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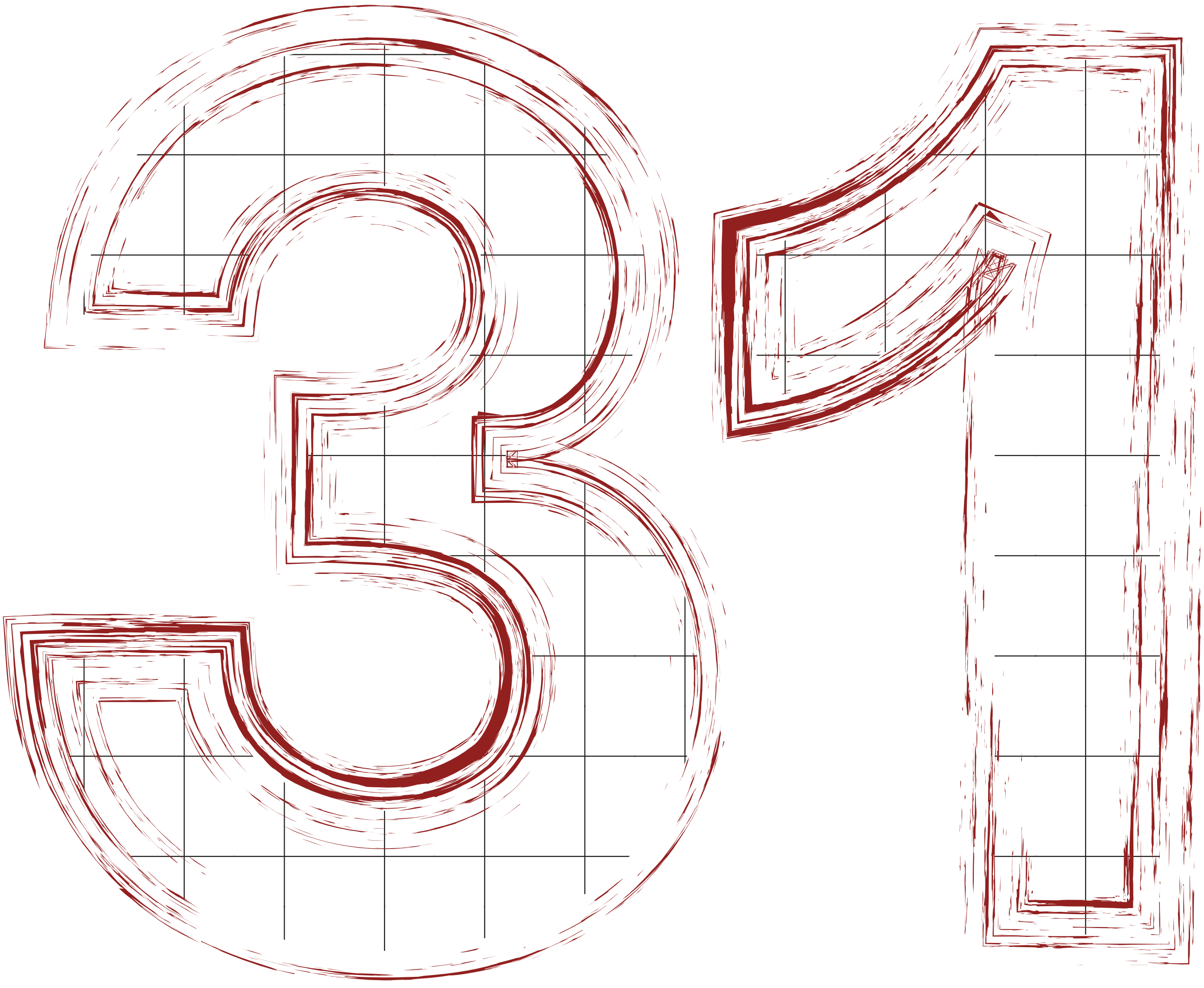

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INDEX

EDITORIAL

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EDITORIAL

ERGONOMICS AND DESIGN FOR ALL: ENHANCING INCLUSION THROUGH HUMAN-CENTERED DESIGN

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The goal of this volume of The Italian Journal of Ergonomics is to explore the intersection of Ergonomics and Design for All, examining how Human Factors knowledge and methods can support the development of inclusive, accessible, and user-centered systems across multiple design domains. As societies become increasingly diverse in abilities, needs, expectations, and contexts of use, the contributions collected here reaffirm ergonomics as a critical enabler of Design for All, understood not as a prescriptive set of solutions but as a transversal, person-centered design philosophy. Aligned with the vision of the IEA Technical Committee on Ergonomics in Design for All (EinDfA), this issue emphasizes the role of ergonomics in integrating real users, addressing expressed and unexpressed needs, and translating inclusivity into measurable, evidence-based design outcomes. Across diverse contexts, ranging from transport infrastructures and healthcare systems to homes, schools, museums, natural landscapes, and cities, the articles converge on a shared premise: inclusion is not an ancillary design goal but a foundational quality that emerges through the integration of ergonomic knowledge, participatory processes, and attention to human diversity. Rather than treating accessibility or usability as isolated requirements, the works presented here frame design as a relational process shaped by interactions among people, environments, technologies, and organizational structures. The contributions collectively articulate an advanced understanding of inclusive design as a systemic, evidence-based, and human-centered practice. However, four interrelated thematic clusters emerge, highlighting convergent issues, methods, and design implications.

ERGONOMICS AS A DRIVER OF INCLUSIVE, SYSTEMIC, AND SERVICE-ORIENTED DESIGN

Two articles foreground the role of ergonomics in reframing design problems at the systems and service levels. John Harding's contribution on inclusive service design thinking in underground transport environments exemplifies this shift by positioning stations as socio-technical systems in which spatial configuration, movement dynamics, and user experience are deeply interconnected. By transferring Service Design methodologies into the built environment and supporting them with empirical studies and modeling tools, the paper demonstrates how inclusivity can enhance both service quality and operational efficiency without increasing costs or spatial demand. A comparable systemic perspective is developed by Lara Pulcina in her analysis of inclusive design methodologies in healthcare. Here, inclusion is framed as a structural and cultural transformation toward person-centered systems that

Attaianese, E. (2025). Ergonomics and design for all: enhancing inclusion through human-centered design. *Rivista Italiana Di Ergonomia*. 31. I-III. DOI: 10.6093/RIE/12731

integrate methodological, organizational, and relational dimensions. In both contributions, ergonomics serves as an enabling framework that supports decision-making in complex contexts, reinforcing inclusion as a strategic design value rather than a compensatory measure.

HUMAN DIVERSITY, SENSORY EXPERIENCE, AND EVERYDAY CONTEXTS

A second cluster focuses on inclusive design by closely engaging with human abilities, sensory experience, and the emotional dimensions of use in everyday environments. The article by Martina Frausin and Giorgia Marialaura Iurilli explores multisensory learning spaces for children with Autism Spectrum Disorders alongside their neurotypical peers, proposing a criteria-driven framework that supports participation without segregation. The emphasis on negotiable, adaptive environments highlights how inclusion can be embedded within shared spaces through careful attention to perception, cognition, and interaction. This focus on everyday inclusion continues in Marthina de Albuquerque Silva et al., who investigate children's appropriation of domestic spaces. Grounded in the Ergonomics of the Built Environment, the study shows that housing design often overlooks children's autonomy and safety and proposes ergonomic adaptations that improve usability without requiring major structural changes. Extending the discussion to technological artefacts, Ester Iacono, Rodolfo Nucci Porsani, and Mattia Pistolesi examine the emotional experience and acceptance of passive exoskeletons in healthcare work. Their findings underscore that inclusive and human-centred design must account for affective responses, expectations, and long-term experience of use, demonstrating that emotional factors play a decisive role in the adoption and sustainability of innovative systems.

CULTURAL ENVIRONMENTS, SPATIAL COGNITION, AND INCLUSIVE COMMUNICATION

A third thematic cluster examines cultural contexts in which inclusion is shaped by spatial intelligibility, communication systems, and experiential continuity between physical and digital environments. Rosita Marchetti's study of the Museo Diffuso Lettomanoppello conceptualizes cultural heritage as an inclusive ecosystem in which accessibility, comfort, and engagement depend on integrating ergonomic principles, participatory processes, and multisensory communication tools. The project illustrates how inclusive design can strengthen cultural identity and participation, particularly in marginal contexts.This cognitive and spatial perspective is further developed by Gianmauro Romagna and Teresa Villani, who propose integrating configurational analysis and agent-based modeling to support inclusive wayfinding in museum environments. By combining predictive spatial analysis with simulations of user behavior, the study demonstrates how an ergonomic approach can inform design decisions that reduce disorientation, improve accessibility, and enhance the overall visitor experience.

MOBILITY, LANDSCAPES, AND THE LIFE-COURSE PERSPECTIVE

The final cluster broadens the scope of inquiry to landscapes and cities, embedding inclusive design within broader spatial and temporal frameworks. Ylenia Di Dario critically reinterprets walkability in natural and peri-urban environments, moving beyond urban-centric indicators toward an ergonomics-

Attaianese, E. (2025). Ergonomics and design for all: enhancing inclusion through human-centered design. *Rivista Italiana Di Ergonomia*. 31. I-III. DOI: 10.6093/RIE/12731

based understanding of movement that accounts for the physical, sensory, and cognitive variability of people walking. Walkability is reframed as a dynamic condition emerging from person–environment interaction rather than a fixed infrastructural attribute. At the urban scale, Mariangela Perillo, Jeannette Nijkamp, and Erminia Attaianese consolidate research on age-friendly urban design from a life-course perspective, advancing the concept of longevity-enabling environments. By integrating ergonomic principles with technological innovation and green and blue infrastructure, the study highlights how a human-centered approach to urban systems can support well-being, autonomy, and human flourishing across all stages of life.

FINAL REMARKS

Across these thematic clusters, a coherent vision emerges: ergonomics provides the conceptual, methodological, and evaluative foundations needed to translate inclusive design principles into effective, measurable, and sustainable outcomes. The contributions show that inclusion is not achieved through standardized solutions but through adaptive, participatory, and evidence-based processes that attend to human diversity in all its forms. Together, the articles reinforce inclusive design as a critical practice for addressing contemporary social, technological, and environmental challenges, positioning ergonomics as a key discipline in shaping environments, services, and systems that are not only accessible but also genuinely usable, meaningful, and equitable for all.

SHORT BIO

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Attaianese, E. (2025). Ergonomics and design for all: enhancing inclusion through human-centered design. *Rivista Italiana Di Ergonomia*. 31. I-III. DOI: 10.6093/RIE/12731

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ADVANCING INCLUSIVE SERVICE DESIGN THINKING IN TRANSPORT BUILDINGS: RESEARCH AND PRACTICE REFLECTIONS

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KEYWORDS: *Auto-ethnography, Built Environment, Inclusive Design, Service Design, Sustainability,Train stations*

ABSTRACT

Addressing the slow progress in developing socially equitable solutions, this research explicates the benefit of 'inclusive service' thinking by integrating Service Design (SD) from financial services with inclusivity in the built environment (BE). The study applied the five-stage SD methodology—observe, synthesise, new idea, refine, and implement—to underground station design. Four empirical studies analysed how vertical and horizontal circulation systems in crowded stations impacted inclusivity and service experiences. Study A used a questionnaire to gather passenger experiences in existing Tube stations, informing the design of studies C and D. Study B captured insights from a participant-observer's experience in a crowded underground station. Study C refined circulation arrangements for new inclusivity proxies, including Level of Service (LOS) and Vertical Severance (VS), using Agent-Based Modelling (ABM). Findings showed that multiple large lifts significantly improved inclusivity and service without increasing station size or cost, revising earlier pedestrian modelling theories. Study C was implemented, and a post-occupancy study at two Red Line stations in Tel Aviv generated new knowledge. Study D evaluated a new mined station, Farringdon Station, on the Elizabeth Line in London. Original contributions include developing a new theory of 'inclusive service' thinking by transferring the SD method from financial services; demonstrating that inclusive underground stations need not be more costly or larger; creating a new theory of design as discourse; revising early-stage design practice for complex underground stations; and establishing SD as a 'next-next' generation design method.

INTRODUCTION

Sustainability, as a concept, depends on economic growth, environmental protection, and social equity. The Brundtland Commission defines sustainability as "meeting the `needs of the present without compromising the ability of future generations to meet their own needs." (WCED, 1987: 35). Moreover, the Rail Sustainable Development Principles call for customer-driven railway developments, putting rail in reach of people, providing an end-to-end journey, being an employer of choice, reducing our environmental impact,

Harding, J. (2025). Advancing inclusive service design thinking in transport buildings: research and practice reflections. *Rivista Italiana Di Ergonomia*. 31. 1-13. DOI: 10.6093/RIE/12732

being carbon smart, supporting the economy, optimising the railway, and being transparent (RSSB, 2016). However, few stations provide access from street to train (GLA, 2010), with excessive gaps between train and platform leading to poor accessibility in underground train stations (Boyle, 2009: 20). Scholars argue that there is a long way to go before “we live and work in an inclusive world” (Clarkson and Coleman, 2015). And, while the rail industry aspires to enhance customer experiences, there is limited literature on what constitutes inclusive service in the BE sector or how to implement this (Harding, 2020b). Placing the study within the field of sustainable-inclusive-service transport buildings.

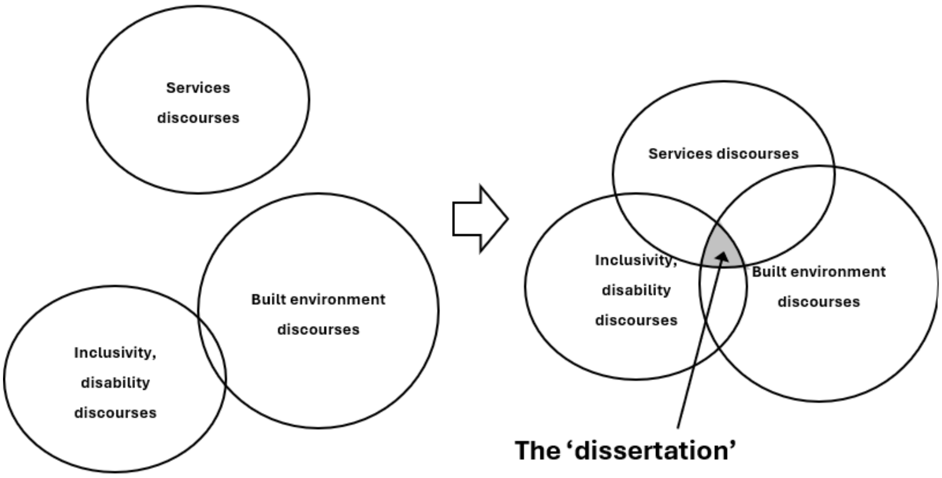

Figure 1. Closing the inclusive service gap in research and practice

Figure 1 illustrates the lacuna between services, disability, inclusivity, and BE discourses. To deliver inclusive service Harding (2020b) identifies service design (SD) as a potentially transferable ‘designerly’ methodology that could address this gap in the BE.

"Service Design is all about making the service you deliver useful, usable, efficient, effective and desirable" (Design Council, 2010)

Prior to this study, SD definitions, such as that of the Design Council, focused on utilitarian value, excluding inclusivity as a core element. To remedy the identified inclusive service gap, the study is placed at the intersection of sustainability, service, and inclusive BE fields of study, as illustrated in Figure 1. However, the extant literature on this intersection was limited (see Article 1). Consequently, by both centring and integrating ‘inclusive services design thinking’ within this investigation and closing the gap, the author makes a critical, original, significant contribution. The following section expands upon that rationale.

Integrating ‘inclusive service design’ theory and practice

Scholars working in the field of inclusivity in product design (Clarkson et al., 2003) and customer experience (Turner, 2003) informed Harding's (2011) thesis. Critical literature reviews (Harding, 2018a; 2018b; 2019) identified that IDEO, a service and product design company, developed the passenger journey concept (Figure 2) by applying the five-step service design (SD) model (Figure 3) (Bhavnani and Sosa, 2008).

Harding, J. (2025). Advancing inclusive service design thinking in transport buildings: research and practice reflections. *Rivista Italiana Di Ergonomia*. 31. 1-13. DOI: 10.6093/RIE/12732

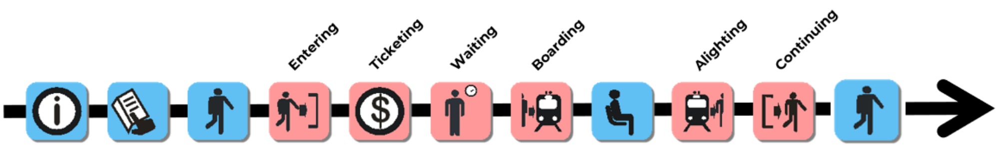

Figure 2. Passenger Journey conceptual model (derived from IDEO)

Figure 3. Five service design stages

SD was created by Shostack (1984) who specialized in the financial services industry. She identified SD as a way of thinking about the services people use, and the quality of experience these deliver. Services are neither a physical object nor a product. They are an experience. Significantly, while SD was transferred to the fields of customer experience (Turner, 2003) and computer interaction (Battarbee, 2004), it had not, until this work, been transferred to develop inclusive service research in the BE. This study, therefore, represents a pioneering and significant extension of SD, addressing a critical lacuna in both scholarship and practice.

'Wicked' problems in the built environment

Harding (2020b) argues that determining how many people require support with inclusivity is a 'wicked' problem, unsolvable through traditional scientific and engineering methods (Cross, 2007). 'Wicked' problems involve unresolved theoretical debates that hinder design progress (see article 1). Martens (2018) underscores this challenge in the context of transport for an ageing population, advocating a shift from universally designed (UD) transport systems towards inclusively designed (ID) systems. UD seeks to accommodate the widest possible range of abilities, whereas ID aims to provide access for everyone. The social model theory of disability underpins UD, on the other hand, ID is underpinned by an interactional theory of disability (Imrie & Luck, 2014). Interactional theory is supported by many philosophers and bioethicists (Riddle, 2013, p. 23) and focusses attention upon, i) removing the impairment from the BE and the body, ii) addressing socio-material-economic-political problems, owing to the lack of resources (Slack, 1999, p. 23), iii) including questions regarding feminist, racial, gender, ethnicity and sexual topics (Stainton, 2000), and finally, iv) investigating complex social-material interactions between people and their equipment needs and material constraints (Bichard, 2014). The UN (2006) endorses UD which seeks to provide access to a broad range of users; the nuance is that ID aims for afford for everyone (Martens, 2018: 122). Harding (2020) argues that without consensus on disability discourses, debates within the BE remain unresolved. Designers cannot determine whether UD or ID will deliver inclusive transport infrastructure. To develop scholarly agreement design studies C1~C3 address these concerns. Harding (2019, p. 27) further warns that ongoing disputes over the meaning of design may undermine the social benefit of inclusive service. Harding situates design as central to addressing these issues. To gain clarity and progress, this study proposes a new meaning: design as discourse. Knowing how many people are affected by what Harding (2013) defines as Vertical Severance (VS). Harding (2013, p. 13) defines VS as the "...separation

Harding, J. (2025). Advancing inclusive service design thinking in transport buildings: research and practice reflections. *Rivista Italiana Di Ergonomia*. 31. 1-13. DOI: 10.6093/RIE/12732

from ground level to the platform that creates spatial mobility and socio-economic concerns for individuals. VS results in less diversity and more exclusivity within transport modes and the cities they serve." VS causes a significant pain point for passengers (see Figure 4) and is a particular 'wicked problem' that was probed in a design study (see study C1~C3). All studies probe this VS concern. (Figure 5).

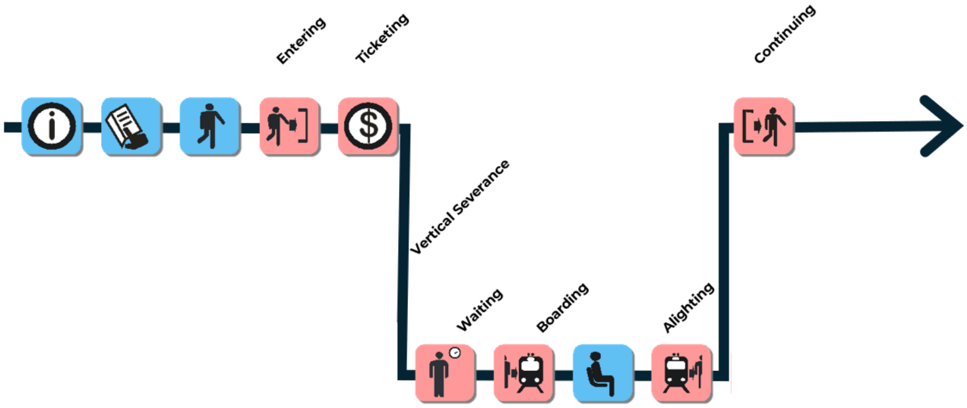

Figure 4. Encountering Vertical Severance within the underground station (Harding, 2024b)

Figure 5 summarises the development of the rationale in this study.

Figure 5. Rationale for the study

Research questions

Research questions were developed from the literature review (Harding, 2020). Table 1 relates the research question to the article to the empirical studies.

Primary Questions	**Article (Section)**	**Empirical Study**
1. It is not possible to integrate the five SD stages (Fig. 3) into the design of a building and this research project.	All	All
2. Providing a high level of accessibility for everyone (ID) in underground rail stations will cost more and require more space, compared to a minimal (UD) approach.	4, 5	C2
3.A new meaning for design, as a form of discourse, will not be useful for developing inclusive transport building design research in the BE industry.	2 (5.5)	A
	6(5.4)	C3
	7 (5.2)	C
	8 (4)	
Secondary Questions		
4.What SD qualitative methods could be used to observe inclusivity and service experiences in crowded underground stations?	2&3	A, B
5.What new ideas could be developed to improve inclusivity and service experience?	All	All

Harding, J. (2025). Advancing inclusive service design thinking in transport buildings: research and practice reflections. *Rivista Italiana Di Ergonomia*. 31. 1-13. DOI: 10.6093/RIE/12732

6. What new quantitative tool could be used to refine inclusivity and service experience?	4 & 5	C2
7. When SD is implemented in new stations, how does the quality of the new inclusivity and service experiences compare to experiences in older stations?	6, 7	C, D
8.What conclusions can be drawn regarding the use of SD to improve inclusive service in stations?	8	A~C2
9.How does SD change practice, and what is next for SD in the wider BE sector?	9	A~C2

Table. 1. Research Questions

METHODOLOGY

To address the research questions and encompass all five SD stages a comprehensive longitudinal mixed-methods case study was chose

Figure 6. Integrating nine articles into the study

Case study research

Case study research enables comparison of rival theories, whether using quantitative or qualitative methodologies (Yin, 1993, pp. 112-113). Moreover, case studies may provide sufficient detail from fieldwork that is detailed, replicable, rigorous, and timely (Yin, 1993) and applicable across diverse disciplines, including education (Yin, 1993) and infrastructure management (Flyvbjerg, 2014). Further, case studies offer a compelling basis for change (Flyvbjerg, 2006). Significantly, this summary and an ennealogy of four empirical studies constitutes a cohesive research framework that delivered compelling scholarly and practical contributions in the field of inclusive service in the BE. To make the longitudinal project feasible, the PhD by Special Regulations route was chosen. Benefits included developing writing projects, obtaining timely peer-reviewer comments, and contributing to international discourse with professionally formatted material. This route allowed for post-occupancy reviews of the operational stations, pauses for unanticipated events, including COVID, work demands, health and life challenges, and family responsibilities. Figure 7 illustrates how the four empirical studies (A~D) relate to the five SD stages, conclusions, and next steps. Figure 8 indicates the research path taken by each constituent study through the four critical gateways.

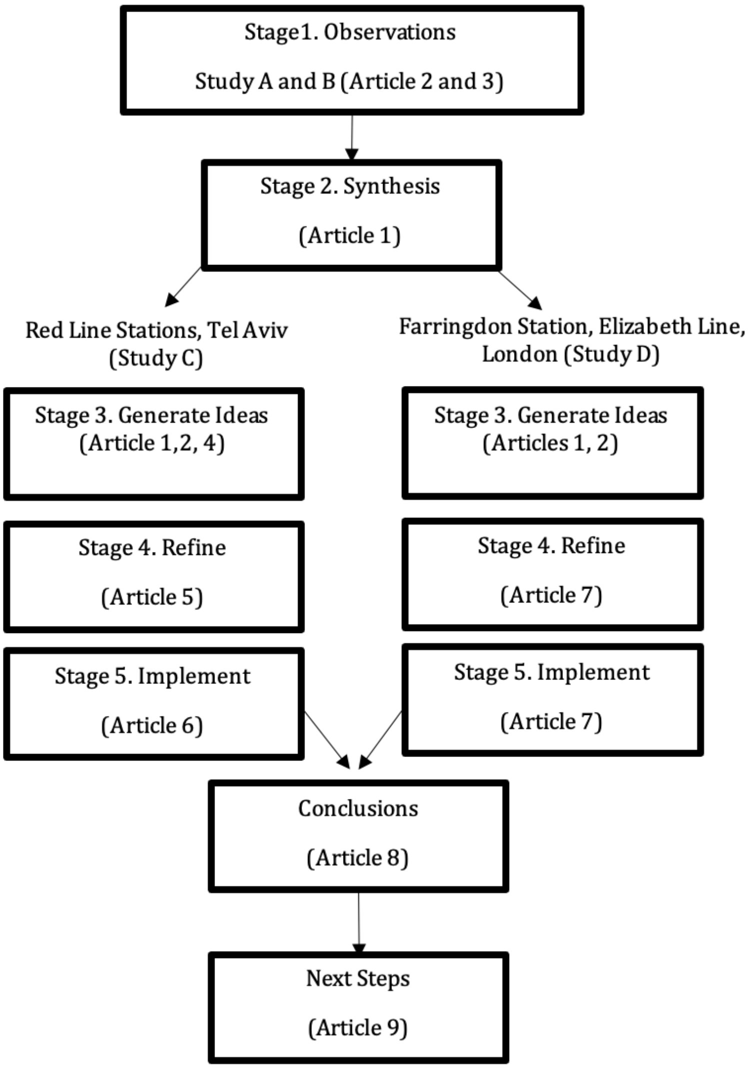

Figure 7. Relating the four empirical studies (A~D) to SD stages

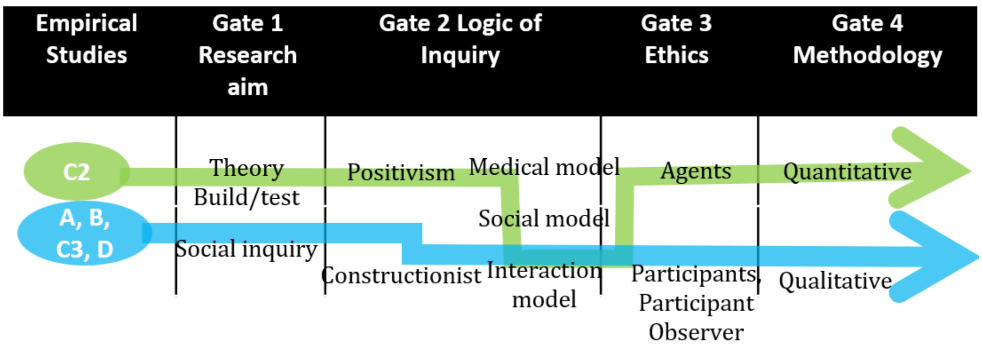

Figure 8. Mixed-Method pathways through four research gateways (adapted from Harding, 2018)

The quantitative Refine study C2 focused on theory-building and aim-testing to determine which theory, UD (case 1) or ID (case 2), provided a satisfactory inclusive service experience in an underground station, without increasing cost or size. The qualitative Observation studies (A and B) contributed new knowledge to the synthesis in article 1, the literature of which generated the research questions addressed throughout this study (see Table 1). Studies A, B, and post-occupancy studies, C3 and D, examined the designer-user co-experiences of inclusive service in-situ, motivated by social inquiry aims. These

Harding, J. (2025). Advancing inclusive service design thinking in transport buildings: research and practice reflections. *Rivista Italiana Di Ergonomia*. 31. 1-13. DOI: 10.6093/RIE/12732

four studies produced nuanced, detailed observations, demonstrating how vertical and horizontal circulation elements in stations (the independent variables) impact passengers' experiences (the dependent variables). Figures. 9~11 summarise the methodology employed for each study

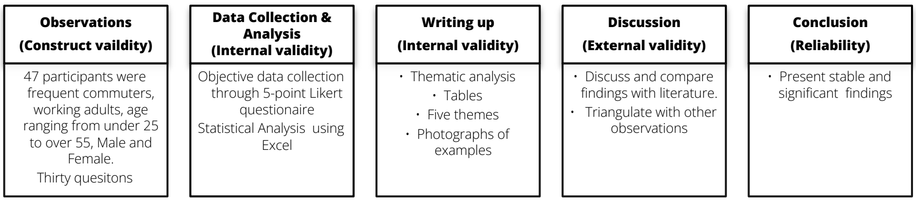

Figure 9. Post-occupancy questionnaire qualitative methodology: article 2 (study)

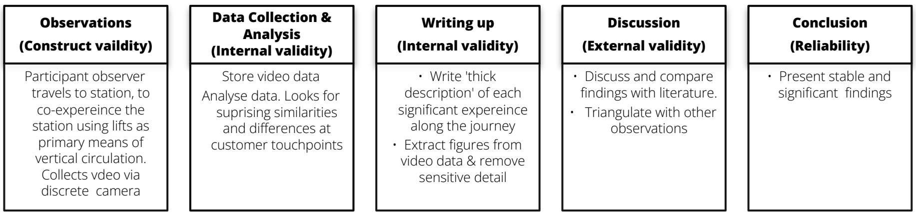

Figure 10. Post-occupancy auto-ethnographic qualitative methodology: article 3 (study B), article 6 (study C3) & article 7 (study D)

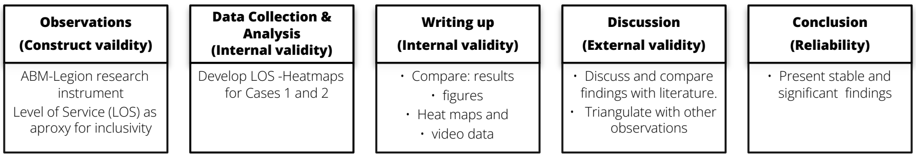

Figure 11. Agent-based modelling quantitative methodology: article 5 (study C2)

Logic of inquiry

Case study C2 had explicit theory-building and testing aims. Hypothetic-deductive logic (Popper, 1972) is a common method of investigation in science and design fields that is associated with positivism. Hypotheses were developed in the original research questions (Table 1), using abduction, 'the process of forming an explanatory hypothesis' (Peirce, 1955: 67 quoted in Stainton-Rogers, 2006, p. 85). Then, ABM was used as a research instrument to compare the two rival cases for inclusivity and service, using deductive logic to disprove the hypotheses. However, positivist epistemological and ontological assumptions create simplistic explanations with less detail and nuance (Stainton-Rogers, 2006, p. 81) and may result in simplistic guidance and standards that produce normative solutions and design fixation issues (Crilly, 2015). To create more detail and nuance, the observation studies (A, B, C3, D) had social inquiry and constructionist aims: these primarily identified inconsistencies, difficulties, and challenges for inclusivity and service. Constructionist theory raises pertinent and thought-provoking questions that helped hone the research aims, including: 'what does it do?', 'how can it be used and by whom', and 'to what ends?', 'whose interest does it serve?', and 'what does it make possible?' (Stainton-Rogers, 2006, p. 81). Analysis required 'looking for surprising similarities between things that are very different' or 'surprising differences between very similar things' (p. 87). Meticulous explication preserves complex details while creating a way to develop meaning from observations. As anticipated, asking such questions from the outset led to

Harding, J. (2025). Advancing inclusive service design thinking in transport buildings: research and practice reflections. *Rivista Italiana Di Ergonomia*. 31. 1-13. DOI: 10.6093/RIE/12732

new insights and paradigm shifts (p. 81). Accordingly, four studies used constructivist theory.

Results

Table 2 summarises the contributions of each article to the longitudinal case study according to SD Stage, study, and method.

	SD Stage	Study	Summary	Method
1	**Synthesis**		The literature review synthesised critical literature to develop new research questions listed in Table 1 (Harding, 2020b)	Literture Review
2	**Observe**	A	A Likert scale questionnaire survey of passenger experiences in existing Tube stations in London developed actionable insights (Harding, 2025a)	Questionaire
3		B	This empirical observational study transferred auto-ethnographic methods to research inclusive service experience in a busy underground station built to late 20th Century accessibility standards. (Harding, 2024b)	Auto-ethnography
4	**New Idea**	C1	A new idea was created to probe inclusive service in stations in crowded places, using agent based modelling was developed (Harding, 2018)	Agent Based Modeling
5	**Refine**	C2	A rival case study refined that new idea. It compared inclusive service within two station circulation systems (case 1 and 2) using agent-based modelling. Case 2 afforded the best inclusive service (Harding, 2019)	Agent Based Modeling
6	**Implement**	C3	Case 2 was implemented in ten stations , and this post-occupancy evaluation reviewed the inclusive service experience in two stations (Harding, 2025b)	Auto-ethnography
7		D	This post-occupancy evaluation reviews Farringdon Station in London, that was recently opened and developed with inclusive service thinking, (Harding, 2024a)	Auto-ethnography
8	**Conclusion**		This article reflects upon the earlier studies and concludes the study (Harding, 2020c)	Literture Review
9	**Next Steps**		This article demonstrates how focussing upon inclusive service changed a large interdisciplinary design practice (Harding, 2020a)	Literture Review

Table 2. Summaries

Methodological reflections

This study is guided by reflexive practice (Schon, 1984) and 'practice what you preach' theories (Reich, 2017) that enable continuous self-evaluation, enhancing the rigour, ethics and impact of the research. Alternative user-centric research approaches were considered. Action research, which seeks to increase understanding of a social situation by focusing on improving social processes and implementing change within a social context collaboratively (Hult & Lennung, 1980). Moreover, Ormerod (2005) claims it is unlikely that a single method or a wide range of participants will be practical in the BE context. To develop nuanced insights into inclusive service interactions in underground stations (Harding, 2020) this research necessitated that the researcher co-experience and empathise with the user (Battarbee, 2004), in both the physical and emotional interactions at critical passenger touchpoints (Bhavnani & Sosa, 2008). Thus, the co-experiential, auto-ethnographic in-situ

Harding, J. (2025). Advancing inclusive service design thinking in transport buildings: research and practice reflections. *Rivista Italiana Di Ergonomia*. 31. 1-13. DOI: 10.6093/RIE/12732

approach was used in post-occupancy studies B, C3 and D. The use of the questionnaire and auto-ethnography is justified by the actionable insights they provide to early researchers and practitioners. Actionable insights were developed using qualitative methods adapted from the social sciences and computer interaction fields (Battarbee, 2004). A new quantitative methodology successfully used ABM to differentiate rival cases and disprove hypotheses in study C2. In conclusion, when the industry relies upon quantitative data for station planning decision-making (N.R., 2015), a mixed-methods approach that is both replicable and detailed is justifiable and desirable.

Generalisability and limitations

It is good practice to triangulate data from multiple sources (Yin, 1993). To increase generalisability and reduce bias this study triangulated data from survey questionnaires (study A), videos (studies B, C3, D) and ABM data (study C2). Nevertheless, to minimise bias, future research should include researchers and participants from a wider demographic background.

