph and Wand’s definition [33] of design: “(noun) a specification of an object, manifested by some agent, intended to accomplish goals, in a particular environment, using

a set of primitive components, satisfying a set of requirements, subject to some constraints.” This process involves identifying the necessary components and their interactions, ensuring that the system meets specific educational needs and is adaptable to various contexts. Design science research (DSR) [34] provides a foundation for this approach, focusing on the creation and evaluation of artifacts intended to solve identified problems. According to Peffers et al. (2007), DSR emphasizes the iterative development of solutions through rigorous testing and refinement, ensuring that the final product is both practical and theoretically viable. Traditional instructional design frameworks, such as ADDIE (Analysis, Design, Development, Implementation, and Evaluation) [35], SAMR (Substitution, Augmentation, Modification, and Redefinition) [36], and TPACK (Technological Pedagogical Content Knowledge) [37], have been widely used in educational settings. ADDIE, for instance, provides a systematic approach to instructional design, ensuring that all critical elements are considered during the development process. SAMR offers a model for integrating technology into teaching, guiding educators in enhancing their instructional methods. TPACK focuses on the intersection of technology, pedagogy, and content knowledge, helping educators effectively integrate technology into their teaching practices.

Although these frameworks have proven to be effective in various educational contexts, their applicability to MMLA is limited. The unique characteristics of MMLA, such as the integration of diverse data sources and the need for real-time data processing and analysis, present challenges that traditional frameworks are not equipped to address. ADDIE, for example, is meant for instructional system design, designing courses, building support tools for training, and performance, which makes it too broad. Similarly, SAMR and TPACK, although valuable for integrating technology into education, do not provide the specific practices needed to develop systems that handle multimodal data [38]. The limitations of existing frameworks highlight the need for novel design models specifically tailored to MMLA [19]. These new models must consider the unique requirements of MMLA, including the collection, processing, and analysis of multimodal data, and the ethical considerations involved in handling such diverse data types. They should also address the need for flexibility and adaptability, ensuring that MMLA systems can be effectively implemented in various educational settings.

Advocating for the development of new design frameworks for MMLA involves demonstrating that existing models are insufficient. Traditional frameworks do not account for the complexity and specificity of MMLA, particularly in terms of data integration and management. Therefore, there is a pressing need for frameworks that can guide the systematic development of MMLA systems, paving the way for more robustness, scalability, and ethical conduct. Developing

these novel frameworks requires a deep understanding of both the theoretical underpinnings and the practical applications of MMLA. It involves design and testing, as well as incorporating feedback from real-world implementations, to refine and enhance the models. By creating and evaluating new frameworks tailored to MMLA, this research aims to bridge the gap between the potential of multimodal analytics and their practical application in educational settings [29], ultimately contributing to understanding and enhancing learning experiences.

## Research Opportunities

Current MMLA practices often suffer from a lack of standardization, wherein systems are typically designed for single-use scenarios and tailored specifically to narrow research objectives or unique educational contexts [19]. This approach limits the scalability and generalizability of these systems, thereby restricting their broader applicability and impact across diverse educational settings [25]. The fragmented nature of MMLA research, which often emphasizes the use of MMLA in designing learning experiences rather than focusing on the systems themselves [19], suggests that the complexities involved in MMLA system design are frequently underestimated. This oversight can hinder the development of robust and reliable systems.

**Table 1.** Gaps identified in MMLA research as well as their respective implications and potential impacts.

Gap	Implications	Actions	Potential Impact
Lack of Standardization (conventionality): MMLA systems are tailored for specific contexts.	This makes MMLA systems difficult to replicate, scale, and evaluate, thereby limiting their broader impact.	Explore design practices and establish design guidelines.	More robust MMLA systems that are easier to be adapted and implemented at scale.
Fragmented Research: MMLA research often focuses on the use of MMLA in designing learning environments, not on the design of the systems themselves.	This indicates that the complexities of MMLA system design may be underestimated, thereby hindering robustness.	Review existing frameworks critically and evaluate and adapt existing models to the needs of MMLA.	This can lead to more reliable, pedagogically relevant, and robust analysis.
Absence of Comprehensive Frameworks: Dedicated	This reveals a lack of tailored design structures to address	Develop new frameworks and models.	This can bring greater clarity, scalability, and

MMLA frameworks and models are scarce and often adapted from other fields.	the unique complexities of multimodal data and pedagogical needs in MMLA.		pedagogical relevance to the field.
MMLA systems involve a wide range of factors.	Without careful design, the potential insights from multimodal data may be lost or misinterpreted, limiting the effectiveness of MMLA systems.	Explore the technical and theoretical factors related to MMLA systems.	This can unlock the full potential of MMLA, leading to more accurate and actionable insights.

Moreover, there is a notable absence of comprehensive, well-established design frameworks that can effectively guide the development of MMLA systems to ensure that they are both effective and ethically sound [24]. Currently, MMLA frameworks and models are often scarce and adapted from other fields, which does not adequately address the unique complexities of integrating multimodal data within educational contexts. This gap highlights the need for a structured framework that can support the integration of various data modalities within ethical and pedagogical constraints, which are crucial factors for advancing MMLA into a reliable and impactful educational tool. Additionally, MMLA commitments [29] represent a set of operational guidelines aimed at enhancing the design and application of MMLA systems. Although these commitments provide valuable insights, they require empirical evaluation and need to be integrated into a broader, more robust framework to influence design practices within the field.

Table 1 outlines the gaps in MMLA system design, along with their implications, proposed actions, and potential impacts. The lack of standardization limits scalability and evaluation, which can be addressed by establishing design guidelines for more adaptable MMLA systems. Fragmented research focuses more on using MMLA in learning environments than on the system design itself, indicating a need to review and adapt existing models for robustness and relevance. The absence of comprehensive frameworks requires the development of new models tailored to the complexities of multimodal data and pedagogy, thereby enhancing clarity and scalability. Finally, without careful design, insights from multimodal data may be misinterpreted. Exploring technical and theoretical factors can unlock the full potential of MMLA, leading to more accurate and actionable insights. The proposed framework aims to address the complexities of MMLA system design by providing a structured, adaptable, and ethically grounded approach that can be applied across various educational environments. By developing this framework, we seek to transform the theoretical potential of



MMLA into practical, actionable systems that enhance educational outcomes and meet the dynamic needs of modern educational settings. This initiative aims to develop common MMLA design practices and to facilitate the creation of MMLA systems that can impact educational research and practice.

# METHODOLOGY

Action Design Research (ADR) [39] was chosen as the overall methodology. ADR is particularly suitable for this research because it emphasizes the creation of artifacts designed to solve problems through iterative cycles of problem definition, intervention, evaluation, and refinement. This approach integrates problem-solving with research, ensuring that the solutions developed are both theoretically sound and practically viable. ADR's iterative nature allows for continuous improvement based on real-world feedback, making it ideal for addressing the complex and multifaceted challenges of designing MMLA systems. ADR involves four main stages: Problem Formulation, Building, Intervention and Evaluation, and Reflecting and Learning.

ADR is a research methodology that integrates action research [40] and DSR [34]. This methodology is designed to generate practical solutions to real-world problems while simultaneously contributing to academic knowledge. ADR is particularly suited for complex, adaptive problems, where solutions require iterative development and continuous feedback from stakeholders. It was first conceptualized to bridge the gap between theory and practice in information systems research. It emerged from the need to create artifacts—such as software, models, or frameworks—that are both theoretically grounded and practically useful. Sein et al. [41] formalized ADR by integrating principles from action research, which focuses on solving immediate problems, with design science research, which aims to create and evaluate artifacts to solve specific problems.

The primary objective of ADR is to create actionable knowledge that is grounded in both theoretical understanding and practical relevance [39]. The key principles of ADR include the following:

- Interventionist nature: ADR involves direct intervention in real-world settings to create and test solutions.
- Iterative process: Solutions are developed and refined through cycles of planning, action, observation, and reflection.

- Collaboration: Engaging stakeholders throughout the research process to ensure the practical relevance of the solutions.
- Dual outcomes: Producing both practical solutions and theoretical insights.

Educational applications often deal with complex, adaptive systems in which multiple variables interact in unpredictable ways [42]. Therefore, traditional research methodologies may not adequately address the dynamic nature of educational environments. ADR's iterative and collaborative approach is particularly suited for educational research, as it allows for continuous refinement of educational interventions based on real-time feedback from stakeholders[43]. Moreover, MMLA systems are complex artifacts that integrate data from various sources to provide a comprehensive understanding of the learning process [18]. The design of such systems requires addressing diverse technical, pedagogical, and ethical considerations. ADR's principles of iterative refinement and stakeholder collaboration ensure that MMLA systems are both practically useful and theoretically robust.

Although DSR emphasizes the creation and evaluation of artifacts through iterative cycles, its primary focus is on the artifact itself [34]. ADR, on the other hand, combines the strengths of DSR with the participatory and problem-solving focus of action research, thereby ensuring that the artifacts are not only rigorously tested but also continuously refined through real-world engagement [44]. Action research's focus on solving practical problems aligns with ADR; however, action research does not necessarily emphasize the creation of innovative artifacts. ADR extends action research by integrating design elements to create new solutions while continuously engaging with real-world contexts. ADR aims to balance the creation of practical solutions with the generation of theoretical knowledge. This dual focus ensures that the artifacts developed are not only effective in real-world applications but also contribute to the academic understanding of the underlying principles and processes. In the context of MMLA, balancing theory and practice is crucial. Theoretical insights help in understanding the complex interactions within learning environments, whereas practical applications ensure that MMLA systems are usable and effective for educators and learners. This balance is achieved through continuous iterations and feedback loops that inform both theory and practice.

ADR involves multiple cycles of planning, acting, observing, and reflecting, as outlined below [39]:

1. Problem Formulation: This stage involves identifying and understanding the key challenges in MMLA design. This was achieved through two studies.

2. **Building, Intervention, and Evaluation:** In this stage, the proposed MMLA design framework is developed and tested in real-world educational settings.
3. **Reflecting and Learning:** This stage involves reflecting on the findings from the previous stages and learning from the research process.
4. **Formalizing the Learning:** The final stage, in which the insights and knowledge gained from the research are consolidated.

