

ERGONOMIA

ORGANO UFFICIALE DELLA S.I.E. - SOCIETÀ ITALIANA DI ERGONOMIA

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- COLLABORATIVE PRODUCTS
- AGE-INCLUSIVE ENVIRONMENTAL DASHBOARD DESIGN
- THE GESTALT OF THE WHEELCHAIR
- INVESTIGATING CONSUMER PREFERENCES IN CHOOSING GARMENTS
- DISCONNECTION AND BELONGING IN
- FULL REMOTE TEAMS
- NEW TECHNOLOGIES FOR SPACE PERCEPTION
- DESIGNING THE FUTURE OF WORKWEAR
- AN ERGONOMIC APPROACH TO THE INCLUSIVE DESIGN OF INDUSTRIAL COBOTS FOR OLDER WORKERS

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RIVISTA ITALIANA DI ERGONOMIA

THE RIVISTA ITALIANA DI ERGONOMIA, of the S.I.E. - Italian Society of Ergonomics, is a scientific journal that operates nationally and internationally for the promotion and development of ergonomics and the study of human factors, and the dissemination and systematization of knowledge and experiences related to the ergonomic approach, in close relationship with the social, environmental and productive realities where human beings, operate and live, coherently with the goals of the SIE.

Supported by an international scientific committee and using a double-blind reviewing process, the journal publishes original contributions from research and applications on ergonomic issues, in its various aspects and related to the different contexts and human activities.

The RIVISTA ITALIANA DI ERGONOMIA is aimed at ergonomic professionals and all those interested in applying the principles and methods of ergonomics / human factors in the design, planning and management of technical and social systems, in work or in leisure.

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EDITORIAL

ERMINIA ATTAIANESE



Evolving trends and challenges in applied ergonomics and human factors: people, technology, and the environment

Several megatrends are reshaping lifestyles and work systems, creating new needs and risks for the planet and for the well-being of populations. Climate issues, demographics, urbanization, economic growth, energy consumption, connectivity, and geopolitics are key strategic forces shaping society and connecting people, technology, and the environment.

One of the key factors driving these interconnected changes is the rising number of elderly populations, which has a direct impact on both economic growth (e.g., new products and services, attention on active ageing and independent living, resilient work conditions etc.) and social inequalities (i.e., market offers that do not meet the users' needs). It affects intergenerational relationships and perceptions of fairness in society, while also being linked to other major concerns, including resources, climate change, conflicts, migration, and healthcare. On the other hand, climate change remains one of humanity's most critical challenges. The warming of the planet poses a threat to food security, freshwater supplies, and human health, particularly for vulnerable populations. Both technical and social systems must find solutions to manage these risks, working on system change to promote different behaviors.

Today's aging society presents challenges to work systems. The increasing number of older workers is creating a more age-diverse workforce, where older employees are interacting with much younger, digitally native colleagues in a work environment characterized by significant age differences. These differences not only affect physical abilities but also cognitive, cultural, and behavioral characteristics. At the same time, a new industrial revolution is underway, replacing traditional work environments and organizational systems with innovative technologies such as collaborative robots, exoskeletons, and augmented reality. In the digital industry, people and technologies must integrate closely and intensively. The growing diversity in the psychological and physical characteristics of the workforce presents challenges in designing and managing systems. Rapid technological advances are increasingly shaping digital and innovative work contexts. A wide range of activities has undergone significant changes, often no longer confined to traditional settings or fixed organizational structures. Sociotechnical systems must adapt to society's changing needs by applying new paradigms and perspectives to develop usable and sustainable solutions for improving how we live and age. By leveraging both physical and digital solutions, individuals and organizations can be provided with the best possible chance to achieve their goals, not only by optimizing resources to increase effectiveness and efficiency but also by being assistive and caring for both humans and the planet.

Applied Ergonomics and Human Factors play a fundamental role in addressing the complex challenges posed by contemporary megatrends. The links between aging populations, climate change, and rapid technological advancements present innovative opportunities for novel studies that can foresee liveable scenarios and the need for innovative tools to advance the body of knowledge.

The aim of Issue 30 of the *Rivista Italiana di Ergonomia/Italian Journal of Ergonomics* was to collect international contributions to fuel the debate on how the integration of human factors into sociotechnical systems can lead to sustainable solutions that enhance productivity and quality of life while prioritizing human and environmental well-being. By

emphasizing the interplay between people, technology, and the environment, the issue's ambition was to focus on how applied ergonomics can drive meaningful change and support the development of resilient work and life systems.

Upon examining the selected articles in the volume, this ambition has been fulfilled: all the topics face, from different perspectives, some of the most pressing socio-technical challenges of today, is discussed through the lens of human factors and ergonomics and reshaped in the light of the human-centred approach.

Users' diversity, including an increasing elderly population and diverse age groups, is confirmed as one of the main questions to address in a societal context characterized by a strong pervasion of digital technologies in daily life. The call for fostering interactions among different age groups emerges, but because so much social interaction now occurs online, there is a need to overcome the generational divide in the use of digital devices, which seems also to be a contributing factor to the increasing isolation of the elderly. The age-friendly dimension of technological systems is a goal that must guide the interface design of devices today, to which ergonomics can make a significant contribution. In this direction, the study presented by Giorgio Dall'Osso, Ludovica Rosato, and Giulia De Camillis appears to reinforce a positive paradox, suggesting that digital technologies can facilitate face-to-face collaboration if interfaces are co-designed with final users, for addressing the abilities and limitations of the intended users. Particularly collaborative products design, may be seen as effective driver for inclusivity promotion and engagement, if this devices are able to link ergonomics principles to inclusive practices. The issue of the generational divide in the use of digital devices, and the need to design these devices to meet the specific needs of elderly users, is also explored in the contribution by Alessio Caccamo and Mattia Francesco Ucciello. They examine the ergonomic features of environmental monitoring dashboards through the lens of age-inclusive design. Their evaluation of twelve modern environmental dashboards, tested by users from various age groups, reveals significant accessibility concerns for older professionals. The age-inclusive design parameters and

guidelines they propose for environmental dashboards support ergonomic solution to address the combined challenges posed by an aging population and the growing need for effective climate change monitoring and adaptation strategies.

As the elderly population becomes an increasingly significant part of both the current and future workforce, new working systems must take their age-related needs into account.

Enrica Cunico's contribution addresses this challenge by exploring how collaborative robots (cobots) can support older workers to alleviate their workload, although current regulations prioritize safety over ergonomics. Ergonomic design plays a crucial role in this regard. A user-friendly and intuitive interaction, enriched by insights from social robotics, is key to fostering acceptance. Moreover, an ethical and multidisciplinary approach is essential to promote inclusivity and well-being within a diverse workforce.