CONTRIBUTIONS OF THE STUDY

Theoretical impact

(RQ1) The study is innovative by transferring SD theory from finance (Shostack, 1984) and SD methods (Bhavnani & Sosa, 2008) to the design of underground stations. Study A generated new observations, insights and suggested proxies for inclusivity, showing how age and gender impact experiences of comfort, security, gentleness and confidence. These observations were synthesised and refined in study C2, and implemented at ten Red Line cut-and-cover stations in Tel Aviv (study C3) and implemented at Farringdon, a mined station in London (study D). The research demonstrates that integrating all five SD stages was successfully implemented in eleven underground stations, which are typically difficult to access (Boyle, 2009), suggesting that SD can also be implemented in simpler buildings. (RQ2) Study C2 case 2 demonstrated that providing a high level of accessibility for everyone was practical and desirable supporting Martens (2018) and underpinning interactional theory (Bichard, 2014; Imrie & Luck, 2014; Riddle, 2013; Slack, 1999; Stainton, 2000). Importantly, case 2 required no additional cost or space, compared to the minimal UD approach of case 1. (RQ3) The study creates a new interpretation that is helpful for theory and practice development: design as discourse. Some argue that research is discourse (Petre and Rugg, 2010: 114), and others argue that 'design is research' (reported by Macmillan, 2010). These studies demonstrate that to proceed to implementation, the design discourse needs agreement to develop and address 'wicked' problems, such as inclusivity. Similarly, if critical theories (e.g., social versus interactional) underpinning design discourses (UD versus ID) do not reach an agreement, practice will likely not improve quickly. This may explain why scholars such as Boyle (2009) and Clarkson and Coleman (2015) observe that it takes so long to deliver inclusivity in practice. (RQ4) Qualitative observation methods used in study B, C3, D, were typically used in the social sciences, and were transferred to review the experience of the inclusive service within busy underground stations in the BE for the first time. i) auto-ethnography, a social-inquiry method used in the social sciences (Buzard, 1997), and ii) co-experience methods developed in the computer interaction field for designers and researchers to observe socio-material interactions with the user (Battarbee, 2004). Article 3 advances methodological debate on exploring inclusive design from a user's perspective, and within empathetic design. These twinned methodologies enabled the researcher/designer to co-experience passenger interactions with station circulation. A new post-occupancy evaluation method, developed in study B, was replicated in studies C and D. This critical post-occupancy observation method provided novel insights unattainable through conventional industry 'tick-box' exercises, (Ormerod, 2005). Moreover, this observation methodology demonstrates theoretical and practical relevance for stations, and the broader BE. (RQ5) New ideas were developed to research inclusive service experiences. For example, Study A revealed new proxies for inclusivity (Table 32025a). To address the need for inclusive service training identified in the earlier survey (Q30 see article 2), new training materials (Harding, 2023) and methods using ABM and video data (Harding, 2016a, 2016b, 2016c, 2024) were provided to BE professionals. A new theoretical model, VS, was developed to explicate the importance of considering vertical movement (Harding, 2013). (RQ6) ABM proved a satisfactory new quantitative tool for examining inclusivity and VS in circulation systems, as illustrated in a rival design studies C1 and 2. The ABM study C2 of two rival underground station simulations revised earlier theories: i) case 1 based on UD paradigms - as favoured by UN (2006) and underpinned by social model theory – did not develop an inclusive experience, compared to case 2. Case 2 was created with multiple-lifts, aiming to provide access for everyone (Martens, 2018) according to ID paradigms, and underpinned by interactional theory to provide a satisfactory experience for everyone. ii) findings were triangulated with post-occupancy evaluations in studies B and C3. iii) case 2 challenges previous assumptions that lifts were of limited utility (John J. Fruin, 1971), or unnecessary at stations due to high cost (Goldsmith, 1976), or multiple lifts were only required for terminal or airport stations (John J. Fruin, 1992). This research critiques and inverts those earlier perspectives in the service of inclusivity. Critically, to develop inclusivity in theory and practice, inclusive design guidance (BSI, 2018), SD theory and its definitions (Council, 2010) require fundamental revision to integrate ID principles. (RQ8) It can be concluded that SD can be considered a 'next, next' generation design method, 'more relevant to architecture and planning' than first-generation approaches (Rittel 1973 cited in Cross, 2007, p. 1) similar to the RIBA Plan of Work (RIBA, 2020) which lack the critical observation and synthesis stages, prior to the ideation stage.

Practical impact

(RQ7) Post-occupancy evaluations of new cut-and-cover stations (study C3), and a new mined station (study D) showed that the application of SD improved inclusive service, compared to the older station (study B). Enhanced user experiences of comfort, security, gentleness, and confidence were observed in the new cut-and-cover stations in Tel Aviv (study c3) and the new mined station serving the Elizabeth Line in London, compared to the older Jubilee Line station (study B) when triangulated with the findings of study A. Significant progress in inclusive service was achieved by reducing VS at stations (Table 3 2025b). Therefore, the research demonstrates that inclusivity for all users improves when the ratio of lifts to escalators is weighted to the former. (RQ9) It was shown that customer experience and inclusivity in the BE were improved by integrating SD stages into a modified RIBA Plan of Work in the early design stage when critical design decisions are made (Figure 12).

Harding, J. (2025). Advancing inclusive service design thinking in transport buildings: research and practice reflections. *Rivista Italiana Di Ergonomia*. 31. 1-13. DOI: 10.6093/RIE/12732

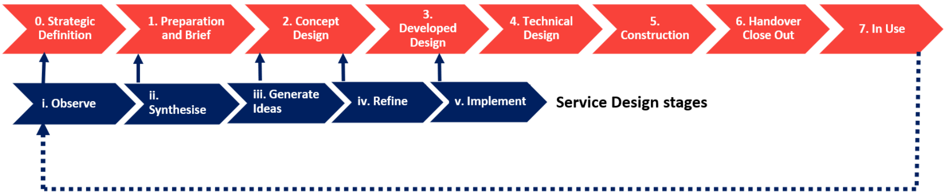

Figure 12. Integrating SD stages into a revised RIBA Plan of Work (Harding, 2020a)

International interdisciplinary research impact

The published articles contributed to the international interdisciplinary research discourse including: transport and inclusivity (Egger, Gemperli, Filippo, Liechti, & Gantschnig, 2024; W. Shi, Mahdzar, & Li, 2025; W. Shi, Mahdzar, Li, Cui, & Zhao, 2025; W. W. Shi, 2021), inclusive service in the BE (Busciantella-Ricci, Aceves-Gonzalez, & Scataglini, 2022; Zecca, McGinley, & Griffiths, 2023), urban design and sustainability (Patil & Gupta, 2023), art and wayfinding in stations (Adhialam, Timms, Sumabrata, & Adwitiya, 2025), and infrastructure project life cycle (Adamtsevich, 2025).

Final thoughts

The advancements to inclusivity in public realm design seen in this study are not guaranteed, given risks from a "woke wave" of opposing 'culture war' discourses that oppose feminist, anti-racist and environmental agendas (de Nadal, 2024), and threaten sustainability (WCED, 1987). As an alternative, this study frames design as discourse; integrates two previously separate fields of inclusivity and service into a new inclusive service theory that demonstrates that everyone may be afforded inclusivity in practice.

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SHORT BIO

John Harding is a practising architect, urban designer and researcher. He has 30+ years of experience in the design, construction and operation of railway buildings internationally. In addition, he has experience as an urban designer, designing new towns (Punggol in Singapore) and cities (Putrajaya in Malaysia). John's academic interests support his work in practice. These include developing practical ways to research and improve inclusive service within transport buildings. He is a PhD candidate and submitted his dissertation to the University of Cambridge in 2025. He has peer-reviewed ICE journals and is a member of the RIBA.

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THE INTEGRATION OF INCLUSIVE DESIGN METHODOLOGIES WITHIN THE HEALTHCARE DESIGN PROCESSES

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KEYWORDS: *Inclusive Design, Healthcare, Person-Centered Design, System Design Process*

ABSTRACT

The implementation of a truly Inclusive Design approach in the medical sector requires the systematic integration of a series of methodological, organizational, and relational components that enable the principles of HCD and Design for Inclusion to be put into practice. Inclusion is not merely an additional element; it represents a paradigm shift from product-centered to person-centered design, emphasizing individuals' abilities and needs. The development of Inclusive Design processes doesn't merely constitute a methodological enhancement of system qualities; it is an essential requirement to address the increasing complexity of healthcare systems, encompassing both healthcare professionals and patients. The involvement of individuals in the decision-making process facilitates the identification of critical issues, latent needs, and barriers that would be challenging to discern through a purely technical approach. The objective of this paper is to provide evidence that Inclusive Design processes applied to the medical sector can enhance not only the usability and accessibility of medical devices but also the psychological acceptance among patients and the overall sustainability of the healthcare system. A comprehensive analysis of inclusive components demonstrates that the transition to an authentically inclusive design model is not merely a technical or aesthetic modification but a fundamental and necessary paradigm shift.

INTRODUCTION

The growing complexity of healthcare systems and the diversity of populations who demand them require detailed planning that involves multiple, flexible approaches, so that the needs of employees, patients, and their families can be met (Kastl et al., 2024). This requires implementing a multifaceted approach that leverages diverse strategies and methodologies. Italy's healthcare system suffers from structural deficiencies that threaten its sustainability and the quality of its services (Barbero et al., 2017). A salient concern pertains to the shortage of staff, with projections indicating a deficit of 65,000 nurses by the year 2025 (ANSA, 2025). Furthermore, in 2022, the proportion of doctors aged 65 and over reached 26.7%, marking the highest percentage in Europe (ANSA,

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2025). The exacerbation of these problems is compounded by demographic trends. Projections indicate that by the year 2050, the population of Italians aged 65 and over is expected to account for 34.6% of the total population (ISTAT, 2025). This demographic shift has increased demand for healthcare, especially in chronic, home, long-term, rehabilitation, and monitoring services, which are highly care-intensive. Relying solely on healthcare professionals isn't enough; the quality, efficiency, and accessibility of medical devices depend on their design. In resource-limited settings, careful design can reduce physical effort, improve mobility, precision, and lower errors (Tosi & Rinaldi, 2015). The Human-Centered Design (HCD) framework uses an inclusive, person-centered approach to manage complexity (Giacomin, 2014). It fosters synergy with inclusion efforts, ensuring that the design process encompasses not only system performance and usability but also the involvement of actual users from data analysis to user testing. Inclusive design, therefore, is a concept that broadens the scope of HCD by placing emphasis on the value of participation and by adapting to the sociotechnical demands of modern society. (Henni et al., 2022). Despite increased focus on patient and caregiver participation, many medical products still follow a top-down approach, involving users only in later stages. This often causes usability, accessibility issues, and resistance, especially when adjustments to routines or interactions are needed. In healthcare, the quality of a product depends not just on technical performance but also on ease of use, understanding, and social acceptance across diverse abilities and backgrounds. Since users are crucial, involving them only at the end is inadequate; they should be involved from the start (Rossi, 2023). Achieving this requires a cultural shift toward a more holistic, participatory design process. Inclusive design offers a proactive alternative, engaging users as active contributors in defining requirements, rather than passive recipients, to create more effective solutions (Salek, 2023). The objective of this contribution is to propose a methodological framework for implementing inclusive processes within the medical sector. This proposal is a partial result of a broader research project conducted over two years of doctoral studies, and it is based on an in-depth critique of the scientific literature and a systematic analysis of relevant case studies. The theoretical investigation has facilitated the identification of interpretative models, design approaches, and primary critical issues pertaining to the themes of accessibility, user participation, and innovation in healthcare environments, as emphasised by the pertinent literature. The following chapters will offer an overview of the methodological phases used to identify the considerations presented, along with the analytical reconstruction of the Invisalign case study. This case was chosen because it exemplifies a process characterised by the significant integration of technological, organisational, and design innovations within the pertinent medical industry.

METHODOLOGY FOR THE ANALYSIS OF THE LITERATURE ON INCLUSIVE DESIGN PROCESSES IN THE MEDICAL FIELD

The first phase of the study involved defining objectives and research questions, followed by a systematic review of the scientific literature to identify, analyse, and summarise existing knowledge on inclusive design processes in the healthcare sector. The methodological process was divided into three main phases. Initially, a systematic search was conducted on academic bibliographic databases such as Scopus, ResearchGate, and PubMed, using specific queries to identify relevant documents. Keywords such as “Inclusive Design” OR “Design for All” OR “Human-Centred Design”; AND “Medical Device” OR “Healthcare” OR “Medical field”; AND “Design Process” OR

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“System Design” OR “Framework” were combined. Subsequently, the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was applied to select the articles (Moher et al., 2009). This protocol allowed for the removal of duplicates, a screening based on title and abstract, and finally, a full-text assessment to verify the eligibility of the papers according to inclusion and exclusion criteria in order to select the most relevant articles. In the second phase, to map the research landscape, the selected papers were analysed quantitatively using bibliometric network analysis software, such as VOSviewer (Rossi & Attaianese, 2023). An analysis of the keywords provided by the authors was conducted to visualise thematic connections and identify the main research clusters. This has allowed the contributions to be grouped into reference clusters, such as “Inclusive Design methodologies”, “Inclusive Design tools”, or “HCD approaches”. The final phase involved a thorough qualitative analysis of the content of the articles within each thematic cluster. The aim was to extract and synthesise information related to methodologies, tools, and stages of inclusive design processes. The results of this analysis facilitated the development of a comprehensive, structured overview of approaches to inclusive design in the medical sector, emphasizing established practices, emerging research areas, and prospective advancements.

METHODOLOGY FOR CRITICAL ANALYSIS AND CLUSTERING OF CASE STUDIES IN THE MEDICAL FIELD

The methodology followed has been applied to critically analyse the case studies of medical design and to classify them based on their degree of innovation, adopting a thematic clustering approach and interpretative analysis. Initially, a significant sample of case studies related to industrial processes, products, services, or communicative artefacts in the medical field was identified and collected, all of which declare to adopt an inclusive design approach. The sources included scientific literature (identified through the previous methodology), company reports, market analyses, and industry product databases. Subsequently, the selected case studies were organised within the FileMaker Pro software and classified according to an evaluation grid developed to measure the degree of innovation:

Process innovation: adoption of co-design methodologies that actively Involve patients, carers, and medical staff in the development process.

Social innovation: the project's impact on reducing stigma, increasing user autonomy, and enhancing community quality of life.

Technological innovation: utilising new technologies (e.g., 3D printing, artificial intelligence, algorithms, sensors) to improve the device's personalisation and usability.

System innovation: products, services, and communicative artefacts that improve accessibility and inclusion (e.g., open-source models, personalised artefacts) (Figure 1).

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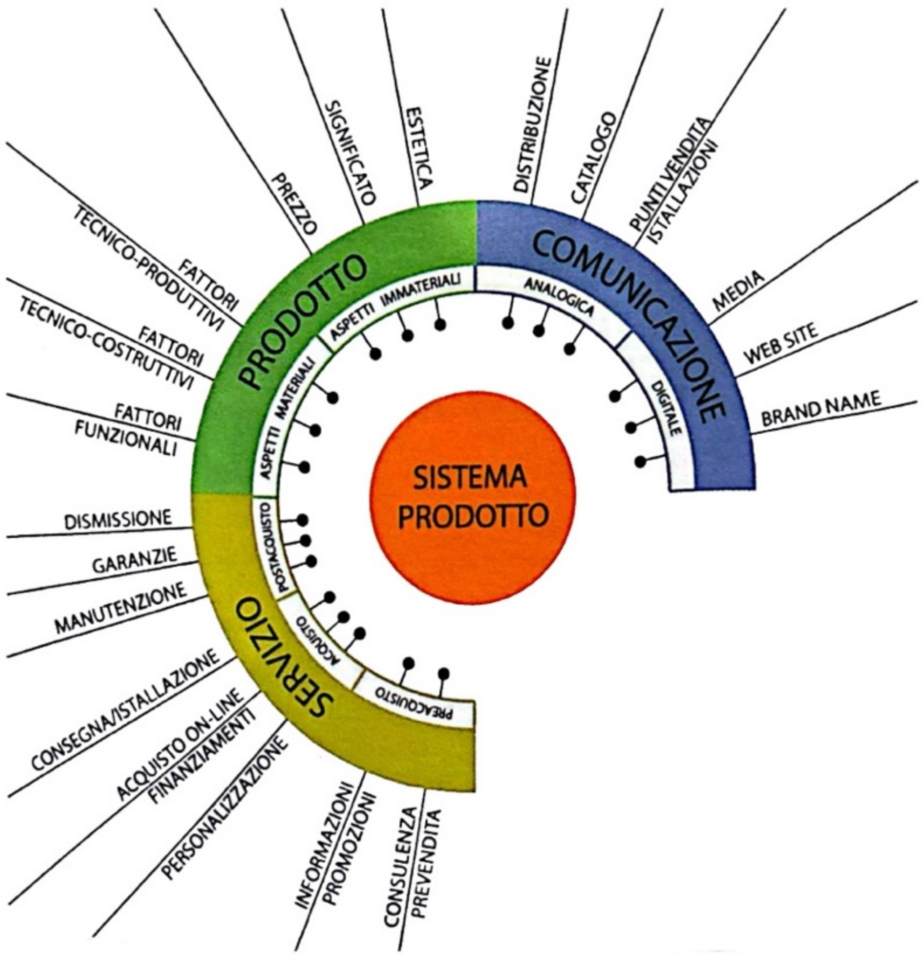

Figure 1. The product System Diagram (Marano, 2017)

Each case study was analysed and critically evaluated against the defined innovation criteria. Using qualitative analysis, the case studies were clustered by degree of innovation. The final analysis focused on the distinctive characteristics of each cluster: recurring patterns, enabling tools, barriers, and radical innovations were identified, providing a strategic view of the future directions of inclusive design methodologies in the medical field. The goal is to highlight the key elements that define Inclusive Design approaches in the medical sector, focusing on the roles of various stakeholders, how individuals interact with technologies, and the critical stages of the design process where inclusion gains strategic importance.

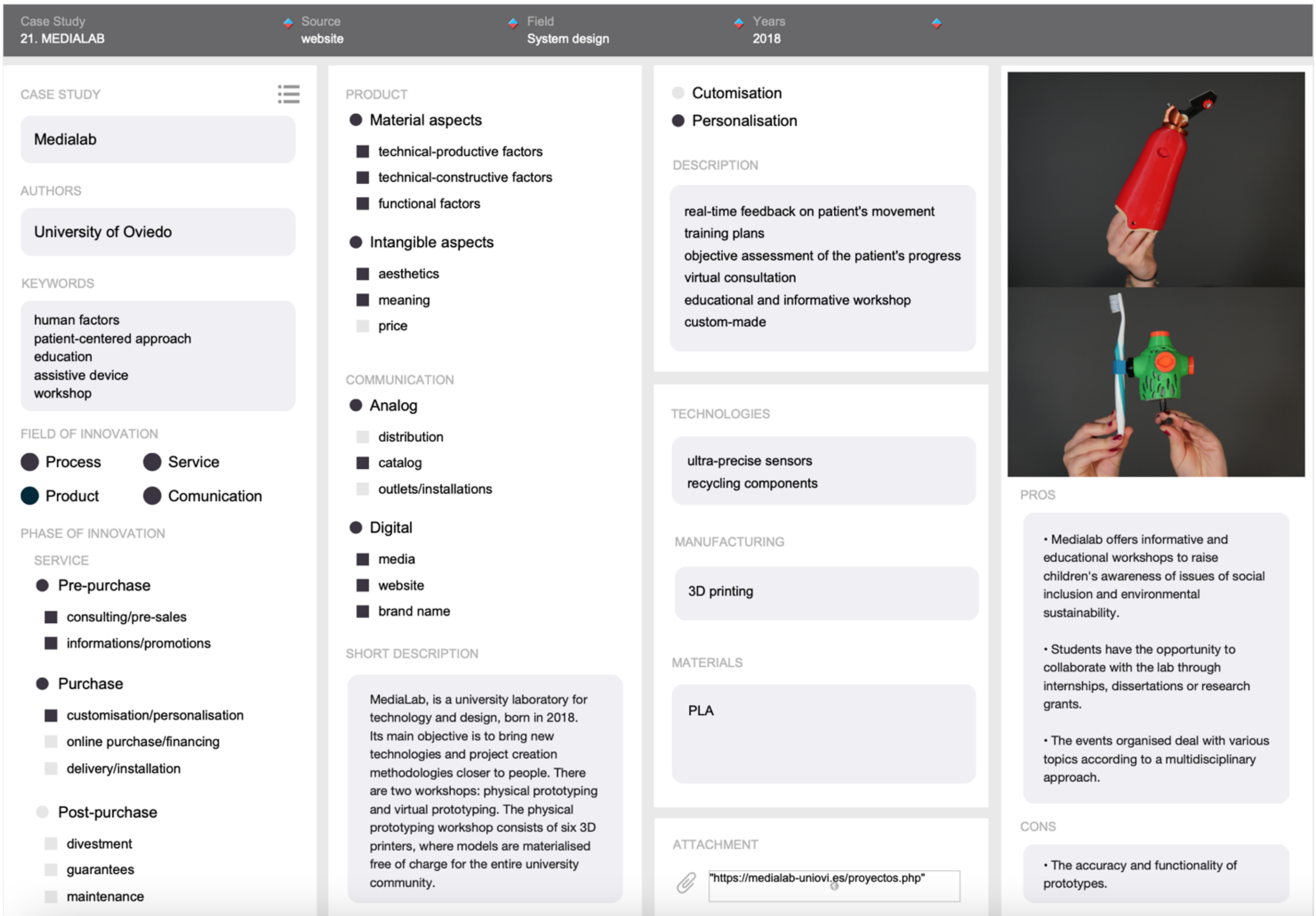

Figure 2. Example of a case study systematized within the FileMaker Pro database and schematized through thematic analysis into clusters.

ANALYSIS OF INCLUSIVE METHODOLOGIES

The methodological approaches, grounded in a critical literature review and case study interpretation, underscore the need to develop a structured theoretical framework. The combined analysis of both shows patterns, issues, and strategies related to inclusive design, with emerging clusters serving as tools connecting technological, organizational, and social aspects. These clusters illustrate that inclusion is not merely an ancillary element of innovation but a fundamental aspect intrinsic to the process. This cross-sectional view reveals recurring principles and practices that define Inclusive Design, emphasizing both functional accessibility and overall quality, and prioritizing individual heterogeneity as a valuable asset (Garofolo & Bencini, 2022). The enhancement of patients' living conditions is imperative, as is the reduction of healthcare staff workload and the strengthening of infrastructure. This section discusses key inclusive elements that, when applied consistently, support people-centered design to meet diverse needs and contexts (Angari & Pontillo, 2025).

The active and continuous involvement of stakeholders.
A key to inclusivity is ongoing participation of patients, families, caregivers, and stakeholders in designing medical devices, using methods like interviews, observations, co-design workshops, and focus groups, plus the collection of user stories from early stages. Studies show that co-design, especially in digital health, reveals needs, barriers, and solutions that are often unseen in technical processes (Henni et al., 2022). The vulnerability of physical and psychological

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states, which change over time due to disease or treatment, requires adaptable, flexible, and intelligent solutions that can recognize evolving needs and support patients throughout treatment (Langella et al., 2023).

The role of the designer as an interdisciplinary mediator.
A second element is the composition of multidisciplinary teams, in which figures such as ergonomists, designers, biomedical engineers, psychologists, healthcare professionals, and patients collaborate on an equal footing. In this context, the designer operates not only as a planner but also as a mediator between the clinical, technological, and social sectors. The designer's objective is to translate complex needs into concrete, usable, and meaningful solutions. (Moseley & Campbell, 2024). This interdisciplinary integration serves to mitigate the risk of a technocentric or regulatory-normative vision, thereby promoting an approach that is centered on people and real contexts of use.

The importance of an accurate analysis of the relationship between individuals and technology.
A further prerequisite encompasses the adoption of rigorous methodologies to analyze the interaction between individuals and technology, including usability, accessibility, user experience, cognitive load, sensory obstacles, conditions of fragility, digital literacy, and various environmental contexts. Such analyses extend beyond ensuring proper technical functionality; they also account for tangible impacts on the user experience. These impacts are particularly significant for elderly, frail, technologically unfamiliar, or otherwise vulnerable people (Bitkina et al., 2020).

Iterative testing carried out with patients in real-world settings.
Moreover, iterative phases and ongoing assessments must be meticulously planned under actual usage conditions. This process involves rapid prototyping, affordance testing with actual users, usage simulations, collection of both qualitative and quantitative feedback, direct observations, and iterative interactions. Such an approach facilitates identifying usage challenges, emerging barriers, and mismatches between the design and the real-world context before the final deployment phase.

*Final assessments and monitoring***.**
Finally, an essential inclusive element is the long-term assessment of acceptability, adherence, and integration into daily routines. Acceptance is not just initial usability but the user's willingness to adopt and sustain device use, influenced by emotional, motivational, relational, and contextual factors (Salek, 2023). It depends on more than convenience; emotional, cognitive, motivational, and relational aspects matter. Users may face physical, emotional, sensory, or cognitive vulnerabilities (Pericu, 2017) and operate within complex organizational environments with roles, hierarchies, and cultural dynamics. Therefore, methods must ensure respect, inclusivity, safety, and prevent feelings of alienation from a product or service with a medical nature.

A comprehensive analysis shows that shifting to an inclusive design model is a fundamental paradigm shift, not just a technical or aesthetic change. It requires a holistic, systematic, sustainable approach focused on individuals' experiences, diversity, skills, limitations, and contexts. These principles form a framework that works best in real, complex settings like the medical sector. It's important to see how these principles can be applied within specific industrial and clinical processes, which face regulatory, technological, and organizational challenges.

Pulcina L. (2025). The integration of inclusive design methodologies within the healthcare design processes. *Rivista Italiana di Ergonomia*. 31. 15-23. DOI: 10.6093/RIE/12737

SYSTEM INNOVATION PROCESS OF MEDICAL DEVICES: THE INVISALIGN® CASE STUDY

The Invisalign® process exemplifies the principles of Design for Inclusion, demonstrating how innovation can integrate clinical, technological, and human dimensions to improve therapeutic effectiveness and the user experience.

The active and continuous involvement of stakeholders.
Invisalign promotes the active participation of the patient from the initial definition and personalisation of the treatment (Sharm et al., 2019). During the preliminary consultation, the patient is encouraged to participate in the treatment plan, monitor expected results, and communicate their preferences. This phase follows co-design processes, where emotional, motivational, and aesthetic aspects are crucial for gathering requirements, ensuring that accessibility and acceptability needs, such as the transparency and discretion of the aligners, are met. Regular consultations with the orthodontist allow for continuous monitoring and the implementation of corrective actions.

The role of the designer as an interdisciplinary mediator.
The personalized, transparent Invisalign® process encourages patient-professional communication, interim assessments, and adjustments. Methodologically, tools such as user journey maps and service blueprints help anticipate user experience evolution and identify issues related to aligner management and instructions. This demonstrates that the process is a patient-centred system that mediates between digital technology, clinical practice, and individual needs, translating complex requirements into concrete solutions.

The importance of an accurate analysis of the relationship between individuals and technology.
The use of digital technologies, such as 3D scanning, additive manufacturing, and monitoring tools, allows for the proactive identification of potential issues, from the management of aligners to understanding instructions. Individual patient characteristics, such as the ability to wear the aligners, oral hygiene, and cognitive needs, are considered, ensuring the treatment's suitability in terms of the interaction between the patient and the device.

Iterative testing carried out with patients in real-world settings.
The treatment is characterised by iterative methodologies and continuous feedback mechanisms. Aligners are developed and updated throughout the course of the treatment. This process includes systematic feedback, adjustments, and assessments based on routine consultations. The integration of digital applications for remote monitoring reinforces this iterative and participatory approach, enabling timely identification and correction of issues.

Final assessments and monitoring.
The final phase with retainers emphasizes clear communication and post-treatment support to maintain results. This approach ensures long-term effectiveness and meets the patient's needs. The process is subject to constant comparison with established clinical standards and the patient's real experience to reduce errors and risks, confirming the importance of acceptability and adherence.

DISCUSSION AND CONCLUSION

The employment of Inclusive Design methodologies, as delineated in this article, facilitates transcending the prevailing paradigm of designing for the “average patient”. Consequently, flexible and adaptive models that accommodate individual variability can be implemented. However, the model may encounter specific operational challenges. The direct involvement of individuals in vulnerable circumstances necessitates that professionals exhibit strong ethical principles, proficient interpersonal skills, and considerable sensitivity. This approach promotes the integration of interdisciplinary knowledge to uphold the principles of equity, diversity, and inclusion (EDI) (Kelly et al., 2022). Promoting participatory practices requires organizational change to foster collaboration and value patients' experiential knowledge. This involves integrating clinical data with narratives, fueled by advances in narrative medicine and personal stories. Despite operational challenges, the participatory approach enhances psychological acceptance of the pathological condition and supports sector progress. Inclusive Process Design can foster more equitable, effective healthcare centered on individual well-being, and preserving the quality of human experience remains the main objective.

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SHORT BIO

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Pulcina L. (2025). The integration of inclusive design methodologies within the healthcare design processes. *Rivista Italiana di Ergonomia*. 31. 15-23. DOI: 10.6093/RIE/12737

RIVISTA ITALIANA DI
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TOWARDS INCLUSIVE MULTISENSORY LEARNING SPACES: A CRITERIA-DRIVEN DESIGN FRAMEWORK

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KEYWORDS: *Autism Spectrum Disorder (ASD), Design for All, Inclusive Design, Multisensory classrooms, Sensory regulation, Spatial usability experience*

ABSTRACT

This article examines the issue of Autism Spectrum Disorder (ASD) in childhood, with particular attention to children aged five to ten who attend primary school, a context in which substantial challenges to inclusion and active participation in school life persist. This condition requires a significant paradigm shift in design, orienting it toward negotiable spaces capable of mediating meanings and fostering relationships among diverse forms of cognition. The research question guiding this article is: which design criteria support the development of a multisensory learning environment that is fully accessible to children with ASD and their neurotypical peers? The purpose of this study is to articulate a coherent framework of design criteria capable of guiding the development of a multisensory classroom accessible to both neurodivergent and neurotypical children, together with strategies required to translate these criteria into effective design practice. The research methodology was based on the collection of qualitative data obtained through semi-structured interviews and a structured validation questionnaire distributed to experts across the therapeutic, educational and design domains. The results revealed overwhelming positive feedback concerning the proposed design criteria. These findings contribute to the fulfilment of the initial research objective, demonstrating how a multisensory approach can provide both a theoretical foundation and a practical framework for designing educational environments that embrace neurodiversity.

INTRODUCTION

Autism Spectrum Disorder (ASD) is a complex neurodevelopmental condition characterised by persistent difficulties across two primary diagnostic domains: social communication and interaction, and restricted, repetitive patterns of behaviour, activities and interests (Hyman et al., 2020; American Psychiatric Association, 2022). At present, diagnosis is articulated through severity levels, which delineate the intensity of symptoms and the extent of individual impairment across the two core domains, correlating these with adaptive functioning and the level of support required (APA, 2022; Gardner et al., 2024). Importantly, the second diagnostic domain encompasses atypical sensory processing, characterised by symptoms of hyper or hypo-reactivity to sensory stimuli, which may coexist within the same individual, as well as by sensory-seeking behaviours, defined as the active pursuit of sensory experiences in the

Frausin, M., Iurilli, G. M., (2025). Towards inclusive multisensory learning spaces: a criteria-driven design framework . *Rivista Italiana Di Ergonomia*. 31. 23-37. DOI: 10.6093/RIE/12745

environment (Posar & Visconti, 2018; APA, 2022; Chaxiong et al., 2022). Moreover, research has shown that atypical sensory responses and sensory-seeking behaviours can adversely influence attentional processes, which enable individuals to focus selectively on relevant information. This, in turn, significantly constrains the ability to sustain high levels of attention over extended periods in response to environmental demands (Brandes-Aitken et al., 2024; Salah et al., 2024). In the school context, children who struggle with sensory processing and attentional regulation inevitably experience adverse effects on their concentration and learning outcomes (Mallory & Keehn, 2021; Hill et al., 2023). This perspective is particularly significant in light of the growing prevalence of students with ASD, which has steadily increased over the past twenty-five years, from 1 in 150 children to 1 in 54 or greater (Mallory & Keehn, 2021; Hill et al., 2023). Furthermore, traditional educational settings continue to exhibit structural limitations, as they are rarely designed with consideration for neurodiversity or the integration of Universal Design for Learning (UDL) principles. In this regard, in recent years, there has been a growing awareness within educational debate of the restrictive and detrimental impact of standardisation in school environments. According to Bluteau et al. (2022), students' interaction with space contributes profoundly not only to their learning, but also to their cognitive, emotional and social development. From an interdisciplinary view, the classroom is no longer conceived merely as a place of instruction, but as a dynamic environment in which children and their surroundings mutually influence and shape one another (Bluteau et al., 2022). This condition calls for a significant paradigm shift in design, orienting it toward negotiable spaces capable of mediating meanings and fostering relationships among diverse forms of cognition. To this end, the study seeks to answer the following research question: How is it possible to design a truly inclusive educational environment? To do so, it presents a coherent framework of design criteria derived from a mixed-method approach combining a literature review with in-field data collection carried out through interviews with professionals from diverse disciplines (from the therapeutic, educational and design fields). This framework aims to guide the creation of multisensory classrooms that are accessible to both neurodivergent and neurotypical children. It also outlines strategies for translating these criteria into effective design practice. Subsequently, the same experts completed a structured validation questionnaire, providing their assessments of the proposed design criteria regarding their pedagogical coherence, design relevance and operational effectiveness. Finally, the article presents an initial pilot project in which these design criteria and strategies are applied.

METHODOLOGY

This study adopted a qualitative research approach, articulated through a multi-step process. In the initial phase, relevant literature in the fields of autism studies, environmental psychology, and inclusive educational design was systematically examined, with particular attention to Autism Spectrum Disorder (ASD) in childhood, atypical sensory processing, attentional regulation, and their implications for school participation and learning. Within this body of knowledge, the ASPECTSS™ Design Index (Mostafa, 2014; Mostafa et al., 2024) was identified as a key reference framework and selected as the conceptual starting point of the study, due to its explicit focus on sensory-informed design for autistic users. Building on this theoretical grounding, the second phase involved in-field data collection through semi-structured interviews with professionals from complementary disciplinary backgrounds, including an architect, a primary school support teacher, a director of a non-

Frausin, M., Iurilli, G. M., (2025). Towards inclusive multisensory learning spaces: a criteria-driven design framework . *Rivista Italiana Di Ergonomia*. 31. 23-37. DOI: 10.6093/RIE/12745

profit organization focused on autism, a cognitive-behavioural psychotherapist, and a behaviour analyst. The interviews aimed to critically interrogate, contextualize, and expand the preliminary design principles emerging from the literature, incorporating practice-based knowledge from therapeutic, educational, and design perspectives. Insights derived from both the theoretical exploration and the expert interviews informed the development of a structured design framework. The framework is articulated into two overarching domains, nine design criteria, and a set of corresponding design strategies intended to support the creation of multisensory, inclusive classroom environments for both neurodivergent and neurotypical children. In a subsequent phase, the proposed framework was subjected to an initial validation process. A structured questionnaire was administered to the same group of professionals to assess the pedagogical coherence, design relevance, and perceived effectiveness of the identified criteria and strategies. The following section presents the resulting framework and summarizes the outcomes of this validation phase. While other components of the research process—such as the full qualitative analysis of interview data and the extended validation of the strategies—are not reported in this article, they remain integral to the broader methodological structure of the study.

RESULTS

For the design of inclusive multisensory environments within the school context, an integrated framework of design criteria has been developed, structured around two interrelated domains: the regulation of sensory stimuli and the spatial accessibility and usability. This articulation arises from the need to integrate factors concerning the perceptual and regulatory quality of the environment with those related to physical and cognitive accessibility, in accordance with the principles of Design for All (DfA). The first design domain (regulation of sensory stimuli) includes all criteria aimed at regulating the intensity, quality and consistency of sensory inputs, including perceptual environmental neutrality, responsive lighting, adaptive acoustics, graduated sensory integration and controlled sensory isolation. The second domain (spatial accessibility and usability) includes all design criteria related to spatial configuration, organization and communication, including dynamic spatial adaptability, sensory zoning, environmental functional capacity and augmentative visual systems. The distinction between the two domains does not imply an operational separation; rather, it constitutes an integrated interpretative framework that highlights a design matrix for an inclusive multisensory classroom, conceived as an adaptive ecosystem supporting and enriching the educational experience. The hierarchical structure of the design framework is shown in Figure 1, illustrating the relationship between domains, criteria and design strategies.