Iterative refinement allows for continuous improvement of MMLA systems. Each cycle provides new insights that can be used to enhance the artifact. This approach ensures that the final artifact is well suited to the dynamic and complex nature of MMLA. Unlike traditional research, wherein the researcher maintains a distance from the subject, action research [40], [41] positions the researcher as an agent of change within the research context. They actively engage with stakeholders, building relationships, facilitating dialog, and co-creating knowledge to address real-world issues. Stakeholders—including educators, students, administrators, and researchers—play a critical role in ADR. Their involvement ensures that the solutions developed are relevant and useful in real-world contexts. Stakeholders provide valuable feedback that informs each iteration of the design process. Stakeholder engagement can be achieved through various methods:

- **Workshops and focus groups:** Gathering diverse perspectives and generating collaborative ideas.
- **Surveys and interviews:** Collecting detailed feedback on specific aspects of the MMLA system.
- **Pilot testing and usability studies:** Implementing the system in real-world settings and observing its impact.

MMLA systems integrate diverse data sources—such as audio, video, physiological signals, and digital interactions—to provide a holistic view of the learning process. Designing such systems involves addressing technical challenges (e.g., data integration and real-time processing), pedagogical considerations (e.g., usability and impact on learning), and ethical issues (e.g., data privacy and informed consent) [45]. ADR’s iterative and active approach is well suited for addressing the multifaceted challenges of MMLA system design. By involving stakeholders throughout the process, ADR ensures that the solutions developed are responsive to the needs and constraints of real-world educational settings. The iterative cycles of ADR allow for continuous refinement of the system, ensuring that technical, pedagogical, and ethical considerations are effectively addressed. Continuous feedback from stakeholders is crucial for the success of MMLA systems. Feedback helps identify areas for improvement and

ensures that the system meets the needs of its users. ADR provides a structured process for collecting and incorporating feedback, facilitating continuous improvement, and ensuring the system’s long-term effectiveness.

## Methods

The methods employed in this research include literature reviews, interviews, field studies, and prototyping. Table 2 provides a summary of the methods used in each of the studies included in this thesis. Literature reviews were used to synthesize existing knowledge and identify gaps in MMLA design practices. This method provided a foundation for understanding the current state of the field and informed the initial design considerations. Semi-structured interviews were conducted with experts to gain deeper insights into MMLA design challenges and evaluate the literature review findings. This method allowed for the collection of rich, qualitative data that contributed to the development of a robust design framework. Field studies involved observing and collecting data in real-world educational settings, such as the Glocal Classroom and the language café. These studies provided practical insights into how the framework could be used and refined in various learning environments. Methods such as observations, inventory, and note-taking were used to gather comprehensive data on the implementation and impact of the MMLA systems. Prototyping was used to develop and refine the MMLA design framework iteratively. This involved creating and testing prototypes in real-world settings, collecting feedback from users, and making necessary adjustments to improve the framework’s usability and effectiveness.

**Table 2.** A summary of the research approach and methods employed in the studies.

Study	Aim	Method	Analysis	Outcome
Licentiate	Reaching flexibility in MMLA Systems	Action Research Research Through Design Systematic Literature Review	Deductive analysis	Identification of the need and lack of design guidelines for MMLA
Paper 1	Exploring MMLA design requirements	Literature Synthesis	Thematic analysis	A set of design considerations
Paper 2	Investigating MMLA design considerations	Semi-structured Interviews	Deductive and thematic analysis	Extended design considerations and MMLA design framework

Paper 3	Designing an MMLA system for the Glocal Classroom through the proposed MMLA design framework	Field study: Observations Technical Inventory Usage Log Data	Thematic and reflective analysis	Refined MMLA design framework and model
Paper 4	Designing an MMLA system for language acquisition through the proposed MMLA design framework	Field study: Weekly Sessions Focus Group	Thematic and reflective analysis	Further refined MMLA design framework and model
Paper 5	Prototyping MBOX	Prototyping	Reflection in action Iterative testing	Evaluated MMLA design framework and model
Paper 6	Investigating MMLA design requirements	Systematic Literature Review	Thematic and deductive analysis	Further extended design considerations and refined MMLA design framework and model

## 1. Problem Formulation

The initial phase of this research focused on identifying the need for a structured MMLA design framework. This stage involved a thorough exploration of existing literature and insights from foundational research, including the licentiate thesis, to establish a comprehensive understanding of the current state and gaps in MMLA system design. The literature synthesis (Paper 1) [46] aimed to consolidate existing knowledge on MMLA systems, highlighting critical design challenges and opportunities. The adopted methods involved a literature synthesis of relevant academic papers. We selected specific studies from a foundational research work [24]. These included two action design research studies focusing on MMLA system architecture design and prototyping [18], [13], a systematic mapping study exploring research trends in MMLA [9], and the licentiate thesis work, which aimed toward designing a flexible MMLA system [12]. This curated selection of studies provided a comprehensive foundation, covering aspects ranging from data management and system architecture to current research trends and technological challenges.

To complement the insights from the literature synthesis, semi-structured interviews [47] were conducted with researchers in the field of MMLA (Paper 2) [48]. The interview protocol was designed to explore deeper insights into the practical challenges and considerations of MMLA system design. Participants

were selected based on their significant contributions to MMLA research, including publication records and practical experience in designing and implementing MMLA systems. The semi-structured interview guide included open-ended questions to allow for comprehensive discussions focusing on both the theoretical and practical aspects of MMLA system design. The interviews were conducted via recorded video conferencing, ensuring a comfortable and confidential setting for the participants. Each interview lasted approximately one hour and was recorded with the participants' consent. Transcriptions were made for detailed analysis. The interview data were analyzed using thematic analysis. This involved coding the transcriptions to identify recurring themes and patterns. These themes provided insights into key design considerations and practical challenges, thereby contributing to the development of the initial MMLA design framework.

## 2. Building, Intervention, and Evaluation

The initial design framework was built by synthesizing insights from the literature review and expert interviews. This synthesis resulted in the development of preliminary design considerations that addressed both the theoretical and practical aspects of MMLA system design outlined in Paper 1. The insights from the literature synthesis and the thematic analysis of the expert interviews were integrated to form a set of preliminary design considerations. These considerations were aimed at addressing the identified gaps and challenges in MMLA system design and focused on usability, data integration, ethical considerations, and scalability. Based on these considerations, an initial MMLA design framework was developed in Paper 2.

In Paper 3, the initial MMLA design framework was applied in the context of the Glocal Classroom [49], an innovative educational environment that integrates students from diverse geographical locations through digital platforms. The objective was to test the framework's applicability and effectiveness in a real-world educational setting. The Glocal Classroom study aimed to enhance cross-cultural communication and collaboration among students. The methods used included detailed observations of classroom interactions, an inventory of the existing technological infrastructure, and reflections in action. This approach provided a comprehensive understanding of classroom dynamics and informed the iterative refinement of the MMLA system.

In Paper 4, the framework was applied in a language café setting, which was designed to facilitate language acquisition through natural conversation. This authentic environment provided a unique context for testing the flexibility and adaptability of the MMLA framework. The methods included focus group

discussions, organizing weekly language exchange sessions over six months, continuous participant observations, and continuous data analysis. This approach allowed for iterative adjustments based on real-time feedback from the participants. In Paper 5, prototypes of the MMLA system were developed and tested based on the refined framework. The prototyping method included the use of audio and video recordings, wearable badges, and various design iterations. Each prototype was subjected to rigorous testing and evaluation to ensure that it met the intended design considerations.

### 3. Reflecting and Learning

Each iterative cycle of framework application and refinement was followed by a detailed reflection. This process involved analyzing the outcomes of each intervention, identifying the lessons learned, and making necessary adjustments to the framework. In Paper 6, an SLR was conducted to compare the developed framework with existing models. The SLR methodology included a comprehensive search strategy, clearly defined inclusion and exclusion criteria, and a thematic analysis of the selected literature. This comparative analysis provided key insights that further informed the refinement of the MMLA framework. Furthermore, the continuous feedback loop facilitated by the iterative ADR process ensured that the framework was constantly improved and adapted to address emerging challenges and opportunities in MMLA system design.

### 4. Formalizing the Learning

The final stage involved consolidating the findings from all research phases. This synthesis provided a comprehensive view of the iterative development process and the evolution of the MMLA design framework. The consolidated insights were used to make final refinements to the MMLA design framework. This process ensured that the framework was robust, scalable, and adaptable to various educational contexts. The refined MMLA design framework was presented as a comprehensive guide for designing and implementing MMLA systems. This framework addressed key design considerations, provided practical guidelines, and included insights from real-world applications.

## Methodological Reflections

The methodologies employed across the various phases of this thesis offer robust approaches to developing and refining the design framework; however, they have limitations. One potential issue is the bias inherent in the selection of the studies and experts, which could influence the breadth and applicability of the findings.



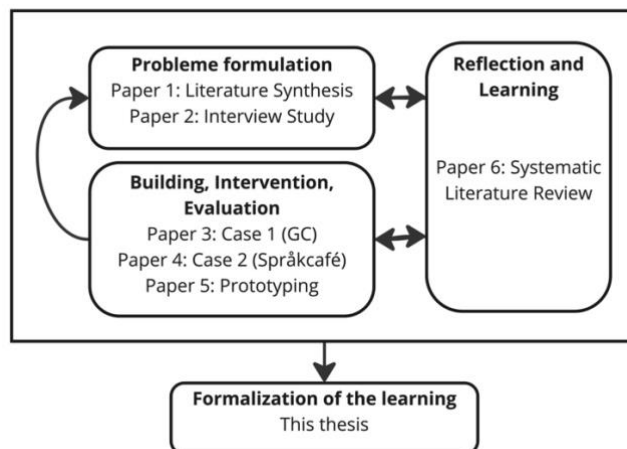
Although effective for iterative development and application, the choice to use a design science methodology may also limit the generalizability of the model outside of controlled or semi-controlled environments, such as those tested in this thesis. Additionally, the reliance on specific educational settings for the application of the proposed framework may not capture the full spectrum of the challenges and opportunities present in more diverse or non-traditional educational contexts. To address these limitations, several strategies were implemented. We made efforts to include a broad range of experts and studies covering various sub-fields within MMLA to ensure a well-rounded collection of insights. The model's adaptability and effectiveness in various contexts were enhanced by applying the framework model in different educational settings and continuously refining it based on feedback. Adhering to strict methodological standards, such as those outlined in PRISMA for systematic reviews, helped maintain the rigor and transparency of the research process, bolstering the reliability of the outcomes.