Diversity among people is a crucial aspect of the inclusive dimension of sustainability. In particular, people with disabilities may not always have equal access to available resources and are disproportionately at risk in any critical situation that may arise. Mobility is a fundamental right, as it is closely linked to autonomy and social participation. While the wheelchair is often seen as the symbol of motor disability, it continues to carry stigmatizing connotations despite technological advancements. Edoardo Amoroso, Ivo Caruso, Silvana Donatiello, and Mariarita Gagliardi contribution try to open a debate starting from the following question: what scenarios can merge digital technologies and digital fabrication in overcoming the traditional challenges faced by people with disabilities? They explore the evolution of the wheelchair, investigating how s 3D printing, parametric design, and AI, along with cultural shifts and media influence, can enhance its performance, by increasing customization, and normalization of use. These advancements, however, need to be driven by user-centered strategies and solutions to be truly effective and fully satisfying.

Similarly, digital technology can play a crucial role in enhancing spatial perception for individuals with visual impairments, as explored by Daniele De Pascale. His work investigates how emerging technologies can support spatial

awareness by offering alternative, non-visual ways of experiencing space. Through case studies, he explores how assistive devices and multisensory approaches help foster greater autonomy and independence. Given the challenges of navigating space without sight, integrating cutting-edge tools in a human factors perspective, is essential for promoting inclusion and improving daily navigation and interaction with the environment.

The volume also highlights concerns the pervasive nature of digital technologies and their potential to either enhance or hinder human performance, activities, and behaviors in the current complex social and environmental landscape. The contribution by Valentina Bonafaccia focuses on full remote work, discussing how it has led to relational disconnection and weakened team cohesion. Through the presentation of a case study concerning a bottom-up ergonomic initiative involving 12 professionals in thematic micro-groups with facilitated meetings, she underscores the importance of aligning participatory practices with systemic support to sustain relational well-being in remote work environments. In fact, the intervention initially fostered engagement and collaboration, but its impact was ultimately limited by a lack of organizational recognition and integration.

The design of future workwear is another example of how smart solutions have the potential to significantly enhance users' quality of life, while also highlighting ergonomic challenges and potential issues. The results presented by Ilaria Di Carlantonio, Martina Frausin, and Alessia Buffagni address this by critically discussing design approaches for future workwear, aimed at managing increased heat stress due to rising global temperatures and extreme weather conditions, while ensuring comfort and health.

Finally, Hanieh Alipou, Seyed Hashem Mosaddad, Omid Mozayani, Parnia Malekpour, and Daniel Akbariani investigate consumer preferences in garment selection, presenting a study on Origami-based design. By identifying the factors that shape user preferences, their findings highlight that emotional responses and past experiences play a significant role in purchase decisions.

ERMINIA ATTAIANESE

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Collaborative Products: Design Practices for Enabling Intersubjective Interaction



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Keywords: Collaborative Products, Co-design, Participation

Abstract

This paper investigates *Collaborative Products*—design artifacts that require the active and synchronous participation of multiple users—as a strategy to promote inclusive and intersubjective interaction. Motivated by the need to create socially and culturally responsive design solutions, the study explores how these objects can foster cooperation, shared responsibility, and relational engagement.

A mixed-method approach was adopted, combining theoretical analysis with empirical exploration. A conceptual framework was developed using typological-temporal and typological-spatial diagrams to classify collaborative design practices. A selection of case studies—both experimental and existing—were analyzed, each case was examined in terms of user composition, ergonomic requirements, and spatial-temporal structure.

Findings reveal that *Collaborative Products* are relational devices that promote accessibility, inclusivity, and engagement through task distribution and shared effort. The research identifies recurring design strategies that link ergonomic principles—such as visi-

bility, usability, and affordance—with inclusive practices. The study concludes by proposing a methodological framework to support future design initiatives aiming to cultivate participation, social cohesion, and meaningful human interaction.

Intersubjective Approaches to Collaborative Activities

Contemporary approaches to design do not limit themselves to considering only the real user (Tosi, 2007), identified during the targeting phase, but rather carry out an in-depth analysis of the entire system of people who come into contact with the project, both directly and indirectly (Sicklinger, 2020), throughout all stages of the life cycle of products, whether tangible or intangible. This expanded focus on the whole system in which artefacts are situated leads to modern perspectives that view the ergonomics and design disciplines require intersubjective analyses (Talamo & Pozzi, 2011), capable of interpreting the experiences of all the actors involved, both individually and collectively.

The complexity of many contemporary issues requires design to adopt strategies capable of simultaneously interpreting and connecting objects, contexts, and events (Easterling, 2021). In this research, we aim to explore in particular those dimensions of design that emerge from a unified reading of the multiple experiences of the individuals involved, in a specific place and time, within a collaborative activity. In such situations, design products contribute to suggesting and conveying behaviours oriented toward a shared goal.

Collaboration is an intersubjective strategy that, within a complex system, can generate effective solutions. It relies on a multiplicity of actors, needs, and constraints, enabling a type of analysis that is inclusive and open to a unified interpretation of the system under examination. Numerous examples can be found in studies focused on improving the efficiency and dynamism of project teams within companies (Hutchison-Krupat & Chao, 2014). These studies clearly show that collaborative solutions do not merely outline operational methods, but instead propose renewed paradigms that impact the knowledge, values, and innovation of all stakeholders involved. When well-structured, coordination activities allow for the visibility and valorisation of the participants' skills, as well as the distribution of specific roles and responsibilities. This, in turn, can lead to increased motivation, a higher perceived quality of the experience, and ulti-

mately, a stronger sense of belonging. An evaluative investigation of design dynamics that can guide individuals toward collaboration across different fields of design appears to have clear implications not only for studies in ergonomics but also for the broader domain of human-environment interaction.

Collaborative activities, stemming from intersubjective approaches, make it possible to orient design projects toward inclusive scenarios involving different cultures, generations (Harley et al., 2012), and species (Meijer, 2017). Design for collaboration thus enables the creation of tools that support the development of meaningful relationships within socially and culturally inclusive environments, while also fostering practices of coexistence, mutual respect, and care.

A Diversity of Practices and Fields in the Design of Collaboration

In order to systematically analyse the wide variety of approaches that design adopts to support collaborative activities, we employ a Cartesian representation in which two conceptual axes intersect. Along the horizontal axis, we position on one side the domain of communicative objects, and on the other, that of functional objects. The former includes both material and immaterial projects aimed at facilitating the exchange of information between individuals; the latter refers to projects that address concrete needs by performing a specific and practical task.

On the vertical axis, two possible distinctions are proposed: one expressing the temporal variable and the other the spatial variable. In the first diagram, the temporal dimension is represented by the opposition between synchronous (or simultaneous) activities and asynchronous ones. In the second diagram, the spatial dimension is expressed through the contrast between same-place and remote-place interactions. These models make it possible to identify several operational macro-areas within which the multiple facets of collaborative design can be situated.