Frausin, M., Iurilli, G. M., (2025). Towards inclusive multisensory learning spaces: a criteria-driven design framework . *Rivista Italiana Di Ergonomia*. 31. 23-37. DOI: 10.6093/RIE/12745

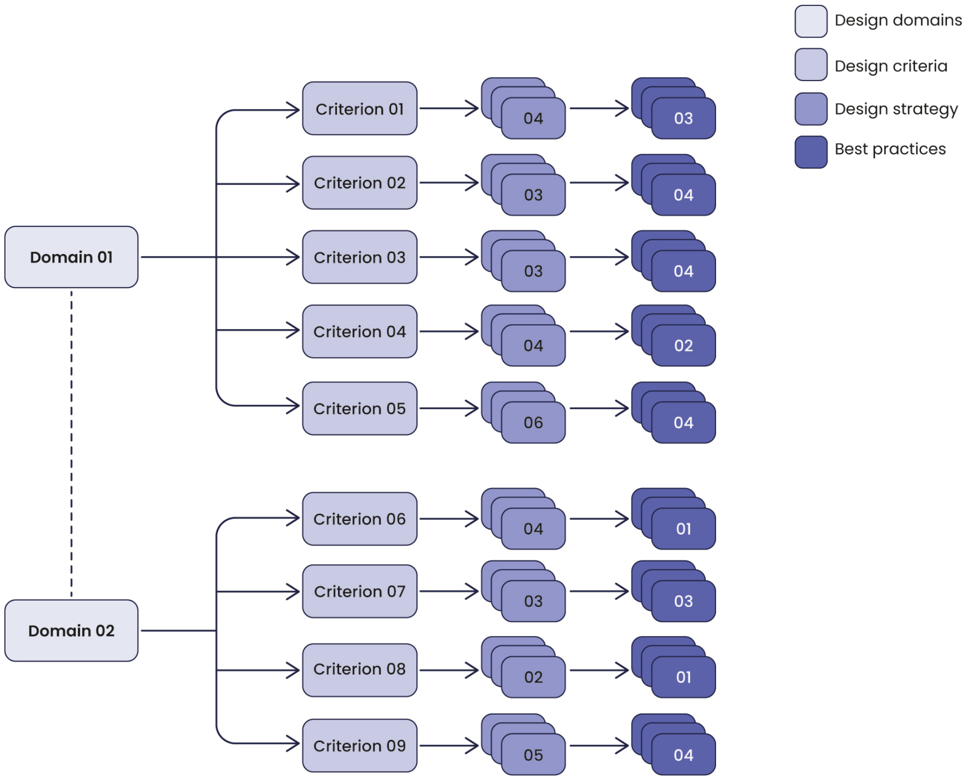

Figure 1. Flowchart of the design framework

Design domain 1 (dd1): regulation of sensory stimuli

The first design criterion (perceptual environmental neutrality) primarily aims to mitigate sensory overstimulation and foster selective attention (Butera et al., 2020; Godwin et al., 2020; Gentil-Gutiérrez et al., 2021). The first design strategy guiding this criterion involves adopting a neutral color palette with low contrast and medium reflectance (Nair et al., 2022; Jiang et al., 2023). A second strategy involves introducing a single accent element within the overall color scheme to provide a visual reference point (Helvacıog˘lu & Olguntürk, 2011; Li et al., 2024). Consequently, perceptual neutrality also extends to the spatial organisation of the classroom, which should be devoid of visual clutter and characterized by an orderly arrangement of materials within designated storage units (Zazzi & Faragher, 2018; Godwin et al., 2020). The final strategy pertains to the tactile and visual quality of surfaces, which should feature uniform textures and be devoid of intricate patterns (Almaz, 2022; Rezaul Karim et al., 2022). The second design criterion (responsive lighting) is conceived as an integrated environmental and educational system in which light plays a central role in shaping a cognitive and relational atmosphere (Mott et al., 2012; Gao et al., 2025). An initial design strategy entails the intentional modulation of light intensity to delineate the different moments of the school routine. In this way, artificial lighting becomes a communicative tool that accompanies and structures the learning process, visually marking the day's phases (Mott et al., 2012; Lech et al., 2023; Gao et al., 2025). A second strategy entails tailoring light intensity and tone to individual sensory profiles. In this context, light functions as a therapeutic and adaptive medium, capable of alleviating sensory overload in children with visual hyper-responsiveness while enhancing stimulation in those exhibiting hypo-responsiveness (Gao et al., 2025; Quiles-Rodríguez et al., 2025). Finally, a third design strategy entails the centralised control of artificial lighting, entrusted to the teacher, to prevent impulsive use or inconsistent stimulation by students (Mott et al., 2012;

Frausin, M., Iurilli, G. M., (2025). Towards inclusive multisensory learning spaces: a criteria-driven design framework . *Rivista Italiana Di Ergonomia*. 31. 23-37. DOI: 10.6093/RIE/12745

Schledermann et al., 2019). The third design criterion (adaptive acoustics) redefines sound from a potential source of stress into an instrument of educational mediation. An acoustically calibrated environment not only mitigates avoidance and discomfort responses but also becomes an integral component of the pedagogical framework, conveying coherent and measurable sensory cues (Danesh et al., 2021; Williams et al., 2021). The first design strategy entails conducting a preliminary acoustic assessment of the classroom to identify potential sources of disturbance such as reverberation, echo or background noise (Williams et al., 2021; Mealings, 2023). The second strategy involves defining calibrated and customisable auditory stimulus gradients across the classroom's functional areas, intending to mitigate sensory overload through spatial sound modulation (Williams et al., 2021; Mealings, 2023). Finally, a third design strategy concerns the optional and adjustable nature of sound stimulation, which should be capable of being activated, modulated or deactivated by the teacher in accordance with the specific sensory needs of the students (Danesh et al., 2021; Williams et al., 2021). The fourth design criterion (graduated sensory integration) advances a relational and adaptive design model whose primary objective is to support the child's autonomous re-engagement with their learning context, enabling the recovery from sensory overload in a regulated yet spontaneous manner (Pfeiffer et al., 2021; Hutson & Hutson, 2024). An initial design strategy involves providing a sensory toolkit[1] calibrated across multiple perceptual channels, enabling interventions to be tailored to individual sensory needs while fostering choice and autonomy within the self-regulation process. A second design strategy concerns the selection of sensory materials within the toolkit, which should be neutral, adaptable and age-appropriate for the students. The third design strategy involves regularly maintaining and monitoring the sensory inserts within the toolkit (Fan et al., 2024; Hutson & Hutson, 2024). The fourth design strategy seeks to ensure educational and sensory continuity between school and home environments using familiar materials from the child's everyday life, thereby promoting the generalisation (Pfeiffer et al., 2011; Jones et al., 2020; Hutson & Hutson, 2024). The final criterion within the DD1 is controlled sensory isolation, which defines a model of adaptive pedagogical architecture wherein the decompression space functions as a diffuse therapeutic environment (Clément et al., 2022; Marwati et al., 2023; Finnigan, 2024). A first strategy concerns adherence to the minimum ergonomic dimensions of the decompression corner, approximately 4,58 m2, sufficient to allow the child to adopt relaxed postures, perform small movements and engage in self-regulatory activities while avoiding any sense of physical constraint (Clément et al., 2022; Marwati et al., 2023). The second design strategy entails providing clearly identifiable and easily accessible decompression zones within the classroom, positioned near the most stimulating areas, ensuring students can easily reach them when needed (Clément et al., 2022; Unwin et al., 2022; Marwati et al., 2023; Finnigan, 2024). As a third design strategy, decompression areas should be positioned laterally to the main space, thereby preventing interference with circulation routes and ongoing teaching activities (Clément et al., 2022; Unwin et al., 2022; Finnigan, 2024). A fourth design strategy entails the functional differentiation of decompression zones within the classroom, calibrated according to their intended purpose and degree of sensory isolation (Marwati et al., 2023; Finnigan, 2024). Furthermore, decompression zones should be modular and upholstered, allowing adaptation to diverse methods of emotional self-regulation. This flexibility enables both students and teachers to adjust the configuration of the area in response to specific emotional and sensory needs. A final design strategy entails the integration of clear visual signals indicating

[1] A set of sensory tools designed and calibrated to operate in a coordinated way across multiple perceptual channels, including the visual, auditory, tactile, olfactory, proprioceptive and vestibular systems.

the status of the decompression space, whether available or occupied, thereby promoting self-regulation and facilitating rotation among students (Unwin et al., 2022; Marwati et al., 2023; Finnigan, 2024).

Design domain 2 (dd2): accessibility and spatial usability

The DD2 is framed by an initial criterion of dynamic spatial adaptability, referring to the environment's capacity to respond flexibly to diverse individual sensory profiles and personalised education plans (Bluteau et al., 2022; Baars et al., 2023; Morris & Imms, 2025). An initial design strategy involves conceiving the classroom as a modular system, wherein spatial components and furniture can be reconfigured, allowing for partial or complete transformations of the environment (Baars et al., 2023; Larose et al., 2024; Morris & Imms, 2025). A second strategy entails the use of mobile, interchangeable and lightweight equipment, enabling periodic reconfigurations of the multisensory classroom to experiment with various perceptual arrangements and assess students' sensory responses (Bluteau et al., 2022; Baars et al., 2023; Morris & Imms, 2025). Another design strategy establishes transition zones between the classroom's primary functions, characterised by mobile and reconfigurable elements that facilitate a gradual and controlled progression between activities. Finally, the fourth design strategy entails the creation of dedicated teacher zones designed to facilitate discrete support and guidance for students (Mallory & Keehn, 2021; Baars et al., 2023; Morris & Imms, 2025). The second design criterion (sensory zoning) addresses the need to minimise spatial ambiguity and facilitate sensory regulation during transitions between different educational and recreational activities (Tola et al., 2021; Habbak & Khodeir, 2023; Al Qutub et al., 2024). A first strategy involves scaling the criterion to the structural conditions of the space: in large environments, a clearly defined functional compartmentalisation may be adopted, whereas in smaller settings, spatial fluidity should be prioritised (Tola et al., 2021; Habbak & Khodeir, 2023). A second strategy entails defining intelligible and predictable micro-spaces, ensuring that each area of the classroom clearly conveys the activity intended to occur within it (Tola et al., 2021; Llorens-Gámez et al., 2022; Habbak & Khodeir, 2023). A final strategy involves designing a unidirectional path that gradually guides students through varying levels of sensory intensity, sequencing areas from the calmest to the most stimulating and back again (Tola et al., 2021; Habbak & Khodeir, 2023). The third design criterion (environmental functional capacity) seeks to regulate social and sensory interaction within the school environment, helping to avoid overstimulation states commonly preceding dysfunctional behaviors in children with ASD (Gentil-Gutiérrez et al., 2021; Al Qutub et al., 2024; Mills et al., 2025). The first design strategy entails configuring the classroom to accommodate small groups of students, intentionally limiting its functional capacity to facilitate closer teacher observation (Banire et al., 2021; Al Qutub et al., 2024; Mills et al., 2025). A second strategy involves setting a maximum number of children per functional area, thereby ensuring a balanced and controlled distribution of students throughout the classroom (Gentil-Gutiérrez et al., 2021; Al Qutub et al., 2024; Mills et al., 2025). The final design criterion addresses augmentative visual systems, aimed at enhancing engagement and fostering active participation among children with ASD (Meadan et al., 2011; Rutherford et al., 2020; Bateman et al., 2023). A first strategy entails the implementation of a structured wayfinding system that facilitates orientation and smooth transitions between the classroom's diverse functional areas and activities (Meadan et al., 2011; Rutherford et al., 2020; Liang et al., 2024). A second

Frausin, M., Iurilli, G. M., (2025). Towards inclusive multisensory learning spaces: a criteria-driven design framework . *Rivista Italiana Di Ergonomia*. 31. 23-37. DOI: 10.6093/RIE/12745

design strategy involves developing three hierarchical levels of visual communication — macro, meso and micro — differentiated according to the scale and communicative function of the conveyed information (Meadan et al., 2011; Rutherford et al., 2020). A third strategy provides mobile supports for the installation of augmentative visual aids, allowing them to be easily relocated and reconfigured in response to shifts in educational and recreational activities (Meadan et al., 2011; Rutherford et al., 2020; Liang et al., 2024). An additional design strategy involves employing augmented visual systems to foster collaboration and rotation among students, conveying information through clear and immediate visual messages (Meadan et al., 2011; Rutherford et al., 2020; Bateman et al., 2023). Finally, the last strategy focuses on fostering intergenerational collaboration among teachers, therapists and parents through the consistent visualisations of personalised education plan objectives (Rutherford et al., 2020; Petersson-Bloom & Holmqvist, 2022; Bateman et al., 2023). The system of design domains, criteria and corresponding strategies discussed above is visually synthesised in Figure 2, which serves as a reference framework for the proposed multisensory classroom design.

Design domains	Design criteria	Design strategies	Best practices
Regulation of sensory stimuli	**Perceptual environmental neutrality**	• Neutral palette with subdued contrast and moderate reflectance. • A single accent element within the overall colour scheme. • Orderly organisation of materials within designated storage units. • Textures should be uniform and devoid of intricate patterns.	• Opt for palettes in ivory, neutral beige, warm grey, desaturated green, or cyan. • Avoid the overlapping of multiple chromatic accents. • Favor regular, anti-reflective textures with matte or satin finishes and smooth or soft surfaces.
	Responsive lighting	• Use of light intensity variations to delineate the school routine. • Adjustment of light intensity and tone to individual sensory profiles. • Centralised control of artificial lighting under teacher supervision.	• Automatically activated before entry (4000 K). • Intensifies at the start of activities (6500 K). • Dynamically modulated during transitions (3500–6500 K). • Softens to warm tones during breaks and at the end of the day (2700–3000 K).
	Adaptive acoustics	• Undertaking a preliminary acoustic assessment of the classroom. • Defining calibrated, customisable auditory stimulus gradients across functional areas. • Optional and adjustable sound stimulation, modulated by the teacher.	• Adoption of acoustic absorbers and/or diffusers, installable on the ceiling. • Introduction of adjustable background sounds, such as white noise, and the selective use of music and natural sounds. • In decompression areas, acoustic environments should be muted. • Localized and directional sound delivery through the individual use of noise-cancelling headphones.
	Graduated sensory integration	• Providing a sensory toolkit balanced across multiple perceptual channels. • Toolkit materials should be neutral, adaptable and age-appropriate. • Regular maintenance and monitoring of the toolkit's sensory inserts. • Use of materials familiar from the child's home environment.	• Select materials with comfortable, uniform, and easy-to-clean textures. • Favor familiar materials commonly used in domestic settings.
	Controlled sensory isolation	• Compliance with basic ergonomic standards for the decompression corner. • Provision of clearly identifiable and accessible decompression zones. • Position decompression areas laterally to the main space. • Functional differentiation of decompression zones within the classroom environment. • Decompression zones should be modular and cushioned. • Integration of clear visual cues indicating the status of the decompression space.	• Position decompression zones near more stimulating areas. • Provide an accessible and clearly signposted access route. • Design semi-open, partially screened zones, avoiding total isolation. • Ensure single-user access at a time.
Spatial accessibility and usability	**Dynamic spatial adaptability**	• Conceiving the classroom as a modular system. • Use mobile, interchangeable and lightweight furnishings. • Definition of transition zones between the classroom's primary functions. • Creation of spaces supporting teacher co-presence.	• Plan periodic furniture re-layouts to assess and respond to students' sensory feedback.
	Sensory zoning	• Adapt zoning to the structural conditions of the space. • Defining intelligible and predictable micro-spaces. • Design a unidirectional path that gradually guides pupils through varying sensory intensities.	• In large spaces, implement clear functional zoning; in smaller ones, promote spatial fluidity. • Provide six distinct functional zones: entrance, teacher-led instruction area, group learning area, play area, decompression area and storage. • Arrange areas from the calmest to the most stimulating, and back again.
	Environmental functional capacity	• Designing the classroom to accommodate small student groups. • Setting a maximum number of pupils per functional area.	• Visually indicate the maximum number of occupants allowed at the entrance of each area.
	Augmentative visual systems	• Implementation of a structured wayfinding system. • Designing three tiers of visual communication: macro, meso and micro. • Provide mobile supports for installing augmentative visual aids. • Use augmented visual systems to foster collaboration and pupil rotation. • Promote intergenerational collaboration through consistent visualisation of personalised education plan objectives.	• Clarify the sequence of experiences and reduce environmental unpredictability. • The visual communication system must be appropriate to the child's age and developmental stage. • The visual communication system should be easily updatable. • Use of coherent, shared infographics outlining the objectives of the Individualized Education Plan.

Figure 2. Summary table of domains, criteria and design strategies

PRELIMINARY VALIDATION OF THE DESIGN FRAMEWORK

A validation questionnaire was developed and administered to assess the coherence, relevance, and perceived effectiveness of the proposed design criteria for a multisensory classroom intended for neurodivergent and neurotypical children aged five to ten, in accordance with the principles of

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Design for All (DfA). The primary aim of this phase was to gather expert-based feedback on the pedagogical and design value of the proposed criteria, as well as to identify potential critical issues and areas for further refinement. The questionnaire was submitted to the same group of professionals involved in the interview phase (n = 5), reflecting an intentionally focused and expert-driven sample. While limited in size, this group represented complementary disciplinary perspectives spanning architecture, education, psychotherapy, behavioral analysis, and autism advocacy. Accordingly, this validation phase should be understood as a preliminary and exploratory step, aimed at testing the internal coherence and conceptual soundness of the proposed framework rather than providing statistically generalizable results. The questionnaire consisted of multiple-choice items rated on a five-point Likert scale (1 = not effective; 5 = very effective), complemented by open-ended questions. This mixed structure enabled both the quantification of consensus levels and the collection of qualitative insights regarding the perceived effectiveness of each design criterion. Participants evaluated the proposed design criteria across the two identified design domains, producing differentiated yet largely convergent outcomes. Within DD1 (regulation of sensory stimuli), results indicated a strong level of agreement among respondents: 80% of experts rated the criteria of perceptual environmental neutrality and responsive lighting as effective, while adaptive acoustics received the highest level of endorsement, with 100% of participants rating it as very effective. The criteria of graduated sensory integration and controlled sensory isolation were also positively assessed, with 60% of respondents rating them as very effective. Evaluations related to DD2 (accessibility and spatial usability) reflected a comparable degree of approval. Dynamic spatial adaptability was rated as very effective by 80% of participants, while sensory zoning received a very effective rating from 60% of respondents. The criterion of environmental functional capacity achieved unanimous agreement, with 100% of experts evaluating it as very effective. More differentiated responses emerged for augmentative visual systems: 40% of participants rated them as very effective and 40% as moderately effective, suggesting an overall positive yet more nuanced perception of this criterion. The distribution of expert evaluations across the design criteria is summarized in Figure 3, which provides a visual synthesis of the results obtained for both the regulation of sensory stimuli and the accessibility and spatial usability domains. Given the exploratory nature of this validation phase and the limited number of participants, future research will necessarily involve the expansion of the evaluation sample to include a broader range of stakeholders, such as additional educators, designers, therapists, and school administrators, to further test, refine, and consolidate the proposed framework.

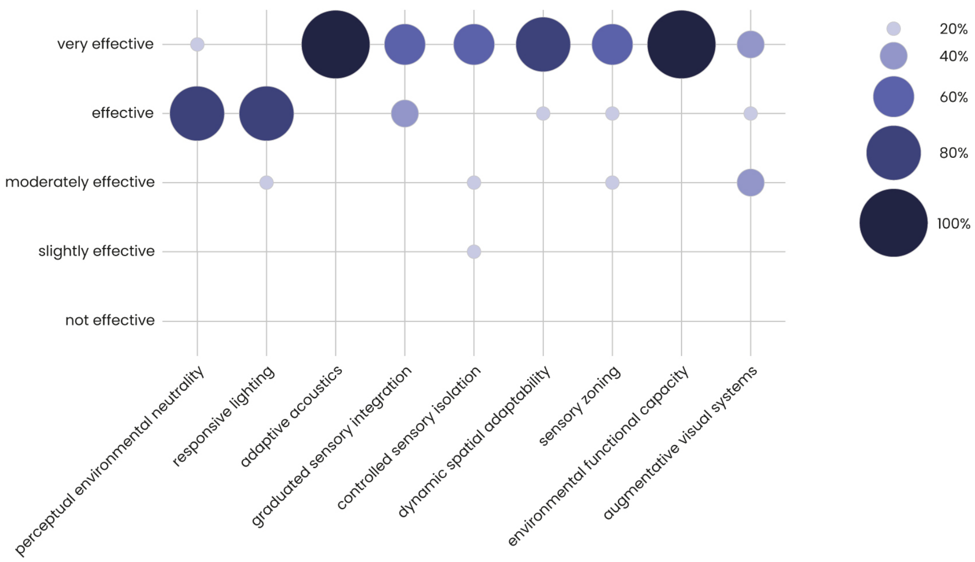

Figure 3. Validation results for all design criteria

A FIRST APPLICATION OF DESIGN CRITERIA AND STRATEGIES: HUDDLE, A PILOT DESIGN PROJECT

This section outlines the initial application of the proposed design criteria through Huddle, a pilot project developed within a standard classroom compliant with Italian educational regulations. Defined by appropriate dimensional and lighting parameters, the space provides a technical framework for testing the integration and replicability of multisensory and inclusive design strategies within a real school context. The design of Huddle is grounded in the principle of perceptual environmental neutrality, aimed at minimizing sensory load and enhancing visual comfort. The project adopts a palette of neutral tones combined with a single system of desaturated accents, used as orientation tools to signal different levels of sensory stimulation and spatial functions, thereby avoiding perceptual fragmentation. From a material perspective, the furniture system primarily employs poplar plywood, selected for its structural properties and its contribution to a visually balanced atmosphere. The uniformity of textures and the organization of materials within dedicated storage areas collectively help reduce visual noise within the classroom. The project incorporates responsive lighting as a tool to support sensory regulation and accommodate the different phases of the school day. Four lighting configurations are defined: neutral lighting at entry to facilitate transition; brighter and cooler illumination during learning activities to support attention; dynamic modulation during transitional phases; warmer and dimmed lighting during breaks and at the end of the day to promote relaxation. Alongside lighting, the project implements an adaptive acoustic strategy aimed at reducing ambient noise and enhancing auditory comfort. Ceiling-mounted sound-absorbing elements and acoustic diffusers are provided to control reverberation, while localized sound delivery in the decompression area is enabled through the use of noise-cancelling headphones. In this space, adjustable sounds may be introduced, or a muted acoustic environment may be maintained as needed. The management of both lighting and sound is centralized and entrusted to the teacher, allowing for control and personalization of the sensory experience. The project introduces the criterion of graduated sensory integration through an analog sensory wall accessible to all students and located within the free-play area. The device provides controlled stimulation of tactile, visual, auditory and proprioceptive

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channels through manipulable modules, low-intensity sound-producing volumes and a tactile pathway organized by texture type and perceptual intensity. The use of common, readily available materials supports the generalization of sensory experiences between school and domestic contexts, while modularity and interaction predictability foster sensory regulation and tactile discrimination without inducing overstimulation. Furthermore, Huddle adopts the criterion of controlled sensory isolation to support moments of self-regulation through a decompression area, which is strategically located near more stimulating zones. Positioned laterally within the classroom, the space offers two alternative configurations: a partially screened option and a semi-open one, balancing perceptual protection and the possibility of teacher monitoring. Conceived as a modular and padded element, the decompression areas integrate seamlessly into the furniture system and adapt to the classroom's various spatial configurations. The project applies the criterion of dynamic spatial adaptability, conceiving the classroom as a modular system in which fixed furniture is designed according to principles of modularity, while mobile components are lightweight and interchangeable. This configuration enables periodic reconfigurations of the layout in response to activities and students' sensory responses. Given the limited floor area of the classroom, spatial continuity is prioritized, while still providing a designated area for teacher co-presence integrated within the frontal teaching zone. In addition, the project applies the criterion of sensory zoning, adapting it to the classroom's structural conditions and favoring a fluid and legible configuration. Functions are organized into six distinct zones, arranged along a progression from lower to higher levels of stimulation and back again: entrance, frontal instruction, group learning, free play, decompression and storage (reserved for teachers). Each area is made immediately recognizable through the use of color as a sensory and functional code indicating levels of stimulation and activity types, while the storage space is deliberately left unmarked to prevent it from being perceived as accessible to students. Huddle addresses the environmental functional capacity, dimensioning the classroom for 25 students while allowing for controlled use by a maximum of 10 students at any given time, in order to ensure well-being and limit sensory stimulation. For each functional zone, a maximum number of users is defined, preventing overcrowding and ensuring a clear correspondence between space and function, thereby supporting differentiated modes of use and the diverse learning and self-regulation needs of students. Finally, the project integrates augmentative visual systems through a structured wayfinding framework designed to clarify the sequence of experiences and reduce environmental unpredictability. Visual communication is organized across three hierarchical levels: macro, to identify classroom zones; meso, to support transitions between areas; and micro, to make rules and daily activities visible. This system complements the physical configuration of the space, supporting predictability and the construction of shared routines, particularly for neurodivergent children. Figure 4 illustrates the floor plan of the Huddle pilot project, highlighting the arrangement of fixed and movable furniture and the organization of the different stimulation zones within the classroom.

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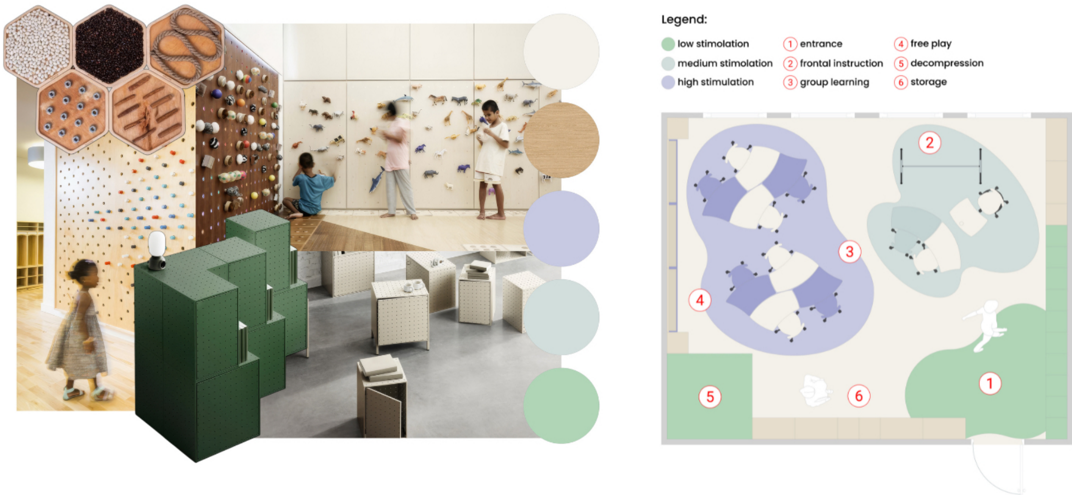

Figure 4. Huddle, a pilot design project for an inclusive learning space

DISCUSSION AND CONCLUSIONS

The article advances the ongoing international discourse on autism-friendly design, building on established frameworks such as the ASPECTSS™ Design Index (Mostafa, 2014) and its updated Second Iteration (Mostafa et al., 2024). It aligns with key assumptions of the ASPECTSS™ model, highlighting how spatial design influences well-being, behaviour, and sensory regulation in individuals with ASD, while incorporating several criteria from both versions of the model. A key distinction, however, lies in the methodology: the proposed framework introduces an explicit hierarchy of domains, criteria, and strategies, providing a systematic, operational tool to translate theoretical principles into best design practices for inclusive learning environments for children with ASD and their neurotypical peers. Moreover, while the ASPECTSS™ model is designed specifically for ASD-oriented environments, this research adopts a broader and inclusive perspective grounded in Design for All (DfA) and Universal Design for Learning (UDL) approach. This enables the design of spaces that can be used by both neurodivergent and neurotypical students within the same educational context. Nevertheless, it is important to note several limitations of the study. The first one concerns the size and composition of the expert sample involved in the validation questionnaire. Although the participants represented three complementary disciplinary fields, the overall number remained limited and thus not fully representative of the broader scientific and professional community engaged in inclusive design. A further methodological limitation lies in the absence of direct empirical evidence derived from the application and monitoring of the criteria within real school settings. Validation to date has relied primarily on expert judgment, with field testing still in progress. The ongoing development of a multisensory classroom based on the proposed framework will enable direct observation of children's behaviours and sensory responses in a fully designed environment. Future research should focus on implementing the proposed design criteria in real school

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environments and testing the model's replicability across educational levels and cultural contexts. This would provide empirical insights into its impact on children's engagement, learning, and sensory regulation, while guiding broader application in inclusive education. Ultimately, this study has contributed to the development of an integrated framework of design criteria for the conception of inclusive multisensory classrooms capable of accommodating both neurodivergent and neurotypical children within a shared educational environment. Despite the study's limitations, the results provide a valuable starting point for discussion. Further contributions are encouraged to refine and enhance the framework, ultimately supporting its development as a practical guide for the design of inclusive school environments. This work offers an original contribution to both the theoretical and practical discourse on inclusive design, advancing a multisensory paradigm that translates the complexity of neurodiversity into concrete and replicable design criteria.

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RIVISTA ITALIANA DI ERGONOMIA
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ADAPTATIONS OF LIVING SPACES FOR CHILDREN'S ACTIVITY IN APARTMENTS: ERGONOMICS INTERVENTIONS FOR AUTONOMY AND SAFETY

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ABSTRACT

Childhood constitutes a fundamental stage in the construction of subjectivities and spatial relationships, and must therefore be recognized as a legitimate social category in urban and architectural planning. This article analyzes how children appropriate the space in their homes, with emphasis on the ergonomic dimensions of apartments. The research adopts a qualitative, interpretative approach, grounded in Ergonomics of the Built Environment, to analyze a case study of a family living in Maceió, Alagoas, Brazil. The analyses reveal imbalances in children's use of indoor domestic environments, as there is often no planning for their safe, autonomous use. In response, the article proposes ergonomic recommendations that enhance the home adaptability and encourage children's autonomy without requiring major structural modifications. The study contributes to advancing reflections on more inclusive forms of dwelling for childhood, with potential for replication across different family contexts.

INTRODUCTION

Housing, as a spatial and cultural category, is a fundamental milestone in architecture, from its most rudimentary forms to its evolution beyond mere physical shelter, becoming a space for intimacy, coexistence, and the building of bonds. The house, understood as a place of habitation in its most diverse forms and dimensions (Dicio, 2024), acquires meaning from the familiarity built up in everyday life, as Massola & Svartman (2018) observed. However, this private character is relatively recent; historically, housing has integrated shared uses and practices in the public domain, as highlighted by Pires (2018). Residential space is similar to a micro-reproduction of urban, cultural, and climatic dynamics. As a collective work, the home "far exceeds the function of shelter" (Leitão, 2009, p.47), reflecting social transformations and ways of life. In recent decades, the reduction of usable areas, especially in apartments, has intensified the need for more flexible design, leading families and professionals to reorganize environments to accommodate children's activities in spaces that are often insufficient for play, study, and interaction. In this regard, studies of the Ergonomics of the Built Environment make fundamental contributions by considering stimulation, safety, and health in the practical and daily use of environments (Attaianese, 2011; Ferrer et al., 2022). Effectiveness in residential

Silva et al. (2025). Adaptations of living spaces for children's activity in apartments: ergonomics interventions for autonomy and safety. *Rivista Italiana Di Ergonomia*. 31. 38-51. DOI: 10.6093/RIE/13366

building refers to how well architectural design supports daily activities without compromising user wellbeing. The ability to identify and address risks that could impact the health and safety of occupants—potentially altering or limiting how the building is used—becomes a key criterion for evaluating a building's functional effectiveness. Such assessments can be carried out by developing protocols to identify and analyze health-related risks (Attaianese & d'Angelo, 2018). Oliveira (2021) argues that child development is inseparable from the child's active relationship with the physical and social environments. This perspective converges with Thibaud (2018) in recognizing the subject as an explorer of space and emphasizing the role of environmental experiences in cognitive, psychosocial, psychomotor, and linguistic development. Despite this relevance, few studies examine the interaction between children and the home environment from an ergonomic perspective that centers the child in the design process. The prevailing literature focuses on anthropometric parameters of adults, neglecting stages of the life cycle such as childhood and old age (Boueri Filho, 2008; Panero, 2016; Iida, 2016). Even in Brazil, where children and youth are a significant population, literature and technical standards, such as NBR 15575-1 (ABNT, 2013), offer generic recommendations focused primarily on the performance of buildings and furniture, without considering the specific needs of children. Given this gap, this article aims to understand how Brazilian children use the indoor environments of an apartment, considering their daily demands for safety, autonomy, and development. The investigation examines the daily life of a middle-class family of four. The study derives from a master's research conducted in the Graduate Program in Architecture and Urbanism at the Federal University of Alagoas, further explored here from the perspective of Ergonomics of the Built Environment.

THEORETICAL FOUNDATION

The theoretical foundations consider three interdependent axes: (i) the child, covering their developmental milestones and relationship with the built environment; (ii) the living space and its role as a mediator and stimulator of child development; and (iii) the ergonomics of the built environment, highlighting the child-activity-environment triad as a design basis for promoting autonomy, safety, and wellbeing. The starting point for this discussion is the idea of home, whose understanding, in the Brazilian context, is linked to family dynamics and social hierarchies. According to Tuan (1930, p. 14), housing constitutes "a concretion of value [...] an object in which one can live," thereby extrapolating its material role and assuming symbolic and affective dimensions. Historically, dwellings have adapted to sociocultural and economic transformations (Villa, 2020), so that their various users and producers become responsible for the continuous reformulation of space and its ambience. Thus, housing expresses complex, changeable processes of appropriation associated with its occupants' living conditions. People spend approximately 15.7h of their day (65%) indoors, including sleep hours; optimizing residential quality and assurance may promote greater comfort, health, and overall wellbeing (Foldvary, 2016). Additionally, children, older adults, and individuals with health issues are particularly susceptible to the adverse effects of poor indoor quality environments (Wu et al., 2017). Environmental Psychology contributes to understanding concepts such as ambience and user-space relationship (Thibaud, 2018; Pinheiro, 2018), considering the home and children's relationship. Each environment has a unique ambience, consisting of social, individual, physical, and affective dimensions that shape behaviors and perceptions. This comprehension is essential for analyzing children's experience of indoor home space, as their daily experiences are defined and controlled by responsible adults, caregivers, or architects (Bezerra et al., 2024). It is in early childhood that they build spatial repertoires, assign meanings to places, and develop perceptions through their movements and interactions with the environment (Erthal, 2023). In this sense, this research places children at the center of scientific debate, understanding childhood as a strategic stage for socio-spatial development. This perspective converges with Ferraro and Azevedo (2023), who recognize that childhoods are everywhere, marked by generational singularities and contextual differences. Such complexity reinforces the need to understand how children construct meanings about the world from the spaces they inhabit, internalizing social hierarchies, behavioral norms, territorialities, and cultural references (Migliani, Almeida & Imbrunito, 2021). The built environment, therefore, acts as an agent of stimulation and mediation, favoring learning, sensory experiences, and emotional bonds that support the child's integral development (Silva & Barbosa, 2024). Just as spaces for adults meet their functional and psychological demands, spaces for children should follow similar premises. Oliveira (2021) points out that the way the home welcomes children and influences their daily experience is an essential part of an ergonomic design answer. Considering anthropometric aspects, physical limitations, and autonomy needs is therefore indispensable for promoting child safety and development. Creating spaces that are sensitive to children's needs entails understanding how children perceive, explore, and redefine housing, and articulating its functional, emotional, and symbolic dimensions (Oliveira, 2021). Investing in more inclusive and responsive environments constitutes a disciplinary and social advance, capable of promoting healthier, more creative, and emotionally rooted developmental trajectories.

METHOD

The research adopted a qualitative, interpretative approach to understand the phenomenon in its social context, as outlined by Sampieri et al. (2013). The aim is to identify how the domestic environment affects children's developmental stages and how direct observation of use experiences contributes to the formulation of ergonomic strategies that make housing safer and more responsive to children's needs. This approach enabled the analysis of meanings, practices, and interactions, contributing to the field of Ergonomics of the Built Environment, focused on creating more humane and egalitarian living spaces. The field collection occurred in two complementary stages: the first is physical, involving detailed characterization of the environment through architectural surveys, photographic records, flow maps, and the identification of daily activities via "icebreakers" moments and walkthroughs. The second stage is cognitive, comprising the systematic observation of environments in use and the identification of "islands of autonomy and learning" based on users' perceptions and spatial appropriation. The data analysis integrated the physical, dimensional, and perceptual aspects of the apartment in use, using a scientific-descriptive and interpretive approach. The project was submitted to and approved by the UFAL Research Ethics Committee under Certificate of Presentation for Ethical Review (CAAE) No. 77289824.7.0000.5013, and each participant received and signed the Free and Informed Consent Form (FICF) after receiving clarification on the objectives and procedures of the investigation.

Silva et al. (2025). Adaptations of living spaces for children's activity in apartments: ergonomics interventions for autonomy and safety. *Rivista Italiana Di Ergonomia*. 31. 38-51. DOI: 10.6093/RIE/13366

Characterization of the research site

As this is a case study (Sampieri et al., 2013), the characterization of the research site focused on the Arlindo Soares Residential Building in the Jatiúca, a neighborhood of Maceió, Alagoas. It is a middle-class multi-unit building, situated in a consolidated urban area near supermarkets, hospitals, and schools; these services provide the family's daily infrastructure and influence children's routines and movements. The apartment unit chosen for the case study is on the sixth floor of the building. It has a living and dining room integrated with a balcony. The service is composed of a kitchen, a laundry, a deposit, and a service bathroom, totaling 95.10 m² (Figure 1). The unit has four bedrooms: the first is the parents' room, the second and third are each child's room, and the last is an office for the whole family.

Figure 1. Apartment 03 - Arlindo Soares Building

Considering Maceió's tropical-humid climate, the building is west-facing, which receives year-round sunlight, contributing to perceptions of inadequate ventilation and high indoor temperatures, as well as to solar incidence on the balcony and bedrooms. The building is located on a corner and has no shading barriers, making this apartment unit the warmest on the same floor.

Characterization of participants

Characterization of participants is fundamental to the proposed ergonomic analysis. The family consists of four members: the parents, father and mother, a 9-year-old son, and a 6-year-old daughter. The family values the quality of the environment and prioritizes organization, cleanliness, and comfort in daily-use spaces. For ergonomic assessment purposes, the anthropometric parameters of the children are described, such as height, upper reach, and lateral reach, as shown in Figure 2.

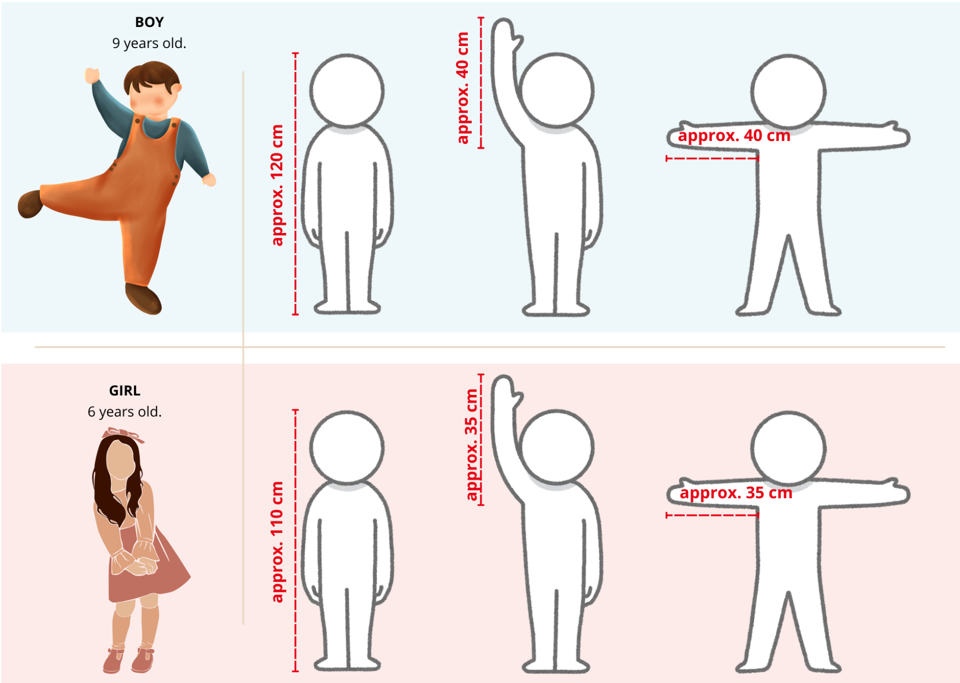

Figure 2. Building Anthropometric measurements of the participating children

All the children's activities take place under parental supervision, as the family has no support network. Although they have the help of a domestic worker, her role is limited to cleaning tasks. The children study in the morning and, in the afternoon, they take part in school and leisure activities, always accompanied by their parents or guardians. In the absence of external support, the parents reorganize their professional schedules to ensure continuous presence and alternate in caring for the children. During recreation periods, the children visit a park near the building or play in the lobby until nightfall, maintaining a fully monitored routine.