This methodology section detailed the structured approach undertaken to address the fundamental challenges in MMLA system design. From the initial problem definition and gap analysis to the iterative design and application phases, each step was aligned with the overarching goal of developing a comprehensive framework capable of enhancing the design and effectiveness of MMLA systems. The use of design science and mixed methods facilitated a dynamic and responsive research process, allowing for real-world testing and refinement of the proposed framework across diverse educational settings. Having outlined the comprehensive methodology and addressed potential limitations, this thesis now transitions to the results section. The next part will present the outcomes of applying the framework model in various contexts, discuss the findings from the SLR, and detail how these results contribute to the field of MMLA.

In all the research activities involving interviews and field studies, we adhered to strict ethical guidelines to protect the rights and privacy of the participants. Before conducting the interviews, we obtained informed consent from all participants, ensuring that they understood the purpose of the research and their right to withdraw at any time. All interview data were anonymized to protect participant confidentiality. In the field studies, we were transparent about the research goals and data collection methods. We obtained consent from both students and educators involved in the Glocal Classroom and language café settings. We also implemented strict data anonymization and security protocols to safeguard participant data. These ethical measures were crucial for maintaining the integrity of the research.

# THE PAPERS

This section provides an overview of the papers included in this thesis. The research focuses on developing a structured design framework for MMLA systems, addressing the critical need for design practices that integrate diverse data sources to enhance educational outcomes. The research employs ADR to develop and refine the framework through extensive literature synthesis, expert interviews, real-world applications, and systematic evaluations. Each paper contributes uniquely to the framework’s development—from identifying foundational design considerations to testing and refining the framework in various educational settings. To provide structural clarity, the studies are organized according to the four stages of ADR, as illustrated in Figure 1. Each study, however, touches on these four stages simultaneously at different levels.



**Figure 1** Papers included in the thesis through the lens of action design research (ADR)

# Problem Formulation

## Paper 1: Exploring Design Considerations

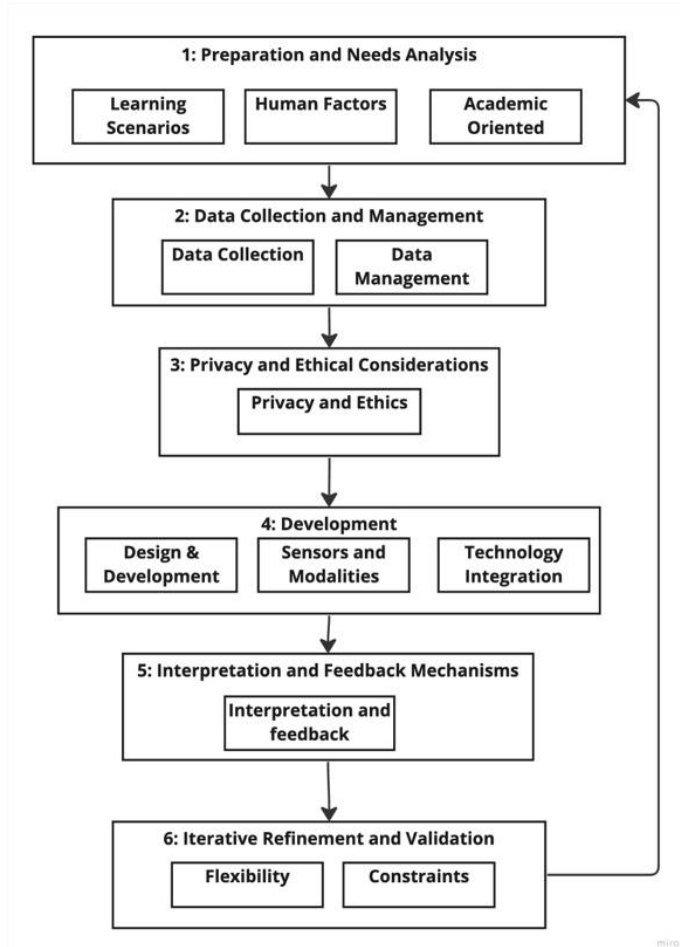
To explore the design aspects of MMLA and collect fragmented knowledge, we began with a comprehensive literature synthesis. The primary goal of this study was to identify and elaborate on the key design considerations that are essential for MMLA systems, thereby initiating the development of a structured design framework. Design considerations are the various factors and constraints that must be accounted for during the planning and development of a product, system, or project [41]. These include functionality, usability, aesthetics, environmental impact, cost, materials, and regulatory compliance. Unlike design requirements, which are specific and measurable criteria that a design must meet, design considerations are broader aspects that influence the design process and help shape the requirements. For example, according to [50], design considerations encompass elements such as ergonomics and sustainability, guiding the decision-making process to ensure that the outcome aligns with the overall goals and constraints of the project.

This process involved a thorough review of existing literature to capture the multifaceted nature of MMLA system design. We selected specific studies from the foundational licentiate thesis, ensuring that they addressed the diverse aspects of MMLA. Notably, these included two ADR studies focusing on MMLA system architecture design and prototyping [25], [51], a systematic mapping study exploring research trends in MMLA [19], and the licentiate thesis, which aimed to design a flexible MMLA system [24]. Through thematic analysis, we identified several key themes related to data management, system architecture, and technological integration. The outcome of this study was a set of preliminary design considerations for MMLA systems [46], [48]. These considerations formed the basis for further exploration and refinement through subsequent studies, ensuring a solid foundation for the development of a comprehensive MMLA design framework.

## Paper 2: Expert Perspectives and Initial Design Framework

Building on the findings of the literature synthesis, the second study aimed to gather in-depth insights from experts in the field of MMLA. The objective was to investigate and extend the preliminary design considerations identified in Paper 1 and to develop an initial MMLA design framework based on expert feedback. We adopted a qualitative research methodology centered on semi-structured interviews [47]. This approach provided the flexibility to explore specific topics while allowing for deeper exploration based on the participants' responses. Participants were carefully selected based on their recognized

expertise and contributions to the field of MMLA, including those with significant publications or practical experience in designing and implementing MMLA systems. The outcome of this study was an extended set of design considerations and an initial MMLA design framework [48]. The expert feedback provided a valuable evaluation of the preliminary considerations and offered new perspectives that enriched the framework. This initial framework served as the foundation for the iterative development and refinement processes in the subsequent stages of the research.



**Figure 2** Initial framework for MMLA design and analysis [48]

## **Building and Intervention**

The second stage, Building and Intervention, represents a critical phase in which the initial design framework is put into practical application, tested, and refined based on real-world feedback [39], [46]. This stage essentially bridges theoretical development and practical implementation, ensuring that the MMLA design framework is robust, adaptable, and effective in diverse educational settings. The Building stage began in Paper 2 with the development of the initial design framework. This framework was constructed from insights gathered from expert interviews, which provided a comprehensive understanding of the key design considerations for MMLA systems. These insights were synthesized into a cohesive framework intended to guide the development of MMLA systems across various educational contexts.

The Intervention stage involves the application of this framework in real-world educational settings. This process is structured to follow the phases of the design framework meticulously. Each phase of the framework is systematically applied to ensure a thorough and comprehensive approach to MMLA system development. This structured approach not only tests the applicability of the framework but also allows for iterative refinement based on continuous feedback from stakeholders. The structured application of these phases ensures that the MMLA design framework is not only tested but also continuously improved based on real-world experiences. This iterative process is essential for developing a robust and adaptable framework that can be effectively implemented across various educational settings. By closely following these phases, the research aims to create MMLA systems that are not only theoretically sound but also practically viable and impactful in enhancing educational outcomes.

### **Paper 3: The Glocal Classroom (GC)**

The objective of Paper 3 was to apply the proposed framework within the Glocal Classroom setting to test its applicability in facilitating the design of MMLA systems. The Glocal Classroom [49], an innovative educational environment that integrates students from diverse geographical locations through digital platforms, presented a unique and dynamic context for this study. This setting was ideal for evaluating the MMLA framework due to its complexity and the necessity for robust multimodal data integration to enhance cross-cultural collaboration and learning. The field study followed the structured phases of the design framework, beginning with an extensive preparation and needs analysis. Initially, we conducted detailed observations and attended lecture sessions to immerse ourselves in the learning environment. This approach enabled us to gain an understanding of the educational content, the dynamics of student interactions, and the overall learning goals. Concurrently, we performed a thorough inventory

of the existing technological infrastructure and identified the available resources and potential constraints. This dual approach ensured a holistic view of the classroom's operational context and informed the subsequent design stages.

We designed a conceptual MMLA system tailored to the Glocal Classroom's specific needs. This design emphasized features that would support knowledge sharing, intercultural interaction, and collaboration among students from diverse backgrounds. The development process involved iterative prototyping, wherein initial designs were continuously refined based on feedback from classroom stakeholders, including students, teachers, and administrators.

#### Paper 4: Språkcafé

The goal of Paper 4 was to apply the MMLA design framework in a language café setting—a unique and informal environment designed to facilitate language acquisition through natural conversation. This setting provided an ideal context for testing the applicability and flexibility of the MMLA framework in supporting language learning and offering insights into learner interactions in a more casual, real-world environment. The language café sessions were organized over three months and included weekly meetings that varied in participant numbers from 4 to 15. This dynamic and variable setting allowed us to explore how the framework could be adapted to different group sizes and interaction styles. The field study was methodically designed to align with the phases of the MMLA design framework. The preparation phase involved understanding the specific objectives of the language café, which included enhancing conversational skills, improving pronunciation, and fostering confidence in speaking a new language. This initial phase was critical for tailoring the MMLA system to the unique goals of the language café and ensuring that it addressed the specific needs of the participants.