Typological-Temporal and Typological-Spatial Diagrams

In the typological/temporal diagram (Fig. 1), within the bottom-left quadrant—resulting from the convergence of asynchronous activities and communicative products—are design approaches aimed at collecting information from a plurality of actors. This quadrant includes

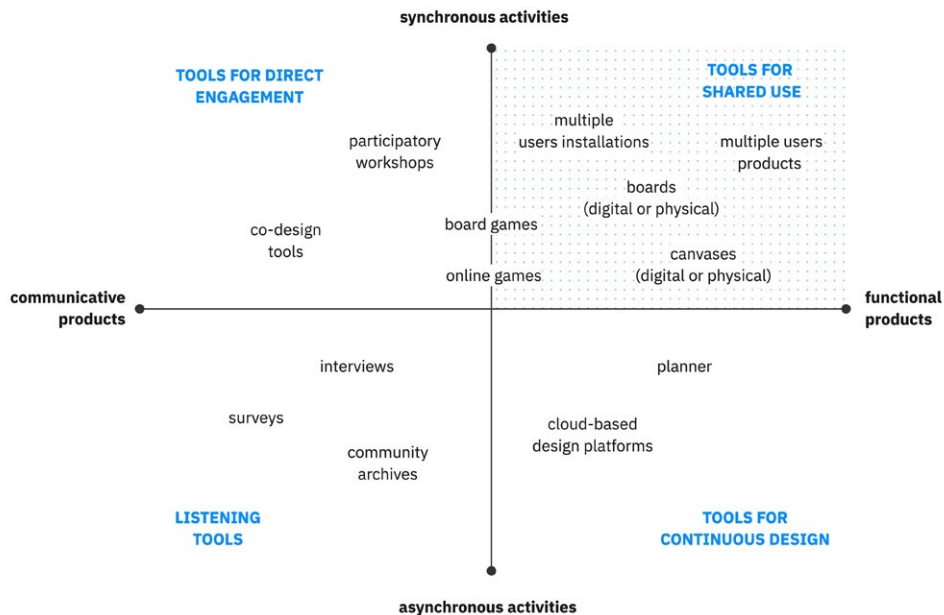


Figure 1. Typological-temporal diagram.

both opinion-gathering systems (e.g., surveys, interviews) and data collection systems such as community archives (Flinn, 2007). Therefore, the projects grouped here can be defined as listening tools.

In the quadrant defined by communicative products and synchronous activities are design practices aimed at directly engaging participants; examples include participatory workshops and typical co-design tools. Regarding functional products, the quadrant of asynchronous activities encompasses tools dedicated to continuous design processes, such as work organization software or cloud-based design platforms. In contrast, synchronous activities involve projects intended for shared use, such as canvases or boards (digital or physical), interactive installations requiring the joint action of multiple users (e.g., interactive projections in museum environments), or objects operated simultaneously by several people (e.g., tandem bicycles, two-handled saws, ploughs, etc.).

In the second diagram, the typological/spatial one, we observe that the previously identified categories largely retain their positions, with a general tendency to shift downward—that is, toward collaborative

activities possible even in remote locations. Actions requiring direct involvement and objects designed for use by multiple users remain within the quadrants associated with same-place activities.

Observing both diagrams, it is evident that tools incorporating digital components are well represented across all quadrants, whereas strictly physical projects are predominantly found in the quadrants related to synchronous activities (Fig. 2). This pattern appears to stem from the capabilities enabled by the digitalization of tools.

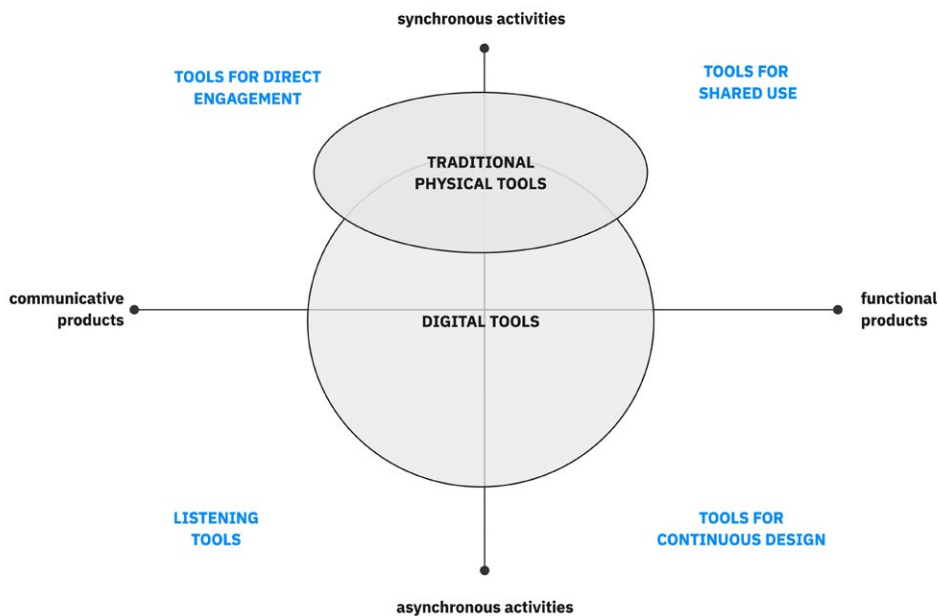


Figure 2. Typological-temporal diagram.

The Scale of Collaboration

A transversal variable in the analysis of collaborative practices is the dimension of participation scale. Some design initiatives are conceived to involve an undefined, potentially large number of people. These initiatives are exemplified in areas such as community-centered design (Meroni, 2008; Villari, 2021), support for placemaking actions (Granata, 2021), or placekeeping. In these contexts, the quality of engagement is directly proportional to the collective validation of

design choices. Conversely, there are initiatives aimed at small working groups, where relational density and role specialization emerge as central elements.

Multi-User Objects: Opportunity or Necessity?

Finally, an additional variable emerges that allows for a more precise distinction of the characteristics of collaborative design initiatives. Most of the categories represented in these diagrams are based on the possibility of involving multiple users within a specific communication or production activity. However, these projects could also be used by a single individual at one or more specific moments. In contrast, some initiatives necessarily require collaboration. To achieve their objectives, two or more people must collaborate. Viewed through the lens of collaboration necessity, our diagrams become significantly simplified.

Research Objectives and Methodology

In this study, we propose an analysis and definition of *Collaborative Products*—objects that create situations of sharing and collaboration within the same space, encouraging individuals to engage with others through synchronous multi-user activities. Referring to the previously mentioned typological/temporal and typological/spatial collaborative design diagrams, we specifically focus on those products located in the upper-right quadrant of the diagrams, which promote activities where collaboration is necessary to ensure the effective usability of a product.

This contribution aims to explore potential design strategies that designers can adopt to activate participatory action. To this end, a selection of case studies involving collaborative products and systems was collected, and two design projects were developed in parallel.

The case studies are categorized into two groups: actual collaborative products derived from industrial solutions and conceptual design projects (n=16); and categories that include multiple projects, such as shared digital archives, collaborative canvases, and similar platforms (n=11). The projects were developed with the involvement of students from the Design degree programs at the University of Bologna through two pathways: a project conducted within a design studio course and a master's thesis. Both projects were informed by analyses concerning the number and type of users involved, the functional response to the intended form of inclusion, the types of input required to activate human action, and the context in which the intervention was to be

implemented. The two most significant case studies of collaborative objects, together with the student projects, were analyzed using a matrix highlighting, for each case, the ergonomic requirements (Tosi, 2018)—including functionality, safety, accessibility, usability, visibility and affordance, emotional and perceptual components, and social models and behavioral components—in relation to the critical issues or opportunities for development from a collaborative perspective. This analysis made it possible to identify design practices applicable to innovative design scenarios.