RESULTS AND DISCUSSION

The analysis of the residential space layout was based on family usage dynamics, focusing on children, considering room dimensions, types of activities, and levels of autonomy. Based on observations and interviews, a floor plan demonstrates (Figure 3) the family's spatial organization, the functional division of rooms, and the activities carried out in each environment. In this floor plan, different colors identify each user, and hatching indicates frequency of use, allowing for comparison of spatial appropriation patterns among family members.

Silva et al. (2025). Adaptations of living spaces for children's activity in apartments: ergonomics interventions for autonomy and safety. *Rivista Italiana Di Ergonomia*. 31. 38-51. DOI: 10.6093/RIE/13366

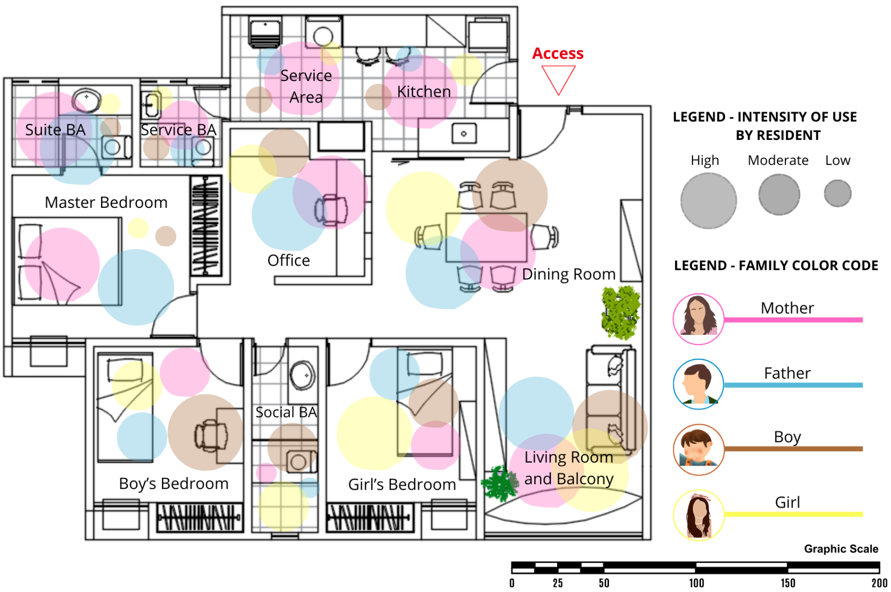

Figure 3. Floor plan of space use and occupancy by the family

The family's routine prioritizes children's needs, who frequently use the surrounding urban infrastructure, especially the neighborhood's natural park, for leisure and family interaction. Inside the apartment, there is homogeneity in the use of spaces, with social environments (living and dining rooms) functioning as collective areas, evidenced by the presence of all the colors representative of the users. In intimate spaces, such as bedrooms and bathrooms, use follows the logic of individual appropriation; however, because the children are very young, parents frequently supervise them. In the kitchen and laundry areas, the presence of risk elements, such as sharp and flammable objects, requires constant vigilance. However, the family encourages domestic tasks suited to the children's abilities. The central functions of this home space are for this family to socialize and rest, and on-site observations showed that children are allowed to cook, study, read, play, and explore the space. Figure 4 synthesizes data on the environment, activities, and risks associated with children's use, to organize information between supervised and unsupervised activities, which are directly related to the family dynamics.

Silva et al. (2025). Adaptations of living spaces for children's activity in apartments: ergonomics interventions for autonomy and safety. *Rivista Italiana Di Ergonomia*. 31. 38-51. DOI: 10.6093/RIE/13366

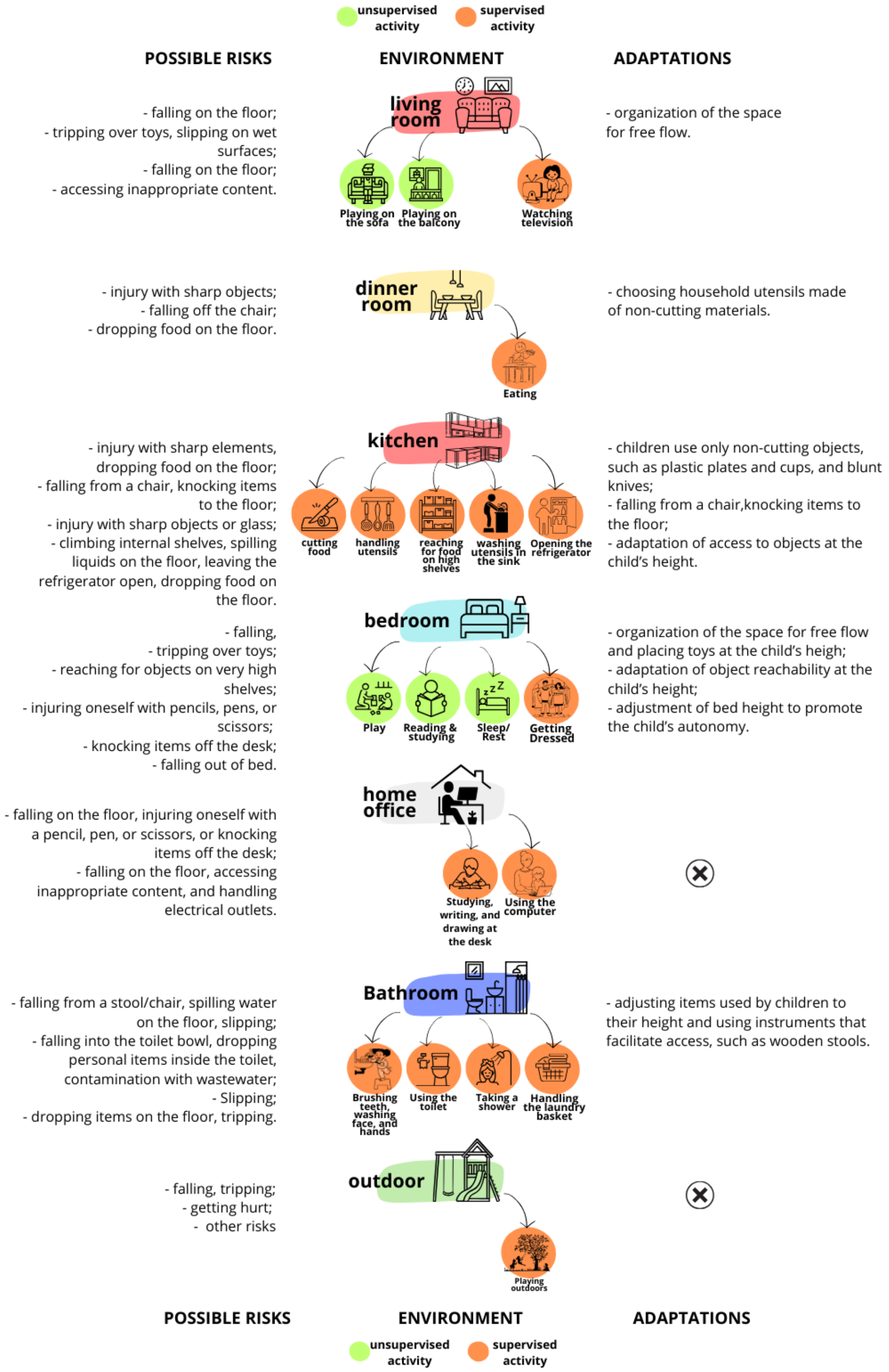

Figure 4. Activities performed by children, possible risks, adaptations, and level of supervision

PROMOTION OF AUTONOMY AND LEARNING ISLANDS (ALI)

Data analysis reveals that specific areas of the apartment are designed to encourage children's activities in an autonomous environment. In other words, children's activities are made possible by layouts and furniture compatible with their age group (Figure 5).

Silva et al. (2025). Adaptations of living spaces for children's activity in apartments: ergonomics interventions for autonomy and safety. *Rivista Italiana Di Ergonomia*. 31. 38-51. DOI: 10.6093/RIE/13366

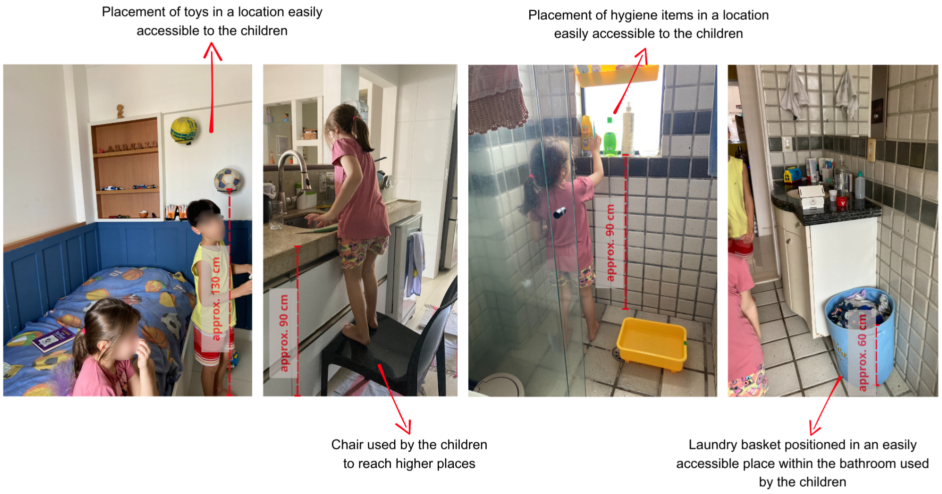

Figure 5. Adaptation of the spaces to support children's autonomy

This family dynamic promotes children's autonomy through specific layout zones inside the apartment, which we denominated - Autonomy and Learning Islands (ALI). These particular zones can be identified in the living room, bedrooms, and bathroom. Research results demonstrate these zones through isometric views of the environments (Figures 6 to 8) that detail their components and discuss positive aspects and challenges of each zone. In the living room and on the balcony, the integration of the environments promotes a necessary fluidity for socialization and family activities (Figure 6). It offers flexibility for playful practices and movable furniture, freeing up central circulation. Although the environment concept had predominantly focused on adults, there are shared elements between adults and children, fostered by comfortable seating and a hammock, which are associated with rest, reading, and leisure, and that contribute to a welcoming, multifunctional atmosphere.

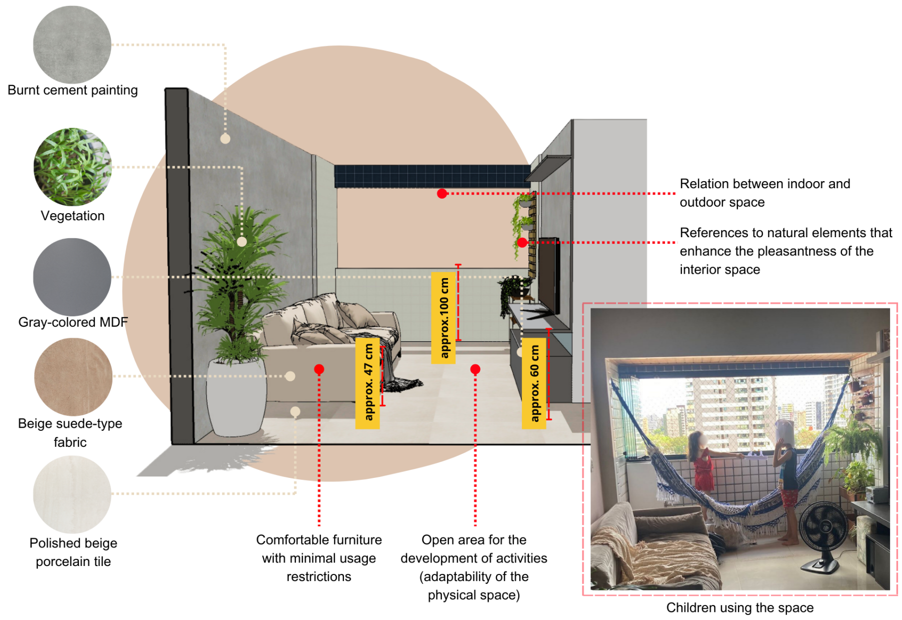

Figure 6. Isometric view of the learning and autonomy islands in the living room and balcony

Silva et al. (2025). Adaptations of living spaces for children's activity in apartments: ergonomics interventions for autonomy and safety. *Rivista Italiana Di Ergonomia*. 31. 38-51. DOI: 10.6093/RIE/13366

In the girl's bedroom (Figure 7), the intention to create a playful environment conducive to autonomy is evident in the choice of furniture and decorative objects. The space combines white wall coverings and furniture with pink details, resulting in a light atmosphere appropriate for the age group. The toy storage furniture is at accessible heights, encouraging independent play and environmental organization.

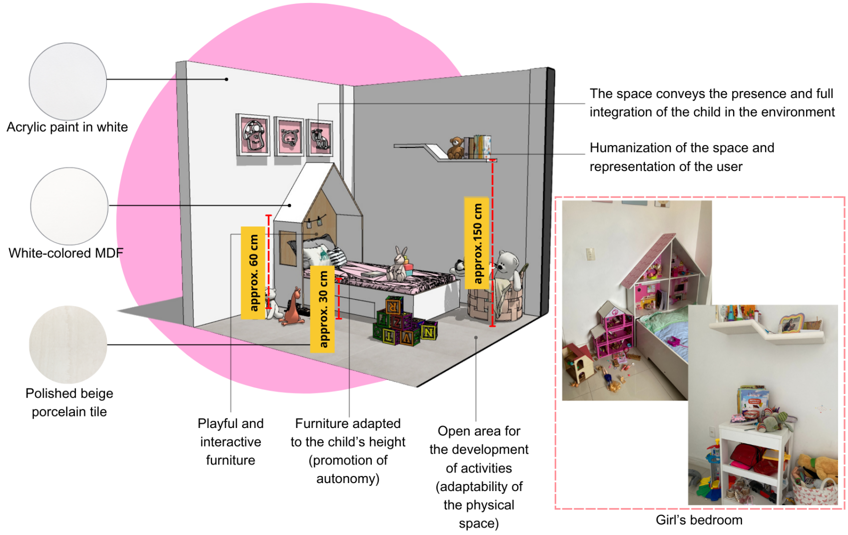

Figure 7. Isometric view of the learning and autonomy islands in the girl's bedroom

In the boy's room (Figure 8), the intention to balance leisure, concentration, and relaxation activities is evident, favored by a spatial arrangement that organizes these functions. Careful attention has been given to the choice of colors, materials, textures, and the strategic arrangement of furniture, stimulating the activities carried out in the environment. The setting incorporates references to the male universe of childhood, present in toys, decorative objects, and chromatic details, reinforcing the user's identity and creating a welcoming atmosphere appropriate for his age group.

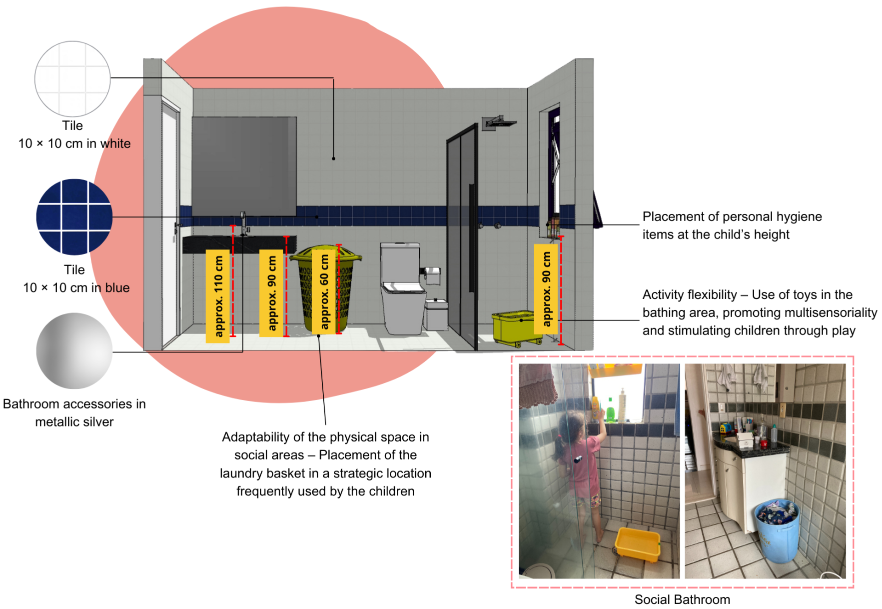

Figure 8. Isometric view of the learning and autonomy islands in the boy's bedroom

The bathroom (Figure 9) promotes children's needs by providing free access to hygiene products. A child-height laundry basket and personal care items on the accessible windowsill (90 cm) encourage autonomy. Bath toys further enhance the space's flexibility by integrating play into the routine.

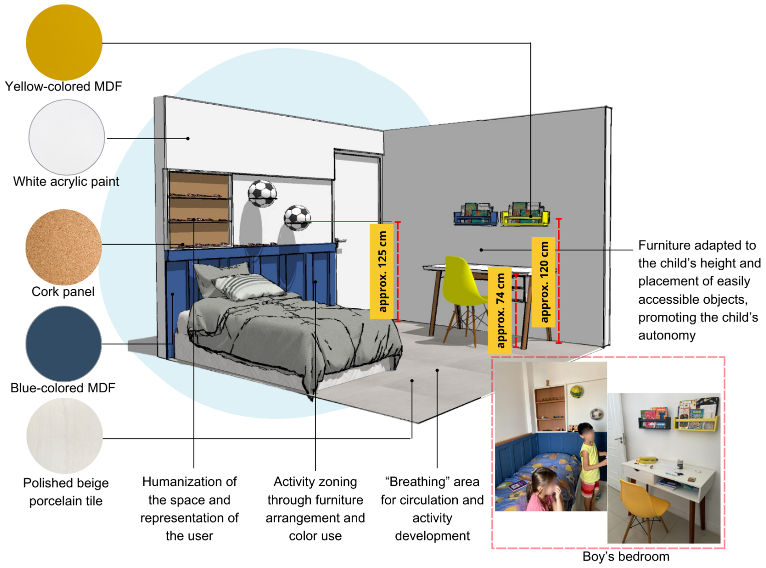

Figure 9. Isometric view of the learning and autonomy islands in the social bathroom

In terms of materials, the bathrooms adhere to the building's original specifications. The mirror, however, is installed at a height compatible with adult use, which occasionally requires a support so children can use it and reach the sink independently. This feature reinforces the need for specific adaptations that account for children's heights when planning shared bathrooms.

DIAGNOSIS AND ERGONOMIC RECOMMENDATIONS FOR CHILDREN'S AUTONOMY

The results reveal that the environment's adaptability to children's needs is most evident in private spaces, such as bedrooms. In contrast, social environments—living rooms, dining rooms, and bathrooms—are designed for adult use, both in terms of functionality and materials. In these areas, children's participation depends on compensatory strategies, such as physical supports and mediations that reduce risks and difficulties in reaching things, highlighting the absence of an ergonomic approach that considers the diversity of users. The diagnosis identified inequalities in children's independent performance of activities, especially in environments designed for adults. To mitigate these effects, adjustments to the spatial configuration are recommended, with an emphasis on functional reach, risk signage, and furniture rearrangement to increase child safety and autonomy (Figure 10).

Silva et al. (2025). Adaptations of living spaces for children's activity in apartments: ergonomics interventions for autonomy and safety. *Rivista Italiana Di Ergonomia*. 31. 38-51. DOI: 10.6093/RIE/13366

Figure 10. Recommendations for adaptations in the living space

Such measures do not require structural interventions and can be implemented progressively, in step with child development and with the necessary degree of supervision, offered by the family dynamic. To increase children's autonomy and safety in the home, the following strategies can be helpful (see Table 1). These recommendations aim to enhance children's autonomy, improve home safety, and foster a more responsive and equitable environment, aligning with Built Environment Ergonomics principles and children's actual needs.

Overcoming unsafe heights	**Use small benches or chairs** that allow children to reach sinks, counters, and tables safely; **A visible and accessible arrangement of everyday objects** promotes independence in daily activities; **Eliminate storing foods over high equipment,** such as over refrigerators or shelves, and prefer storing snacks and sweets in secure, closed cabinets and drawers.
Provide safe transportation of objects	**Light and castered furniture**, such as chests, cabinets, or organizers that facilitate the transport of objects and expand the play space beyond bedrooms, encouraging autonomy and organization.
Promote socializing during meals	**Booster seats or adaptable chairs** enable children to participate comfortably and integrally in family meals at the dining table.
Promote autonomy in the kitchen	**Introduction of safe cutting and glass materials,** such as scissors, blunt knives, and glasses intended for children's use, appropriate for their age group, stimulating practical and cognitive skills related to food preparation, under adult supervision.
Avoid domestic dangers	**Visual signage of risk areas**, with icons at child height, in the kitchen and laundry areas, such as cleaning product cabinets, the stove, the washing machine, and the trash can, promotes hazard recognition and accident prevention; **Do not reuse food packaging,** such as bottles and ice cream tubs, to avoid misinterpretation of the contentes; **Provide cleaning products exclusively inside closed cabinets;** **All windows and glazed openings must be covered with a safety net**;

Silva et al. (2025). Adaptations of living spaces for children's activity in apartments: ergonomics interventions for autonomy and safety. *Rivista Italiana Di Ergonomia*. 31. 38-51. DOI: 10.6093/RIE/13366

	Protect the power board against unauthorized access and tampering by children.

Table 1. Strategies to protect children from domestic dangers and also offer autonomy through routine activities

FINAL CONSIDERATIONS

In general, interior design tends to prioritize adults' preferences and needs. However, this study's results show that simple interventions, such as accessible furniture, objects within reach of children, and the creation of an Autonomy and Learning Island (ALI), can significantly expand children's capacity for exploration, independence, and creativity. By promoting environments that are more responsive to children, architecture contributes to living experiences that are more inclusive, equitable, and consistent with the diversity of users inhabiting the space. In this sense, the construction of ergonomic child-friendly spaces is strategic not only for improving the domestic experience but also for strengthening family bonds and promoting healthier coexistence. Recognizing children as active participants in the production of space implies designing environments that not only protect but also encourage exploration, play, curiosity, and integral development from the earliest years of life. As a case study, this research has limitations inherent to a small context. However, its findings point to relevant directions for future investigations, especially regarding the formulation of replicable design strategies and the evaluation of accessible adaptations across different housing typologies. Advancing in these directions can help establish design guidelines that make contemporary housing more inclusive for children, promoting domestic environments that welcome, stimulate, and sensitively accompany child development.

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EMOTIONAL EXPERIENCE AND ACCEPTANCE OF PASSIVE EXOSKELETONS IN HEALTHCARE SECTOR: INSIGHTS FROM A HUMAN-CENTERED DESIGN APPROACH

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ABSTRACT

Wearable exoskeletons hold promise for reducing the physical strain of healthcare workers, yet their emotional and experiential impact remains underexplored. This study, part of the Exo.Care program, investigated healthcare workers' emotional responses and user experience during a 30-day trial of a passive exoskeleton in residential and home-care settings. Using the Geneva Emotion Wheel (GEW) and the User Experience Questionnaire (UEQ), results showed that initial interactions elicited predominantly positive emotions, such as interest and admiration, reflecting the novelty effect. After prolonged use, positive emotional intensity decreased, while fear and disappointment emerged, highlighting gaps between expectations and actual performance. UEQ results revealed usability challenges in efficiency, dependability, and stimulation, though novelty and attractiveness were positively rated. Findings underscore the importance of integrating emotional and ergonomic factors in exoskeleton design to enhance acceptability, facilitate adoption, and ensure these devices can be effectively incorporated into healthcare workflows.

INTRODUCTION

The aging population and growing demand for continuous care increase the physical workload for healthcare workers, particularly those who transfer and move patients within healthcare facilities. Recent trends in research and development in wearable robotics applied to the healthcare sector (Vallée et al., 2024) suggest that exoskeletons can improve work procedures, reducing fatigue and injuries among operators (Latina et al., 2020; Petrini et al., 2019) and improving the care service for patients. Despite its potential, exoskeleton technology brings with it numerous challenges, such as poor environmental adherence, high development costs, resistance to technological adoption due to its limited use, and, finally, psychosocial, organizational, and emotional aspects of acceptance. The scientific literature on wearable technologies—particularly upper-limb assistive exoskeletons—focuses primarily on biomechanical, engineering, and control-related aspects (Gull et al., 2021; Mahfouz et al., 2024; Gull, Bai & Bak, 2020; Tian et al., 2024; Galbert & Buis,

Iacono, E., Porsani Nucci, R., Pistolesi, M. (2025). Emotional experience and acceptance of passive exoskeletons in healthcare sector: insights from a human-centered design approach. *Rivista Italiana Di Ergonomia*. 31. 52-62. DOI: 10.6093/RIE/13408

2024). Studies address issues such as accurate modeling of the human arm's degrees of freedom, the selection of lightweight and compliant actuation systems—such as pneumatic artificial muscles or cable-driven mechanisms—and the development of advanced control strategies, often based on decoding motor intentions through physiological signals (sEMG, EEG). These studies demonstrate a significant effort to improve device effectiveness, portability, and usability across clinical and industrial environments. However, despite the breadth and rigor of technical studies, the role of emotions in the interaction between users and exoskeletons remains surprisingly underexplored. Yet this is a crucial dimension: emotional perception of the device directly affects acceptability, willingness to use, and the integration of the exoskeleton into daily work practices. The emotional experience can either support or hinder a calm, natural, and lasting interaction with the technology, substantially shaping its real-world effectiveness in care and work settings. The design—particularly experience-oriented ergonomic design—can play a decisive role in addressing this gap. Research in medical design has long emphasized that emotional factors—such as perceived control, dignity, aesthetic familiarity, and non-stigmatization—are essential for the adoption and sustained use of assistive technologies (Norman, 2004; McCarthy & Wright, 2004; Desmet & Hekkert, 2007). In adjacent fields such as orthotics and prosthetics, physical rehabilitation, and daily living aids, numerous studies have shown that assessing emotional impact enables the creation of devices that are more welcoming, less intrusive, and capable of fostering an empathetic relationship between user and technology (Iacono, 2022). Aesthetic perception, familiarity of form, the sense of safety, and a device's ability to avoid making users feel "ill" or "dependent" are also fundamental variables influencing adoption and consistent use. Factors such as users' sense of identity (Shinohara & Wobbrock, 2016), device aesthetics (Dos Santos et al., 2022), the social perception of assistive tools (Nierling & Maia, 2020), and the emotional experience of interaction (Desmet, 2012) directly affect perceived dignity, hedonic quality, and overall acceptability (Siedl & Mara, 2021; Elprama et al., 2022; Gutierrez et al., 2024; Dufraisse et al., 2025). These contributions show that without careful attention to emotional dimensions, even technologically advanced solutions risk being rejected, abandoned, or perceived as stigmatizing. Within this context, the field of assistive exoskeletons remains largely unexplored from an emotional perspective, despite the intimate and prolonged contact between body, machine, and relational environment making such analysis indispensable. An exoskeleton is not merely a mechanical device that redistributes loads and supports complex postures—it is a wearable artifact that intervenes in the operator's physical presence, self-perception, and direct interaction with patients. Understanding how these aspects shape feelings of competence, trust, comfort, and control is essential for designing technologies that are not perceived as intrusive or stigmatizing, but rather as familiar, reassuring, and pleasant to wear. Incorporating an emotional perspective means designing devices that are not only functional, but also capable of being worn naturally, comfortably, and with a sense of empowerment—a necessary condition for these technologies to become a genuine part of healthcare workers' daily routines. The study described in this paper focuses on emotional aspects and was conducted as part of the Exo.Care research program, funded by the Tuscany region. The research program involves a partnership consisting of three research organizations, two social cooperatives, and two metalworking companies. The overall objective of the research is to develop and test an innovative passive exoskeleton designed to support nursing activities and hygiene practices for people living in residential care facilities for the elderly (RSA), as well as patients living in their own homes. This study analyses the

Iacono, E., Porsani Nucci, R., Pistolesi, M. (2025). Emotional experience and acceptance of passive exoskeletons in healthcare sector: insights from a human-centered design approach. *Rivista Italiana Di Ergonomia*. 31. 52-62. DOI: 10.6093/RIE/13408

role of ergonomics in design as a methodological framework for identifying and evaluating the emotional factors that positively or negatively influence the acceptability, hedonic quality and usability of exoskeletal devices. From a Design for All perspective, the ergonomic approach supports the design of inclusion solutions able of responding to the variability of users and application contexts in the healthcare sector. The systematic integration of ergonomic and emotional aspects into design process contributes to the development of exoskeletons that not only meet functional and safety requirements but also improve the overall user experience and adoption of the device over time. Finally, the manuscript contributes to bridging the scientific gap in design research and industrial product design by providing qualitative data for a sector that is in its infancy but has excellent potential for future development.

METHODOLOGY

Thanks to Ergonomics for design and, more specifically, to the Human-Centered Design approach and its methodological framework, several methods were selected that enabled the research team to explore the main problems, primary and secondary needs, and, eventually, the desires experienced by those providing healthcare assistance both in nursing homes and in home-care settings. The methodology used to conduct the study on the analysis of healthcare workers is part of Ergonomics research applied to design. The study adopted a mixed-methods approach that combines qualitative and quantitative methods. It investigated the perception of pleasantness, emotion, usability, and user experience, as well as the physical workload required of social and healthcare operators during personal care activities. More specifically, the following methods were used Geneva Emotion Wheel (GEW) and User Experience Questionnaire (UEQ). The GEW Protocol (Geneva Emotion Wheel) is a metric proposed by Scherer (2005), based on a systematic circular model used to measure individuals' emotions during an activity. It is structured on a Cartesian plane, systematically organized into two dimensions: on the horizontal axis, it indicates valence (negative and positive), and on the vertical axis, it represents activation (high and low), dividing emotions into four quadrants, as recommended by Sacharin et al. (2012). The protocol used is presented in version 2.0 in a circular format and is composed of 20 emotional reactions (10 positive and 10 negative). For each emotion, a five-anchor radial scale is provided, varying emotional intensity according to the size displayed (small: low intensity; large: high intensity). At the center, there are the options "no emotion" and "other emotion," which allow the participant to describe the emotion they are feeling and the perceived intensity, in accordance with the principles established by Scherer et al. (2013). The effectiveness of the GEW method has been demonstrated in scientific studies (Desmet and Schifferstein, 2012; Alaniz and Biazzo, 2019; Coyne et al., 2020), which confirm that emotional evaluation can positively influence the process of generating new product ideas. Meanwhile, the User Experience Questionnaire (UEQ) made it possible to evaluate the user experience of healthcare professionals after using the exoskeleton. At the end of the 30-day experimentation period, each operator was asked to complete the UEQ questionnaire. User Experience (UX) refers to the set of emotions, perceptions, and reactions that a person experiences when interacting with a product or service. In other words, it corresponds to the subjective degree of alignment between expectations and satisfaction during interaction with a system, whether physical or digital. UX is therefore a design dimension that places users' characteristics and needs at the center, focusing on the entirety of experiences within a specific context of use. The UEQ consists of 26 items, each representing a semantic differential in which every item is composed of two

Iacono, E., Porsani Nucci, R., Pistolesi, M. (2025). Emotional experience and acceptance of passive exoskeletons in healthcare sector: insights from a human-centered design approach. *Rivista Italiana Di Ergonomia*. 31. 52-62. DOI: 10.6093/RIE/13408

terms with opposite meanings (Laugwitz et al., 2009; UEQ-Online). The order of these terms is randomized for each item; more specifically, half of the items begin with the positive term, while the other half begin with the negative term. To quantify user experience, the UEQ employs a 7-point Likert scale, where −3 represents the most negative response (value 1/7 on the Likert scale), 0 represents a neutral response (value 4 on the Likert scale), and +3 represents the most positive response (value 7/7 on the Likert scale). The effectiveness of the method has been tested in international studies (Schrepp et al., 2014; Lappalainen et al., 2016; Rauschenberger et al., 2013), which have shown how the User Experience Questionnaire (UEQ) can reveal a series of quantitative data that will allow researchers and designers to make assumptions about possible areas for future improvement of the product being analyzed. The UEQ is structured into six scales comprising 26 items, as follows:

- Attractiveness: overall impression of the product. Do users like or dislike the product?
- Perspicuity: Is it easy to become familiar with the product? Is it easy to learn how to use it?
- Efficiency: Can users complete their tasks without unnecessary effort?
- Dependability: Does the user feel in control of the interaction?
- Stimulation: Is it exciting and motivating to use the product?
- Novelty: Is the product innovative and creative? Does it capture users' attention?

Attractiveness represents a pure valence dimension, whereas Perspicuity, Efficiency, and Dependability correspond to pragmatic quality aspects (goal-oriented). Stimulation and Novelty, in contrast, correspond to hedonic quality aspects (non-goal-oriented). The Attractiveness scale contains six items, while all other scales contain four items each.

Figure 1. Simulated patient handling tests conducted by healthcare workers (OSS) while wearing the passive exoskeleton in a controlled real-world environment. Task: lifting and moving a patient from one seat to another.

For the needs analysis, and in agreement with both the wearable robotics company and the social cooperatives, it was decided to leave the exoskeleton for a 30-day trial period. The participants selected by the facility managers who wore the exoskeleton completed the Geneva Emotion Wheel (GEW) twice. The

Iacono, E., Porsani Nucci, R., Pistolesi, M. (2025). Emotional experience and acceptance of passive exoskeletons in healthcare sector: insights from a human-centered design approach. *Rivista Italiana Di Ergonomia*. 31. 52-62. DOI: 10.6093/RIE/13408

first GEW completion took place after observing the exoskeleton (T0). The second occurred after testing the exoskeleton at the end of the 30 days (T30), each participant completed the UEQ questionnaire at T30. Regarding the users, four social and healthcare workers (3 women and 1 man) of varying ages and experience levels were involved in the study (see Table 1). Their tasks include assisting, moving, caring for, and providing hygiene support to older adults. Within this context, the type of older adults who benefit from this care service is heterogeneous: some are cooperative and cognitively active, while others are uncooperative and cognitively passive. This condition affects the quality of the service provided, as well as the need for one or more social and healthcare workers.

User	Nursing home	Service	Gender	Age	Employment	Nationality
1	Uscita di sicurezza - Orbetello (Grosseto)	Healthcare assistance in RSA	F	47	OSS	Italian
2	Uscita di sicurezza - Orbetello (Grosseto)	Healthcare assistance in RSA	F	56	OSS	Italian
3	NOMOS, cooperativa sociale (Firenze)	Home healthcare assistance for the patient	F	37	OSS	Italian
4	NOMOS, cooperativa sociale (Firenze)	Home healthcare assistance for the patient	M	48	OSS	Italian

Table 1. Meta-data of participants involved in the study.

RESULTS

Below are the GEW findings that emerged from the experimentation. With regard to the GEW, the results indicate that at (T0), after a moment of familiarization and trust-building with the exoskeleton, participants were asked to complete the GEW. In this phase, the emotions expressed by the four participants were mostly positive. We believe this result is related to the potential offered by wearable technology. It is important to note that not all emotions were positive; in fact, two participants reported negative emotions such as shame and fear. The following graph shows the trend and intensity of the emotions experienced by the four operators before using the exoskeleton. GEW after use (T30): After the 30-day period, participants were reassessed regarding their emotional perception of the exoskeleton usage experience. The results indicate a decrease in the intensity of positive emotional responses following familiarization with the technology. The interest factor decreased (T0 average: 5.0 / s.d.: 0 to T30 average: 3.5 / s.d.: 2.38), as did amusement (T0 average: 2.25 / s.d.: 2.63 to T30 average: 0.75 / s.d.: 1.5), contentment (T0 average: 1.75 / s.d.: 2.06 to T30 average: 1.0 / s.d.: 2.0), and admiration (T0 average: 2.0 / s.d.: 2.45 to T30 average: 0.75 / s.d.: 1.5). Perceptions of fear (T0 average: 1.25 / s.d.: 1.5 to T30 average: 1.25 / s.d.: 1.5) and pleasure (T0 average: 1.25 / s.d.: 2.5 to T30 average: 1.25 / s.d.: 2.5) remained at the same low intensity after the usage period. The shame factor decreased (T0 average: 0.75 / s.d.: 1.5 to T30 average: 0 / s.d.: 0), which may indicate greater acceptability of the technology with continued use and learning. Additionally, disappointment (T0 average: 0 / s.d.: 0 to T30 average: 0.25 / s.d.: 0.5) and relief (T0 average: 0 / s.d.: 0 to T30 average: 1.0 / s.d.: 2.0), which were not reported at T0, were identified at T30.