#### Paper 5: Prototyping

The objective of Paper 5 was to further develop the MMLA design framework by incorporating the lessons learned from previous studies, with a focus on prototyping rather than field studies. This phase aimed to refine the framework through iterative prototyping, ensuring its robustness and adaptability across different educational settings. The insights gained from the Glocal Classroom and language café applications informed the design and implementation of this prototyping phase. The process of prototyping involved the development and testing of the MMLA system in a controlled environment, utilizing a variety of data collection methods to capture the multifaceted nature of learning interactions. We employed a range of technologies, including video and audio

recordings, to comprehensively document and analyze learner behaviors and interactions. Video recordings were used to capture visual cues, body language, and group dynamics, whereas audio recordings focused on capturing the nuances of spoken language, such as tone, pitch, and pace. This multimodal approach was essential for developing a system capable of providing real-time, nuanced feedback to learners and educators. The iterative prototyping process began with the development of an initial prototype based on the refined MMLA design framework.

## **Reflecting and Learning**

### **Paper 6: Systematic Literature Review (SLR)**

The SLR aimed to compare the developed MMLA design framework with existing models and frameworks in the literature. This comprehensive review provided a broader context for understanding the strengths and weaknesses of the proposed framework and identified areas for further refinement and evaluation. A synthesis of the findings from the systematic review allowed for a comprehensive comparison of different approaches to MMLA design. This comparison evaluated how well each model addressed key design considerations, such as scalability, adaptability, and user engagement. These insights were critical for further refining and evaluating the proposed MMLA design framework. The systematic review highlighted the strengths and weaknesses of existing methodologies, offering concrete improvements for the proposed design framework.

Through this reflective and learning stage, the research reinforced the proposed MMLA design framework and identified areas for further enhancement. This iterative process of reflection and learning ensured that the framework remained responsive to real-world needs and adaptable to various educational contexts. The findings from the SLR provided a solid foundation for formalizing the learning and ensuring that the developed framework was grounded in both theoretical and practical insights. This stage underscored the importance of continuous learning and adaptation in the development of effective MMLA systems, contributing to the advancement of the field.

## Formalizing the Learning

The findings from each paper were carefully analyzed and integrated to develop the final MMLA design framework. Paper 1 provided preliminary design considerations through literature synthesis, establishing a foundational understanding of the key elements required for effective MMLA systems. Paper 2 expanded on these considerations through expert interviews, refining and extending the design framework based on expert feedback. In Papers 3 and 4, the framework was applied in authentic educational settings—the Glocal Classroom and the language café, respectively. These studies tested the applicability of the framework and provided valuable insights into its refinement. The field studies highlighted practical challenges and opportunities, leading to improvements in the framework. Paper 5 focused on prototyping and incorporating the lessons learned from previous applications to make further adjustments to the design framework. The SLR conducted in Paper 6 played a critical role in this stage. By comparing the developed framework with existing models and frameworks in the literature, the review provided a broader context for understanding the strengths and limitations of the proposed framework. This comparative analysis ensured that the final framework incorporates best practices and addresses the gaps identified in other approaches.

The final stage of the ADR methodology involves formalizing the learning. This stage consolidates the insights and findings from all previous stages into a coherent framework. The work done in this thesis serves as a container for the several studies conducted, synthesizing their contributions to present a robust and practical MMLA design framework. The goal of this stage is to distill the knowledge gained throughout the research process into actionable guidelines that can effectively guide the design and implementation of MMLA systems across diverse educational contexts. Each paper contributed unique insights and empirical data, which were systematically integrated to develop the final framework. The process of formalizing the learning involved a meticulous synthesis of the findings, ensuring that the final framework addresses the initial problem formulation and provides practical solutions to the challenges identified.

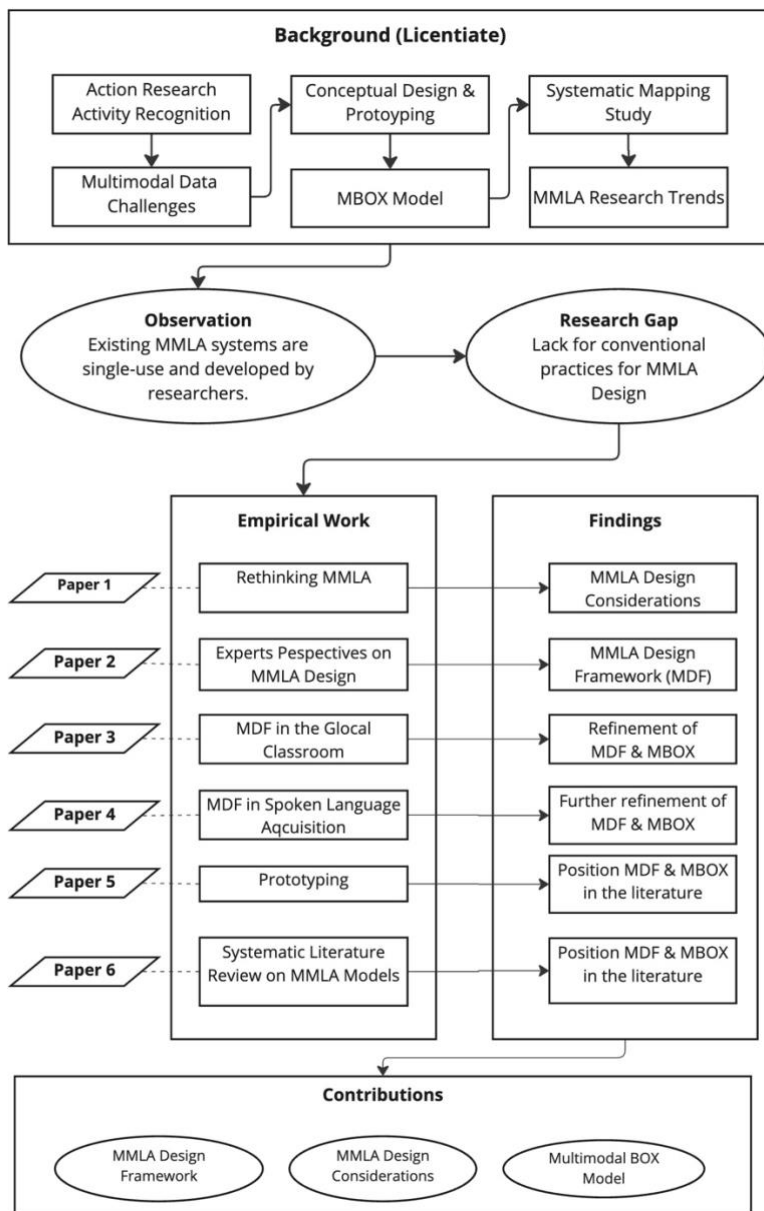
Therefore, the final MMLA design framework represents a solution to the initial problem formulation. It offers practical guidelines for facilitating the design of MMLA systems and addresses key design considerations. The framework is structured to be flexible and applicable across various educational contexts, ensuring that it can address the diverse needs of educators and learners.



# RESULTS

The development of MMLA systems presents a multifaceted challenge due to the diverse and complex factors that influence this process [46]. The primary objective of this research is to facilitate the design process for MMLA systems for various educational contexts. The results of this study are organized to systematically address this objective through two research questions. The first research question (RQ1) explores the factors that impact the design process of MMLA systems. This inquiry focuses on identifying essential elements, referred to as design considerations, that guide the development of these systems. The second research question (RQ2) investigates how the design process can be organized to facilitate design and development. This involves developing a workflow that outlines the steps necessary to design and implement MMLA systems.

By addressing these research questions, this thesis offers answers through a series of studies that result in the development of a design approach. This approach facilitates the design process, making it more manageable for researchers and practitioners across different learning environments. The results section will present the findings in a manner that connects the identified design considerations and the structured workflow to the overarching goal of enhancing the design process of MMLA systems. This structured presentation will demonstrate how each element of the research contributes to answering the central research question and advancing the field of MMLA system design. Figure 1 illustrates how this thesis systematically addresses the gap identified in MMLA system design. Each phase of our research built upon the previous, resulting in a comprehensive solution encompassing essential design considerations, a robust framework, and a practical system model. These contributions provide a strong foundation for more standardized and effective MMLA system design, thereby paving the way for significant advancements in the field of educational analytics.



**Figure 3** Thesis map illustrating the background, empirical work, and thesis contributions

This process began with building a knowledge base. Our foundational research comprised two action design studies that offered practical perspectives on designing MMLA systems, along with an SLR and thesis work focused on

flexible MMLA design. These studies led to the identification of a crucial gap: the lack of standardized or conventional design practices for MMLA. To address this gap directly, Paper 1 [46] focused on exploring design considerations for MMLA systems. This paper synthesized the existing body of literature to establish an initial set of design considerations. These considerations lay the groundwork for the development of effective and robust MMLA systems. To further expand these considerations, we incorporated the invaluable perspectives of experts within the field. In Paper 2 [48] we conducted semi-structured interviews with MMLA researchers. The insights from these interviews led to an extension set of design considerations and, crucially, to the proposal of an initial MMLA design framework. This framework offers a structured approach for guiding the development of effective MMLA systems that address the multifaceted nature of their design. Papers 3, 4, and 5 shifted the focus toward the application, evaluation, and prototyping of MMLA systems. These papers explored the applicability of the proposed MMLA design framework in authentic educational settings (the Glocal Classroom and language acquisition environments). The practical experiences within these settings yielded valuable feedback, resulting in refinements to the framework and the development of a conceptual MMLA system model. To benchmark the proposed framework against existing models, Paper 6 revisited the SLR methodology. This comparative analysis offered insights that informed targeted refinements of the framework, ensuring that it remained aligned with cutting-edge advancements in the field of MMLA. The following subsections present how the two research questions and the main objective were addressed.