In the conclusions, the main findings are systematized, and several potential design practices are proposed. These practices illustrate how product design can activate social, cultural, and emotional conditions of sharing and collaboration through objects specifically designed to foster an inclusive relational system.

Contemporary Collaborative Products as a Design Strategy for Inclusivity

In this context, the research focuses on *Collaborative Products*, understood as tools that activate social relationships and dynamics of mutual aid, enhancing individual abilities within shared processes. Their effectiveness is based on the presence of the other: collaboration is not an option, but a necessary condition for their functioning, requiring coordination, interaction, and the construction of a common rhythm.

During the research process, few cases emerged that fully met the definition of *collaborative product* as we have adopted it. Most of the identified examples concern digital experiences in which sharing is primarily emotional, and the outcome of the process is also digital in nature. *Building Hopes* by Giorgia Lupi¹, for instance, is an interactive augmented reality installation that transforms answers to the question “What gives you hope?” into abstract visualizations. Each participant contributes an emotional datum that flows into a collective composition, activating processes of personal reflection and empathetic connection. The work fosters visual, participatory, and narrative interactions, making data a vehicle for relationship-building. However, in this case, interaction occurs exclusively in a digital environment, lacking a physical dimension or a form of mutual aid—both of which are central to collaborative products.

A physical dimension is instead present in *River of Grass* by formula D_², an interactive immersive environment designed for the Patricia

¹ <https://giorgialupi.com/building-hopes>

² https://formula-d.com/our_work/river-of-grass-immersive-environment/

and Philip Frost Museum of Science, which introduces children to the Everglades ecosystem through play. Participants explore animated landscapes and local species via wall and floor projections, encouraging learning and environmental awareness through narrative and embodied interaction. Despite the physical involvement, the experience does not involve genuine collaboration among users, making it only partially aligned with the criteria identified.

³ [https://
alexandergrasser.com/
VoxelCO](https://alexandergrasser.com/VoxelCO)

More in line with our definition is VoXelCO by Alexander Grasser³, a modular collaborative system in which remote users co-design physical structures through a shared digital interface. Each intervention generates a tangible transformation in space, carried out by robotic actuators, thus activating a distributed form of cooperation between humans and machines, based on reciprocal contribution. However, even in this case, the objective remains primarily design-oriented, without a direct focus on social inclusion.

Additional collaborative products fall within the realm of games (e.g., teqball courts, seesaws), the realm of work (two-handed saws, ancient ploughs, emergency stretchers, walkie-talkies), and other areas (tandems, rickshaws).

The research thus highlighted the difficulty of identifying products that fully integrate all the essential characteristics of collaborative products. Many cases include relevant elements but remain partial in relation to the adopted definition. In this contribution, we will present four case studies that we believe comprehensively represent this design category.

Building on these reflections, the research is structured around two types of case studies: on one hand, exemplary cases selected for their inspirational value and their capacity to represent the essence of *Collaborative Products*— in particular, *Sidekicks* and the *Teamwork* installation; on the other hand, experimental cases developed within the project to concretely test the analyzed theoretical principles. Two projects will be examined in greater detail: the collaborative carder and the digital scorekeeper *Smatch*.

These case studies were selected because they represent strictly *Collaborative Products*, expressions of a design approach that centers on relationships, encounter, and care through simple devices capable of generating social and cultural value.

Sidekicks: A Projector Designed for Collaborative Interaction

The Sidekicks projector (Fig. 3) (“Matteo Bandi’s Device-Powered Objects Designed to Beat Smartphone Addiction,” 2018) represents a collaborative device that encourages sharing and mutual presence. Designed to be used simultaneously by two people, the projector activates only when both users physically insert their smartphones inside it, which serve as the light and content source. In this way, the visual experience cannot be enjoyed individually: the participation of both users is necessary for the projection to take place. The act of “leaving” one’s phone thus becomes a synchronized and symbolic gesture, temporarily disabling the personal screen—often a source of distraction and isolation—to make room for a more intimate and immersive shared viewing moment. Sidekicks therefore configure itself as a relational object, placing collaboration at the core as an essential condition for accessing the experience, transforming an everyday action into a small collective ritual.



Figure 3. Sidekicks

Teamwork Installation

Similarly significant is one of the interactive installations *Teamwork* created by the design studio Migliore+Servetto for the exhibition *The Home of The Human Safety Net* in Venice (Migliore & Servetto, 2024). The installation consists of a horizontal model onto which lights and

images are projected: the projection activates only through the joint action of two people. Each user is invited to turn a knob, but for the content to become fully visible, both users must continuously and synchronously rotate their respective knobs. Only through coordination and the establishment of a shared rhythm is it possible to achieve a clear view. Thus, the installation makes the value of collaboration visible, transforming the interaction between people into an essential condition to access the narrative and experiential content.

Collaborative Carding Machine

The *collaborative carder* project (Fig. 4) was developed as part of a master's thesis in Advanced Design by Giulia De Camillis, aiming to explore the potential of *Collaborative Products* in promoting social inclusion. The *collaborative carder* was designed in response to an analysis of the physical, cognitive, and relational challenges faced by elderly people, with particular attention to mobility limitations and social isolation.

Intervening in a traditionally manual activity, such as carding, reflects the desire to valorize artisanal practices with strong cultural potential, which are often inaccessible to this target group due to their operational complexity. Focusing on the carding process highlights the value of simple yet demanding activities, which, if undertaken alone, can be tiring and difficult to access. The project symbolically and functionally divides the effort required to perform the task by distributing it between two users. By making the activity shared, it overcomes individual limitations, transforming a strenuous task into an accessible and participatory experience.

The formal and functional design choices of the device, intended for simultaneous use by two people, stimulate user interaction and engagement (Fig. 5). The actions are supported by the adoption of contrasting colors aimed at facilitating the identification of the product's components, thus guiding users in operating the device. The design was focused on ergonomics and accessibility to minimize physical effort and ease use. Elements such as the pantograph mechanism, the mobile trolley, and the non-slip handles align with this logic, ensuring comfort, safety, and usability.

Moreover, the *collaborative carder* is intended to be placed in public and community spaces, such as neighborhood centers, to further enhance the social dimension of the activity and encourage opportunities for gathering and participation.

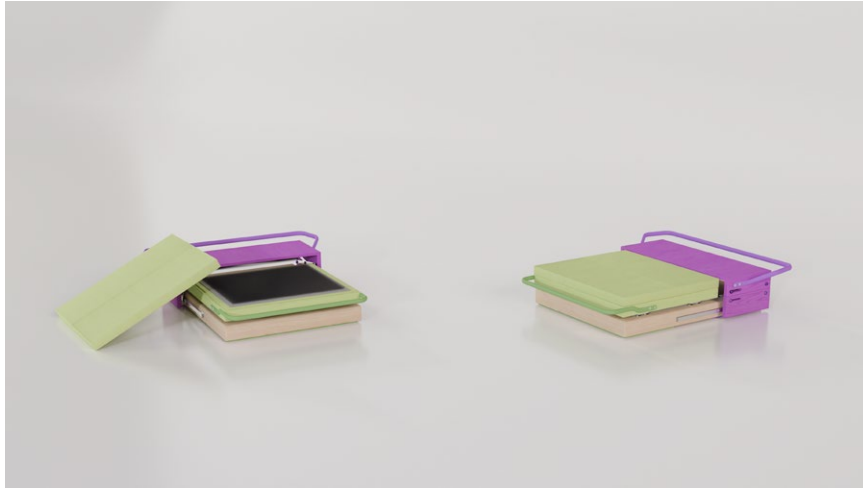


Figure 4-5. Collaborative carder

Smatch: A Digital Scoreboard

The digital scoreboard Smatch (Fig. 6) represents a second experimental case study of a Collaborative Products. Developed within the Advanced Design degree program⁴, it was designed to foster intergenerational relationships within public space (D'Alessandro & Dall'Osso, 2024).