Iacono, E., Porsani Nucci, R., Pistolesi, M. (2025). Emotional experience and acceptance of passive exoskeletons in healthcare sector: insights from a human-centered design approach. *Rivista Italiana Di Ergonomia*. 31. 52-62. DOI: 10.6093/RIE/13408

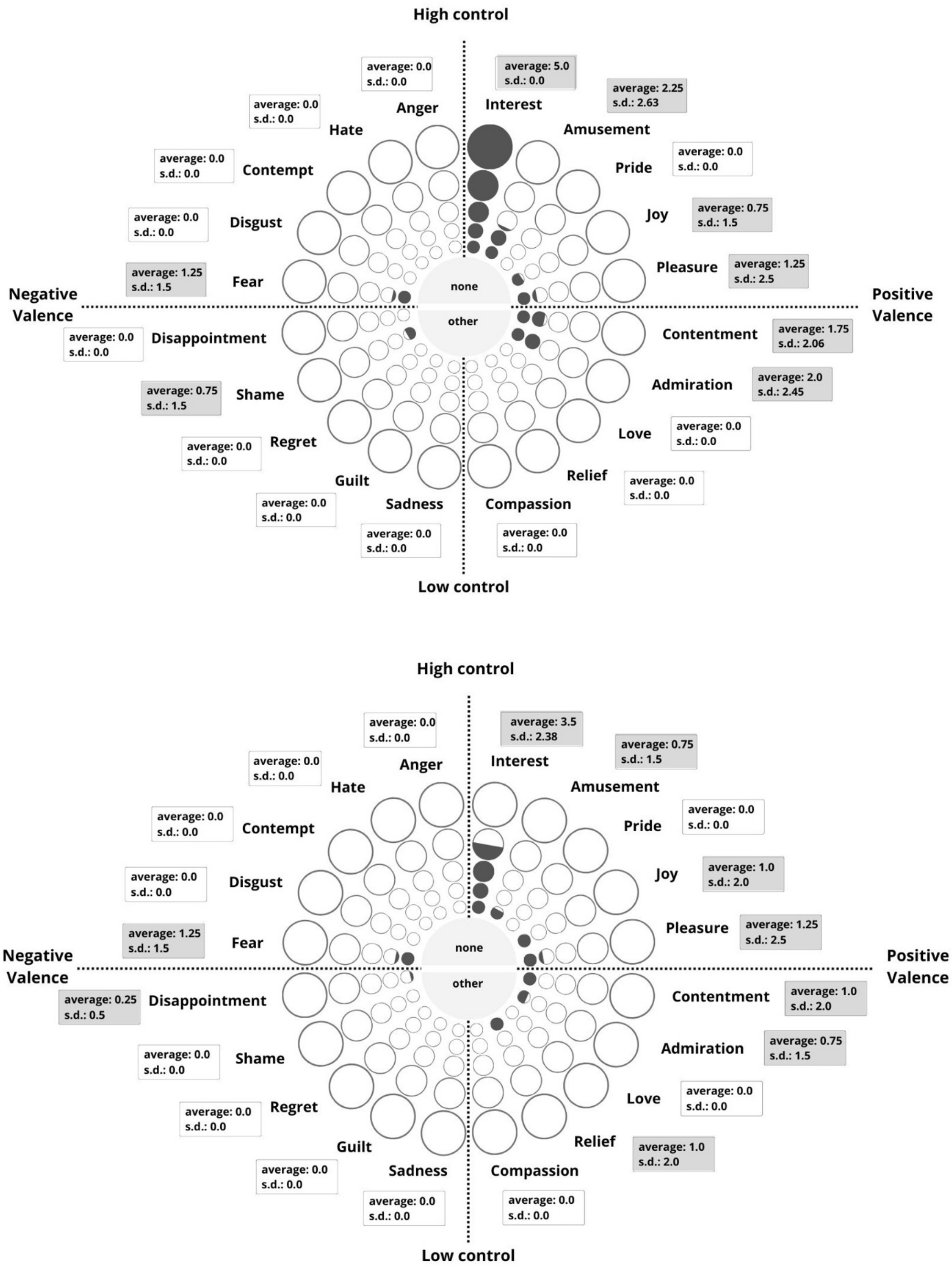
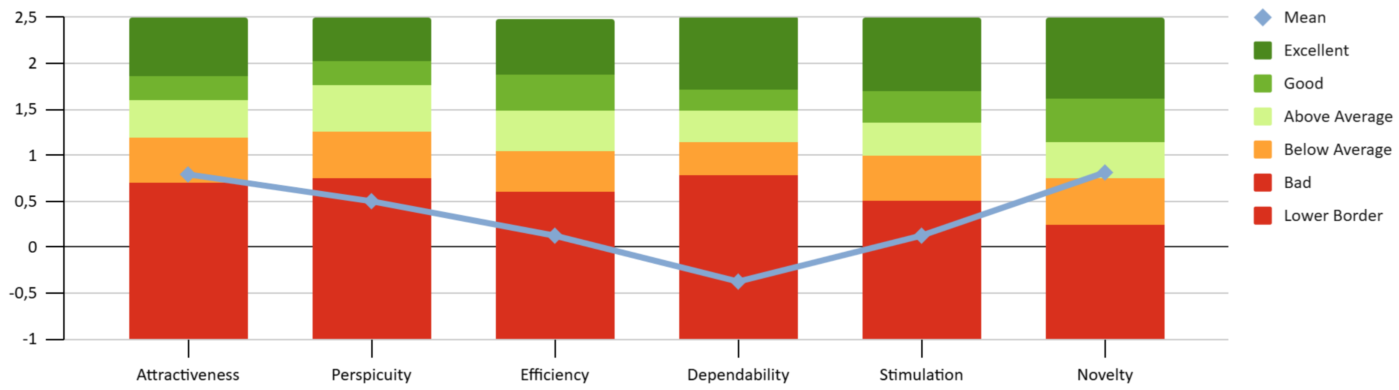


Figure 2. T0 (top) and T30 (bottom) GEW Results

In summary, after the 30-day period, a significant reduction in the intensity of reported positive emotions was observed (particularly interest, amusement, contentment, and admiration), which may be related to the process of familiarization and acceptance of the technology. Additionally, only two negative emotional indications were maintained at T30: fear, which may be associated with usability factors and potential injury risks for both the OSS user and the patient, and disappointment, which, although low in intensity, may reflect some level of frustration regarding the user's prior expectations of the equipment. Thanks to the UEQ questionnaire, it was possible to collect a considerable amount of data. For this reason, only the most relevant results are reported below and presented together. The standard interpretation of the scale highlights that values between −0.8 and 0.8 represent a neutral assessment of the UX, while values > 0.8 indicate a positive evaluation. Conversely, values < −0.8 indicate a negative evaluation. Finally, the value −3 represents an extremely poor rating, whereas the value 3 represents an extremely good one (UEQ Online). As evidenced in Figure 3, the individual

Iacono, E., Porsani Nucci, R., Pistolesi, M. (2025). Emotional experience and acceptance of passive exoskeletons in healthcare sector: insights from a human-centered design approach. *Rivista Italiana Di Ergonomia*. 31. 52-62. DOI: 10.6093/RIE/13408

scales indicate a User Experience (UX) with the exoskeleton that tends toward neutral to negative. The lowest results correspond to three fundamental aspects of exoskeleton technology, efficiency (n = 0.13), stimulation (n = 0.13) and dependability (n = −0.38). The reasons underlying these scores have already been extensively discussed in the previous sections. An interesting finding, as anticipated, concerns the aspects of novelty (n = 0.81) and attractiveness (n = 0.79), whose values are to be considered positive.



Mean	Comparisson to benchmark	Interpretation
0,79	**Below average**	50% of results better, 25% of results worse
0,50	**Bad**	In the range of the 25% worst results
0,13	**Bad**	In the range of the 25% worst results
-0,38	**Bad**	In the range of the 25% worst results
0,13	**Bad**	In the range of the 25% worst results
0,81	**Above Average**	25% of results better, 50% of results worse

Figure 3. UEQ Results.

The analysis of the User Experience Questionnaire (UEQ) results indicates that the overall experience with the exoskeleton tends toward a neutral-to-negative evaluation across most of its dimensions. The scales related to Perspicuity, Efficiency, Dependability, and Stimulation fall within the range of the 25% worst results in the UEQ, revealing difficulties in learning to operate the device, low operational efficiency, a reduced sense of control during use, and limited motivational engagement. Attractiveness obtained a slightly below-average score, suggesting moderate acceptance but limited overall satisfaction. In contrast, Novelty was the only positively rated dimension, classified as above average, indicating that the exoskeleton is perceived as innovative and capable of capturing users' interest. Overall, the findings suggest that although the technology is recognized as original and somewhat appealing, significant usability challenges remain, particularly concerning ease of learning, operational performance, and perceived control, highlighting the need for improvements in ergonomic design, interaction quality, and training support.

CONCLUSIONS AND FINAL CONSIDERATIONS

The results of this study offer an initial understanding of the emotional dynamics and user experience associated with the use of a passive exoskeleton by healthcare workers in a care setting. The adoption of wearable technologies in the healthcare sector, while showing significant potential for improving the physical well-being of workers and reducing the biomechanical load during handling activities, is accompanied by a series of psychological and usability implications that deserve attention. Emotion analysis using the Geneva Emotion Wheel (GEW) showed that initial contact with the exoskeleton

Iacono, E., Porsani Nucci, R., Pistolesi, M. (2025). Emotional experience and acceptance of passive exoskeletons in healthcare sector: insights from a human-centered design approach. *Rivista Italiana Di Ergonomia*. 31. 52-62. DOI: 10.6093/RIE/13408

generated predominantly positive emotions, such as interest, admiration, and curiosity. This is consistent with the 'novelty' effect typical of emerging technologies, which tends to generate high expectations and initially favorable perceptions. However, not all reactions were positive: the presence of emotions such as fear and shame indicate that the introduction of visible, mechanized body devices can also influence aspects related to self-perception, professional image, and perceived safety. After 30 days of use, the intensity of positive emotions decreases significantly. This phenomenon suggests a process of normalization and familiarization with the technology, but also a possible gap between initial expectations and actual perceived and experienced performance. The emergence of feelings such as disappointment and relief indicate a more pragmatic reflection on the real impact of the exoskeleton on daily work activities. At the same time, the results of the User Experience Questionnaire (UEQ) confirm significant operational difficulties. The aspects with the lowest scores—efficiency, stimulation, and reliability—show that the exoskeleton was not perceived as an immediately useful, easy-to-integrate, or particularly motivating tool. The critical issues identified could be related to the perceived weight of the device, its adjustment methods, the adaptation time required, and potential interference with the established routine of healthcare assistants during care activities. Despite this, the novelty and attractiveness of the device support the perception that it has significant potential and represents an innovative solution in the healthcare sector. This result reaffirms the interest of operators in technologies that can reduce physical strain and increase safety at work, provided that they are truly human-centered, intuitive, and integrated into work processes. It should also be emphasized that the emotional dimension plays a primary role in the acceptability of wearable technologies. Negative emotions such as fear or discomfort can be an obstacle to adoption, while good user-centered design can help minimize these effects and promote the integration of the device into care practices. From a methodological point of view, this study confirms the importance of a human-centered approach and the combination of qualitative and quantitative tools to understand not only the technical functioning of technologies but also the emotional and perceptual experience of operators. In conclusion, the research experience presented emphasizes that, although the exoskeleton is perceived as an innovative and potentially useful device, its perceived effectiveness and level of usability are still limited in the real work context. The main findings suggest that:

- The initial emotional impact is strongly positive, but tends to diminish over time, highlighting the need to improve consistency between expectations and actual performance.
- Some negative emotions persist, such as fear, related to safety factors, perceived risk, and complexity of use.
- The overall user experience tends to be neutral or negative, especially in relation to pragmatic aspects such as efficiency, comprehensibility, and sense of control.
- The perception of novelty remains high, indicating that the technology is seen as promising and arouses interest, but requires significant improvements to become truly integrable into care practices.
- Overall, the results indicate that the introduction of exoskeletons in the care sector must be accompanied by:
- more refined ergonomic design in line with the real needs of potential end users, focusing on differences in physical abilities, age, gender body type and work experience among healthcare workers;
- ergonomic design that takes into account different contest of use such as nursing homes and homes of older people;

Iacono, E., Porsani Nucci, R., Pistolesi, M. (2025). Emotional experience and acceptance of passive exoskeletons in healthcare sector: insights from a human-centered design approach. *Rivista Italiana Di Ergonomia*. 31. 52-62. DOI: 10.6093/RIE/13408

- adequate and personalized training of staff aimed at raising awareness of the future use of exoskeletons in the healthcare context;
- gradual adaptation processes necessary to satisfy the technology-human-environment relationship.

Only through improved usability and constant support for operators will it be possible to transform initial interest into stable and informed adoption, with concrete effects on reducing physical strain, increasing safety, and improving well-being in the workplace. In conclusion, the integration of ergonomics, HCD and Design for all plays a crucial role in identifying and analysing often unexpressed needs in order to create people-centred products and understand the changes hat ageing brings to daily routines, usage patterns, attitude and perceptions of products.

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RIVISTA ITALIANA DI
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THE ENHANCEMENT OF CULTURAL ECOSYSTEMS THROUGH AN INCLUSIVE DESIGN APPROACH: THE CASE STUDY OF THE "MUSEO DIFFUSO LETTOMANOPPELLO"

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KEYWORDS: *Digital solutions, Inclusive Design Approach, Interaction Design, User Experience, Wayfinding*

ABSTRACT

Enhancing the usability, accessibility, comfort, and user experience of cultural heritage, particularly within small or dispersed museums, has become a key challenge for contemporary design research. In these contexts, the lack of technological infrastructures, effective wayfinding systems, and inclusive and ergonomic communication tools often limits visitor engagement, resulting in cultural and perceptual exclusion and diminishing local identity. Ergonomics and Design for All offer valuable frameworks to address these limitations by promoting a systemic approach that integrates human-centred, inclusive, and sustainable principles across different design domains. This paper investigates how these principles can be applied to cultural heritage through digital solutions, interaction design, service design, and communication systems that connect physical and digital experiences. The study presents the Museo Diffuso Lettomanoppello, an open-air museum in the Abruzzi Region, conceived as a living laboratory for experimentation of multisensory and inclusive design. By combining contextual analysis, participatory co-design, and the development of ergonomic and accessibility metrics, the project demonstrates how the integration of Design for All and Ergonomics can transform small cultural sites into dynamic, connected, and inclusive ecosystems. The findings highlight the potential of such combined approach to strengthen identity, participation, and sustainable development within marginal cultural contexts.

INTRODUCTION

In recent years, the integration of cognitive ergonomics with Design for All has played a pivotal role in innovating design processes applied to cultural heritage within systemic design frameworks (Martins & Gabriele, 2013). The progressive digitisation of museum experiences, combined with the need to ensure physical, cognitive, and digital accessibility for diverse audiences, requires careful consideration of usage models, communication interfaces[1], and the relationships between body, space, and information (Yap et al., 2024).

[1] In this paper, the term interface is used in an expanded sense, referring not only to digital tools but also to physical and communicative artefacts—such as signage, spatial markers, and interactive installations—that mediate the user experience within the museum environment.

Marchetti, R. (2025). The enhancement of cultural ecosystems through an inclusive design approach: the case study of the "Museo diffuso Lettomanoppello". *Rivista Italiana Di Ergonomia*. 31. 63-73. DOI: 10.6093/RIE/13409

In small Italian towns [2], promoting cultural heritage—both tangible and intangible—is crucial for triggering territorial regeneration. In contexts marked by depopulation, loss of identity, and marginalisation, identifying sustainable and participatory revitalisation strategies becomes essential. Innovative forms of cultural engagement, such as open-air and distributed museums (Lerario, 2025), are emerging as dynamic networks connecting people, art, and territory rather than closed, centralised institutions. Within this framework, ergonomic design plays a systemic role by reinforcing the relationship between users and their environment through sensory comfort, clear information, and usable interfaces, while fostering inclusion and active participation in heritage processes (Kasemsarn, Harrison, & Nickpour, 2023). This aligns with the new ICOM definition (2022), which defines museums as “permanent, accessible, inclusive, and participatory institutions that work with and for communities.” Inclusion, when sided with sustainability thus become strategic levers for heritage enhancement in smaller towns. These concepts have been applied in the design and implementation of the Museo Diffuso Lettomanoppello, an experimental cultural laboratory developed in Lettomanoppello, a small town in the Abruzzi Region. The project addresses a widespread condition in small towns: despite a rich tangible and intangible heritage, they often lack digital infrastructures and participatory strategies for cultural development, as traditional top-down approaches overlook the social and experiential dimensions of accessibility. The Museo Diffuso Lettomanoppello was conceived as a living laboratory integrating research and co-design with local stakeholders and citizens – as per Design for All Approach (Rossi & Barcarolo, 2018). Characterised by its stone heritage—over forty pietrales (Figure 1) engravings in Majella stone—and contemporary sculptures integrated into the landscape, the town lacked digital and communication systems, limiting their visibility and accessibility. The Museo Diffuso Lettomanoppello was conceived as a living laboratory integrating research and co-design with local stakeholders and citizens – as per Design for All Approach (Rossi & Barcarolo, 2018). Characterised by its stone heritage—over forty pietrales (Figure 1) engravings in Majella stone—and contemporary sculptures integrated into the landscape, the town lacked digital and communication systems, limiting their visibility and accessibility. The project therefore adopted a systemic, interdisciplinary approach combining technological innovation, sustainability, inclusiveness, and ergonomics to create an integrated ecosystem of physical and digital artefacts, branding strategies, and accessible routes that foster participation and multisensory engagement.

[2]Italy has over 5,500 small municipalities (fewer than 5,000 inhabitants), covering about 70% of the national territory and housing nearly 10 million people. These inland and mountain areas face persistent challenges of depopulation, ageing, and limited access to services and culture (ISTAT, *Atlante dei Piccoli Comuni*, 2022).

Figure 1. Examples of “pietrales” in Lettomanoppello.

Marchetti, R. (2025). The enhancement of cultural ecosystems through an inclusive design approach: the case study of the “Museo diffuso Lettomanoppello”. *Rivista Italiana Di Ergonomia*. 31. 63-73. DOI: 10.6093/RIE/13409

RESEARCH OBJECTIVES

The study aimed to develop and validate a preliminar model for a distributed inclusive museum, created through co-design and inclusive design principles, to promote sustainability, social inclusion, territorial cohesion, and technological innovation in cultural heritage. To do this, both principles of cognitive and Design for All have been applied to enhance the enjoyment of widespread cultural routes. Furthermore, a systemic approach was adopted across different design areas with the goal of developing solutions that were usable by the widest possible population of users, both visitors and local stakeholders (i.e., citizens). The specific objectives were:

- To design and integrate digital solutions, services, communication systems, and wayfinding tools within a widespread museum model, enhancing overall user experience and engagement.
- To evaluate the value of the Museo Diffuso Lettomanoppello as a scalable model for similar contexts, on the basis of socio-economic, human-centred, collaborative, and cultural metrics.
- To assess how ergonomic principles improve inclusiveness and accessibility, and to identify indicators suitable for evaluating the effectiveness of communication and digital tools in terms of usability and user engagement.

METHODOLOGY

The research adopted an integrated 3-stage approach, combining both qualitative and quantitative methods used in Design studies (Shuttleworth, 2008) with on-site live sessions that involved local stakeholders to translate insights into design outlines. This ensured that the project addressed the needs of all social groups, including people with disabilities, and different age and socio-economic groups. The aim was to reduce the technological gap affecting the accessibility and "usability"[3] of cultural heritage in Lettomanoppello case study, through systemic strategies grounded in ergonomic design principles. To achieve these objectives, the project applied the Method for System Design for Sustainability (MSDS) (Vezzoli, 2007), which is a flexible sociotechnical design-oriented approach that integrates sustainability principles at a systemic level while promoting responsible design practices (Figure 2).

[3]In this study, "usability" extends beyond the ISO 9241-11:2018 definition to include the experiential quality and overall accessibility of the cultural heritage environment, interpreted through ergonomic and systemic design principles.

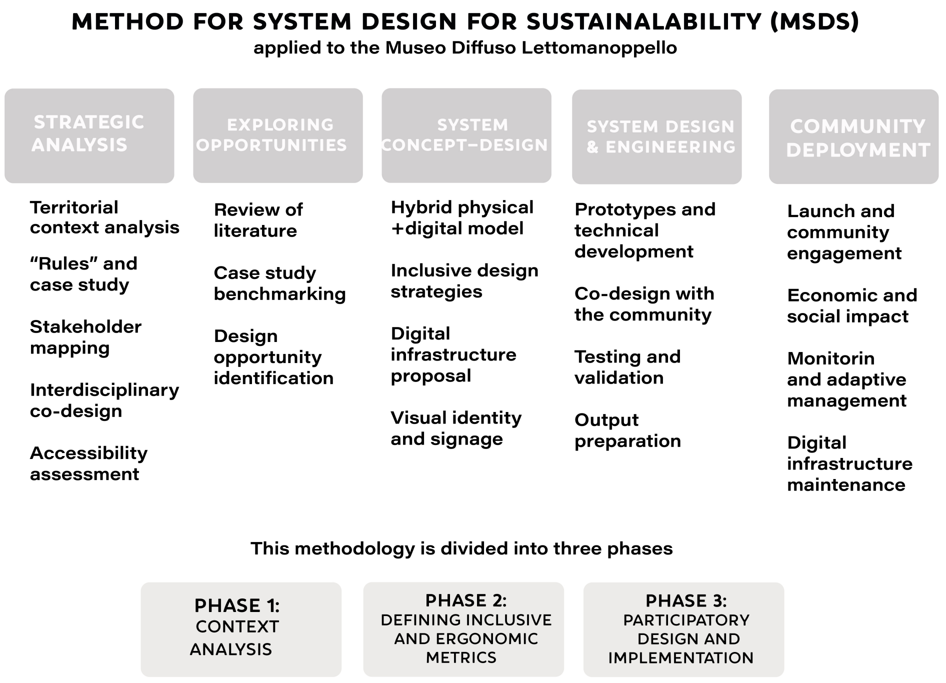

Figure 2. Adapted Method for System Design for Sustainability (MSDS) applied to the Museo Diffuso Lettomanoppello

This framework supports a holistic approach to sustainability, ensuring that digital design solutions are effective, ergonomic, and durable while enabling a comprehensive exploration of the widespread museum phenomenon.

Context analysis

The local context analysis followed three main steps: (1) literature review, (2) field data and interviews, and (3) mapping of artworks. The review addressed three main thematic areas: (a) the diffuse museum and its theoretical evolution, (b) urban art for territorial regeneration, and (c) ergonomic and inclusive design in cultural contexts, with an emphasis on improved user experience. A contextual study of Lettomanoppello examined the *pietrales* (and their socio-cultural relevance, focusing on accessibility and usability through site surveys and documentation. Fieldwork and interviews with artists and residents revealed local perceptions and expectations. As noted by Groat and Wang (2013), such analyses are crucial for understanding community needs and guiding targeted accessibility strategies. Stakeholders—including local authorities, cultural associations, and artists—were identified. Particular attention was paid to the potential needs of users with diverse abilities (e.g., blind and partially sighted persons, deaf and hard of hearing persons) during the analysis. The results confirmed the lack of digital, communicative, and wayfinding systems, with fragmented information and limited access routes hindering user interaction. Overall, Phase 1 revealed major gaps in accessibility and digital infrastructure, reinforcing the need for an inclusive, ergonomic approach to enhance user engagement and cultural participation

Defining inclusive and ergonomic metrics

This phase established clear design objectives and evaluation criteria aligned with ergonomic and Design for All principles to improve accessibility, usability, and the experiential quality of urban artworks. A benchmark of national and international case studies enabled the definition of metrics for physical, digital, and cognitive accessibility, economic sustainability, tourism impact, and

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community engagement. These provided strategies tailored to the context of Lettomanoppello, with particular attention to cognitive ergonomics, interaction, and service design. The resulting metrics were translated into ergonomic indicators such as (a) accessibility, (b) interface readability, (c) perceptual comfort, and (d) communicative clarity, which were used later to guide and assess the effectiveness of design solutions developed. Ergonomics was treated not as a final verification step but as an active, iterative element within the design process.

Participatory design and implementation

The design phase embodied the inclusive principles of Design for All, translating them into digital, communicative, and spatial solutions centred on the user experience. An integrated system of products and services was developed to enhance public art and the local stone heritage through physical and digital artefacts (Giaccardi, 2015), creating an accessible, participatory, and multisensory experience. Through participatory co-design, the community, artists, and stakeholders contributed in three iterative steps. The initial phase—critical mapping—focused on accessibility. To facilitate improved access to "pietrales", a set of accessibility design actions were undertaken to remove architectural barriers and eliminate the tone-on-tone effect effect (re: white stone-made artwork on/sided on white walls),that hindered their visibility. A new pietrales route was developed, offering short, medium, and long itineraries to provide a diversified experience appropriate for diverse target groups (Figure 3).

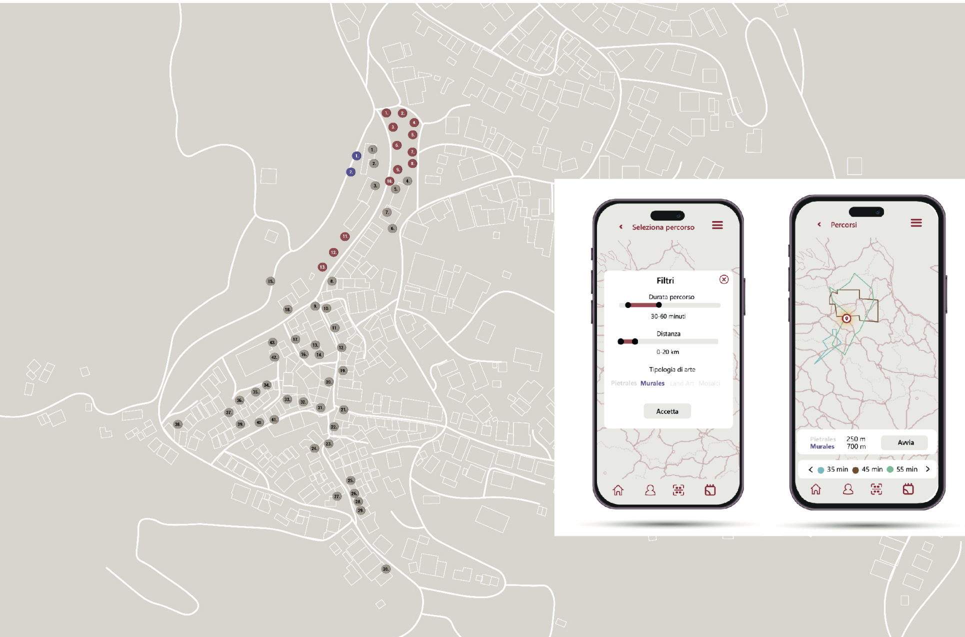

Figure 3. Map of the 'Pietrales Route'

Simultaneously, the digitisation of the stone heritage has begun, consisting of photographing the works and creating an archive. The integration of augmented reality in a mobile application facilitates access to multimedia content, in-depth information, and audio guides during physical visits (Figure 4).

Marchetti, R. (2025). The enhancement of cultural ecosystems through an inclusive design approach: the case study of the "Museo diffuso Lettomanoppello". *Rivista Italiana Di Ergonomia*. 31. 63-73. DOI: 10.6093/RIE/13409

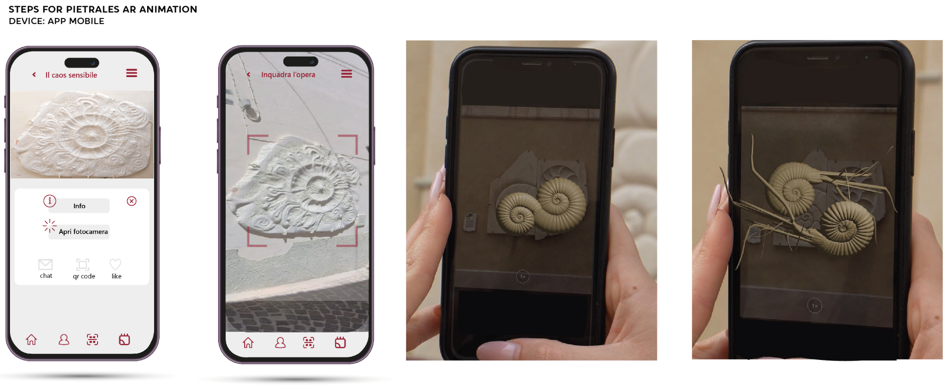

Figure 4. Digitalisation process and augmented reality integration

The inclusive visit experience phase developed hybrid phygital works, reinterpreting pietrales through augmented reality and digital storytelling co-created by stonemasons and digital artists. Digital interaction was designed to be intuitive and accessible, following ISO 9241-210 (2019) human-centred design principles and a Design for All approach, ensuring usability for users with cognitive, visual, and hearing impairments. The museum as a platform phase envisioned the Museo Diffuso Lettomanoppello as a regional hub connecting art, territory, and community. Long-term sustainability strategies—microfunding, residencies, and creative calls—promote belonging and a circular cultural economy. The museum operates as an evolving ecosystem linking people, spaces, and information, accessible both on-site and remotely. The project demonstrates how integrating ergonomics and Design for All can transform a diffuse museum into an inclusive, technology-driven system fostering participation and sustainable territorial development.

DEVELOPMENT OF THE PROPOSED MODEL

The proposed model for the Museo Diffuso Lettomanoppello defines an integrated cultural ecosystem (Figure 5).

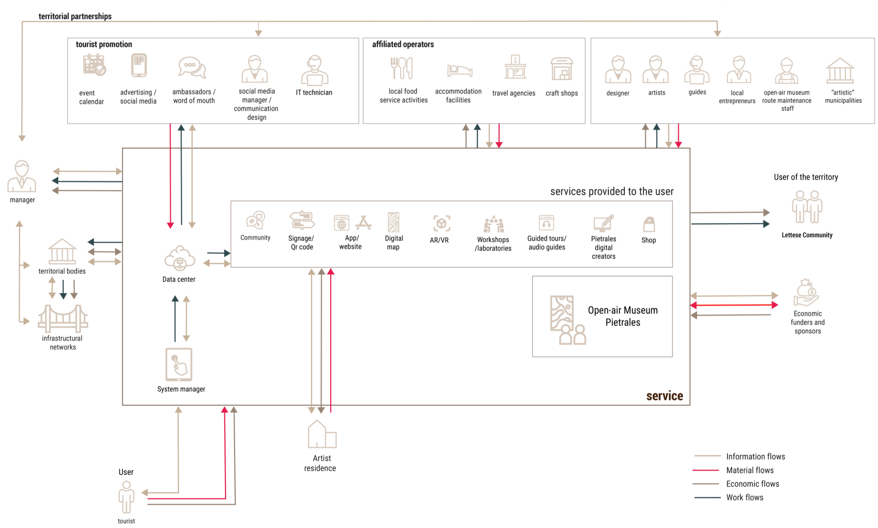

Figure 5. System Map

The user experience combines digital solutions, interactive devices, communication systems, and physical and cognitive orientation tools. The aim was to outline a model replicable in other museums and urban contexts. This system embodies human-centred design principles, where technology

Marchetti, R. (2025). The enhancement of cultural ecosystems through an inclusive design approach: the case study of the “Museo diffuso Lettomanoppello”. *Rivista Italiana Di Ergonomia*. 31. 63-73. DOI: 10.6093/RIE/13409

enhances visitor access, understanding, and comfort. The model adopts a modular use of digital infrastructures—a web platform, a mobile app, and on-site interactive devices—allowing users to engage with content before, during, and after their visit. Consistent with Allen and Lupo (2012), contemporary museums as relational communication environments in which technological mediation fosters participation, engagement, and knowledge construction. The web platform operates as an archive and a virtual space for participation, collecting digital artworks, technical data sheets, and thematic maps. The website also tasks as a digital hub for users and artists, featuring a membership and customer loyalty section. This segment encompasses initiatives related to donations, the commissioning or adoption of artistic works, and pertinent contact information. In addition, the website contains a login section and an online store where users can purchase branded merchandise. The mobile application integrates augmented reality (AR) and geolocation functions with proximity notification activation, enabling digital narrative layers to be superimposed on physical works along the museum's routes and improving visitor autonomy and safety. In addition to the provision of 'augmented' navigation, the ARTCreator tool facilitated the co-creation of content by users, allowing them to design their own work and participate in contests, thereby increasing their engagement during their visit. The digital solutions that have been designed to reduce the digital divide have been developed to support both on-site visits and remote, on-demand experiences. The promotion of accessibility of heritage and the inclusive and sustainable enjoyment of culture is, thus, a key objective of these solutions. The visitor experience employs interaction design principles, offering tailored itineraries based on interests, time, and accessibility The museum's communication system and visual identity are underpinned by principles of accessibility and information design (Frascara, 2015), structured within a multi-level information hierarchy that ensures clear, multilingual, and interactive content designed according to visual ergonomics criteria. The wayfinding system (Figure 6) is founded on the principles of cognitive and environmental ergonomics, and has been designed to facilitate intuitive orientation, even in the absence of digital support.

Marchetti, R. (2025). The enhancement of cultural ecosystems through an inclusive design approach: the case study of the “Museo diffuso Lettomanoppello”. *Rivista Italiana Di Ergonomia*. 31. 63-73. DOI: 10.6093/RIE/13409

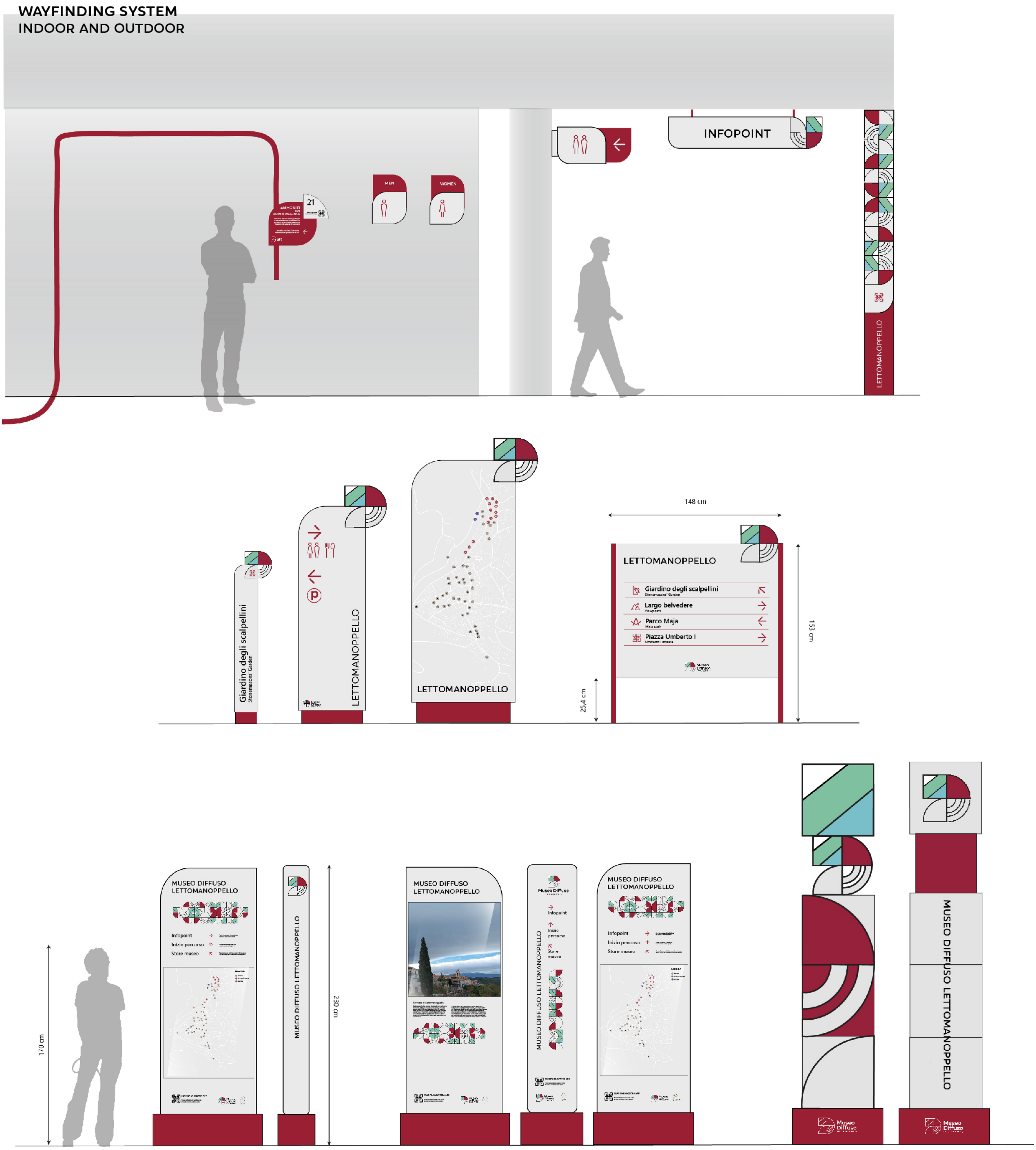

Figure 6. Wayfinding system and signage design

The system has been meticulously designed to assist visitors in navigating navigate the museum and comprehending its interconnections with the surrounding area. The signage is intended to ensure optimal visibility at different distances and comprises the following elements:

- museum information panels with interactive displays for personalised content;

Marchetti, R. (2025). The enhancement of cultural ecosystems through an inclusive design approach: the case study of the “Museo diffuso Lettomanoppello”. *Rivista Italiana Di Ergonomia*. 31. 63-73. DOI: 10.6093/RIE/13409

- vertical and horizontal directional signage for both indoor and outdoor environments;
- multisensory maps featuring tactile reliefs;
- decorative totems serving as recognisable museum symbols.

Furthermore, ad-hoc floor signage (Figure 7) has been proposed to facilitate navigation throughout the museum without the necessity of additional digital or physical tools, such as apps or paper maps.