## **RQ1: What are the factors that impact the design process of MMLA systems?**

Design considerations emerged as the primary factors impacting the design process of MMLA systems. At their core, design considerations [52] are the factors, constraints, and guiding principles that inform and shape the design process. They are the “what we need to think about” [53] elements that guide decision-making throughout the creation of a product, system, or experience. Design considerations are a fundamental aspect of almost all design processes. They are used whenever a new or improved solution is created, and the context and goals of the design dictate the specific considerations that are most relevant. Here are some common scenarios in which design considerations are critical:

- **Novel and Complex Design:** When dealing with new problems or technologies, such as the MMLA system, there are no established best practices [54]. Design considerations help break down complexity and

guide innovation. For example, when designing autonomous vehicles, developing new medical devices, or creating innovative educational tools, these considerations are crucial [55].

- **User-Centered Design:** Understanding and prioritizing the needs, preferences, and behaviors of end-users is paramount [56]. Design considerations ensure that the design is truly focused on the people who will use it. This is evident in designing user interfaces for mobile apps, creating accessible websites, or developing ergonomic furniture.
- **Ethical and Social Impact:** Design choices can have profound consequences [17]. Design considerations help designers anticipate and mitigate potential negative impacts while maximizing positive outcomes. Examples include designing artificial intelligence (AI) algorithms with fairness in mind, creating sustainable packaging, and developing ethical guidelines for genetic engineering.
- **Resource Constraints:** Design is often constrained by limited budgets, materials, timeframes, or other resources [57]. Design considerations help prioritize what is most important and find creative solutions within limitations. This is particularly relevant when designing affordable housing, creating energy-efficient appliances, or developing low-cost medical devices for underserved populations.
- **Regulatory Compliance:** Several industries have strict regulations and standards that must be met [55]. Design considerations ensure that the final product or system adheres to all applicable rules and laws. This is critical when designing pharmaceuticals, constructing buildings to code, or developing software that complies with data privacy regulations.

In the context of MMLA systems, design considerations are broad principles that influence various stages of the design process, providing a flexible structure for developing specific requirements. Unlike fixed requirements or specifications, design considerations offer adaptability and responsiveness to the unique demands of different educational contexts and evolving technological landscapes. The rationale for employing design considerations over fixed requirements is rooted in the complexity and variability inherent in MMLA systems. These systems need to integrate multiple data sources and accommodate diverse educational practices, making flexibility and adaptability crucial. According to Worsley et al. [29], flexibility is essential to address the dynamic needs of learners and educators in educational technology design. Blikstein [6] also emphasized the need for an adaptable approach due to the multifaceted nature of learning analytics, which must respond to various types of data and user interactions.

Design considerations are not as rigid as requirements or specifications; instead, they provide directions within which specific requirements can be developed [50]. They include elements such as technical specifications, data integration methods, user interface design, ethical issues, and pedagogical impact. This approach allows for the incorporation of context-specific elements, making MMLA systems more relevant and effective in diverse educational settings. Educational contexts vary widely, and a one-size-fits-all approach is often ineffective. Design considerations support iterative development processes, allowing for the continuous integration of feedback to refine and improve the system. This aligns with ADR principles, which emphasize iterative refinement and stakeholder engagement.

Design considerations facilitate the setting of specific requirements and guide decision-making throughout the design process. They provide a comprehensive checklist that ensures that all relevant factors are addressed systematically, thus enhancing the robustness and reliability of MMLA systems. Cukurova et al. [9] highlighted that a structured yet flexible approach to system design can significantly improve the effectiveness of learning analytics implementation by ensuring that all critical elements are integrated thoughtfully. Design considerations streamline the design process by providing clear guidelines and principles that influence various stages of development. Each consideration implies specific actions and decisions, ensuring a comprehensive approach to system development. This method not only addresses immediate system needs but also supports long-term adaptability and scalability, which are essential for the evolving landscape of educational technology. By incorporating design considerations, MMLA systems can be developed more effectively, ensuring that they are robust, adaptable, and responsive to the needs of both educators and learners.

## **RQ2: How can the design process of MMLA systems be organized?**

The answer to this question lies in the use of a well-structured workflow. A workflow [58] is a sequence of steps or tasks designed to achieve a specific outcome, providing a structured approach to organizing and managing work. This structured approach is essential for the efficient and effective design of MMLA systems. At its core, a workflow is a series of defined steps that outline the process of completing a task or project. These steps are designed to be repeatable and scalable, ensuring that each task is carried out consistently and efficiently. Workflows can be applied to various processes, from simple administrative tasks

to complex projects, such as software development or the implementation of educational tools.

As an approach, workflows are widely common and adopted in various sectors, such as business, information systems, healthcare, and academic research [58], [59]. By defining clear roles, responsibilities, and deadlines for each step in the process, workflows eliminate redundancies and bottlenecks. This streamlined approach reduces wasted time and resources, allowing teams to work more efficiently and achieve their goals faster. Establishing clear guidelines and procedures for each task ensures consistency and standardization, which, in turn, reduces errors and variations, thereby leading to higher-quality outputs and improved customer satisfaction. Effective communication and collaboration are facilitated by providing a shared understanding of the process and its goals [60]. This transparency enables team members to work together more effectively, share knowledge and expertise, and resolve issues quickly. Additionally, having a clear overview of the process and its progress allows managers to identify potential problems early on and make informed decisions, thereby preventing delays, minimizing risks, and optimizing outcomes. Assigning clear ownership and responsibility for each task ensures that everyone knows what they need to do and when, fostering a sense of ownership and commitment that leads to better performance and results.

The development of the workflow for MMLA systems was a gradual process that evolved through empirical studies and practical applications, specifically from Papers 2 to 5. In Paper 2, the initial design framework was developed based on expert interviews and a literature synthesis. This framework identified key design considerations and outlined a preliminary structure for organizing these elements. In Paper 3, the proposed framework was applied within the Glocal Classroom, an innovative educational environment designed to connect learners from different parts of the world. This study demonstrated the framework's capacity to handle diverse educational contexts, showcasing its flexibility in integrating various data modalities and its effectiveness in enhancing collaborative learning experiences. Similarly, Paper 4 extended the application of the design consideration and the framework to the context of language acquisition, specifically within language café settings, wherein AI voice assistance was employed to support spoken language learning. This application highlighted the framework's ability to facilitate the design process and cater to the unique demands of language-learning environments. The results of Paper 5, which focus on prototyping the MBOX system, played a crucial role in demonstrating the practical application of the proposed framework. This study showcased the integration of various data modalities, such as video, audio, and digital badges, into a cohesive MMLA system. Through iterative testing and refinement, the MBOX prototype provided

valuable insights into the effectiveness and adaptability of the MDF in real-world educational settings.

The workflow developed through these studies organizes and sorts the design considerations and the order in which they will be addressed. This structured approach ensures that each phase of the design process is methodically planned and executed, leading to the more efficient and effective development of MMLA systems. By incorporating workflows, the design process becomes more manageable, allowing for continuous improvement and adaptation based on feedback and evolving requirements. This approach not only addresses immediate system needs but also supports long-term adaptability and scalability, which are essential for the evolving landscape of educational technology.

## **Toward a Framework for MMLA Design**

Facilitating the design of MMLA systems for researchers and practitioners requires a structured and systematic approach. A design framework serves as this foundation, providing a set of considerations and a workflow to organize and manage complex processes effectively. A framework is a structured approach used to organize and systematize complex processes. Frameworks are essential in fields where processes are multifaceted and require a structured approach to ensure consistency, efficiency, and efficacy [57], [59]. In scenarios that involve complex systems or projects, a systematic method is required to manage various interdependent components. They are instrumental in areas such as software development, project management, education, and research. In these fields, frameworks help delineate clear processes, ensure adherence to best practices, and provide a basis for iterative improvements [61]. By offering a structured pathway, frameworks enable practitioners to navigate complex tasks with greater clarity and purpose, ultimately leading to more reliable and scalable outcomes.

In the context of MMLA systems, a framework is particularly indispensable. The design and implementation of MMLA systems involve integrating diverse data sources, addressing ethical considerations, ensuring usability, and meeting pedagogical objectives [27]. The multifaceted nature of these tasks necessitates a structured approach to managing the complexity effectively. A framework in this scenario serves as the foundation that organizes design considerations and workflows into a cohesive strategy, thereby facilitating the overall design process. The framework proposed in this thesis is the result of a synergistic integration of design considerations and an iterative workflow. Design considerations encompass the broad principles and factors that influence the design process. These considerations ensure that all critical aspects of the system

are addressed thoughtfully and comprehensively. However, design considerations alone are insufficient without a structured process to implement them. This is where a workflow comes into play, providing a sequential, step-by-step approach to organizing and managing the tasks involved in developing MMLA systems. By integrating design considerations with a well-defined workflow, the framework facilitates the design process. This synergy ensures that the design process is organized and methodical. The workflow delineates the order in which design considerations are addressed, ensuring that each phase of the process builds on the previous one, leading to a coherent system. This structured approach minimizes the risks of oversight and inconsistencies, enhancing the reliability and scalability of MMLA systems [48].

### Refinements on the MMLA Design Framework

The proposed MMLA design framework [48] operates on a phased and iterative approach, systematically guiding design activities and ensuring continuous improvement and adaptation based on feedback and evolving requirements. Through the three studies documented in Papers 3, 4, and 5, several refinements were made to the framework, highlighting its practical application. Initially, the design framework included six phases in the following order: 1- Preparation and Needs Analysis, 2- Data Collection and Management, 3- Privacy and Ethics, 4- Development, 5- Interpretation and Feedback, and 6- Iterative Refinement and Validation. Each phase addressed specific design considerations to ensure a structured process. However, through real-world applications and feedback in the studies conducted in the Glocal Classroom and the language café, as well as through iterative prototyping, critical refinements were identified and implemented to enhance the framework's applicability.