Situated in the urban context, *Smatch* emerges from the observation of a widespread dynamic: elderly people often inhabit public spaces as silent spectators of young people's activities, without finding real opportunities for involvement. In this scenario, the object functions as a

⁴ The Smatch project was conceived by R. Montemurro, D. Paccamonti, F. Piattellini, F. Scalise F. Vespasiano.

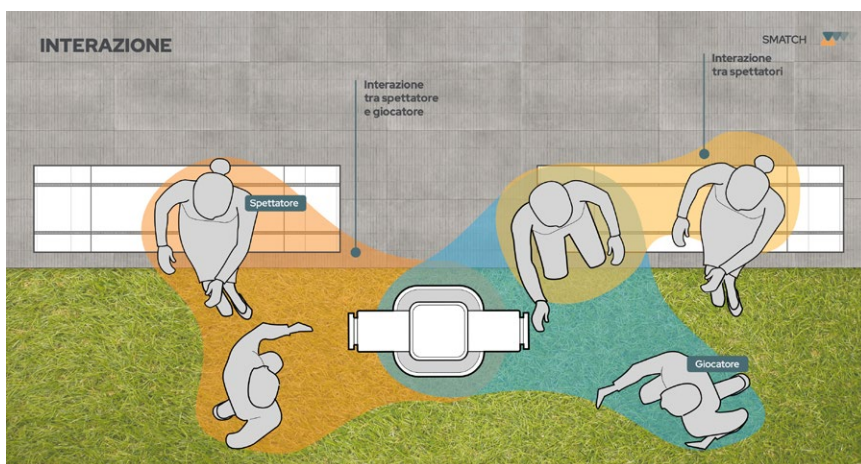


Figure 6-7. Smatch.

bridging device, capable of activating simple and accessible participation through the act of scoring points—particularly by older individuals—during games played on park sports fields. Its operation requires interaction between players and observers, establishing a direct connection between generations.

The spatial positioning of the object in public space is carefully considered: placed at a distance from the play area, it allows children the freedom to move, while its proximity to benches ensures accessibility for older adults, encouraging effortless and immediate interaction (Fig. 7). In this way, collaboration is not optional but necessary, and *Smatch* creates the spatial conditions for an encounter, trans-

forming an ordinary urban space into a place of engagement and relational exchange. The action, enhanced by tactile and luminous feedback, is designed to be inclusive and intuitive, as it does not require digital skills or explicit numerical literacy.

Designing for Collaboration: Towards a Relational Framework

From the analysis of the case studies, it emerges that collaboration is a structural—not accessory—component; a necessary condition for activating the user experience. The observed devices highlight the potential of design to enable forms of interaction, inclusion, and participation. Based on this evidence, it has been possible to relate the recurring features of *Collaborative Products* to ergonomic requirements, paving the way for the definition of design practices that broaden the meaning of those requirements through a relational lens.

Design Practices for Collaborative Products

Ergonomic requirements are the parameters to which a design must respond in order to meet the needs of the people it engages with (Tosi, 2018). To develop design guidelines useful to product designers, we connected ergonomic requirements with the characteristics of *Collaborative Products* that emerged from the analysis of case studies and experimental projects. The resulting design practices extend the meaning of ergonomic requirements to suggest directions for the design of *Collaborative Products*.

ERGONOMIC REQUIREMENTS (Tosi, 2018)	COLLABORATIVE PRODUCTS opportunities	design considerations	design practices
Functionality			
Safety		Ensuring safety for all users	
Accessibility	Collaborative use enabling access for users with limitations		<ul style="list-style-type: none"> • Combining efforts allows users to achieve the intended function according to their abilities. • Task division enables users to complement each other's motor or perceptual skills to reach a shared goal.
Usability	<ul style="list-style-type: none"> • Multiple users divide tasks and subtasks to ensure usability. • Resources are shared based on users' motor and cognitive abilities. • Each user contributes within their means, fostering mutual support and collaboration. 	Ensuring learnability and memorability for every user	<ul style="list-style-type: none"> • Task and time division make collaboration essential to activate the product. • Combining efforts maximizes available resources based on users' abilities and space. • Including users with diverse abilities enhances satisfaction. • Relational space is built by guiding users' actions toward shared focus.
Visibility and Affordance	New interaction opportunities: Designing controls for multi-user engagement	Ensuring command recognizability to support product functionality	<ul style="list-style-type: none"> • Different stations to ensure command recognizability • Identical stations with synchronous actions • Recognizability of stations and commands through language, form, and material
Emotional and perceptual component	Interaction of multiple subjectivities	Interaction of multiple subjectivities	
Social models and behavioral component	Interaction across culturally diverse user groups	Interaction across culturally diverse user groups	

Figure 8. Ergonomic requirements table.

We developed a table (Fig. 8) that links ergonomic requirements with *Collaborative Products* by analyzing opportunities, design considerations, and design practices. Some ergonomic requirements do not generate specific design practices, as they are by definition transversal to any ergonomics-related project. Accessibility, usability, visibility, and affordance, on the other hand, require specific definitions, as they are strongly influenced by the number and type of users, as well as by the time and place in which the product is used.

Accessibility

Accessibility refers to the possibility for individuals with reduced mobility or limited motor or sensory abilities to use an object. *Collaborative products* enable interaction and cooperation among individuals with different abilities by distributing tasks in a way that makes their capabilities complementary. In the presence of motor limitations (e.g., reduced finger strength or range of motion that hinders turning handles) or perceptual limitations (e.g., visual or tactile perception, attention span), the following strategies can be applied:

- Distributing physical effort, allowing users to collaborate and combine their energy to achieve a function. In the *Collaborative Carder* project, two users can activate the mechanism using trolleys and pantographs, reducing individual effort and utilizing shared force to generate motion.
- Dividing tasks so that users' motor or perceptual abilities can complement one another, enabling them to collaboratively perform the intended function of the product. In the *Smatch* project, one user marks points while the other sets the game mode, leveraging complementary abilities.

Usability

Usability supports the achievement of objectives such as effectiveness, efficiency, and user satisfaction. Effectiveness refers to how fully people reach intended goals, efficiency concerns the resources spent relative to those goals, and satisfaction is the absence of discomfort in using the product (Tosi, 2018). In applying the proposed practices, a key aspect is designing the timing and spatial distribution of individual contributions based on users' available resources.