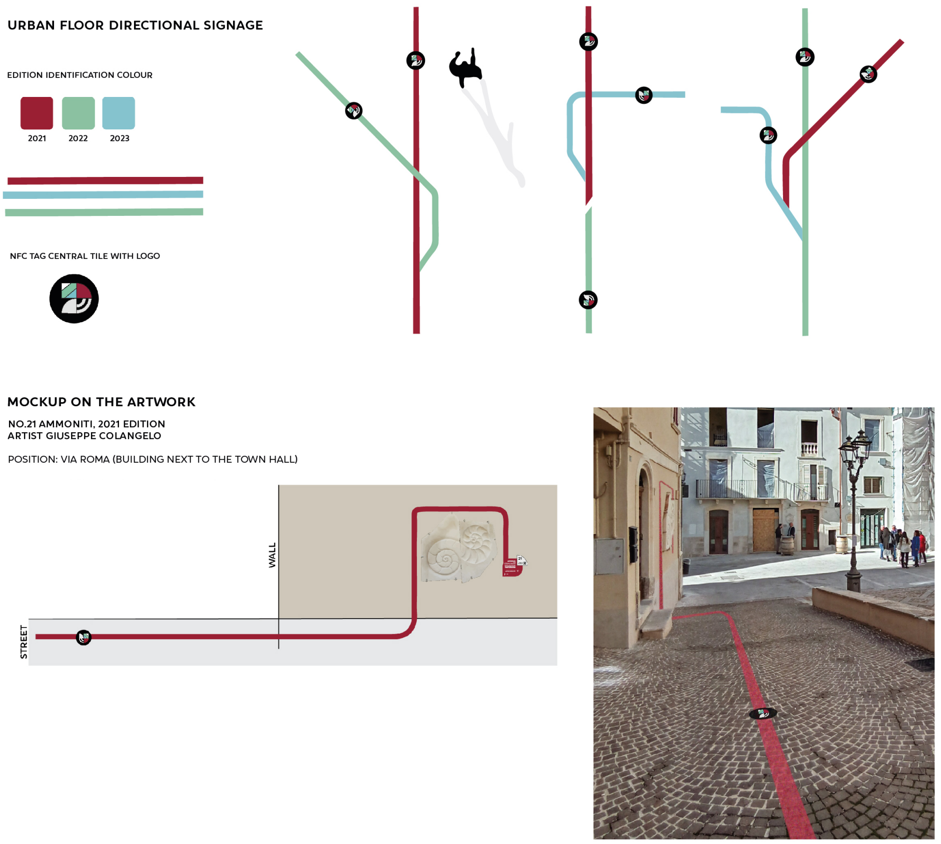

Figure 7. Floor and wall wayfinding elements

This removable, repositionable, and recyclable wayfinding also frames artworks as wall signage, ensuring immediate visibility. Explanatory plaques are to be found alongside all works on the museum route, and these are equipped with QR codes and NFC tags. The latter allow immediate access to text descriptions, accessible information sheets, multilingual audio guides, and videos in Italian Sign Language (LIS). The integration of these user-friendly digital technologies, open-source platforms and physical communication artefacts facilitates the replication of the system in other territorial contexts.

DISCUSSION

The project developed in Lettomanoppello generated observable results demonstrating the validity of a systemic model for art and cultural heritage promotion, along with the value of ergonomic and inclusive approaches in the enhancement of 'small-towns' heritage. It showed that, when guided by human-centred design principles, technology becomes a means for improved access and participation that broadens the usability and experiential scope of heritage. The initial phase went beyond cataloguing and digital archiving by applying organisational ergonomics to involve residents in data collection and decision-making, fostering shared responsibility and local ownership. The designed thematic routes identified informed an integrated wayfinding system

Marchetti, R. (2025). The enhancement of cultural ecosystems through an inclusive design approach: the case study of the "Museo diffuso Lettomanoppello". *Rivista Italiana Di Ergonomia*. 31. 63-73. DOI: 10.6093/RIE/13409

that combined physical and digital tools to meet cognitive ergonomics and the phygital heritage approach (Lo Turco & Giovannini, 2020). This ultimately resulted in improving orientation, accessibility, and visitor experience. Phase 3 confirmed the effectiveness of this approach by showing how the integration of ergonomics and Design for All can foster tangible improvements in usability, comfort, and community engagement. Cognitive ergonomics optimised information hierarchies and interaction consistency, reducing cognitive load and improving orientation. Human Centred Design guided route accessibility and signage placement, enhancing visibility and comfort, while Design for All sustained participation and co-creation of context-based identity. The creation of digital pietrales and their virtual placement acted as participatory interfaces, transforming heritage interpretation into a shared, inclusive experience. Overall, the Lettomanoppello model demonstrates how an ergonomic and inclusive framework can enhance accessibility and user experience, offering a replicable model for small-town cultural systems.

CONCLUSIONS

The inclusive enhancement of cultural heritage in small towns has become a key strategy for reducing regional inequalities, countering inland abandonment, and promoting sustainable development. In this context, a systemic and inclusive approach has been proven to be an effective strategy for addressing the complexities of these territories. The design process employed for the creation of the Museo Diffuso Lettomanoppello demonstrates an innovative model for applying ergonomics and inclusive design principles across multiple fields—exhibition, interaction, cultural heritage, service, and communication design—resulting in an open-air museum where digitalisation and communication promote sustainable and inclusive visit experiences. Integrated digital solutions- e.g., website, apps, and interactive devices – have enhanced accessibility and redefined the parameters of cultural enjoyment. The combination of communication strategies with physical and digital artefacts proved effective in fostering inclusivity. The model also showed that integrating communication systems and wayfinding supports inclusion while activating participation, cultural micro-economy, and territorial cohesion. The vision set for open-air museum is no longer tied to a “place of passive contemplation”; it is now more aligned to a “living (eco-)system of relationships where knowledge is built through interaction and sharing” (interpreted from: Cipolla & Manzini, 2009). Combining user experience design, interaction design and service design paves the way for new inclusive museum paradigms, where technology becomes a tool for expression, relationships and a sense of belonging. As Jelinčić (2017) argues, cultural innovation extends beyond technological advancement. It involves the creation of participatory and sustainable ecosystems that strengthen local identity and empower communities. Likewise, Borowiecki et al. (2016) highlight how digital transformation reshapes cultural heritage practices, redefining accessibility and engagement within changing social contexts.To conclude, the Museo Diffuso Lettomanoppello's modularity, adaptability, and capacity to engage the community serve as a strategic exemplar for analogous initiatives and demonstrates how ergonomics and design can together build a more human-centred future for cultural heritage.

Marchetti, R. (2025). The enhancement of cultural ecosystems through an inclusive design approach: the case study of the “Museo diffuso Lettomanoppello”. *Rivista Italiana Di Ergonomia*. 31. 63-73. DOI: 10.6093/RIE/13409

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SHORT BIO

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INTEGRATING CONFIGURATIONAL ANALYSIS AND AGENT-BASED MODELING FOR INCLUSIVE WAYFINDING: AN ERGONOMIC FRAMEWORK FOR MUSEUM ENVIRONMENTS

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ABSTRACT

Designing a museum visitor experience is a complex challenge that involves both exhibition aspects and the cognitive processes involved in reading/interpreting the space and understanding pathways. From an ergonomic perspective that focuses on the interaction between the museum environment and visitors, it is important to consider wayfinding in an adaptive and inclusive way to ensure expanded usability, especially for users with special needs. The potential offered by the digitization of heritage today allows the use of models capable of simulating scenarios of use in relation to the spatial configuration, the exhibited content, and visitor behavior. Studies conducted on the Space Syntax methodology show how spatial configuration influences the perception and interpretation of routes and artworks. At the same time, Agent-Based Models simulate the behavior of different users in virtual environments that match real-world conditions, providing information on disorientation, crowding, and accessibility. Although these models are available, they are often applied separately, preventing a unified view of usage dynamics. Their operational convergence would allow for a deeper understanding of how space is used, considering that people's movement structures space and, conversely, influences behavior and exhibition choices. This paper therefore explores this integration to support flow assessment and guide design decisions. The case study of the "Amedeo Maiuri" archaeological museum in Veroli made it possible to test predictive models on a controllable scale. Preliminary results highlight critical issues in spatial interpretation and suggest design directions to improve its intelligibility. Future integration into BIM-based tools could enable coordinated management of inclusive wayfinding systems.

COGNITIVE AND PERCEPTUAL ERGONOMICS FOR WAYFINDING IN MUSEUMS

In complex contexts, such as museums, space is not simply a container of functions, but an active component of the cultural experience. Every defining element, from morphology to dimensions, from material characterization to lighting, contributes to guiding the exhibition narrative. Therefore, the space's ability to be read and interpreted by visitors becomes an integral part of the experience itself, guiding their perception and movements.nConsidering how

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these dynamics shape experience, cognitive and perceptual ergonomics, which studies the mental processes connected to environmental perception, including attention, memory, and orientation (Francis & Amadi, 2015), provides a valuable theoretical lens for understanding how space shapes interpretive processes. This is even more relevant when considering the museum environment as a device capable of activating relationships between visitors (Di Benedetto, 2021). As a result, design quality must account for the social, cognitive, and emotional factors that influence the visiting (Zammuner, 2006). From this perspective, environmental intelligibility (Lynch, 1960), or the ability of built space to offer a clear and recognizable structure, becomes fundamental for the formation of coherent mental maps and for orientation. Its enhancements become tools for wayfinding, understood not as a simple study of signage, but as a cognitive process shaped by spatial configuration (Arthur & Passini, 1992; Farr et al., 2012). Wayfinding is also recognized as a core element of universal accessibility, and measures to address and manage it are an integral part of the PEBA (Strategic Plan for the Elimination of Architectural Barriers in Museums, Libraries, and Archives) (MiC, 2018). Recommendations for facilitating intelligibility, interpretation, and independent navigation of spaces fall squarely within the principles of Universal Design (Mace, 1997; Clarkson et al. 2013). Given this close relationship, the design of cultural sites should take route management and orientation as guiding criteria, understood as a dynamic relationship between people's movement and the perception of spaces, always interconnected with the cultural dimension and the construction of an equitable experience of heritage (Lisney et al., 2013). The study of these aspects is now facilitated by the digital transition, which enables knowledge and predictive management of the built environment (Daniotti et al., 2020; Casini, 2021) and opens new perspectives for building integrated information models capable of interpreting, simulating, and optimizing the visitor experience (Andersen et al., 2021; Ferretti et al., 2022) and the management of spaces and content (Centorrino et al., 2021; Ceccarelli et al. 2024; Villani et al. 2024). In this context, the paper explores the contribution of digital technologies to the ergonomics approach applied to analyzing the spatial intelligibility of cultural sites. It highlights how simulation models that study movement based on spatial and behavioral factors can incorporate Universal Design principles, ensuring human-centered design that supports accessible and inclusive cultural experiences. It proposes an integrated predictive framework that, by combining simulations based on both spatial syntax and behavioral agent modeling, allows for the inclusive assessment and improvement of the intelligibility and usability of museum spaces, supporting design decisions for wayfinding. The originality of the proposed framework, validated through a case study, lies in the systematic integration of two simulation fields previously treated and applied separately, allowing for the correlation of spatial structure, cognitive orientation processes, and behavioral dynamics within a unified predictive framework for evidence-based and inclusive design.

PREDICTIVE MODELS FOR THE EVALUATION OF SPATIAL INTELLIGIBILITY AND THE STUDY OF MOVEMENTS: SPACE SYNTAX AND AGENT-BASED MODELING

The use of digital tools to simulate the interaction between users and built spaces constitutes a strategic research area for inclusive design and management of cultural sites. Understanding how spatial morphology impacts perception, behavior, and wayfinding processes has led to the development of predictive models capable of translating person-environment relationship into objective metrics supporting design decisions. Within this framework, two

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main interpretative approaches have emerged in the literature, each linked to a specific simulation paradigm. The first, which focuses on spatial layout and the role of geometric organization in the comprehensibility of environments, involves configurational analysis, based on the theory of Space Syntax (Hillier & Hanson, 1989; Hillier, 2007), which interprets space through graphs and quantitative metrics (visual integration, connectivity, etc.), assessing environmental intelligibility in relation to visual permeability. The results, in the form of color maps, enable the prediction of movement patterns and the identification of central or marginal areas, providing concrete support for design. Widely applied in museums (Hillier & Tzortzi, 2006), this technique has proven effective in predicting visitor flows and optimizing visitor routes. Rohloff (2009) analyzes the Yale Center for British Art (YCBA), the Museum of Modern Art (MoMA) in New York, and the High Museum of Art (HMA) in Atlanta by comparing spatial configurations and their influence on visitor routes, demonstrating how more integrated areas tend to receive greater attention, while peripheral or poorly connected spaces are rarely used, regardless of the quality of the works exhibited. Similarly, Dursun (2007) highlights that, in the proposed expansion of the Tate Britain in London, solutions that are most integrated with existing spaces are preferable; while at the British Museum, some central galleries act as attractor nodes, leaving less connected areas marginalized. Despite its analytical effectiveness, this approach is based on a homogeneous representation of human behavior, which is poorly suited to capturing the complexity of real-world cognitive strategies, especially when considering people with special needs, whose ways of orienting, perceiving, and interacting with the environment may deviate significantly from standardized models. The second interpretative axis, Agent-Based Modeling (ABM), fits precisely in this direction. It is a simulation paradigm oriented towards emergent behavior (Helbing, 2012) that is based on the modeling of virtual agents that interact with the environment and with each other, following customizable decision-making rules (Helbing & Grund, 2013). Unlike Unlike flow-based mathematical models (Hughes, 2003; Farooq et al., 2020), ABM represents individuals as distinct entities, profileable based on age, ability, familiarity with space, and interests, offering greater realism. Although still little used in the museum sector (Feng et al., 2020), it has found consolidated application in highly complex environments, such as stations (Liu & Chen, 2023), airports (Li & Wu, 2025), hospitals (Zambrano et al., 2016), and mass events (Mahmood et al., 2017), to simulate flows, prevent congestion, and test management strategies. The dynamic and highly customizable results include density maps, time and critical area analyses, and alternative scenario evaluations. However, technical complexity and computational demands require interdisciplinary collaboration, representing both a challenge and an opportunity for inclusive design processes. Given the limitations and potential of both tools, the need for an integrated approach emerges, combining the analytical robustness of configurational analyses to formalize spatial structure with the behavioral flexibility of ABM. Only a design vision capable of articulating both dimensions can support the creation of truly accessible, cognitively legible, and user-centered museum spaces. The integration of the two approaches enables the development of robust predictive models to support evidence-based design decisions, in line with cognitive ergonomics, the principles of Universal Design, and the digital transition applied to cultural experience.

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CASE STUDY: THE “AMEDEO MAIURI” ARCHAEOLOGICAL MUSEUM OF THE ITALIC PEOPLES IN VEROLI

The integration of these predictive models finds concrete application in the "Amedeo Maiuri" Museum, selected as a case study for its ability to represent, on a small scale, the challenges of digitally managing spatial intelligibility within an inclusive framework. The museum is housed in the eighteenth-century Palazzo Marchesi Campanari, in the historic center of Veroli (FR), spread over four floors, including a basement, connected by a central staircase. The building, characterized by vaulted rooms and a fine decorative apparatus, reflects its noble origins through significant architectural stratification. Established in 2023, the museum presents the history of the pre-Roman populations of southern Lazio, particularly the Hernici, Volsci, and Latini. Since its opening, it has hosted a series of exhibitions that have defined its curatorial profile, including Ancient Italic Peoples: the Ernici, the Volsci, and the Others (December 2023) and Poet of Archaeology. Amedeo Maiuri between Lazio and Campania (December 2024). The new exhibition, scheduled for inauguration in early 2026, encompasses three of the four levels and represents the outcome of a comprehensive renovation project co-financed under the PNRR – Mission 1, Investment 1.2: Removal of physical and cognitive barriers in museums, libraries, and archives. The renovated spatial and experiential itinerary includes the main entrance in the basement (Figure 1a), dedicated to service functions, including the ticket office, restrooms, deposit, and a conference room. A new elevator (under construction) provides access to the ground floor (Figure 1b), home to the permanent exhibition where the curatorial narrative spans the cultures, languages, and territories of the Italic peoples. In addition to the direct exit onto Via Umberto I, the floor also features two immersive rooms: one dedicated to the history of the building, through an interactive podcast, and one dedicated to the practice of transhumance, configured as a multisensory experience, designed with the participation of associations for people with disabilities in the province of Frosinone. Finally, the first floor (Fig. 1c), also served by an elevator, hosts temporary exhibitions, with a specialized focus on necropolis and on the work of archaeologist Amedeo Maiuri, to whom the main hall is dedicated. The project is part of a broader framework of initiatives aimed at promoting universal accessibility to this site and is the subject of a research agreement between the Department of Planning, Design, and Architectural Technology (PDTA) of the University of Rome "La Sapienza" and the Regional Directorate of National Museums (DRMN) of Lazio. This collaboration aims to test advanced solutions for wayfinding and multisensory accessibility, combining approaches from architectural technology and digital disciplines. From this perspective, the museum's characteristics (small scale, morphological complexity, historical value) make it an experimental laboratory for technological innovation and cultural inclusion, a benchmark for defining quality standards in the management and valorization of cultural heritage for all.

(a) Basement floor

Access to the court
Main entrance to the building

Intended uses

I.1 Deposit
I.2a Acceptance
I.2b Ticket office
I.3 Lounge
I.4 Staff restrooms
I.5 Public restrooms
I.6 Exhibition hall (TPC materials)

(b) Ground floor

Exit
Main start of the visit route
Secondary start of the visit route
Project curated by DRMN Lazio
Immersive rooms

Intended uses

II.1 Exhibition hall - The story of archaeology
II.2a Exhibition hall - The model of the territory
II.2b Exhibition hall - Language and languages
II.2c Exhibition hall - The history of Palazzo Campanari
II.3 Exhibition hall - Presentation of the Italic peoples
II.4 Public restrooms
II.5 Exhibition hall - Sanctuaries and the sacred
II.6a Sittings/Stops
II.6b Exhibition hall - Sanctuaries and the sacred
II.6b Exhibition hall - The forms of living
II.7 Lobby
II.8 Exhibition hall - The routes

(c) First floor

Main start of the visit route
Secondary start of the visit route

Intended uses

III.1 Exhibition hall - The Hernic necropolises
III.2 Exhibition hall - "Amedeo Maiuri"
III.3 Exhibition hall - The necropolis of Frosinone
III.4a Public restrooms
III.5 Exhibition hall - The other Volscians
III.6 Exhibition hall - Towards romanization

Figure 1. The plans of the new exhibition of the Archaeological Museum of the Italic Peoples "Amedeo Maiuri" in Veroli: (a) the main entrance and public services in the basement, (b) the permanent exhibition and the immersive rooms on the ground floor (c) the temporary exhibition and the "Maiuri" room on the first floor.

TOWARDS AN ERGONOMIC FRAMEWORK FOR MUSEUM WAYFINDING: ARTICULATION OF THE METHODOLOGY

The methodological approach of this study stems from the need to integrate the contribution of cognitive ergonomics applied to museum wayfinding design with the potential of the mentioned predictive models and is structured into three distinct but complementary phases (Figure 2). In line with a human-centered approach (Attaianese & Duca, 2012), the first phase (Design Briefing) aims to clarify the needs of the wayfinding project by identifying factors influencing route intelligibility and the desired level of accessibility and inclusion. To this end, (i) the project objectives are defined, aligned with the spatial layout and curatorial strategy, (ii) the preferred users, and (iii) the key cognitive and motor tasks required during the visit (i.e., task analysis). The second phase concerns the integrated analysis of spatial intelligibility through the combined use of the two complementary predictive models. Within Space Syntax, the analysis involves the use of the pen-source software DepthmapX 0.8.0 (UCL Space Syntax, 2025). The first area of investigation concerns the exhibition rooms, in which spaces are modeled as nodes and connections. From this structure, it is possible to generate the visibility graph, from which the main indicators are calculated. First, connectivity, which measures the number of spaces immediately accessible from each node and provides an indication of its physical usability; second, visual integration (HH), which expresses the average visual distance from all other points in the spatial system and reflects the potential visibility and recognizability of each space. A second area of investigation concerns a more detailed analysis, dividing the spaces into a regular grid, which allows for a comparison of the local distribution of the same indicators, highlighting intra-space variations. Finally, agent analysis simulates flows based exclusively on the visibility of grid points, highlighting areas with greater or lesser traffic density based on the potential intuitive movement of homogeneous users. Within ABM, the analysis is based

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on the use of Anylogic 8.9.4 software (The Anylogic Company, 2025), a multi-method simulation platform available free of charge in the Personal Learning Edition (Borshchev, 2014). Following the modeling of the museum environments, an initial investigation focuses on the dynamic behavior of visitors throughout the entire visit. Using the Pedestrian Library, logical graphs can be constructed consistent with the task analysis (ideal vs free visit). The simulations produce density maps and movement analytics. Finally, a second, more detailed analysis concerns individual rooms to evaluate possible functional alternatives aimed at improving their usability. The third and final phase (Critical synthesis), in line with the need for a holistic understanding of accessibility as a generative ecosystem (Lauria & Ndrega, 2025), involves the integration of the results. A comparative assessment enables the identification of areas with low spatial intelligibility: spaces with poor visual integration, ambiguous routes, and nodes subject to congestion or low attractiveness. Finally, the integrated approach supports the definition of design directions geared toward inclusive wayfinding, in which both dimensions of usability (space and people) become essential parameters within an ergonomic framework for museum environments, useful for guiding the project towards more legible spatial solutions consistent with the diverse needs of users.

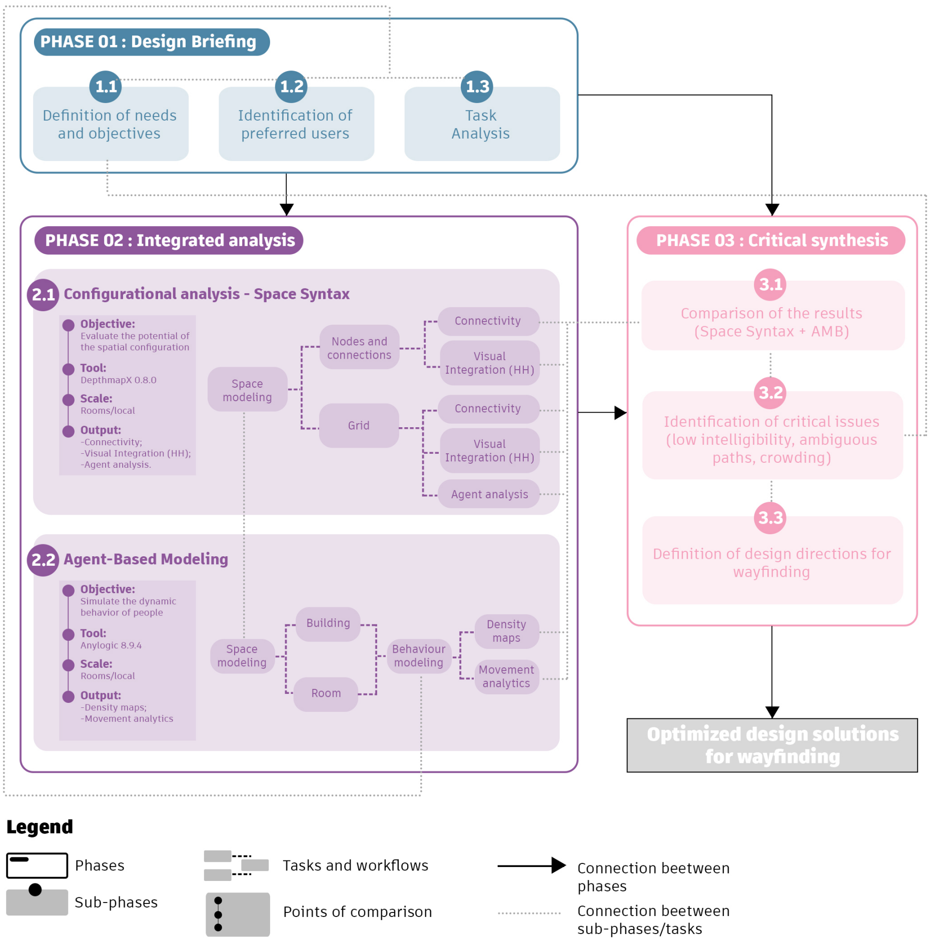

Figure 2. Methodological framework for museum wayfinding, structured in three phases: Design Briefing, Integrated Analysis (Space Syntax and Agent-Based Modeling), and Critical Synthesis, aimed at identifying critical issues and defining optimized, inclusive wayfinding design solutions.

EVIDENCE AND DESIGN DIRECTIONS FOR INCLUSIVE WAYFINDING

The experimentation, conducted within the “Amedeo Maiuri” Museum and structured across the three methodological phases, highlighted a set of evidence useful for defining design strategies aimed at spatial accessibility and inclusive wayfinding. The first phase defined the specific objectives of the

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wayfinding project, which included improving spatial intelligibility, fostering users' autonomy in perception, and reducing moments of decisional uncertainty. Attention was focused on the conscious use of architectural components as primary orientation resources, reducing reliance on redundant signage systems. Subsequently, preferred users were defined as those visitors for whom difficulty interpreting space could represent a significant barrier to cultural enjoyment: people with sensory or mild cognitive disabilities, elderly visitors, and individuals with low cultural literacy. On this basis, a task analysis was developed to break down the museum experience into specific cognitive and motor tasks. In the basement, after identifying the main entrance, users must locate the ticket office and navigate the vertical connections, preferring to use the new elevator. On the ground floor, tasks become exploratory, such as reading the thematic narrative, recognizing immersive rooms, and then reach the exit or the first floor. Finally, within the temporary exhibition, users must understand the thematic discontinuity and decide when to conclude their visit, preferring to return to the basement by elevator. At each level, specific cognitive junctions were identified, i.e., decision points where the visitor must interpret the space to make a directional or functional choice. These junctions constitute discrete behavioral units, the combination of which describes the user's action sequence along the entire journey. The second phase involved the integrated application of simulation tools to assess spatial intelligibility. First, the configurational analysis (Figure 3) allowed us to analyze the space on two scales: by individual rooms (nodes and connections) and by detailed areas (grid). At the first scale, connectivity (Figure 3a) shows, in the basement, greater connectivity of the distribution spaces (entrance and corridors towards the stairs and elevator), while the conference room is less connected. On the ground floor, Rooms 2 and 6 stand out for their high values, while the two immersive rooms and Room 9 are less connected. On the first floor, the "Maiuri" Room shows the highest values, without evident critical issues. Visual integration (HH) (Figure 3b) shows the main corridor towards the stairs as the most integrated spaces in the basement. On the ground floor, the highest values are concentrated in Rooms 2, 6, and 10, while the two immersive rooms and Room 9 show, again, critical values. The first floor shows the same values as the first analysis. Delving deeper into the scale, the analysis (Figure 3c) shows high connectivity in the basement along the entrance-ticket office-cafeteria axis, with decreasing values toward the connection leading to the new elevator. On the ground floor, the entire exhibition route is well connected, apart from the immersive rooms and Room 9. The first floor shows no significant anomalies. Visual integration (HH) (Figure 3d) confirms these trends. Finally, validation using Agent Analysis (Figure 3e), which simulated the entry of 50 agents at each level, confirms the disadvantages of the route to the elevator, the immersive rooms, and Room 9. Second, ABM allowed us to simulate the dynamic behavior of visitors, again on two observation scales. The first investigated the scope of the plan and focused on two types of behavior: an "ideal" visit, adhering to the pre-established itinerary, and a "free" visit, in which only entrances and exit points are defined. The second scale instead examined a single room, with the aim of analyzing the spontaneous distribution of visitors, the order in which they viewed the artworks, and preferential exits.

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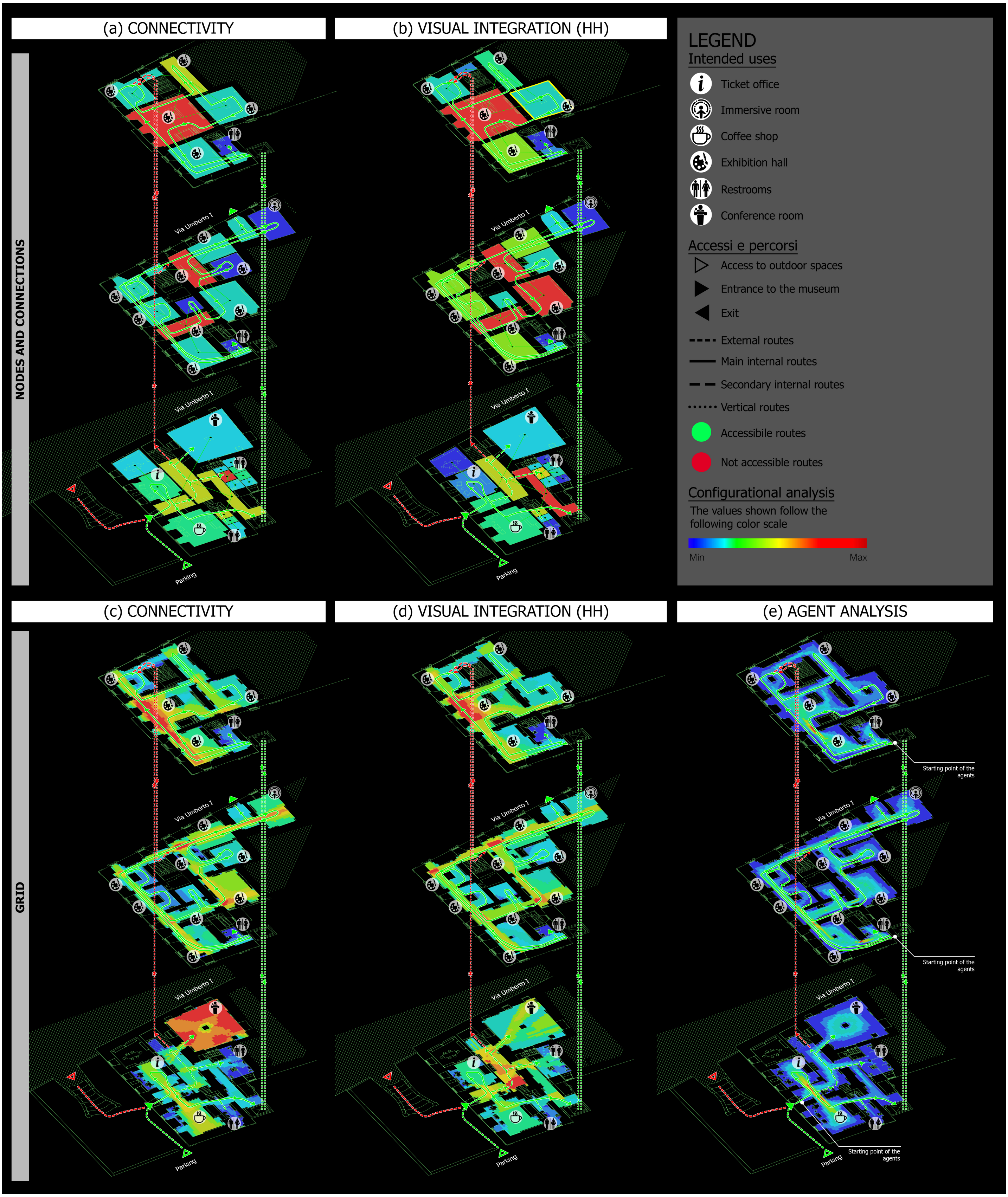

Figure 3. Results of the configurational analysis applied to the "Amedeo Maiuri" Museum at the two investigation scales. The nodes-and-connections model illustrates (a) connectivity and (b) visual integration (HH), while the grid-based analysis shows (c) connectivity, (d) visual integration (HH), and (e) agent analysis.

For the first scale, we provide the example of the ground floor (Figure 4), considered the most critical in terms of distribution and orientation. Modeled the space (Figure 4a) and the two behavioral profiles (Figure 4b,c), two simulations were conducted, involving 50 agents and recording the results at

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three time intervals (15, 30, and 60 minutes): density maps (Figure 4d) and visitor distribution graphs for each room (Figure 4e). In the ideal visit profile, the density maps show low attendance in Rooms 4,5 and in both immersive rooms.

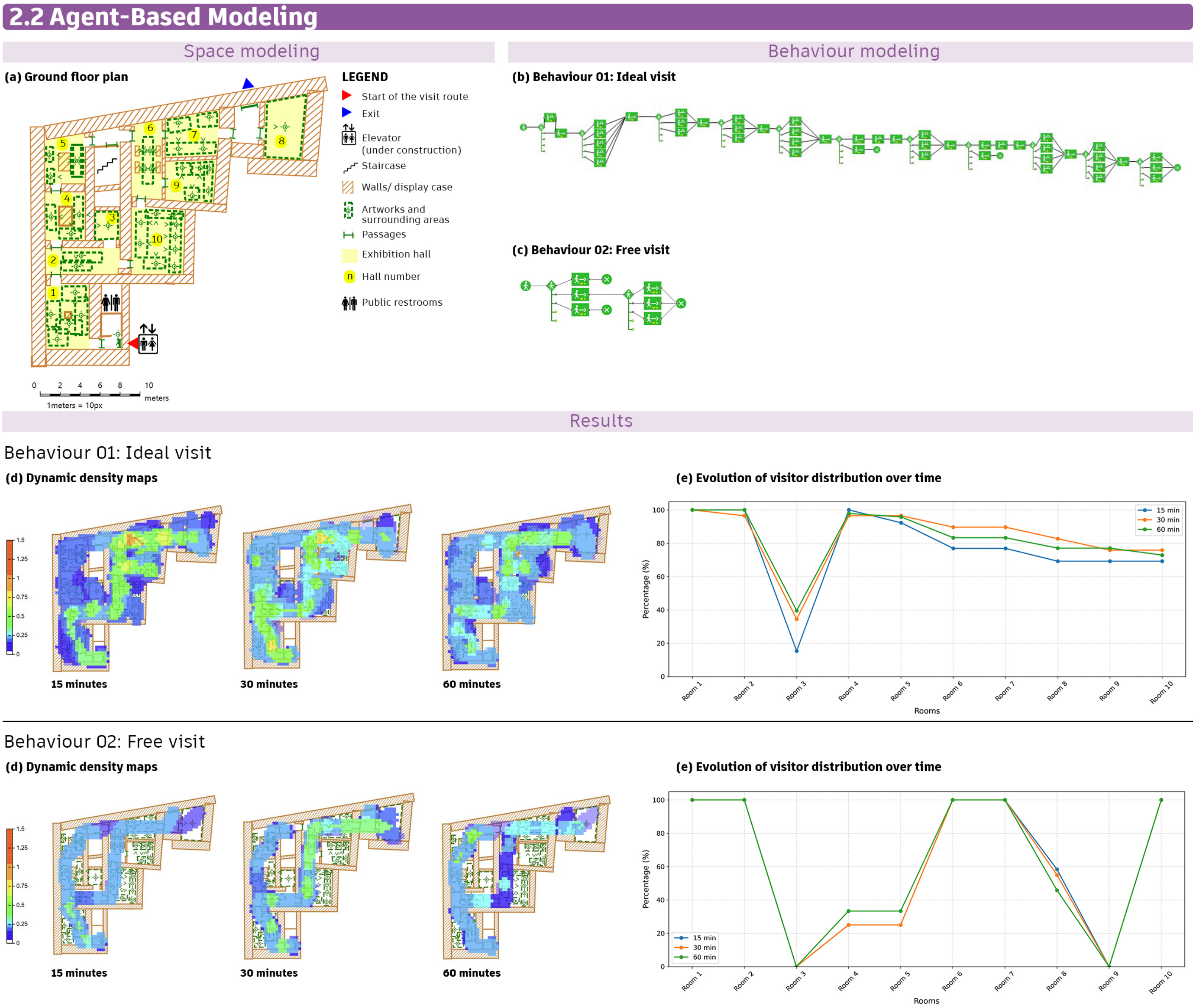

Figure 4. Agent-Based Modeling applied to the ground floor of the "Amedeo Maiuri" Museum: (a) the space model, the behavioral graphs for (b) the ideal visit and (c) the free visit and the simulation results in terms of (d) dynamic density maps at different time intervals and (e) the evolution of visitor distribution over time for both behavioral scenarios.

The graphs confirm full visibility in the initial rooms (1 and 2), with a progressive decrease in the subsequent ones. Room 3 (the immersive room dedicated to Palazzo Campanari) is particularly critical. In the case of a free visit, the maps show a total lack of interest in Rooms 3 and 9. Furthermore, after passing Room 2, most visitors tend to head right (Room 10) rather than left (Room 4). The distribution graphs confirm this trend, which remained stable across the three periods analyzed. For the second scale, we provide the example of the "Maiuri" room on the first floor, the most significant of the entire itinerary (Figure 5a). The room, currently characterized by an important decorative apparatus (Figure 5b), will house heterogeneous artworks in the exhibit project, arranged according to different spatial logics in relation to the entrances, circulation axes, and fields of vision. As shown in the plan (Figure 5c), Artwork 1 (Context of the Porta Nocera Necropolis: copy of a cast and

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columelle) is placed marginally with respect to the main trajectories of movement; Artwork 2 (19th-century marble top with utensils from the House of Menander) occupies a central position in the space; Artwork 3 (Documentary “Pompeii. Twenty Centuries Later”) is arranged along one of the longitudinal walls, near an opening; while Artwork 4 (Frescoes of Bosco Reale; Trapezophore Royal II) is placed on a lateral wall visually accessible from both entrances. This configuration makes the room particularly suitable for evaluating how visibility, proximity to access points, and centrality influence the observation sequence and visitors' movement choices through ABM (Figure 6). Modeled the environment (Figure 6a) and the behavioral combinations of the 50 agents (Figure 6b), the same three time intervals were observed, and the results were expressed in the form of density maps (Figure 6c) and piecharts of the order of the visited works (Figure 6d,g) and the chosen exits (Figure 6h). Density maps show a homogeneous distribution with a concentric trend.