Initially, the Development phase included the selection of sensors and modalities. However, it became evident during the Glocal Classroom study in Paper 3 that these planning decisions needed to be made earlier in the process to ensure a cohesive development phase. Consequently, the consideration for sensors and modalities was moved to Phase 2—Data Collection and Management. This shift allowed for a more streamlined development phase wherein advanced data analytics techniques and real-time feedback loops could be integrated. Additionally, this study highlights the need for a clearer separation between data collection and data management. Although data collection involves selecting appropriate data types and sources, data management entails developing strategies to organize and store multimodal datasets. Consequently, data management considerations were moved to the Development phase so that the data collected could be managed and utilized for real-time feedback and advanced analytics. This refinement also allowed for more distinction between preparations



and development. The application of the framework in the language café, an authentic setting for language acquisition through conversation, provided further insights into the framework's adaptability. This study demonstrated that essential planning decisions regarding analytical models and tools need to be addressed before the actual development phase. Therefore, Phase 4, previously termed Development, was restructured to become Phase 5, and Phase 5, previously termed Interpretation and Feedback, was adjusted accordingly. This reorganization ensured that critical planning activities, including the selection of analytical models and tools, were conducted before the commencement of the development phase, thus providing a more structured and strategic approach to system development.

The prototyping phase, as documented in Paper 5, further emphasized the value of iterative design and continuous refinement. This phase focused on prototyping rather than field studies, allowing for the controlled development and testing of the MMLA system. The key adjustments identified during this phase included improvements in the user interface, data processing algorithms, and the integration of more sophisticated analytical tools. Although these refinements pertain more to the prototype than to the design framework, they helped identify the need to address the issues identified in earlier iterations. Consequently, Phase 6 was renamed Evaluation and Refinement to more accurately reflect the iterative process of assessing and improving the MMLA system. The refinements derived from the studies in Papers 3, 4, and 5 culminated in a more adaptable MMLA design framework. The restructured phases are now structured to ensure that the framework addresses the practical design considerations encountered in real-world educational settings.

In summary, we identified a set of design considerations for the development of MMLA systems [46]. These considerations cover a broad spectrum, including data management, privacy and ethics, user interaction, adaptability to different learning environments, and integrating various data modalities. This comprehensive set of design considerations is a foundational guide for researchers and practitioners in the field. By addressing these key areas, the designed MMLA systems can be more responsive to the needs of learners and educators, ensuring that the systems are both effective and ethically sound. These considerations also help in standardizing the approach to MMLA system design, which needs to be more cohesive and consistent [45]. The framework was developed as a structured approach to guide the entire process of designing and evaluating MMLA systems [interview]. It incorporates the design considerations identified and is structured to be iterative, thereby allowing for continuous refinement based on real-world application feedback. The framework represents a significant advancement in the systematic design of MMLA systems. It

provides a scalable and replicable framework that can be adapted across various educational contexts. Furthermore, by standardizing the design process, the framework enhances the reliability and effectiveness of MMLA systems, facilitating broader adoption and more impactful educational outcomes. The MBOX system [25], developed as a specific application of the framework, exemplifies the practical implementation of the framework within an MMLA system. It integrates the theoretical aspects of the framework with operational components, creating a fully functional MMLA system designed to enhance language learning experiences using multimodal data analytics. This model serves as a proof of concept for the framework, demonstrating how it can be applied to create robust and adaptive MMLA systems. It highlights the framework's versatility and effectiveness in addressing real-world educational challenges, particularly in the context of language learning. The model not only showcases the practical applicability of the framework but also contributes to the field by providing a tangible example of advanced MMLA in action.

[46][45][25] **Table 3.** Descriptions of the results from each study.

<b>Study</b>	<b>Results</b>
Paper 1	Initial set of design considerations
Paper 2	Extended design considerations and an initial MMLA design framework
Papers 3, 4	Application and refining the MMLA design framework
Paper 5	Prototyping the MBOX system
Paper 6	Comparing the proposed framework with models from the literature.

Table 3 captures the key results from each of the studies undertaken as part of this thesis, providing a clear progression in the development and refinement of MMLA design framework. Starting with Paper 1, the research establishes an initial set of design considerations, which are then expanded upon in Paper 2, alongside the creation of an initial MMLA design framework. Papers 3 and 4 focus on applying and refining this framework in real-world educational settings, demonstrating the practicality and adaptability of the MMLA approach. Paper 5 moves into the prototyping phase with the MBOX system, testing the framework's effectiveness in a tangible product. Finally, Paper 6 engages in a comparative analysis, positioning the proposed framework against existing models from the literature and highlighting its distinctiveness and contributions to the field. This table not only delineates the outputs of each study but also illustrates the cumulative building and testing process that enhances the robustness and applicability of the MMLA design framework. These contributions advance the field of MMLA by providing structured approaches and practical applications, as well as setting the stage for future innovations and

research in enhancing technology integration in education. This section will delve further into each contribution, detailing the processes involved in their development and the specific outcomes they have achieved.

# CONTRIBUTIONS

This thesis contributes to the field of MMLA by developing a design framework and identifying design considerations. Through a synthesis of existing literature and expert perspectives, followed by empirical testing in diverse educational settings, we have advanced the theoretical understanding and practical implementation of MMLA systems. The following sections detail these contributions, starting with the identification of the design considerations, development and refinement of the framework, and development of a conceptual system as a proof of concept. Each contribution is relevant for moving the field toward more conventional MMLA design practices that can be adapted across various educational environments. In the Results section, we addressed the research questions at a high level of abstraction. For RQ1, we provided an overarching explanation that the answer lies in identifying key design considerations. We elaborated on the importance and concept of these considerations without delving into the specific details. Similarly, for RQ2, we explained that the answer involves developing a structured workflow and discussed the concept and its significance in organizing the design process, again without detailing the specific steps. In this Contributions section, we revisit these research questions and provide concrete answers. Here, we present the actual set of identified design considerations and offer a refined version of the workflow framework. This section serves to deliver the tangible outcomes and detailed solutions developed through our research, thus completing the journey from abstract concepts to specific actionable items.

## Design Considerations

Design considerations are key in developing MMLA systems, as they provide a structured approach to managing the complexity and variability inherent in these systems. By addressing key aspects, such as technical specifications, data management, user experience, and ethical concerns, design considerations serve as guiding principles that shape the development process, ensuring that the

resulting systems are robust, scalable, and aligned with educational objectives. Several research studies were used to identify and refine these design considerations. Initially, in Paper 1, a thorough literature synthesis was conducted to identify a preliminary set of design considerations. This process involved reviewing existing research and best practices in the field of MMLA to capture a wide range of factors that influence system design. The aim was to establish a foundational understanding of the elements required for MMLA systems.

Building on this foundation, Paper 2 expanded and refined the initial design considerations through expert interviews. These interviews provided valuable insights from researchers and practitioners who had experience in designing and implementing MMLA systems. The feedback from these experts helped reinforce the initial findings and offered new perspectives that enriched the design considerations, making them more comprehensive and applicable to real-world educational settings. The practical applications and iterative feedback loops were further explored in Papers 3, 4, and 5. These studies focused on the implementation of the design considerations in various educational contexts, including the Glocal Classroom and language acquisition environments. Through these applications, additional elements were incorporated, such as Related Actions, Influencing Factors, and Key Decisions. These elements provide a more detailed and actionable approach for each consideration.

**Table 4.** Design considerations, respective actions, and decisions.

<b>Consideration</b>	<b>Related Actions</b>	<b>Influencing Factors</b>	<b>Key Decisions</b>
Learning Scenarios	Investigating the learning context, tools, and activities	Learning objectives, environment characteristics	Identifying learning indicators
Human Factors	Identify who are the users, stakeholders, practitioners...	User experience, common language	Human-centric orientation of the system
System Orientation	Research, decision making, and/or learning	Use cases	Defining contextual usage and deployment
Data Collection	Choose data collection methods; identify data types and sources	Data relevance (learning theory), accessibility, and quality	Selecting tools and techniques for data collection; connecting data types to learning indicators
Sensors and Modalities	Select appropriate sensors; integrate multiple data modalities	Sensor availability, data integration challenges	Matching the learning indicators with potential sensors and modalities

Privacy and Ethics	Establish ethical guidelines; obtain user consent	Legal requirements, ethical standards	Ensure that all design choices uphold privacy and ethical principles
Interpretation and Feedback	Implement analysis algorithms; set up feedback loops	Data complexity, real-time processing capabilities	Mechanisms for delivering actionable insights; connecting with the system's orientation
Design & Development	Apply system design principles; prototype testing	Scalability, adaptability, user requirements	Choosing design methodologies and development platforms
Data Management	Develop data storage and security protocols	Compliance with data protection laws, storage capacity	Deciding the data architecture and security measures
Technology Integration	Integrate with existing educational technologies	Compatibility with current systems, integration complexity	Decide how to seamlessly incorporate new technologies with existing infrastructures
Flexibility	Adapt to evolving educational needs and technologies	Modularity and scalability measures	Designing modular and adaptable systems that can accommodate future changes
Constraints	Assess budget and resources; define technological limits	Budget limits, technology availability, timeline	Determining project scope and feasibility based on constraints

The design and development methodology directly influences the scalability, adaptability, and overall functionality of an MMLA system. Equally important are human factors, especially the design of user interfaces and the overall user experience. Intuitive and accessible systems are essential for their adoption and effective use across diverse stakeholders (students, educators, etc.). In addition, how data are analyzed, interpreted, and communicated as feedback to users is critical for facilitating actionable insights and improving learning outcomes. Finally, ethical considerations and the integration of the latest research findings are paramount when designing MMLA systems, and adherence to privacy principles and grounding system design in sound educational theories fosters responsible innovation and promotes user acceptance within educational settings.