- To ensure effectiveness, it is necessary to distribute tasks and usage times so that the product's function can only be achieved through user collaboration. In the *Sidekiks* project, projection is activated

only when both users place their mobile phones into the projector. Moreover, this project introduces an additional interesting design element by removing potential distractions (such as mobile phones) in the shared space to foster collaboration.

- To ensure efficiency, it is possible to leverage the resources of all users involved by designing task distribution methods based on each individual's specific abilities. In *Smatch*, the system leverages the competencies and interactions of users from different generations to manage scoring and game modes effectively and fluidly.
- The inclusion of users with diverse abilities contributes to user satisfaction. The *Collaborative Carder* project allows people with limited mobility to participate in a meaningful and shared process. This approach improves user satisfaction by enabling each participant to contribute according to their means, fostering supportive and collaborative engagement.

Visibility and Affordance

The visibility of an object's parts or components determines how well users can identify their functions. Designing command visibility in multi-user products can foster new interaction opportunities—for example, controls that require input from multiple users. At the same time, this approach must ensure that all involved users can recognize the newly designed controls.

Affordance (Norman, 2013) refers to the real and perceived properties that indicate how an object can be used. For *Collaborative Products*, it is crucial that these properties are recognizable by all users in order to fulfill the product's functionality.

Based on the conducted research, we identified three design strategies:

- Providing distinct stations to ensure command recognition. In the *Collaborative Carder*, each user has their own station with visually differentiated controls, aiding action recognition.
- Designing identical stations where energy or task are distributed. As in the *Teamwork* installation, the projector is activated only when two identical knobs at separate stations are turned simultaneously.
- Making stations and commands recognizable through material, shape, and language differentiation. In the *Collaborative Carder*, the two user stations are distinguished by color.

Conclusions

This paper presents a research project situated within the field of product design and, more broadly, within collaborative, intersubjective, and inclusive design approaches. The aim of the study is to offer a comprehensive analysis of so-called *Collaborative Products*—artifacts designed to prompt people to engage with one another through synchronous, multi-user activities.

Collaborative Products represent an object category that is still underrepresented in contemporary design, largely because digital technologies allow for shared actions without requiring users to be present in the same place at the same time. The analysis of selected design projects, along with experimental work conducted by the researchers, made it possible to identify a set of recurring characteristics, summarized as follows:

- Task fragmentation and distribution (combining the energy of multiple people; dividing tasks based on the complementary abilities of users).
- Simultaneity of action (spatial and temporal constraints that require coordination between multiple individuals).
- Visibility and recognizability of workstations (guiding each user toward their respective actions).
- Construction of a relational space (fostering interpersonal engagement through design constraints that encourage active participation).

The concept of *Collaborative Products* also reveals certain critical issues, particularly concerning the perception of meaning by end users. These objects focus on the process of action generation rather than the performance or efficiency with which the product's functional goal is achieved. This divergence contributes significantly to the limited adoption of such objects in private contexts.

Conversely, promising opportunities emerge for the development of new *Collaborative Products* intended for public spaces. These environments often reveal a clear need to promote social interaction among people from different generations and cultural backgrounds. In relation to these contexts, the study envisions the potential to expand the range of case studies through new projects. Real-world experimentation, combined with structured testing, may further reinforce the value of implementing *Collaborative Products* in spaces shared by communities.

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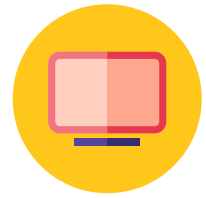
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Age-Inclusive Environmental Dashboard Design. How Ergonomic Interfaces Bridge Generational Gaps in Natural Capital Data Interpretation



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Keywords: Cognitive Ergonomics, Age-Adaptive Interfaces, Climate Monitoring Systems, Data Visualization, Information Design, Natural Capital

Abstract

The article analyses the ergonomic aspects of environmental monitoring dashboards from the perspective of age-inclusive design, addressing the dual challenges of demographic ageing and climate change monitoring. A multi-method assessment was conducted to evaluate the accessibility of twelve contemporary environmental dashboards to diverse age demographics. The present study adopted a multifaceted approach encompassing System Usability Scale measurements, Cairo's Visualisation Wheel analysis, Visual Vocabulary mapping, and a rigorous examination for adherence to recognised information design principles. The findings demonstrate a substantial correlation between interface complexity and age-related accessibility issues, with older users exhibit-

ing heightened vulnerability to data density, level of abstraction, and interaction discontinuity. Highly effective dashboards utilizing progressive disclosure principles and redundant visual coding effectively mitigate age-related performance differences. Multivariate analysis demonstrated that optimal ergonomic design can reduce the correlation between age and performance from $r=0.67$ to $r=0.23$ in environmental data interpretation tasks. These findings carry significant implications for socio-technical systems in environmental monitoring, particularly.

Ergonomics at the Nexus of Demographic and Climate Challenges

Natural capital management faces unprecedented challenges at the intersection of accelerating climate change and demographic ageing. Environmental monitoring dashboards function as critical interfaces between complex ecological systems and human decision-makers with varying technological literacy and cognitive processing capacity (IPCC, 2022). Contemporary workplaces comprise multiple generations, from digitally native younger workers to older colleagues with varying technological familiarity (Bennett et al., 2017).

The ergonomic challenges manifest in three areas: physically, interfaces must accommodate visual and motor abilities; cognitively, they must translate complex environmental data into understandable formats; and organizationally, they must facilitate collaborative decision-making across disciplines and generations.

Contemporary environmental management tools lack capabilities required to enable sustainable development in rapidly changing environments (Likwela et al., 2023). Environmental dashboards serve as cognitive interfaces between ecological processes and human decision-making, with ergonomic design directly influencing temporal responsiveness, interpretation accuracy, and adaptive potential.

Climate resilience depends on ecological knowledge transfer across generations. Experienced personnel must collaborate with subsequent generations to implement long-term adaptation measures (IPCC, 2022). Ergonomically designed interfaces serve as conduits for intergenerational knowledge transfer, overcoming disparities in technological literacy and cognitive processing styles. Delays in cognitive processing in environmental management can increase climate adaptation costs by 12-17% due to missed intervention opportunities (Newell et al., 2021).

Cognitive and Physical Ergonomics in Environmental Visualization

Environmental dashboards function as cognitive interfaces requiring adaptation to human information processing capabilities. Effective data visualization necessitates balanced consideration of cognitive dimensions, namely: abstraction/configuration, functionality/decoration, density/lightness, multidimensionality/unidimensionality, originality/familiarity, and novelty/redundancy (Cairo, 2016). These dimensions must account for age-related differences in processing speed, working memory capacity and attentional allocation. In this scenario, cognitive ergonomics becomes particularly salient in age-heterogeneous user populations. Older users prefer less dense information presentations with more explicit navigation cues, while younger users typically process higher information densities (Grainger et al., 2016). This cognitive divergence necessitates adaptive interface designs accommodating divergent processing styles while maintaining information integrity.

Physical dashboard ergonomics encompasses visual accessibility, motor control requirements, and adaptation to diverse physical abilities. Tufte's (2001) data-ink ratio provides a critical metric for evaluating graphical representations, emphasizing optimization of information-bearing components within data visualizations.