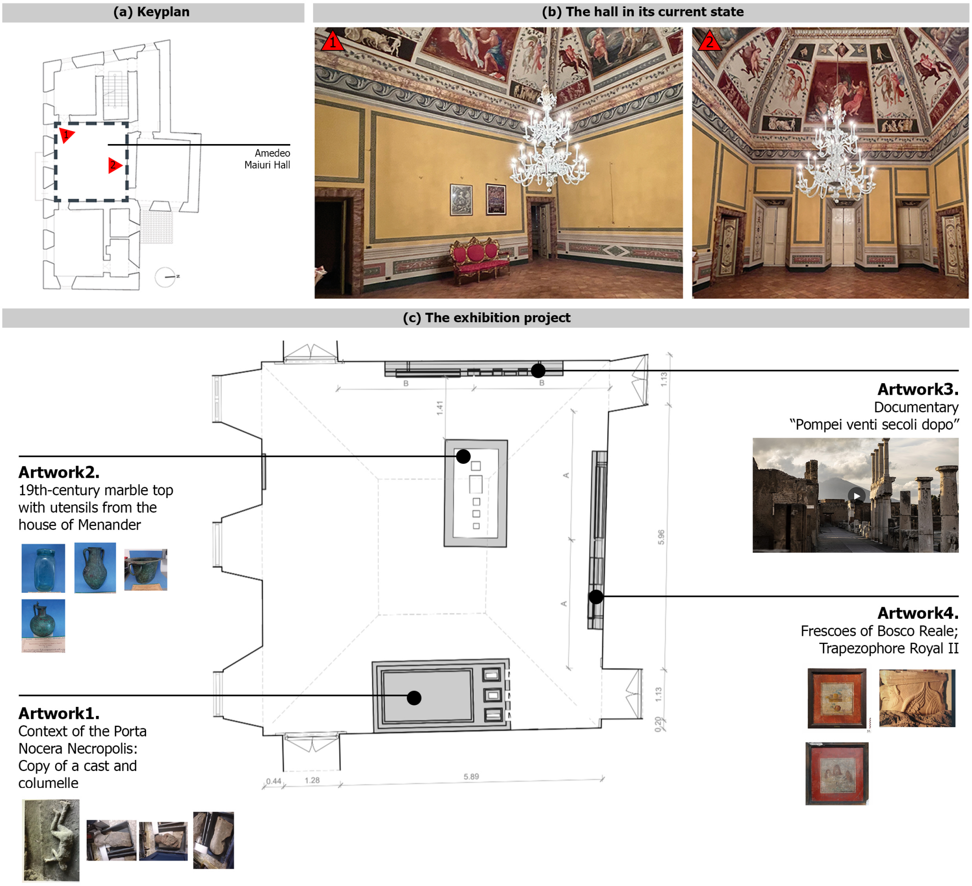

Figure 5. The “Maiuri” Room: (a) Key plan of the first floor showing the location of the room; (b) images of the room in its current state and (c) the exhibition project with indication of the artworks analysed in the ABM simulation.

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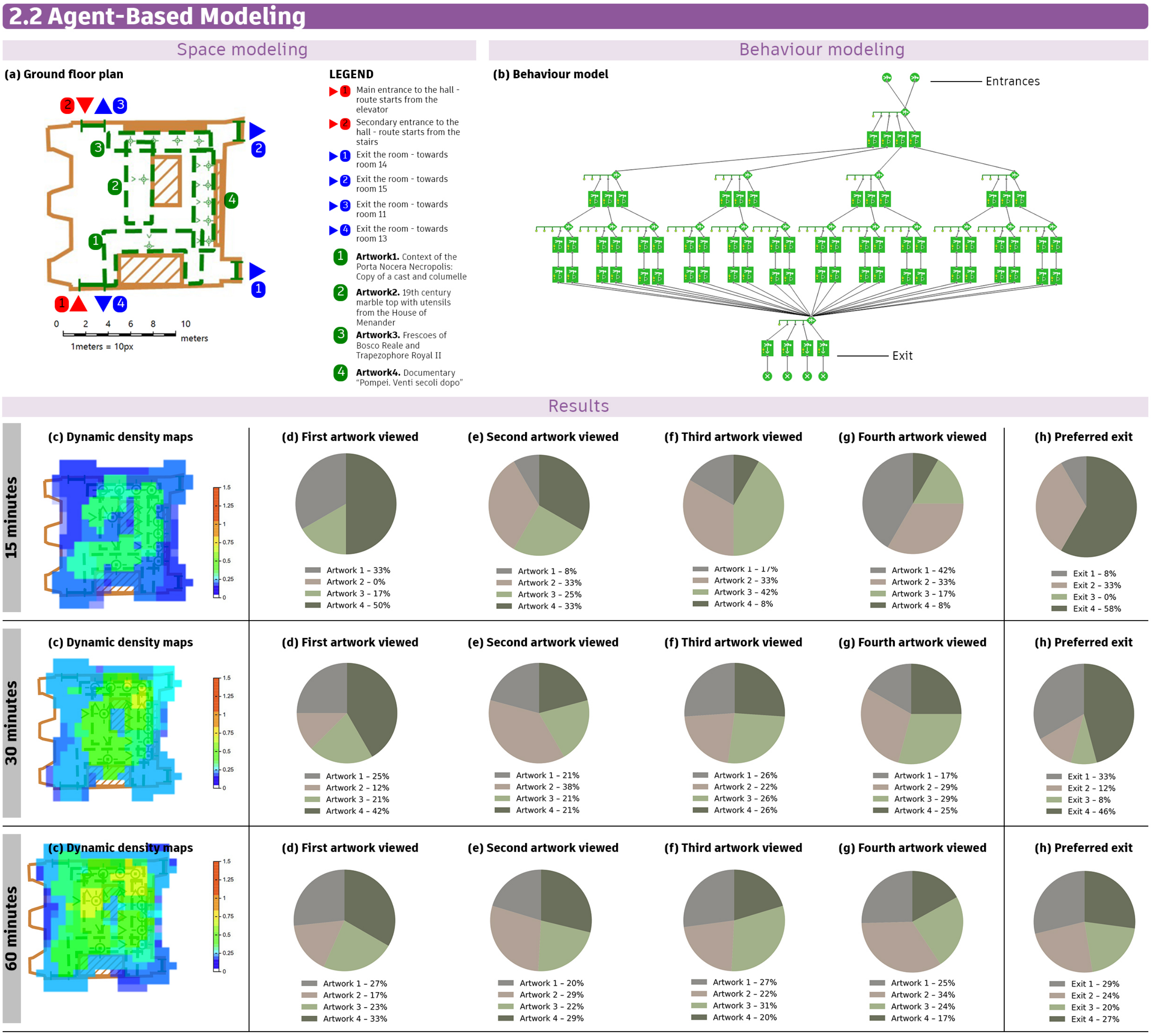

Figure 6. Agent-Based Modeling applied to the “Maiuri” Room: (a) the space model, (b) the behavioral model, and the simulation results in terms of (c) dynamic density maps at different time intervals, (d–g) the sequence of artworks viewed (first to fourth), and (h) the preferred exit.

The order of visit graphs indicates that Frescoes and Trapezophore (Artwork 4) Artwork, immediately visible from both entrances, systematically constitute the first point of attention, while the central work (Artwork 2) is never chosen first in the first 15 minutes. As the second artwork, there is initially a balance between these two (33%), but at 30 minutes the central one prevails (38%), with a re-balance at 60 minutes (29%). Context of the Porta Nocera Necropolis (Artwork 1) is the least viewed at this stage. The third most viewed work is the multimedia content (Artwork 3), while Artwork 4 become the least viewed in this intermediate phase. As the last artwork viewed, Artwork 1 initially prevails, but at 60 minutes Artwork 2 is most frequently seen last. As for exits, after 15 minutes over half of the agents (58%) use Exit 4, while Exit 3 is never chosen. At 30 minutes, the trend rebalances slightly; at 60 minutes, preferences are more evenly distributed, with a slight prevalence for Exit 1, which leads to room 14. In the third and final phase, comparing the results of the two models highlighted a significant consistency between the spatial structure and user movement patterns. Specifically, environments characterized by low

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connectivity and visual integration in the Space Syntax were found, in the ABM simulations, to be often excluded from the itineraries, both in the ideal and free modes. This allowed us to identify critical areas: in the basement, the connection leading to the elevator and on the ground floor, the immersive rooms and Rooms 4,5, and 9. The situation appears more balanced on the first floor, where the linearity of the path favors a more homogeneous distribution, as confirmed by the analyses carried out in the "Maiuri" Room. Based on this evidence, it was possible to define a series of design directions to improve the museum's inclusive experience. In the basement, for example, to effectively direct visitors to the new elevator, visual direction could be strengthened by placing adhesive floor markers or installing lighting fixtures that emphasize perspective depth. Furthermore, reducing distractions along alternative routes (such as those leading to the stairs) can further facilitate intuitive navigation. On the ground floor, immersive and low-traffic rooms require greater architectural emphasis: gates highlighted by color or light variations and multisensory devices can help make these spaces more recognizable and attractive. Finally, analysis of the "Maiuri" room suggests that, even at the microscale, the intelligibility of exhibits and the position of gates influence visitor behavior. The visual focus of key works and gates should be emphasized through focused lighting, architectural elements that guide the gaze, and installations that facilitate sensory accessibility. In summary, the critical synthesis phase demonstrated how spatial intelligibility, if properly designed, can become the primary driver of inclusion in cultural venues. The integration of layout and behavior not only allows us to identify the weak points, but also provides the tools to transform them into design opportunities, capable of enhancing the visitor experience in its plurality. The case study of the "Amedeo Maiuri" Museum demonstrates, in this sense, the potential of an evidence-based approach in defining truly effective accessibility strategies that can be replicated in similar contexts.

CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper highlights the operational value of an integrated approach between Space Syntax and ABM as a decision support tool for designing accessible and cognitively readable museum environments. The complementarity of the two models has provided a dynamic, complex, and measurable picture of the actual modes of interaction between space and visitor. The ability to identify areas of low visual integration and critical decision points, simulate different visitor profiles, and pre-test the effectiveness of design solutions represents a concrete advantage for implementing wayfinding strategies geared toward inclusion, reducing cognitive load, and enhancing the perceptual autonomy of each user type. From this perspective, the proposed methodology is configured as an evidence-based design tool, replicable in similar contexts and integrable into broader processes of digital transformation of cultural heritage. The limitations of this study are primarily due to the small scale of the case study, which, while allowing for precise control of spatial and behavioral variables, does not yet allow for a full test of the framework's robustness in museum contexts of greater size and morphological complexity. A further limitation concerns the difficulty in defining the agents' behaviors, which is inevitably simplified compared to the actual heterogeneity of potential visitors, whose variability in terms of skills, familiarity with the spaces, and cognitive abilities makes comprehensive modeling difficult. Finally, the framework has not yet been subjected to post-occupancy validation, which is an essential step in verifying the correspondence between simulated results and actual

Romagna, G., Villani, T. (2025). Integrating configurational analysis and agent-based modeling for inclusive wayfinding: an ergonomic framework for museum environments . *Rivista Italiana Di Ergonomia*. 31. 74-88. DOI: 10.6093/RIE/13410

behaviors. This validation may be initially conducted in a virtual environment and, subsequently, after the implementation of the wayfinding design solutions, through the application of Post Occupancy Evaluation (POE) methodologies, in order to consolidate the model's predictive reliability through direct user feedback. In any case, the framework's potential suggests future developments that include extending its application to more complex museum contexts, refining behavioral models through a more detailed characterization of user profiles, including with the support of the International Classification of Functioning, Disability, and Health (ICF), to represent behaviors in relation to users' different functional conditions and their modes of interaction with the space, and studying ways to integrate it with post-occupancy empirical validation procedures. Further future developments include integration with BIM-based environments for the simulation and validation of alternative scenarios, aligned with new paradigms for using PEBA as an iterative digital tool across the entire museum lifecycle. Finally, the use of artificial intelligence systems and IoT (Internet of Things) sensors would allow learning from behavioral data and generating adaptive and personalized pathways, strengthening the proposed method's potential as a digital infrastructure for inclusive museum design.

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RIVISTA ITALIANA DI
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RETHINKING WALKABILITY THROUGH UNIVERSAL DESIGN: AN ERGONOMICS-BASED FRAMEWORK FOR GREEN INCLUSIVE PATHWAYS IN NATURAL LANDSCAPES

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KEYWORDS: *Environmental ergonomics, Human-Centred Design, Human variability, Natural pathways, Universal Design, Walkability*

ABSTRACT

In recent decades, the concept of walkability has been mainly developed in urban contexts through indicators focused on the physical and infrastructural characteristics of pedestrian spaces. In natural and peri-urban contexts, however, the use of pathways is influenced by greater morphological, environmental, and experiential variability, making it necessary to rethink walkability from an inclusive perspective. This contribution proposes a critical reinterpretation of walkability in natural contexts, understanding it as the dynamic outcome of the interaction between individuals, the environment, and conditions of use, in line with an ergonomic and Environment and Human-Centred Design approach. The methodology is based on the analysis of paradigmatic user profiles and on the identification of physical, sensory-perceptual, and cognitive barriers that affect the use of natural pathways. These profiles are not intended as exhaustive categories, but as representative cases that help to make the complexity of person-environment interaction more explicit. Through a synthesis of recurring functional manifestations, the contribution highlights how difficulties such as physical fatigue, disorientation, reduced environmental legibility, and cognitive overload emerge transversally across different user profiles. Within this framework, Universal Design principles are used as a conceptual support to guide the identification of shared functional requirements, without prescriptive intent. The study is positioned as an exploratory contribution to the debate on inclusive walkability, offering a conceptual framework that may support future methodological developments, evaluation tools, and design processes that are more attentive to human diversity and overall well-being in natural environments.

INTRODUCTION

Over the last two decades, many studies have examined the effects of the built environment on pedestrian mobility within cities. The need to understand how appropriate urban areas are for walking has led to the development of definitions and metrics for evaluating walkability (Telega et al., 2021). The literature identifies around 80 indices for measuring walkability, referring to objective characteristics of the urban environment, users' perceptions, or a combination of both, at both neighborhood and city scales (Gargiulo et al.,

Di Dario Y. (2025). Rethinking walkability through universal design: an ergonomics-based framework for green inclusive pathways in natural landscapes . *Rivista Italiana Di Ergonomia*. 31. 89-98. DOI: 10.6093/RIE/13417

2021). More recently, walkability has been linked to health, highlighting the relationship between pedestrian use and an ergonomic approach to spatial design. Urban health does not depend only on physical or infrastructural features, but mainly on the interactions between people and the built environment (Appolloni et al., 2020). In this context, natural elements, although associated with evidence-based health benefits (Hartig et al., 2014; Markevych et al., 2017), are still mostly considered through quantitative and spatial indicators (Francis et al., 2012). Indicators such as green space per capita, proximity to parks and gardens, or distance from ecological corridors and water bodies are useful in urban settings; however, they don't consider the morphological, perceptual, and sensory qualities of natural landscapes. These limitations become more evident when peri-urban areas, regional parks, or large natural environments are considered, where pedestrian use depends on more complex person-environment interactions. According to the WHO's International Classification of Functioning (ICF) (2001), disability results from the interaction between individual characteristics and contextual factors. Anyone may experience temporary or permanent conditions of vulnerability, latent or evident, that can cause discomfort and increase exposure to risk (Magarò, 2019). Therefore, making natural heritage accessible through inclusive interventions does not concern only people with certified disabilities, but a wide and diverse part of the population. From an applied perspective, evidence from national initiatives such as the Progetto Parchi Accessibili confirms a growing interest in inclusive access to natural environments, while also highlighting an uneven adoption of strategies for the design and management of green pathways (Solinas, 2004). Within this framework, this contribution, developed as part of the PNRR research project Cultural Heritage Active Innovation for Sustainable Society (CHANGES), aims to extend urban-centered walkability metrics through a methodological approach based on Ergonomics and Universal Design principles. The approach connects the physical, sensory, and cognitive characteristics of different user profiles with the requirements needed to support broader and more inclusive pedestrian use in natural contexts

BACKGROUND

Although natural areas are often characterized by morphological and infrastructural conditions that limit accessibility, due to physical, sensory-perceptual, and cognitive barriers, national and international regulations remain fragmented and lack shared and consistent references. For this reason, several public and private institutions, operating in different national contexts, have developed operational documents that pursue similar goals but adopt heterogeneous approaches and levels of detail (Mantuano & Bruno, 2025; Godtman & Ioannides, 2019). A comparative critical review of existing guidelines was conducted (Figure 1), focusing on documents developed in the United Kingdom (1997-2005), Sweden (2005), the United States (2012), Italy (2018), Ireland (2018), and Greece/Bulgaria (2019). These documents were identified through institutional sources and references in the scientific literature. They were selected as representative of different geographical contexts and design approaches, with the aim of highlighting recurring principles, methodological differences, user groups addressed, technical contents, and shared limitations.

Di Dario Y. (2025). Rethinking walkability through universal design: an ergonomics-based framework for green inclusive pathways in natural landscapes . *Rivista Italiana Di Ergonomia*. 31. 89-98. DOI: 10.6093/RIE/13417

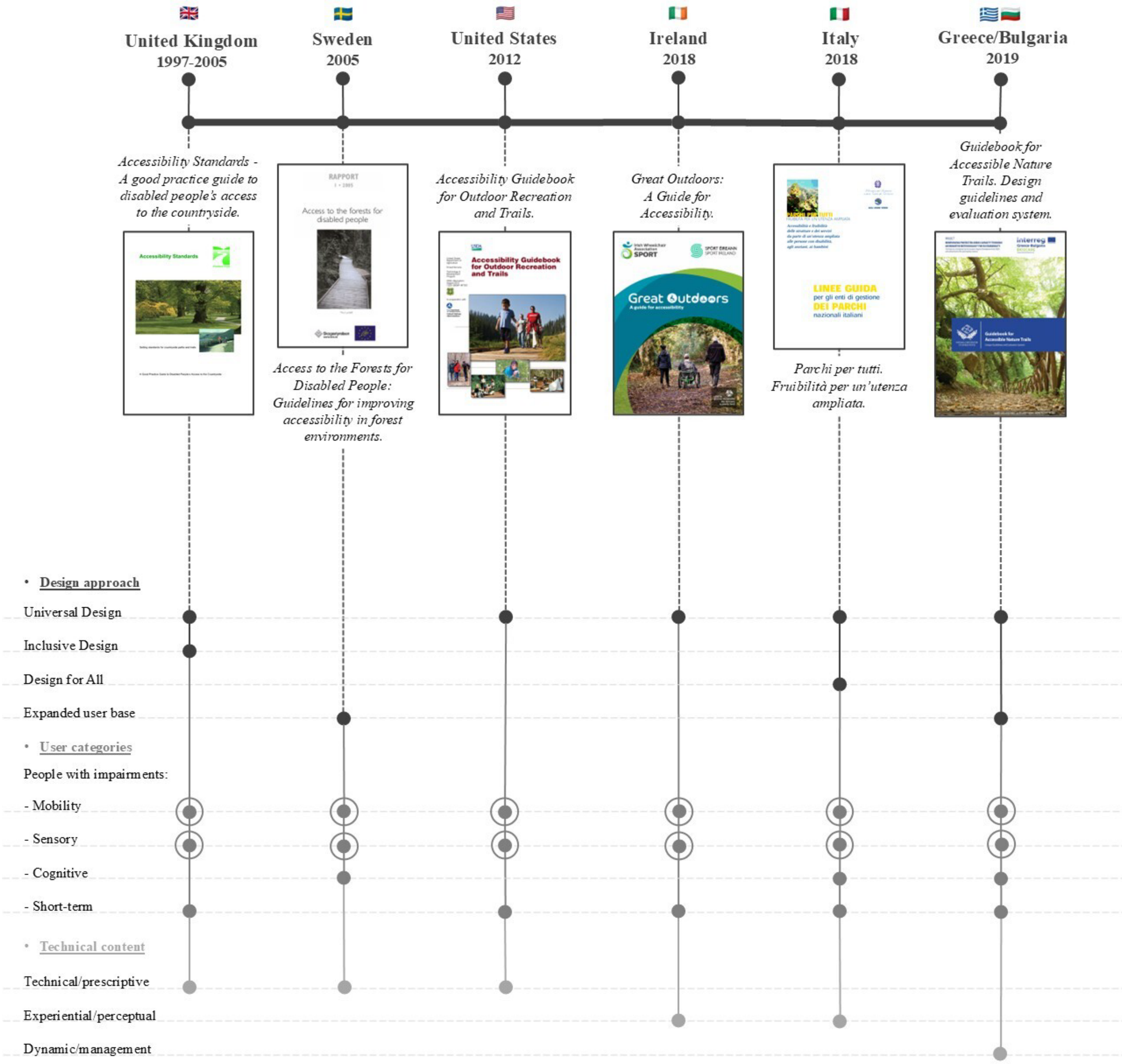

Figure 1. Comparative timeline of national guidelines and good practices for accessibility in natural and peri-urban environments

The analysis reveals significant cultural differences in the way accessibility is framed, starting from the titles of the documents themselves. In the United Kingdom and Swedish guidelines, explicit references to people with disabilities indicate a clear focus on specific user groups. This reflects a sector-based and compensatory approach, where accessibility is still mainly conceived as a response to particular needs. In contrast, more recent documents, such as those from Ireland and Italy, avoid explicit references to disability in their titles, shifting the focus from individual deficits to the diversity of user experiences and the possibility for everyone to engage with natural environments. In this perspective, accessibility is no longer treated as a special provision, but as an ordinary and expected quality of natural spaces. An intermediate position is represented by the Greece/Bulgaria guide, where the term "accessible" is

Di Dario Y. (2025). Rethinking walkability through universal design: an ergonomics-based framework for green inclusive pathways in natural landscapes . *Rivista Italiana Di Ergonomia*. 31. 89-98. DOI: 10.6093/RIE/13417

retained but framed in operational and evaluative terms rather than identity-based ones. Overall, this shift from disability-focused terminology to more universal formulations reflect the consolidation of an approach in which accessibility is increasingly understood as an environmental, social, and landscape quality, capable of ensuring equal opportunities for interaction with nature. Another relevant aspect concerns the design approaches adopted in the reviewed documents. Most guidelines explicitly refer, to different extents, to Universal Design (UD), Design for All (DfA) or Inclusive Design (ID). However, these concepts are sometimes reduced to terminological frameworks rather than applied as concrete operational tools. This limitation also affects the way user profiles are represented. There is a widespread tendency to focus primarily on motor and sensory impairments (visual and auditory), while cognitive diversity and neurodivergence receive limited attention. Although occasionally mentioned, these conditions are rarely explored in depth or translated into specific design or communication strategies. From a technical perspective, the guidelines from the United Kingdom, Sweden, and the United States adopt a predominantly prescriptive approach, characterized by regulatory language and a strong focus on measurable parameters. These include walking surface characteristics, path widths and narrowing points, longitudinal and transversal slopes, distances between resting areas, maximum level changes, steps and thresholds, surface interruptions, path edges, bridge and boardwalk dimensions, mesh sizes of perforated surfaces, and the characteristics of barriers and gates. The main objective is to define measurable standards that ensure consistency and replicability. However, this approach tends to prioritize technical compliance over experiential quality. In particular, perceptual and cognitive dimensions are rarely addressed, reducing accessibility to a set of physical requirements rather than an integrated concept of usability. In contrast, the Irish and Italian guidelines introduce a more experiential and perceptual perspective, where technical aspects are combined with attention to human experience and interaction with the natural environment. In the Italian case, multisensory experience, environmental legibility, perceived safety, and comfort play a central role. Accessibility is no longer limited to the removal of physical barriers but is understood as an environmental quality that supports well-being, autonomy, and inclusive use of natural areas. Nevertheless, even in these cases, the operational translation of such principles remains partial, with a limited number of tools or indicators available to systematically assess perceptual and cognitive aspects. The Greece/Bulgaria document, while maintaining a functional approach, promotes a more dynamic and management-oriented perspective, focused on maintenance, monitoring, and continuous improvement. It introduces an evaluation system based on quantitative and qualitative indicators organized into seven categories covering the entire user experience: access and connections, route layout, surfaces, safety and barriers, resting areas and facilities, signage and information, and cognitive and perceptual comfort. The overall score allows paths to be classified into three levels of accessibility. Overall, the review highlights the need to overcome the traditional separation between technical prescriptions and experiential dimensions, recognizing human diversity as a design resource rather than a condition to be compensated for. Accessibility is still often interpreted mainly in terms of removing physical or sensory barriers, while perceptual, cognitive, and relational dimensions, crucial for inclusive enjoyment of natural environments, remain underexplored.

METHODS

The methodology adopts an Environment and Human-Centred Design approach, aiming to manage the complexity of the relationships between individuals, systems, and activities (Attaianese, 2016). It integrates users' characteristics and use-related needs with the expected performance of technological, spatial, and environmental systems. In a first phase, three paradigmatic user profiles were identified. These profiles are considered representative because they interact with the environment in different ways. Through these models, it is possible to interpret the complexity of use conditions and to analyse how different types of environmental barriers affect the walking experience in natural contexts. In a second step, each profile is associated with specific characteristics and use-related needs emerging from an ergonomic analysis of person–environment interaction. This approach allows moving beyond an interpretation based solely on individual limitations, shifting the focus toward environmental conditions that facilitate or hinder action, orientation, and spatial understanding. To translate these needs into design-oriented guidance, the methodological framework integrates the principles of Universal Design, which are adopted as a conceptual reference. Universal Design is used to relate the identified interaction patterns to design criteria capable of addressing, in a transversal way, the variability of human conditions. Finally, to make overlaps between different vulnerability conditions explicit, the method introduces a matrix of recurring manifestations and behaviours. This matrix highlights shared person–environment interaction patterns and provides the basis for identifying a set of requirements for the design and evaluation of natural pathways.

RESULTS

Since defining user profiles in a comprehensive way is particularly complex, an interpretative framework is proposed [Table 1] to highlight the relationship between three paradigmatic need-based profiles, corresponding to three types of environmental barriers, and the seven principles of Universal Design.

Barrier category	Paradigmatic user profiles	Use-related needs	UD principles
Physical	People with: – mobility impairments using manual or powered wheelchairs.	Route continuity; propulsion effort; surface stability.	(UD1) Equitable Use (UD6) Low Physical Effort (UD7) Size and Space for Approach and Use
Sensory, perceptual and communicative	– total visual impairments using a long cane or guide dog; – partial visual impairments; – hearing impairments.	Environmental legibility; orientation; perceptual continuity; multisensory information.	(UD1) Equitable Use (UD2) Flexibility in Use (UD4) Perceptible Information (UD5) Tolerance for Error
Cognitive	– age-related cognitive impairments; -neurodiversity.	Predictability; coherence; cognitive load reduction; stimulus management.	(UD1) Equitable Use (UD3) Simple and Intuitive Use (UD4) Perceptible Information (UD5) Tolerance for Error

Table 1. Relationship between barrier categories, paradigmatic user profiles, use-related needs, and Universal Design (UD) principles

PHYSICAL BARRIERS

Physical barriers refer to environmental characteristics and elements that may

Di Dario Y. (2025). Rethinking walkability through universal design: an ergonomics-based framework for green inclusive pathways in natural landscapes . *Rivista Italiana Di Ergonomia*. 31. 89-98. DOI: 10.6093/RIE/13417

cause discomfort for pedestrian mobility in general, and in particular for individuals with reduced or impaired motor abilities, whether permanent or temporary. The analysis of these profiles allows the assessment of walkability conditions in natural paths in relation to route characteristics and the physical effort required for propulsion. In this sense, physical barriers include obstacles that affect not only physical well-being but also the safety of the walking experience, as they may induce potentially unsafe behaviours aimed at overcoming them. Typical examples include uneven walking surfaces and materials, excessive slopes, the presence of obstacles along paths, unfavourable microclimatic conditions, level changes (steps, edges, height differences, stairs), as well as the absence of connecting ramps and narrow passage spaces. The use-related needs associated with physical barriers mainly concern route continuity, surface stability, and the reduction of physical effort during walking. In relation to these needs, several Universal Design principles are particularly relevant, namely Equitable Use, considered a transversal principle across different barrier categories; Low Physical Effort, referring to the minimization of required effort; and Size and Space for Approach and Use, related to access and manoeuvrability conditions along the path.

SENSORY-PERCEPTUAL AND COMMUNICATIVE BARRIERS

Sensory-perceptual and communicative barriers refer to the absence or inadequacy of measures, signage, and support elements that enable users to perceive relevant environmental information for safe and effective use, such as the presence of essential or hazardous objects, level changes, and route variations (Roveredo, 2024). These barriers primarily affect individuals for whom the use of one or more sensory channels is difficult or impossible, with particular reference to visual and auditory impairments. By contrast, limited attention has been paid to alterations involving other sensory channels, such as taste, smell, and touch. Beyond requirements related to orientation, safety, and comfortable usability, inclusive use of natural paths also depends on environmental communicability, understood as the ability of spatial elements and facilities to be perceivable and understandable by all users, and especially by people with sensory or cognitive difficulties (Laurìa, 2002). The degree of communicability is influenced by the presence of intentional environmental cues, arising from spatial layout, typological systems, or dedicated informational aids, as well as by unintentional environmental cues, such as natural or built landmarks and reference lines. However, in natural contexts, the reliability of such cues may change over time, making orientation more complex and uncertain.

COGNITIVE BARRIERS

Cognitive barriers include typological, technological, or organizational elements of a spatial system that hinder use or represent a source of risk because they lead to an inadequate understanding of information related to comfortable usability. They constitute an obstacle to the process of knowing and interpreting the environment, as they fail to adequately meet users’ needs for orientation, safety, and information, interfering with processes of memory, reasoning, and interpretation (AA.VV., 2014). From this perspective, cognitive barriers also include spatial conditions that alter proxemics and multisensory aspects of perception, proprioception, and kinaesthesia, affecting users’ ability to understand and anticipate spatial organization. These barriers take different forms depending on the variability of individual conditions, which may be related to mental and experiential factors, also in connection with physical and

Di Dario Y. (2025). Rethinking walkability through universal design: an ergonomics-based framework for green inclusive pathways in natural landscapes . *Rivista Italiana Di Ergonomia*. 31. 89-98. DOI: 10.6093/RIE/13417

sensory limitations, as well as to forms of neurodiversity, whether typical or atypical. Recurring examples include inadequate physical, technical, or environmental control, such as inconsistent acoustic or lighting solutions, as well as the absence of appropriate informational strategies resulting from morphological or material choices that make spatial understanding difficult. Such conditions influence environmental perception in terms of light and sound reflection or absorption, color schemes, textures, and spatial configuration, producing effects of spatial compression or expansion and generating difficulties in spatial and social interaction (Conti, 2019). The use-related needs associated with cognitive barriers mainly concern environmental predictability, information coherence, simplification of informational content, management of sensory stimuli, and reduction of cognitive load. In relation to these needs, several Universal Design principles are particularly relevant, including Equitable Use, as a transversal principle ensuring equal conditions of understanding and use; Simple and Intuitive Use, referring to ease of environmental interpretation; Perceptible Information, supporting clarity and legibility of information; and Tolerance for Error, aimed at reducing the negative consequences of misunderstandings or unintended actions. In this sense, attention to cognitive barriers allows moving beyond the traditional focus, widely found in the literature and international guidelines, on mobility and sensory impairments, extending the analysis toward a more articulated understanding of person-environment interaction. Within this framework, the association between environmental barriers, use-related needs, and Universal Design principles does not aim to define specific design solutions, but rather to guide the identification of functional requirements for the inclusive use of natural pathways. Since these needs cannot be uniquely attributed to single user profiles but may emerge across different conditions, the profiles considered assume a paradigmatic value. Accordingly, Table 2 summarizes recurring functional manifestations in the use of natural paths, highlighting overlaps and shared patterns of person-environment interaction that provide the basis for identifying transversal functional requirements.

Relevant manifestations for use	**Mobility impairment**	**Visual impairment**	**Hearing impairment**	**Cognitive decline**	**Neurodiversity**
Physical fatigue during walking	✓			✓	
Spatial orientation difficulties		✓		✓	✓
Reduced environmental legibility		✓	✓	✓	✓
Difficulties in information processing				✓	✓
Need for high route predictability	✓			✓	✓
Sensitivity to sensory stimuli					✓
Difficulties in information communication			✓	✓	✓
Reduced perception of environmental risks		✓		✓	
Cognitive overload in complex environments				✓	✓

Table 2. Recurring functional manifestations in natural pathway use across the considered paradigmatic profiles.

Di Dario Y. (2025). Rethinking walkability through universal design: an ergonomics-based framework for green inclusive pathways in natural landscapes . *Rivista Italiana Di Ergonomia*. 31. 89-98. DOI: 10.6093/RIE/13417

CONCLUSIONS

This contribution has proposed a critical reinterpretation of the concept of walkability in natural and peri-urban contexts, shifting the focus from the mere measurement of the physical performance of paths toward a broader and more systemic understanding of inclusive use. From this perspective, walkability is not considered only as a geometric or infrastructural property of a route, but as the dynamic outcome of the interaction between individuals, the environment, and conditions of use, in line with an ergonomic and human-centred approach. The analysis of physical, sensory-perceptual, and cognitive barriers has highlighted that difficulties in use cannot be attributed to single user categories, but rather emerge transversally across the life course, in the presence of permanent, temporary, or situational impairments, as well as under conditions of fatigue, cognitive decline, or neurodiversity. In this sense, the identified profiles assume a paradigmatic rather than categorical value, allowing vulnerabilities to be interpreted as recurring functional conditions rather than as static individual attributes. The synthesis presented in Table 2 shows that manifestations such as physical fatigue, orientation difficulties, reduced environmental legibility, and cognitive overload are distributed across different user profiles. This evidence suggests the need to define shared functional requirements rather than sector-specific design solutions. Within this framework, the association between barrier categories, use-related needs, and Universal Design principles is not intended to provide prescriptive answers, but to guide decision-making processes toward performance-oriented criteria capable of supporting equitable, continuous, and safe use of natural pathways. These considerations are consistent with findings from recent international literature. In particular, the systematic literature review by Gupta et al. (2025) highlights that the application of Universal Design in public open spaces is often fragmented, mainly focused on physical accessibility, and only partially extended to the cognitive, perceptual, and communicative dimensions of use. Similarly, the review emphasizes that the effectiveness of Universal Design principles depends on their integration from the early stages of the design process and on their adaptation to specific territorial, cultural, and environmental contexts, rather than on their application as mere normative standards. Within this perspective, the present work contributes to the ongoing debate by proposing a conceptual shift from accessibility assessment as a compliance requirement toward the definition of inclusive use as an intrinsic dimension of environmental quality. This implies recognizing route continuity, multisensory legibility, spatial predictability, and cognitive load management as relevant components of walkability, especially in natural contexts characterized by greater morphological and environmental variability. Finally, this contribution suggests that the design of accessible natural pathways can hardly be addressed through isolated technical checklists alone but instead requires an integrated approach capable of combining Universal Design, Design for All, and ergonomic knowledge within a performance-based and use-oriented framework. In this direction, the identified functional requirements represent a possible reference base for the development of evaluation tools and design-support processes aimed at promoting more inclusive natural environments and enhancing overall user well-being.

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SHORT BIO

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URBAN DESIGN ACROSS THE LIFE COURSE: TOWARDS LONGEVITY-ENABLING ENVIRONMENTS

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ABSTRACT

Since the early 2000s, global population ageing has significantly reshaped how urban design and planning address the human experience of city life. In this evolving context, age-friendly urban design has emerged as a transdisciplinary field aimed at configuring spatial systems that sustain autonomy, participation and wellbeing in later life. This study involves the theoretical and operational consolidation of the field by tracing its foundations in major UN and WHO frameworks and examining how these have been translated into technical standards, regulatory instruments and evaluative models, emphasising the ergonomic dimension of age-inclusive environments. The paper positions ergonomics and human factor as key interpretive lenses for understanding how the integration of accessibility and usability issues with environmental quality may shape inclusive urban settings across the ageing process in a life course perspective. The focus is on two critical application domains: technological innovation, encompassing smart-city infrastructures, participatory digital platforms and assistive systems, and urban green and blue infrastructures (UGBI), conceived as integrated strategies that support environmental resilience and multisensory restoration especially in later life. By combining theoretical perspectives with empirical evidence, the study synthesises current knowledge of age-friendly urbanism and identifies persistent conceptual and methodological fragmentation. It ultimately promotes a shift toward longevity-enabling environments, designed as adaptive, inclusive and evidence-based spatial systems that support human health through wellbeing, functional ability and human flourishing, not only during aging but across the entire lifespan.