Table 4 presents a detailed matrix of the design considerations for MMLA systems and outlines the related actions, influencing factors, and key decisions that drive the design process. Each row of the table captures a specific aspect of system design, from constraints and data collection to privacy and technology integration, thereby providing a structured approach to addressing the multifaceted challenges in MMLA system development. For instance, constraints such as budget, resources, and technology, as highlighted by Shankar et al. [62], were integrated into decision-making processes. Data collection, emphasized by

Di Mitri et al. [22], was refined to encompass the selection of methods and the identification of relevant data types and sources. Robust data management protocols, including storage and security measures, addressed by Shankar et al. [63], were incorporated to ensure data integrity and protection. Furthermore, the design and development process, as discussed by Di Mitri et al. [64], was enhanced with a focus on system design principles and prototype testing. Ethical concerns, stressed by Worsley [29] and Alwahaby [17], were incorporated into the design considerations, ensuring the protection of user privacy and adherence to ethical data practices. The interpretation of feedback, as emphasized by Chen et al., was evolved to prioritize the development of AI models that provide clear [65], actionable insights for learners [65]. Furthermore, learning scenarios were tailored to specific contexts, drawing inspiration from Cukurova et al.'s analysis of collaborative problem-solving [66].

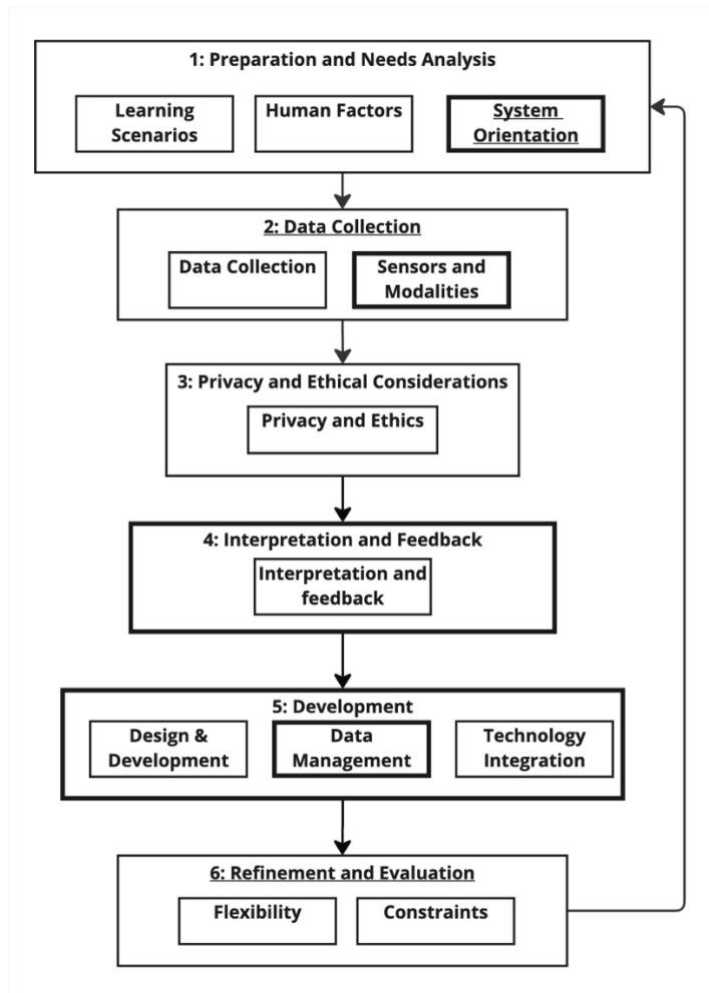
This iterative refinement process, driven by research and practical application, resulted in a comprehensive set of design considerations that address the multifaceted nature of MMLA systems. Considerations such as technology integration, as discussed by Shankar et al. [67], and the selection of appropriate sensors and modalities, as seen in Cukurova et al. [27], ensured seamless compatibility with existing educational technologies and data sources. Moreover, the emphasis on flexibility, as exemplified by modular and adaptable systems, allows MMLA solutions to evolve alongside changing educational needs and technologies. The evolution of design considerations in MMLA reflects a dynamic and responsive approach to system development. It underscores the commitment to facilitating MMLA system design.

## **MMLA Design Framework (MDF)**

The primary contribution of this thesis is the development of a novel MDF. This framework represents an advancement in the field, providing a systematic approach to the design and effective implementation of MMLA systems. The framework adopts a phased approach consisting of six interconnected phases: Preparation and Needs Analysis, Data Collection, Privacy and Ethics, Interpretation and Feedback, Development, and Iterative Refinement and Validation. Although these phases are presented in a linear sequence, the framework is inherently iterative. Each phase builds upon the insights and outcomes of the previous phases, creating a continuous cycle of refinement and improvement. This iterative nature allows for flexibility and adaptation throughout the design process, ensuring that the resulting MMLA system is well aligned with evolving educational needs and technological advancements.

The phases within the framework are sequentially interdependent. The success of each subsequent phase relies on the thoroughness and accuracy of the preceding phases. For instance, the Data Collection phase can only be effectively executed with a clear understanding of the learning scenarios, human factors, and system orientation established in the Preparation and Needs Analysis phase. Similarly, the Interpretation and Feedback phase depends on the quality and relevance of the data collected in the previous stage. This interdependence emphasizes the importance of a systematic and comprehensive approach to MMLA system design. The MDF offers an approach for facilitating the design of MMLA systems' design in various educational settings. By adhering to the principles and processes outlined in this framework, researchers and practitioners can navigate the complexities of MMLA system design with clarity, ultimately contributing to advancing education and educational technology.





**Figure 4** The refined MMLA Design Framework (MDF). The thickened box outlines and underlined text highlight the changes

1. **Preparation and Needs Analysis:** The first phase, Preparation and Needs Analysis, involves thoroughly examining the educational context and identifying specific system requirements. This phase addresses learning scenarios, human factors, and system orientation. Understanding learning scenarios includes investigating educational tools, activities, and environments to align the system with educational goals [27]. Analyzing human factors involves assessing users' needs, preferences, and behaviors, thereby ensuring a user-centric design, which Worsley et al. highlight as crucial for system acceptance and

effectiveness. System orientation defines the overarching goals and strategic direction of the MMLA system, setting the stage for subsequent development activities.

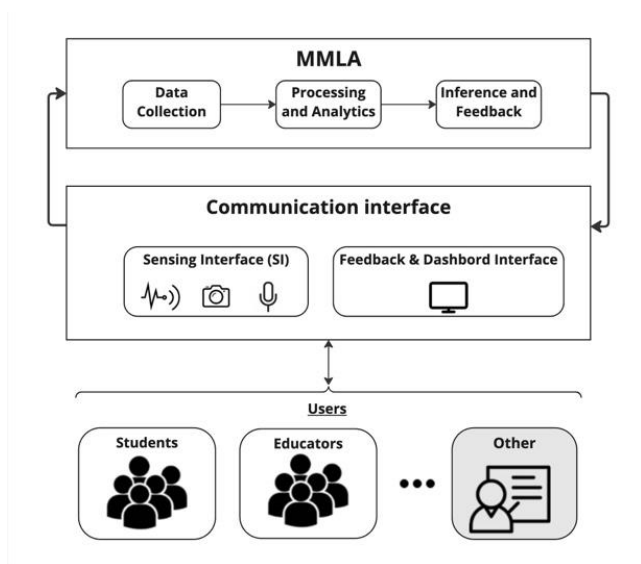
2. **Data Collection:** The second phase, Data Collection, focuses on gathering the relevant data necessary for the MMLA system's operation. This involves selecting appropriate data collection methods and identifying relevant data types and sources. The choice of accurate and relevant multimodal data collection methods is key to supporting comprehensive analytics [63]. Additionally, integrating various sensors and data modalities ensures a richer and more insightful dataset. This phase ensures that the collected data are both accurate and relevant, forming the foundation for effective learning analytics.
3. **Privacy and Ethics:** Ensuring ethical data use and maintaining user privacy are paramount concerns, which are addressed in the third phase, Privacy and Ethics. Establishing robust ethical guidelines and obtaining informed consent are critical actions [17]. This phase ensures that the MMLA system complies with legal requirements and ethical standards, fostering trust and responsible data practices. Implementing stringent data protection measures helps maintain user confidentiality and integrity, which is essential for building trust among users and stakeholders.
4. **Interpretation and Feedback:** This phase involves analyzing the collected data and translating it into actionable insights. Implementing sophisticated analysis algorithms and feedback mechanisms is crucial for providing meaningful and interpretable feedback to users [32]. This phase ensures that the data support informed decision-making and enhance learning outcomes. By delivering real-time, actionable insights, the MMLA system can effectively support educational processes and improve learner engagement and performance.
5. **Development:** This phase encompasses the technical aspects of building the MMLA system. This phase includes design and development, data management, and technology integration. Applying sound system design principles and conducting prototype testing are essential for creating scalable and adaptable systems [22]. Robust data management protocols, including storage and security measures, are critical for ensuring data integrity and compliance with regulations. Moreover, ensuring compatibility with the existing educational technologies facilitates seamless integration and enhances the system's overall functionality, thereby contributing to a more cohesive and user-friendly educational environment.
6. **Iterative Refinement and Evaluation:** The final phase involves the ongoing evaluation and refinement of the MMLA system to ensure its

effectiveness and relevance. This phase addresses flexibility and constraints, allowing the system to adapt to evolving educational contexts and technological advancements. Continuous assessment and feedback loops help maintain the system's viability and scalability, ensuring long-term success. By regularly evaluating and addressing budgetary, technological, and time constraints, developers can maintain realistic and feasible system development.

The enhancements made to the MDF have implications for MMLA design practices. They ensure that MMLA systems can be more effectively integrated into diverse educational settings, thereby providing actionable insights tailored to the specific needs of these environments. Furthermore, the iterative development process embedded within the MDF exemplifies a best practice for ongoing improvement in educational technology, ensuring that MMLA systems remain at the cutting edge of pedagogical innovation. Overall, the MDF stands as a testament to the power of structured and feedback-driven development in creating effective and ethical educational technologies. Its application across various settings demonstrates its flexibility and potential to enhance learning analytics practices globally.

## **The MBOX system**

The MBOX [25] system stands as a practical embodiment of the MDF and is designed to operationalize the theoretical components of frameworks within actual MMLA systems. MBOX's primary purpose is to serve as a model that can be readily implemented in educational settings to enhance learning through sophisticated data analytics. It is structured to be integrated seamlessly with the design framework, utilizing its guidelines and protocols to ensure a robust and ethical approach to MMLA.