Older users encounter particular physical ergonomic challenges: adapted font size and contrast for vision changes; simplified interaction patterns for compromised motor precision; and information chunking for reduced extended visual focus capacity. Multimodal interaction across visual, auditory and haptic channels compensates for sensory impairments, ensuring information accessibility regardless of individual capabilities.

Indeed, effective environmental management depends on sharing reliable, relevant information across organizational boundaries. Dashboard organizational ergonomics concerns how interfaces support collaborative sense-making and decision-making among diverse stakeholder groups (Fancy & Bennetts, 2012). This collaborative capacity proves particularly important for intergenerational environmental management teams, with dashboards facilitating knowledge exchange between professionals with different disciplinary backgrounds and technical skills (Bennett & Gadlin, 2012).

Research Metodology

The study integrates conventional ergonomic evaluation methodologies with environmental dashboard-specific assessment techniques. Research was structured in three phases: (1) exploratory analysis of selected dashboards representing climate change, environmental and anthropogenic impacts; (2) systematic ergonomic analysis using standardized analytical models; and (3) interpretive integration of age-related ergonomic patterns. The selection criteria are presented as follow in Table 1.

Selection Aspect	Category/Criterion	Description
Inclusion Criteria	Public Accessibility	Platforms must be freely accessible without specialized subscriptions or institutional access requirements
	Environmental Focus	Dashboards must primarily display environmental, climate, or natural resource data
	Active Maintenance	Platforms must demonstrate regular updates within the past 12 months
	Multi-stakeholder Design	Interfaces must target diverse user groups rather than single-domain specialists
Exclusion Criteria	Proprietary or Restricted Access	Enterprise-only platforms, subscription-based services, or government-restricted databases
	Beta or Development Versions	Platforms in pre-release stages or marked as experimental
	Single-Language Interfaces	Non-English platforms without multilingual support capabilities
	Narrow Technical Focus	Highly specialized tools designed exclusively for scientific researchers
Search Strategy	Academic Database Search	Systematic review of environmental informatics literature (2020-2024) identifying mentioned platforms
	Government Portal Survey	Examination of major environmental agencies' recommended tools (EPA, EEA, UNEP)
	Stakeholder Consultation	Interviews with 15 environmental professionals across age demographics to identify commonly used platforms
Selection Rationale	Impact Category Distribution	Final selection of 12 dashboards represents three impact categories (4 platforms each): Climate Change Impact, Environmental Impact, and Anthropic Impact
	Design Diversity	Stratification ensures diverse visualization approaches, data types, and user interaction paradigms while maintaining comparability across evaluation metrics
Limitations	Geographic Bias	Bias toward Western-developed platforms
	Language Constraint	English-language limitation potentially excluding regional solutions
	Temporal Scope	Temporal snapshot representing 2024 availability rather than longitudinal platform evolution

Table 1. Dashboard selection criteria reflecting a socio-technical systems approach that considers multiple evaluation dimensions beyond mere technological features.

The framework categorizes dashboards by impact domain as shown in Table 2.

Impact Category	Platform Name	Description
Climate Change Impact	Copernicus Climate Atlas	Offers climate trend analysis and projections globally and regionally, supporting understanding of climate change impacts.
	NASA Earthdata Worldview	Interactive global satellite imagery viewer for real-time monitoring and climate applications.
	EEA Air Quality Dashboard	Displays real-time European air quality data, helping interpret pollution levels.
Environmental Impact	Global Forest Watch	Real-time monitoring of global forests to detect deforestation and support conservation.
	ReefCloud	Uses AI to analyze coral reef images for efficient reef health monitoring.
	GEMStat Water Quality	Provides scientifically validated global water quality data for environmental assessment.
	Natura 2000 Viewer	Shows EU protected areas under the Natura 2000 network for biodiversity preservation.
	AQI.in	Communicates daily air quality index and related health effects to the public.
Anthropic Impact	Yosemite Observer	Visual dashboard of weather, air quality, fire, and river conditions in Yosemite National Park.
	Eyc on the Reef	Citizen science tool for reporting coral reef conditions in the Great Barrier Reef.
	Global Fishing Watch	Tracks industrial fishing activities to support transparent, sustainable ocean management.
	MPA Monitor	Provides data and visualizations on Marine Protected Areas (MPAs) to support their management.

Table 2. Dashboard Selection Divided by Impact Category.

The research employed six complementary analytical tools, selected to capture the multidimensionality of ergonomic quality in environmental dashboard displays, as summarised in Table 3.

Platform Name	SUS Score	Decoration /Functionality	Complexity /Simplicity	Originality /Familiarity	Few's Principles	WCAG 2.2 Compliance Score	Data-Ink Ratio
Aqi.in	85	+1	+1	0	+1	4	1.35
EEA Air Quality Dashboard	70	0	-1	0	0	3	1.25
Copernicus Climate Atlas	65	0	-1	+1	0	3	1.20
ReefCloud	80	+1	+1	0	+1	4	1.30
Yosemite Observer Dashboard	68	0	0	0	0	3	1.25
Global Forest Watch	75	+1	0	0	+1	4	1.28
MPA Monitor	60	0	-1	-1	-1	2	1.15
Natura 2000 Viewer	65	0	-1	-1	-1	2	1.18
Eye on the Reef - Tourism	70	0	0	0	0	3	1.25
NASA Earthdata Worldview	68	0	-1	0	0	3	1.20
GEMStat Water Quality Dashboard	72	0	0	0	0	3	1.25
Global Fishing Watch	75	+1	0	0	+1	4	1.28

SUS Score: System Usability Scale score (0-100), where scores above 68 are considered above average.

Decoration/Functionality, Complexity/Simplicity, Originality/Familiarity: Evaluated using the Cairo Visualization Wheel, with scores of +1 (positive), 0 (neutral), and -1 (negative).

Few's Principles: Assessment based on adherence to Few's Information Design Principles, using the same scoring as above.

WCAG 2.2 Compliance Score: Overall accessibility compliance score on a scale from 0 (non-compliant) to 5 (fully compliant).

Data-Ink Ratio: Measure of data presentation efficiency, ranging from 0 (inefficient) to 1 (highly efficient).

The sampling method employed purposive stratification in order to ensure the full range of environmental dashboard stakeholders were included. The study comprised 126 respondents, stratified by age and divided into three groups: 18-30 (n=42), 31-55 (n=42) and 56+ (n=42). The study population was demographically representative, with 46% of participants identifying as female and 54% as male. Furthermore, 68% of respondents had received a tertiary education, while the remaining 32% had not. The heterogeneity of the participants was achieved through the inclusion of three broad user groups spanning different age demographics:

1. The study will focus on public administrators and policy makers aged between 30 and 45, between 46 and 60, and between 60 and 60+.
2. The present study will include environmental scientists and academics within the following age ranges: 25-40, 41-55, and 56+.
3. The demographic under discussion comprises members of civil society, categorised into three age groups: 18-30, 31-50, and 51+.

The age-stratified design enabled the evaluation of dashboard ergonomics across a range of technical expertise, professional orientation and age-related characteristics. The test methods employed encompassed quantitative assessments, including SUS scores, time on task, and error rate, as well as qualitative assessments, such as semi-structured interviews and think-aloud protocols.