INTRODUCTION: URBAN DESIGN FOR AN AGEING POPULATION

The accelerating demographic transformation associated with global population ageing constitutes one of the most profound challenges for twenty-first-century urbanism. This demographic shift compels a reconceptualization of how cities are designed, governed, and experienced, calling for environments capable of sustaining wellbeing, autonomy, and participation across the later phases of life. This perspective aligns with the dynamic concept of health as the ability to adapt and self-manage in the face of contemporary

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challenges (Huber et al., 2011). Within this context, the paradigm of active and healthy ageing reframes later life as a dynamic period of contribution, in which knowledge, skills, and civic engagement of older adults enrich collective urban life, reflecting the social-justice orientation of the age-friendly movement, which emphasises empowerment and co-production among older citizens (Buffel & Phillipson, 2018). A central corollary of this paradigm is the concept of ageing in place, formulated in the late 1970s to enable individuals to grow old within familiar physical and social environments, where emotional attachment, identity, and community belonging are deeply embedded (Woolrych & Li, 2024). Therefore, urban design constitutes an active catalyst of wellbeing in everyday settings, highlighting the need of specific environmental attributes in public-space evaluation, which structure liveability for senior users (Mehta, 2014). This perspective aligns with the broader objective of Ergonomics and Design for All, which emphasise human abilities, usability, and experiential quality as core determinants of inclusive and age-responsive environments. Within the evolving discourse on population ageing, the concept of urban ageing has emerged as a framework that analyses the interaction between socio-demographic transformations and urban dynamics associated with increasingly long-lived populations (Marston & van Hoof, 2019).Over the past two decades, this conceptual evolution has been accompanied by the progressive institutionalisation of age-friendly policy agendas. Notable initiatives include the Positive Ageing Indicators Report (New Zealand, 2007), which introduced national indicators for wellbeing in later life; Advancing an Age-Friendly NYC (2009), which emphasised community participation and adaptive urban design; and the South Australia Age-Friendly Guidelines (2012), establishing a regulatory framework for integrating ageing considerations into urban and regional planning. More recent strategies, such as the UK Age-Friendly Programme (2017–2020), Age-Friendly DC Strategic Plan (2018–2023), and Liverpool Ageing Strategy (2022–2026), have adopted a multisectoral, life-course approach that embeds digital inclusion, intergenerational solidarity, and equitable access to urban resources (Rashid et al., 2021). The design of public open spaces remains a significant cornerstone, particularly in relation to promoting physical activity and social interaction among older adults. Empirical evidence from Taichung, Taiwan, demonstrates that specific physical and environmental attributes of urban greenways, such as continuous paving, natural paths, resting areas, vegetation density, and proximity to water features, substantially influence older adults' participation in outdoor activities (Chang, 2020). Consistently, indicator-based studies of public open space demonstrate measurable associations between environmental qualities and community health outcomes, offering transferable metrics for age-supportive design (Villanueva et al., 2015). These findings underscore the importance of integrating interconnected dimensions into urban design as a foundational strategy for realising environments that are truly health-promoting and socially cohesive. Current research highlights that achieving such environments requires an operational culture of evidence-based and mindful design, where spatial, sensory, and emotional factors are explicitly considered to sustain wellbeing across the life course (Aslanoğlu et al., 2025).

THEORETICAL AND POLICY BACKGROUND: THE EVOLUTION OF GLOBAL FRAMEWORKS ON AGE-FRIENDLY URBAN DESIGN

The conceptual underpinnings of age-friendly urban design are deeply rooted in the policy frameworks advanced by the United Nations (UN) and the World Health Organization (WHO). In 2002, the Second World Assembly on Ageing in Madrid culminated in the adoption of the Madrid International Plan of Action

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on Ageing (MIPAA), which defined population ageing as both a challenge and an opportunity for the twenty-first century. The Assembly underscored the imperative of fostering an inclusive society for all ages, thereby establishing ageing as a global policy priority and linking demographic change to social, economic, and environmental dimensions (United Nations, 2002). Building upon this foundation, the WHO Active Ageing Framework (2003) introduced a multidimensional perspective centred on health, participation, and safety, laying the groundwork for more targeted approaches to urban environments. A pivotal milestone was the WHO Global Age-Friendly Cities Guide (2007), developed through the Vancouver Protocol, which defined the core attributes of an age-friendly city, acknowledging the diversity of older people, valuing their participation across community life, respecting individual choices, and responding flexibly to age-related needs. The Guide operationalised these principles into eight interrelated urban domains, thus providing the first comprehensive global framework for designing urban environments responsive to ageing populations. The evolution of the WHO Age-Friendly Cities agenda has strengthened participatory governance by integrating older citizens' voices into urban policy (van Hoof & Marston, 2021) and was further institutionalised with the establishment of the Global Network for Age-Friendly Cities and Communities (GNAFCC) in 2010. In parallel, the European Innovation Partnership on Active and Healthy Ageing (EIP on AHA) was launched in the same year, as a large-scale public–private partnership aimed at extending healthy life expectancy in the EU by two years by 2020. To achieve this goal, the initiative structured its work into thematic Action Groups, including domains such as medication adherence (A1), falls prevention (A2), frailty prevention and health promotion (A3), integrated care (B3), independent living solutions (C2), and age-friendly environments (D4) (European Commission, 2021). The Active Ageing Index has since provided a quantitative framework linking participation, independent and healthy living, and enabling environments, supporting cross-country monitoring and policy benchmarking (UNECE, 2018). More recently, the UN Decade of Healthy Ageing (2021–2030) has articulated a comprehensive framework for coordinated global action, reinforcing the principle that cities are essential to enabling people to live longer and healthier lives. Collectively, these initiatives have positioned age-friendly urban design as a core element of international policy discourses on ageing. Recent global assessments, such as the OECD report "Cities for All Ages" (2025), underscore the need to translate these frameworks into integrated strategies that align urban design, housing, transport, and healthcare infrastructures, ensuring inclusivity for diverse ageing trajectories.

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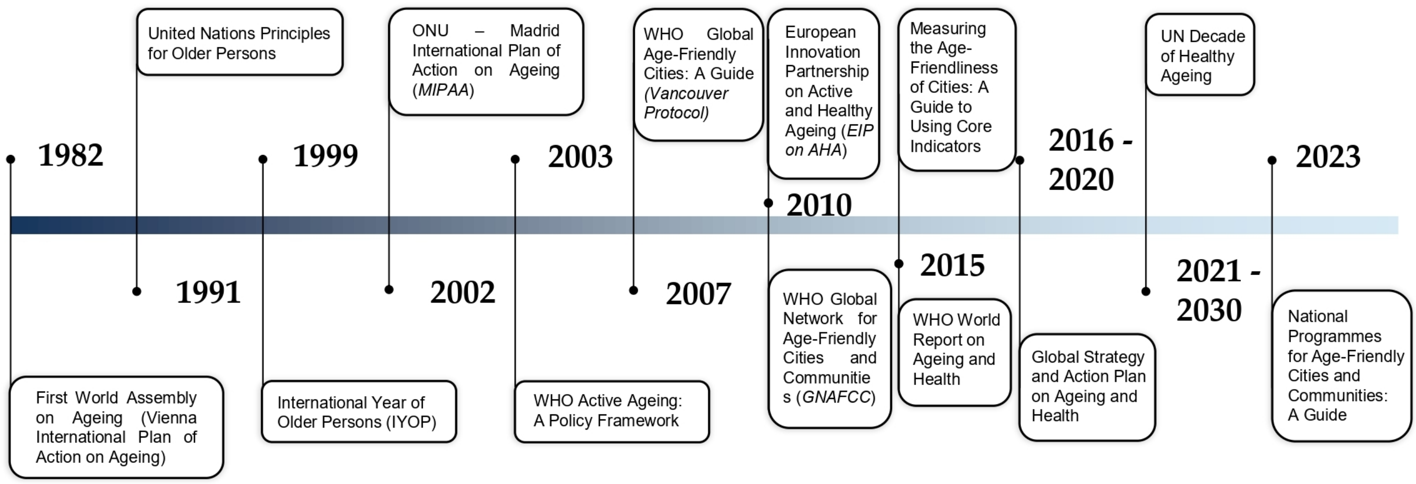

Figure 1. Timeline of major UN and WHO policy frameworks addressing ageing and urban design

METHODOLOGICAL AND ANALYTICAL FRAMEWORK: OPERATIONALISING AGE-FRIENDLY URBANISM

The translation of age-friendly principles from global policy frameworks into the operative domain of urban design has progressively relied on a diverse set of normative, methodological, and evaluative instruments. Over the past two decades, an articulated corpus of international standards, design guidelines, and assessment tools has emerged, defining how the built environment can respond to the evolving needs of ageing populations. At the international level, ISO and CEN standards, such as ISO 21542, ISO 21801, EN 17210, and EN 17161, provide the technical foundations for physical, sensory, and cognitive accessibility, embedding Universal Design and Design for All principles into both architectural and urban environments. Complementary regional and national frameworks, including the South Australia Age-Friendly Guidelines (2012), the WHO National Programmes for Age-Friendly Cities and Communities: A Guide (2023), and the Centre for Ageing Better toolkits (2025), translate these principles into actionable guidance for public authorities and practitioners. At the municipal scale, documents such as the City of Markham Age-Friendly Design Guidelines (2022) operationalise age-supportive criteria through context-sensitive approaches to neighbourhood planning and public-realm design. In parallel, indicator-based and evaluative frameworks have strengthened the measurement dimension of age-friendly urbanism. These include the Canadian and WHO age-friendly indicator sets, highlighting the evaluative backbone of municipal action (Kano et al., 2017), the Wijkscans voor Ouderen tool (2025) in the Netherlands, an integrated diagnostic instrument that combines spatial audits with participatory assessment of neighbourhood quality, enabling municipalities to prioritise interventions for safety, active mobility, and social interaction. Comparative studies have also broadened the indicator landscape across diverse socio-territorial contexts, revealing marked variability in the applicability of WHO domains along urban–rural gradients and differing stages of economic development (Rugel et al., 2022). Complementary

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approaches, such as the spatial-indicator framework proposed by Davern et al. (2020), operationalise the lived environment through measurable dimensions (accessibility, safety, and aesthetics), bridging subjective wellbeing with objective spatial data. Concurrently, a series of evaluative instruments has consolidated the analytical dimension of age-friendly urbanism, from the WHO Checklist of Essential Features of Age-Friendly Cities (2007) to the AARP Livability Index 2.0 (2023), that provide both diagnostic and participatory mechanisms for assessing quality of spaces for older adults. Related public-space evaluation approaches converge on a core set of attributes, accessibility, comfort, and perceived safety, as practical proxies for inclusive urban quality (Mehta, 2014). In 2021, the WHO also has strengthened the emphasis on environmental determinants of health through its consolidated reviews on green and blue spaces, which highlight their relevance for mental health, stress reduction and overall wellbeing (WHO, 2021). Collectively, these standards, guidelines, and evaluative instruments mark a shift from prescriptive accessibility norms toward more integrated frameworks that recognise the physical, cognitive, and environmental dimensions of urban experience. Yet they largely remain fragmented and seldom converge into a coherent design methodology. Contemporary scholarship underscores the need for integrative strategies that couple environmental performance with experiential wellbeing, moving beyond checklist-based approaches toward adaptive frameworks capable of aligning policy intentions with lived urban conditions (Aslanoğlu et al., 2025; Buffel et al., 2018). From an ergonomics and human factors perspective, these limitations reflect the lack of a systematic consideration of usability, perceptual and sensory experience, and human–environment interaction within existing urban age-friendly instruments. Accessibility norms primarily address essential functional requirements, yet they often do not encompass the cognitive, behavioural and experiential dimensions that ergonomics identifies as central to inclusive environmental quality. Such integration strengthens transdisciplinary collaboration across environmental design, public health, and social policy, positioning the built environment as an active mediator of functional ability and social participation in later life (Rugel et al., 2022). The following Table 1 summarises the main standards, guidelines, and evaluative tools that operationalise age-friendly frameworks across international, national, and municipal scales.

Source	**Year**	**Content**	**Field of Application**
Standards and Technical Codes			
BS 8300-1 Design of an Accessible and Inclusive Built Environment – Part 1: External Environment	2018	Defines human performance-based principles and technical criteria for accessibility and inclusive use in external built environments, including access routes, pedestrian circulation, streetscapes, open spaces, and approaches to buildings	Urban & Built Environment
EN 17161 Design for All – Accessibility Following a Design for All Approach in Products, Goods and Services	2019	Specifies an organisational framework for embedding Design for All principles in the design, development, provision and management of products and services	Governance & Services
ISO 21801-1 Cognitive Accessibility – General Guidelines	2020	Provides general guidelines for cognitive accessibility in systems, products, services and built environments, addressing perception, orientation and usability for people with cognitive disabilities	Cognitive & Built Environment Ergonomics
ISO 21542 Building Construction – Accessibility and Usability of the Built Environment	2021	Specifies international requirements for accessibility and usability in building access, internal circulation areas, and external routes directly connected to buildings	Urban & Built Environment
EN 17210 Accessibility and Usability of the Built Environment –	2021	Defines functional accessibility and usability requirements for indoor and outdoor built	Urban & Built Environment

Perillo, M., Nijkamp, J., Attaianese, E. (2025). Urban design across the life course: towards longevity-enabling environments. *Rivista Italiana Di Ergonomia*. 31. 99-114. DOI: 10.6093/RIE/13418

Functional Requirements		environments, grounded in Design for All and Universal Design principles	
Guidelines and Toolkits			
WHO – Global Age-Friendly Cities: A Guide	2007	Provides foundational guidance for designing age-friendly urban environments, outlining principles, priority domains, design implications and participatory processes for older adults	Urban Policy & Planning
South Australia Age-Friendly Guidelines	2012	Defines a policy and planning framework for integrating age-inclusive planning and design principles into urban and regional development	Urban & Regional Planning
Good Practices of Accessible Urban Development (UN-Habitat)	2016	Presents international good-practice case studies and policy lessons advancing accessible and inclusive urban planning and public space design	Urban Policy & Planning
The Inclusive Imperative: Towards Disability-Inclusive and Accessible Urban Development	2016	Outlines key strategic recommendations for embedding accessibility, inclusion and Universal Design principles into sustainable urban development processes	Urban Policy & Planning
Enabling Inclusive Cities: Tool Kit for Inclusive Urban Development (Asian Development Bank)	2017	Provides practical tools and methodologies for inclusive, barrier-free, and age-responsive city planning	Urban Policy & Planning
City of Markham Age-Friendly Design Guidelines (Canada)	2022	Provides municipal design guidance for neighbourhoods, geared toward supporting ageing in place and inclusive communities for people of all ages	Neighbourhood & Public Realm
AccessibleEU – Resource Centre for Accessibility (European Commission)	2023	EU-wide digital platform providing a knowledge base, standards repository, case studies and best practices to support accessibility in the built environment	Urban & Built Environment
WHO National Programmes for Age-Friendly Cities and Communities: A Guide	2023	Outlines procedures and strategic recommendations for establishing and sustaining national programmes on age-friendly cities and communities	Urban Policy & Governance
Centre for Ageing Better – Age-Friendly Communities: A handbook of principles to guide local policy and action	2025	Provides a comprehensive set of policy principles and design criteria for local authorities, covering walkability, accessibility, environmental quality, participation and service delivery across the eight domains of age-friendly communities	Public Realm & Local Policy
Evaluation and Assessment Instruments			
AARP Livable Communities: An Evaluation Guide	2005	Provides a participatory framework, including survey tools and checklists, for assessing community livability and accessibility from the perspective of older residents	Urban Assessment & Evaluation
WHO Checklist of Essential Features of Age-Friendly Cities	2007	Establishes qualitative indicators and observational criteria for assessing the eight domains of age-friendly cities, including outdoor spaces, mobility, social participation and community support	Urban Assessment & Evaluation
Atlanta Regional Commission – Lifelong Communities Initiative: Principles for Housing and Neighbourhoods	2009	Defines key planning and design principles for developing age-inclusive, walkable and socially connected neighbourhoods	Neighbourhood & Public Realm
UK Department for Communities and Local Government – Lifetime Neighbourhoods	2011	Defines principles and evaluative criteria for neighbourhoods that support ageing in place, walkability, social participation, accessibility and wellbeing across the life course	Neighbourhood & Public Realm
Measuring the Age-Friendliness of Cities: A Guide to Using Core Indicators	2015	Provides a structured indicator framework to measure age-friendly performance across the eight age-friendly WHO domains	Urban Assessment & Evaluation
AARP Livability Index 2.0 (USA)	2023	Offers a quantitative assessment framework that evaluates core dimensions of community livability and age-friendliness	Urban Assessment & Evaluation

Table 1. Key standards, guidelines and tools translating age-friendly frameworks into urban design practice

RESULTS: EMERGING DOMAINS INTO AGE-FRIENDLY URBAN DESIGN

Evidence[1] reveals a gradual broadening of the age-friendly discourse toward more integrative and adaptive interpretations of the urban environment. Rather than a prescriptive focus on accessibility or risk mitigation, recent approaches conceive urban design as an active enabler of functional ability, participation, and wellbeing across the life course. Within this evolving framework, two complementary domains stand out for their transformative potential. The first concerns technological innovation, through which digital infrastructures, smart systems, and participatory platforms are reshaping the interaction between people, space, and data. The second pertains to urban green and blue infrastructure, which embeds ecological and restorative processes into the built environment, enhancing environmental quality and comfort, resilience, and social cohesion. Together, these domains converge toward a broader vision of longevity-enabling urban environments, intended as an adaptive spatial system that sustain health, inclusion, and quality of life throughout the different ageing processes.

[1]The literature search across PubMed, Web of Science, and Google Scholar addressed conceptual and operational dimensions of age-friendly urban design, spanning WHO frameworks, technical standards, and recent developments in digitally enabled spatial interventions and nature-based urban design practices. Studies published from 2000 onward and relevant to urban or environmental design were included. Of 67 records identified, 34 met the inclusion criteria.

TECHNOLOGICAL INNOVATION IN THE URBAN ENVIRONMENT

Technological innovation in age-friendly urban design represents an exemplary shift from tailored solutions toward adaptive, data-informed, and co-created urban settings (Perillo, 2025). Within this transformation, frameworks such as Smart Healthy Age-Friendly Environments (SHAFE) have redefined technology as an embedded capability of the urban fabric, mediating autonomy, safety, and social connection across the life course (Dantas et al., 2021). Rather than focusing solely on accessibility or risk prevention, emerging approaches aim to produce responsive, participatory, and ethically grounded environments that evolve with the changing needs of ageing citizens, aligning with broader conceptions of the built environment as a key determinant of liveability and age-friendliness (van Hoof et al., 2021). Within this perspective, public-space evaluation criteria offer a transferable benchmark for assessing whether smart deployments substantively enhance inclusive urban experience (Mehta, 2014). Across the reviewed literature and pilot initiatives, three complementary trajectories can be identified. First, monitoring and prevention systems, exemplified by City4Age and ACTIVAGE, use interoperable IoT infrastructures, together with wearable sensors and mobile interfaces, to detect early signs of frailty, monitor mobility and enable personalised care interventions (Medrano-Gil et al., 2018). Second, interactive and participatory public spaces, such as those tested in UrbanLife+ and MUSA, deploy smart urban objects (SUOs), such as adaptive lighting, interactive benches, and gamified navigation systems, to enhance safety, orientation, and social engagement (Fietkau & Stojko, 2020; Padrón-Nápoles et al., 2021). Third, predictive and planning-oriented models, those developed in the URBANAGE project, employ Local Digital Twins (LDTs) and city information models to integrate accessibility data, simulate scenarios, and co-create inclusive urban solutions with citizens (Villanueva-Merino et al., 2024). To these trajectories, large-scale integrative ecosystems, such as PHArA-ON and GATEKEEPER, add a broader governance and interoperability dimension. Both projects demonstrate how distributed IoT infrastructures, AI, and cloud-based systems can link domestic and urban scales, promoting continuous and person-centred ageing support (D'Onofrio et al., 2022). Although originally developed to enhance independent living and health monitoring, both initiatives increasingly operate at the interface between technological and spatial systems. Their pilot regions demonstrate how digital infrastructures, when scaled to the urban fabric, can function as territorial

Perillo, M., Nijkamp, J., Attaianese, E. (2025). Urban design across the life course: towards longevity-enabling environments. *Rivista Italiana Di Ergonomia*. 31. 99-114. DOI: 10.6093/RIE/13418

enablers, integrating data on mobility, accessibility, and environmental quality. Taken together, these innovations signal the role of technology as a catalyst for equity, resilience, and participatory urban intelligence. Yet significant challenges persist, ranging from usability and digital literacy to data privacy and governance (Ciobanu et al., 2024), but also to the lack of meaningful involvement of older citizens, a condition that risks reproducing new forms of exclusion (Marston & van Hoof, 2019). Current scholarship underscores the need for ethical inclusion, embedding participatory design, accessibility-by-default, and data accountability across the full innovation cycle (van Hoof et al., 2021). Evidence further indicates that citizen-generated data enhances contextual accuracy while empowering older adults as co-producers of urban knowledge, thereby reinforcing digital-age inclusivity (Wood et al., 2022). Therefore, emerging technologies may operate as enablers of adaptive, socially cohesive, and longevity-oriented urban environments, particularly as their impacts intersect with wider urban dynamics, such as densification-driven changes in mobility, environmental stressors, and social cohesion, whose cumulative effects on mental health and wellbeing are increasingly recognised as non-linear and mediated by feedback mechanisms (Beenackers et al., 2024). Advances in neuroadaptive architecture extend this trajectory by introducing responsive spatial systems that attune to users' cognitive and affective states, enhancing environmental comfort and psychological wellbeing across age-diverse populations (Makanadar, 2024). Table 2 synthesises representative international projects that translate the integration of smart technologies into actionable design and governance models for age-friendly cities. Together, they illustrate the gradual shift from technology as assistive infrastructure to technology as an urban enabler of inclusion, participation, and wellbeing.

Project	**Period**	**Technologies**	**Main Outcomes**	**Relevance for Age-Friendly Urban Design**
City4Age (The ultimate city for the elderly population)	2015–2018 (EU/non-EU multi-site pilots)	Smartphones, wearable sensors, Bluetooth beacons, ambient sensing, urban information systems, behaviour-monitoring analytics	Demonstrated the feasibility of unobtrusive, behaviour-based monitoring to detect early changes in mobility, social activity and cognitive patterns among older adults across multiple pilot cities	Enables proactive, context-aware interventions that support autonomy, safety and participation of older adults in everyday urban environments, informing smarter and more responsive age-friendly city services
ACTIVAGE (ACTivating InnoVative IoT smart living environments for AGEing well)	2017–2020 (EU)	IoT interoperable ecosystem, wearable devices, environmental sensors, smart-home and smart-city IoT nodes, mobility and health monitoring platforms	Validated the first large-scale IoT pilots for Active and Healthy Ageing across different sites in Europe, integrating mobility, social participation and health data through an interoperable architecture	Demonstrates how scalable, interoperable smart-city systems can enhance autonomy, social inclusion, safety and wellbeing of older adults in community and urban environments
UrbanLife+	2015–2020 (Germany)	Smart Urban Objects (SUOs), including adaptive	Tested smart urban interfaces in real urban	Shows how interactive, co-designed technological elements can enhance safety, comfort and participation in public spaces, supporting age-friendly

Perillo, M., Nijkamp, J., Attaianese, E. (2025). Urban design across the life course: towards longevity-enabling environments. *Rivista Italiana Di Ergonomia*. 31. 99-114. DOI: 10.6093/RIE/13418

		lighting systems, interactive benches, sensor-based interfaces and gamification tools for social engagement	settings, demonstrating improvements in perceived safety, orientation, social interaction and overall experiential quality of public spaces for older adults	environments through experiential and responsive urban design
URBANAGE (Enhanced URBAN planning for AGE-friendly cities through digital twins)	2021–2024 (EU)	Local Digital Twins (LDT), City Information Models (CIM), geospatial analytics, AI-based prediction models, accessibility and mobility data integration, citizen-input interfaces	Developed predictive planning tools that combine accessibility, mobility and environmental data with citizen input to model inclusive scenarios for ageing populations across three European pilot sites	Demonstrates how data-driven, simulation-based approaches can support participatory and evidence-informed planning, enhancing accessibility, mobility and service provision for older adults in urban environments
MUSA (Mobiliario Urbano Sostenible y Avanzado)	Pilot 2018–ongoing (Municipal Pilot Project, Madrid)	IoT-enabled bus stops, interactive smart traffic furniture, automatic passenger counters (APC), multi-modal travel interfaces	Implemented prototype inclusive transport infrastructures in Madrid combining sensorized buses and smart stops, interactive displays and data systems to improve real-time service planning and user experience	Enhances urban mobility experience, wayfinding and safety for all users via inclusive transport infrastructure and interactive public-realm hardware
GATEKEEPER (Smart Living Homes - Whole interventions demonstrator for people at health and social risks)	2019–2023 (EU)	Standard-based open platform, IoT devices and sensors, AI analytics, data federation architecture, interoperable multi-stakeholder ecosystem	Established a large-scale, open and ethical data architecture engaging 40k + older users across European regions, enabling personalised services through interoperable health, mobility and environmental data flows	Demonstrates cross-domain data governance and interoperability models applicable to urban systems, supporting integrated approaches to mobility, health, safety and community services for ageing populations
PHArA-ON (Pilots for Healthy & Active Ageing in Europe)	2019–2024 (EU)	IoT sensors & devices, wearables, AI analytics, cloud/edge computing, big data platforms,	Validated multi-site digital ecosystems across Europe linking domestic,	Connects digital infrastructures across scales to support inclusive governance, mobility, service provision and longevity-oriented urban policies for ageing populations

Perillo, M., Nijkamp, J., Attaianese, E. (2025). Urban design across the life course: towards longevity-enabling environments. *Rivista Italiana Di Ergonomia*. 31. 99-114. DOI: 10.6093/RIE/13418

		open interoperable ecosystems	community and urban services for active ageing, leveraging interoperable platforms and integrated data flows	
SHAPES (Smart and Health Ageing through People Engaging in Supportive Systems)	2019–2023 (EU)	IoT devices and sensors, wearables, ambient assisted living systems (AAL), AI analytics, robotics, cloud/edge computing, federated digital platforms for cross-domain service integration	Validated a multi-country ecosystem linking home, community and care services through interoperable digital platforms, enabling personalised support, remote monitoring and coordinated service delivery for older adults across 15 pilot sites	Demonstrates how cross-scale digital infrastructures can connect domestic, neighbourhood and urban services, supporting inclusive governance, integrated mobility and care pathways, and longevity-oriented policy frameworks

Table 2. Key projects integrating technological innovation into age-friendly urban design

Across these initiatives, interoperability, user co-creation, and ethical data governance emerge as the strongest predictors of sustained impact. Projects that combine technological intelligence with participatory design generate more inclusive, context-sensitive outcomes, while isolated device-based pilots often fail to scale (van Hoof et al., 2021; D'Onofrio et al., 2022). Local Digital Twins, when embedded in transparent governance frameworks, represent a bridge between individual-level sensing and neighbourhood-scale decision-making, offering new pathways toward evidence-based, longevity-enabling urbanism (Villanueva-Merino et al., 2024).

URBAN GREEN AND BLUE INFRASTRUCTURE

Urban green and blue infrastructure (UGBI) have emerged as a cornerstone of contemporary age-friendly urban design, reframing the relationship between environmental quality, health, and longevity, while also operating as an infrastructure of social health that supports intergenerational interaction and community belonging (Buffel & Phillipson, 2018). UGBI integrates ecological, social, and health-promoting dimensions into urban systems, providing restorative, inclusive, and preventive environments for ageing populations. Design-oriented frameworks such as the ECN Adaptive Circular Cities project demonstrate how green and blue infrastructures can be designed to co-deliver ecosystem services and health outcomes, translating parameters such as temperature regulation, air purification, and noise reduction into spatial strategies that promote healthy urban living (ECN, 2022). However, as highlighted in the OECD's Cities for All Ages (2025) report, the benefits of green and blue infrastructure are maximised only when urban policy and planning are coordinated across housing, mobility, public space, social infrastructure, and service accessibility. Empirical evidence further shows that compact-city strategies frequently lead to the loss and fragmentation of green areas,

Perillo, M., Nijkamp, J., Attaianese, E. (2025). Urban design across the life course: towards longevity-enabling environments. *Rivista Italiana Di Ergonomia*. 31. 99-114. DOI: 10.6093/RIE/13418

weakening the continuity and effectiveness of UGBI networks and intensifying exposure to heat, noise, and crowding, that undermine the restorative and climate-regulating functions natural environments provide, particularly for older adults (Berghauser Pont et al., 2021; Balikçi et al., 2022). Quantitative findings also indicate that proximity to green infrastructure alone is insufficient to generate truly health benefits for older populations unless coupled with adequate design and maintenance (Davern et al., 2020). At the same time, exposure to green–blue environments is consistently associated with improved mental health and stress recovery (Dennis et al., 2019; Andreucci et al., 2019; White et al., 2020), a conclusion reinforced by recent WHO evidence linking access to diverse and accessible natural spaces with mental resilience, cognitive benefits, and reductions in all-cause mortality in later life (WHO, 2021). Recent research and practice converge on the need for environments that combine spatial design with systemic governance. Frameworks such as the WHO Age-Friendly Indicators (Kano et al., 2017) and the Active Ageing Index (UNECE, 2018) underscore the interdependence of environmental quality, accessibility, and participation as intertwined aspects of urban wellbeing. These insights reinforce the importance of multi-scalar, evidence-based approaches capable of linking ecological performance with public-health outcomes, echoing calls for integrated assessment models of outdoor environments (Mehta, 2014; Davern et al., 2020). Such approaches operationalise environmental quality through transferable indicators—proximity, connectivity, microclimatic regulation, and perceived safety, closely associated with the wellbeing of ageing communities (Villanueva et al., 2015; Davern et al., 2020). Collectively, these initiatives show how UGBI is conceived as multifunctional infrastructure underpinning urban environments conducive to healthy longevity. This integrative perspective aligns with emerging paradigms of evidence-based and reflexive design, which prioritise experiential quality, affective resonance, and human–environment reciprocity in the built environment (van Hoof, 2025). It advances the conception of cities that not only accommodate but actively foster healthy ageing, converging with the age-friendly movement's emphasis on equity and co-production (Buffel & Phillipson, 2018) and with international policy frameworks that recognise ecological infrastructures as crucial enablers of wellbeing in ageing populations (UNECE, 2018; Kano et al., 2017). The initiatives summarised in Table 3 exemplify how Urban Green and Blue Infrastructure (UGBI) strategies integrate ecological, social, and health objectives within age-friendly urban design, linking environmental performance with wellbeing and inclusion across the life course.

Source	**Period**	**Objective**	**Relevance for age-friendly urban design**
NYC Greenstreets Programme	1996-ongoing	To convert underused traffic islands and paved residual spaces into micro-greenspaces that enhance walkability, stormwater management and local microclimates throughout New York City's neighbourhoods	Improves neighbourhood-level walkability through distributed micro-green "rest points", offering shade, seating opportunities and cooler microclimates that support older adults' comfort, mobility and outdoor independence in dense urban areas
Cheonggyecheon River Restoration (Seoul, South Korea)	2003–2005	To transform a dismantled elevated highway into a continuous blue–green urban corridor that enhances walkability, microclimatic cooling, ecological restoration and public-realm quality, creating an accessible linear landscape integrated into the dense city centre.	Demonstrates how a revitalised blue–green corridor can support safe walking, thermal comfort, social activity and intergenerational use of public space, making dense environments more age-friendly and health-supportive

Perillo, M., Nijkamp, J., Attaianese, E. (2025). Urban design across the life course: towards longevity-enabling environments. *Rivista Italiana Di Ergonomia*. 31. 99-114. DOI: 10.6093/RIE/13418

Tokyo Green Road Network (Japan)	2007-ongoing	To create a metropolitan-scale network of tree-lined pedestrian paths, ecological corridors, riverside promenades and pocket parks designed to increase walkability, reduce heat exposure and enhance green connectivity across Tokyo's dense neighbourhoods	Improves thermal comfort and reduces heat-related risks—which disproportionately affect older adults—while providing shaded walking routes, rest areas and accessible ecological corridors that facilitate safe everyday mobility and outdoor activity for ageing populations
NHS Forest Programme (United Kingdom)	2009–ongoing	To integrate trees, pocket woodlands and green infrastructure into healthcare facilities and surrounding communities through large-scale planting, restorative landscape design and participatory greening, with the goal of improving environmental quality, supporting physical and mental health, and strengthening community engagement	Shows how therapeutic and climate-responsive green infrastructure embedded in healthcare and neighbourhood environments can enhance recovery, environmental comfort, walkability and social connectedness for older adults, contributing to healthier and more inclusive urban settings
Melbourne Urban Forest Strategy (Australia)	2012–ongoing	To expand and diversify the city's urban forest through large-scale street tree planting, micro-forest patches, and integrated blue–green infrastructure, with the goal of reducing urban heat, improving air quality, increasing walkability, and enhancing the ecological and social performance of public spaces	Strengthens age-friendly environments by mitigating heat stress—one of the major environmental risks for older adults—while improving shade, thermal comfort, pedestrian safety and opportunities for low-intensity outdoor activity, thereby supporting healthier, more resilient ageing in dense urban areas
Pocket-Park Interventions in Copenhagen (Denmark)	2014–ongoing	To implement small-scale "lommepark" interventions—compact neighbourhood greenspaces integrated into streetscapes and residual plots—to provide shade, seating, and opportunities for informal social interaction	Demonstrates how distributed micro-greenspaces within dense urban districts can support restorative breaks, social contact, and safe outdoor mobility for older adults, enhancing wellbeing in high-density settings.
Singapore Therapeutic Gardens Network	2016–ongoing	To develop a network of accessible therapeutic and sensory gardens within neighbourhoods and urban parks to promote psychological restoration, stress reduction, and cognitive engagement—particularly supporting seniors, including those with mobility limitations or mild cognitive impairment	Demonstrates how restorative landscape infrastructures integrated into everyday public environments can enhance mental wellbeing, sensory stimulation, and emotional comfort in later life, contributing to age-friendly urban spaces that support cognitive health, relaxation and safe outdoor activity
Barcelona Superblocks Programme (Spain)	2016–ongoing	To reorganise the structure of urban blocks to prioritise pedestrians, reduce vehicular traffic, and increase green and social spaces for community interaction	Enhances active mobility and outdoor sociability, improving cardiovascular health, reducing environmental stressors and promoting community interaction among older residents

Table 3. Representative initiatives integrating Urban Green and Blue Infrastructure (UGBI) into age-friendly urban design

DISCUSSION: TOWARD INTEGRATIVE AND ADAPTIVE FRAMEWORKS FOR LONGEVITY-ENABLING URBAN DESIGN

Across contemporary debates on age-friendly urban design, a growing alignment across the literature recognises that prescriptive checklists, static indicators and technical standards are no longer adequate for guiding interventions in increasingly complex, dense and dynamic urban

Perillo, M., Nijkamp, J., Attaianese, E. (2025). Urban design across the life course: towards longevity-enabling environments. *Rivista Italiana Di Ergonomia*. 31. 99-114. DOI: 10.6093/RIE/13418

environments. Although international frameworks, from the WHO Age-Friendly Cities agenda to the UN Decade of Healthy Ageing, have consolidated important normative foundations, their operational translation into urban design practice remains fragmented. Persistent gaps concern the limited ability of existing instruments to link environmental performance, experiential qualities and health outcomes (Kano et al., 2017; UNECE, 2018; Buffel & Phillipson, 2018). A central limitation concerns the lack of integration of emerging digital and smart city technologies and urban green and blue infrastructure strategies, two domains that have become structurally decisive for later life wellbeing. Even though UGBI is widely recognised for its contributions to microclimatic regulation, restorative benefits and enhanced walkability, qualities of particular value for older adults who are sensitive to heat, noise and environmental stressors (Dennis et al., 2019; Davern et al., 2020; WHO, 2021), these insights remain marginal within mainstream age-friendly standards. Similarly, rapid advances in IoT ecosystems, Local Digital Twins and AI-supported monitoring present substantial opportunities for older adults, offering enhanced environmental sensing, early risk detection and more responsive urban services that can support autonomy and safety in daily mobility (Wood et al., 2022; D'Onofrio et al., 2022). Yet their integration into guidelines often overlooks issues of usability, trust, behavioural adaptability and data governance. These gaps reveal a structural mismatch in which contemporary urban environments are increasingly shaped by densification pressures, technological infrastructures and climatic instability. Consequently, current frameworks struggle to articulate how environmental, technological and experiential dimensions interact to shape autonomy, mobility and wellbeing across their life course. Therefore, these limitations underscore the need for a new generation of instruments through integrative and adaptive approaches that connect environmental performance (e.g. microclimate regulation, ecological connectivity, accessibility), experiential qualities (e.g. comfort, legibility, perceived safety), and health and wellbeing outcomes (e.g. stress recovery, functional ability, resilience). Adopting an ergonomics and human factors lens helps clarify that these challenges are partly rooted in a narrow operationalisation of accessibility that tends to overlook the interdependence between usability, sensory comfort, environmental performance and behavioural adaptability. Thus, an ergonomics-informed perspective provides a conceptual bridge for integrating emerging digital technologies and UGBI into holistic models of environmental support for ageing populations, as it explicitly positions human–environment interaction at the core of everyday functioning and of the adaptive and inclusive design strategies. Within this expanded operational and conceptual landscape, the paper advances the transition from age-friendly urban environments to longevity-enabling environments. This shift reframes the goal from providing universally "age-friendly" features to designing dynamic socio-environmental systems capable of sustaining functional ability, autonomy and wellbeing across the entire life course. The longevity-enabling approach to urban environments foregrounds the need to monitor and respond to the continuous interaction between changing individual capabilities of users and evolving environmental conditions. In this perspective, a proactive orientation provides a strong pathway for including digital technologies and UGBI into contemporary urban design practices, strengthening their potential to sustain functional ability and support more adaptive, future-ready environments.

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SHORT BIO

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