**Figure 5** The MBOX system

MBOX was applied in a real-world educational setting to evaluate its functionality and demonstrate its effectiveness. This application involved deploying MBOX in a university classroom setting, where it was used to collect, analyze, and interpret data from various sources—including video recordings, student interactions, and digital learning tools. The purpose was to provide educators with deeper insights into student engagement and learning processes, thereby enabling more informed instructional decisions. During its deployment, MBOX successfully demonstrated its capability to handle real-time data inputs, integrate them into a cohesive analytical framework, and provide actionable feedback to both learners and educators. The system’s design allowed for adjustments based on specific classroom needs, showcasing its flexibility and adaptability to different teaching styles and educational objectives. The MBOX system serves as a concrete example of how the MDF can be applied in practice, bringing to life the theoretical constructs of the framework within a functional system. It exemplifies the potential of MDF-guided systems to enhance the field of learning analytics by providing conceptual system design. The model demonstrates how MMLA systems can be integrated into everyday educational practices without disrupting existing workflows, thereby increasing the likelihood of adoption and positive impact. MBOX illustrates the practical applicability of the MDF and contributes to the broader discourse on how multimodal data can be harnessed to enrich educational outcomes. Through its

deployment, MBOX can provide valuable case studies and data that further the understanding of effective and ethical MMLA practices. It underscores the potential of the MDF in guiding the development of future MMLA systems, ensuring that they are both technologically advanced and aligned with educational needs and ethical standards.

## Synthesis and Implications

In addressing the main research question, this study systematically explores the essential considerations for designing effective MMLA systems through a series of targeted sub-questions. First, we identified key design considerations and best practices for MMLA systems by synthesizing the existing literature and gathering insights from expert perspectives. This comprehensive review and expert engagement culminated in a robust set of guidelines that formed the basis of our proposed MMLA design framework. Second, the versatility and adaptability of this framework were rigorously tested through its application within diverse educational settings, specifically the Glocal Classroom and language acquisition environments. These practical applications demonstrated the framework's capability to meet varied educational needs and scenarios, effectively showcasing its utility across different learning contexts. Finally, by comparing our proposed framework with existing models in the literature, we were able to highlight its strengths and areas for improvement, which provided practical guidance for its future implementation. This thorough investigation and application of the MDF across multiple contexts collectively responded to the overarching research question, establishing a comprehensive and adaptable approach for designing MMLA systems that can be tailored to a wide range of educational settings. The comprehensive set of design considerations, the development of the MDF, and the practical application of the MBOX system collectively represent advancements in the field of MMLA. Each component played a role in pushing the boundaries of how MMLA systems are designed and implemented.

- **Design Considerations:** These considerations helped us establish a robust foundation for the development of MMLA systems, ensuring that every aspect, from data collection to user privacy, is meticulously considered. This not only enhances the functionality and ethical standards of these systems but also aligns them more closely with the diverse needs of educational environments.
- **MDF:** As a structured framework, the MDF guided the systematic design and refinement of MMLA systems, providing a replicable and scalable approach that could be adapted across various educational settings. This framework bridges theoretical concepts with practical

implementation, offering a clear pathway for the continuous improvement of MMLA technologies.

- **The MBOX system:** Serving as a conceptual illustration of the MDF, the model demonstrated the viability and effectiveness of the framework. It can provide educators and researchers with a tool to enhance learning experiences through detailed analytics.

These results collectively meet the original objectives of the thesis, which aimed to enhance the design, development, and application of MMLA systems. Through the establishment of detailed design considerations and the creation of both a guiding framework (MDF) and a practical system (MBOX), this research contributes to the facilitation of MMLA system design. It provides actionable insights and tools that can be used to address the complex challenges of modern educational settings, ensuring that MMLA systems are more effective, ethical, and user-friendly.

This section detailed the iterative development and application of the MDF, the integration and practical testing of the MBOX system, and the formulation and refinement of critical design considerations. Each element was explored in depth, illustrating how it contributes to the advancement of MMLA systems theoretically and practically. The findings presented here will be discussed in conjunction with the existing literature in the next section. We will analyze the implications of these advancements by comparing them with existing models and practices in MMLA. In addition, we will explore the practical applications of the research and discuss how the insights gained can be applied to real-world educational challenges, potentially guiding the usage and adoption of educational technology.

The implications of facilitating the design process of MMLA systems are significant, particularly for researchers and practitioners in the field of learning analytics and educational technology. By developing a structured framework for MMLA systems design, this research aims to address the current need for standardized practices and fragmented knowledge in the field. This can lead to several key implications. The establishment of a structured framework can lead to the development of standardized design practices for MMLA systems. This can enhance the replicability and reliability of these systems, making them more accessible and applicable across different educational contexts. By addressing key design considerations, such as data integration, user interface design, and ethical concerns, the framework can guide the development of more effective MMLA systems. These systems can provide more accurate and meaningful insights into the learning process, leading to improved educational outcomes. MMLA systems involve a wide range of human factors not only for users but also

for other stakeholders. For example, the framework can be used to facilitate collaboration between researchers, educators, and technologists in the design process. This can foster interdisciplinary collaboration and knowledge sharing, leading to more innovative and impactful solutions. The framework highlights the ethical considerations involved in collecting and analyzing multimodal data. By incorporating ethical guidelines into the design process, the framework can help ensure that MMLA is developed and used responsibly, thereby protecting the privacy and rights of learners. The development and dissemination of a structured framework can contribute to the advancement of the MMLA field. It can provide a common language and set of practices for researchers and practitioners, facilitating knowledge-sharing and accelerating progress in this rapidly evolving area. In conclusion, the implications of this research extend beyond the technical aspects of design. By addressing the need for establishing standardized practices, improving system effectiveness, fostering collaboration, and promoting ethical design, this research can significantly impact the field of learning analytics and educational technology. The development of a structured framework can pave the way for more impactful and widespread use of MMLA systems, ultimately benefiting learners, educators, and researchers alike.

## DISCUSSION AND CONCLUSION

The primary aim of this research was to develop a structured framework for the design and analysis of MMLA systems and to address the need for conventional design practices in this evolving field. The research was guided by key questions regarding the factors impacting MMLA system design and how to organize the design process. By addressing these questions, the study provides a cohesive and adaptable framework that facilitates the design and implementation of MMLA systems across various educational contexts. Under the umbrella of ADR [39] as an overall methodology, diverse methods were employed in this research, ranging from literature synthesis and expert interviews to field studies and prototyping. This multifaceted approach ensured that the findings were robust and applicable in real-world settings. The use of ADR allowed for an iterative process of development, application, and refinement, ensuring that the proposed framework was continuously improved based on practical feedback. This approach was essential in addressing the complex and multifaceted nature of MMLA system design.

Key findings from the research highlight the importance of several design considerations that impact the development of MMLA systems. These considerations include integrating diverse data sources, user-centric design, ethical issues, and the impact of MMLA systems on education. The research provides a practical guide for developers and researchers by synthesizing these considerations into a structured framework. The framework's applicability was tested in authentic educational settings, such as the Glocal Classroom [49] and language acquisition, demonstrating its adaptability and effectiveness. These real-world applications provided valuable feedback, leading to refinements that enhanced the framework's usability and impact. The research offers a set of design considerations that address the relevant aspects of MMLA systems. The



proposed framework provides a structured approach for developing these systems, ensuring that they are robust, scalable, and adaptable to various educational contexts. This work bridges the gap between theoretical research and practical implementation, providing a foundation for future developments in the field.

Additionally, the development of the MBOX [25] system, a conceptual model demonstrating the framework's principles, offers a practical tool for facilitating the broader adoption and integration of MMLA. Compared with existing literature [68], the proposed framework stands out for its more comprehensive approach. Although previous research has often focused on specific aspects of MMLA, such as data collection or user interface design, this study provides a holistic view that integrates these elements into a cohesive framework. This comprehensive approach ensures that all critical factors are considered during the design process, enhancing the reliability of MMLA systems. A systematic comparison with existing models through a literature review further validated the framework, highlighting its strengths and identifying areas for improvement.

The practical implications of this research are useful for researchers and practitioners. The framework offers a tool that mitigates the complexity of building MMLA systems and facilitates their design process. By providing real-time feedback on student engagement, comprehension, and emotional states, MMLA systems enable educators to tailor their instructional strategies to better meet the needs of their students. This data-driven approach fosters a more personalized and responsive learning environment. For policymakers and educational technologists, the framework provides guidelines for developing and implementing MMLA systems at scale, ensuring that these systems are robust, ethical, and effective.

However, this research is not without its limitations. One of the primary challenges was the reliance on specific educational settings for the application of the framework. Although these settings provide valuable insights, they may need to capture the full spectrum of challenges and opportunities present in more diverse or non-traditional educational contexts. Additionally, the selection of studies and experts could introduce bias, potentially influencing the breadth and applicability of the findings. While beneficial for continuous improvement, the ADR methodology's iterative nature may also limit the generalizability of the model outside of controlled or semi-controlled environments. Future research should focus on testing the framework in a wider range of educational settings to

enhance its generalizability. Exploring new data modalities and refining the philosophical analyses initiated in this thesis could also provide deeper insights into the design and implementation of MMLA systems. Further studies could investigate the long-term impact of MMLA systems on educational outcomes and student engagement, providing a more comprehensive understanding of their effectiveness.

In conclusion, this research makes a significant contribution to the field of MMLA by providing a structured and adaptable framework for the design and analysis of these systems. The iterative and practical approach adopted in this thesis ensured that the framework was continuously refined and improved based on real-world feedback, enhancing its applicability and effectiveness. The findings offer valuable insights for educators, technologists, and policymakers, supporting the broader adoption and integration of MMLA systems in diverse educational contexts. The potential of MMLA to transform educational experiences by providing rich, data-driven insights is vast, and this research provides a crucial foundation for realizing this potential. Through continued exploration and refinement, the field of MMLA can enhance the understanding of educational experiences and outcomes, thereby fostering more personalized and effective learning environments.

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