Ergonomic Patterns in Environmental Dashboards

The ergonomic study revealed statistically significant relationships between interface design parameters and age-stratified usability metrics. System Usability Scale (SUS) scores demonstrated considerable variability (range: 60-85), with significant age-related perceptual pattern differences. Results demonstrated robust negative correlation ($r = -0.76$, $p < 0.01$) between perceived usability and interface complexity for older adults. In the 56+ group, higher data-to-ink ratios and progressive disclosure principles resulted in higher usability ratings, consistent with research showing significant cognitive load tolerance decline after age 65 (Hawthorn, 2007). These findings complement research on age-specific technology interaction patterns (Charness & Boot, 2009), illustrating how interface complexity places disproportional

tionate cognitive demands on older users.

Dashboard Category	18-30 Age Group	31-55 Age Group	56+ Age Group	Age-related Variance
High Functionality/Low Complexity	83.7	82.5	79.8	3.9
High Functionality/High Complexity	77.4	68.3	54.6	22.8
Low Functionality/Low Complexity	72.1	68.9	65.7	6.4
Low Functionality/High Complexity	65.8	59.2	48.3	17.5

Table 4. Age-stratified SUS scores across dashboard categories.

The investigation revealed an exponential increase in the discrepancy of SUS scores with interface complexity ($r^2 = 0.81$), thereby underscoring the pronounced accessibility challenges faced by older professionals when confronted with complex environmental dashboards.

Interface Design Dimensions and Cognitive Accessibility

Visualization Wheel analysis (Cairo, 2019) revealed systematic relationships between visual design parameters and age-mediated cognitive accessibility. Multivariate regression analysis identified three design dimensions with statistically significant intergenerational usability effects. First, the decoration/functionality ratio demonstrates a strong correlation between functionality emphasis and intergenerational usability ($r = 0.73$, $p < 0.01$), with dashboards prioritizing functional visualization over aesthetics (AQL.in, ReefCloud) significantly reducing task completion times across age groups, aligning with research demonstrating decorative elements' cognitive processing burden for older users (Meyer et al., 2019). Second, the abstraction/figuration balance reveals a substantial interaction effect intensified between user age and abstraction level ($F = 12.37$, $p < 0.001$), where younger users (18-30) demonstrated equivalent proficiency in figurative and abstract visualizations, while older users (56+) showed 23% performance decline with highly abstract visualizations, consistent with research on age-related differences in processing abstract data representations (Blascheck et al., 2019). Finally, data density calibration emerges as a critical factor, with adaptive data density control systems enhancing cross-generational usability, aligning with research on age-related differences in information-rich visualization processing capacity (Keller et al., 2017).

High-Performing vs. Problematic Dashboard Ergonomics

High-performing environmental dashboards exhibited specific design features substantially enhancing usability across age demographics. AQI.in (SUS: 85) exemplifies optimal ergonomic design through progressive disclosure principles, presenting essential air quality information at first interaction level while allowing deeper exploration without cognitive overload. This approach proved particularly effective among older users, with 56+ age group reporting 87% satisfaction rate, significantly higher than cross-platform average of 61%.

The platform's implementation of spatial contiguity principles (Mayer & Moreno, 2003) through proximal organization of related data elements reduced cognitive load across age groups. Eye-tracking analysis revealed 41% reduction in regressive saccades in older users compared to platforms with distributed information architecture, suggesting lower working memory requirements.

ReefCloud (SUS: 80) achieved high intergenerational usability through adaptive color difference mechanisms and hierarchically structured information. The achievement of preattentive visual attributes (Ware, 2012) facilitated rapid pattern recognition across age groups. Indeed, Neurophysiological recordings revealed consistent P300 amplitude across age groups during pattern recognition tasks, indicating effective compensation for age-related visual processing pathway variations. ReefCloud's redundant visual encoding (location, shape, colour) facilitated perception across cognitive profiles, a property that proved particularly valuable for older users with declining visual acuity. The 56+ age group demonstrated comparable task completion scores to the younger cohort (difference = 7.2%, $p = 0.34$, not significant).

Conversely, ergonomically challenged platforms demonstrated how complex interfaces with low familiarity create accessibility barriers. MPA monitor (SUS: 60) suffered from 'excessive information entropy'—absence of perceptual scaffolding for complex data structures (Harrison et al., 2015). This challenged older participants, with 56+ age group taking 42% more time and making 37% more errors than 18-30 age group. Poor ratings on originality/familiarity and complexity/simplicity dimensions resulted in excessive extraneous cognitive load (Sweller, 2011).

In a similar vein, the Natura 2000 Viewer (SUS: 65) demonstrated ergonomic limitations arising from the utilisation of domain-specific

visualisation conventions that lacked sufficient perceptual guidance. The tailored GIS interaction patterns created 'interaction discontinuities' (Blascheck et al., 2017) – sudden changes in behaviour triggered by contextual changes. This phenomenon had a particularly marked effect on the self-efficacy of older users, with the 56+ age group demonstrating a significantly lower level of confidence in comparison to younger users (mean difference = 1.8 points on a 7-point scale, $p < 0.01$).

Processing Efficiency and Age-Adaptive Interface Design

Chronometric analysis revealed systematic age-related differences in information processing latencies between dashboard interfaces. After adjusting for environmental information familiarity, older users (56+) exhibited significantly longer processing time for high-complexity visualizations (mean difference = 3.87s, $p < 0.001$), while performance remained comparable for low-complexity visualizations (mean difference = 0.63s, $p = 0.31$, not significant). This aligns with processing speed theory of aging, suggesting cognitive aging impact primarily derives from processing speed changes rather than comprehension (Salthouse, 1996).

Dashboards implementing "overview first, zoom and filter, then details-on-demand" principles (Shneiderman, 1996) effectively compensated for chronometric differences, allowing comparable performance across age groups. Time series analysis demonstrated ergonomically designed dashboards (AQI.in, Global Forest Watch) significantly reduced age-performance correlation ($r = 0.23$, not significant) compared to ergonomically demanding platforms ($r = 0.67$, $p < 0.01$). This demonstrates that appropriate ergonomic design can effectively mitigate age-related performance differences in environmental data interpretation.

Implications for Sustainable Sociotechnical Systems

The findings of this study indicate that dashboard ergonomics significantly influences knowledge sharing effectiveness between generations in environmental management contexts. Three key dimensions emerge from this relationship.

Intergenerational Knowledge Transfer

Asymmetric technology adoption patterns fundamentally shape environmental knowledge transfer across generational boundaries. Following digital divide conceptualization (Van Dijk & Hacker, 2003), this study demonstrates that technology adoption disparities create systematic impediments to shared environmental awareness. Dashboards incorporating "cultural interfaces" facilitating cross-generational knowledge exchange proved 38% more effective than standard interfaces.

Platforms employing progressive engagement patterns facilitate knowledge spiralization—converting tacit environmental knowledge into explicit, transferable knowledge (Nonaka & Takeuchi, 1995). This proves particularly important for preserving experiential ecological knowledge held by veteran professionals, addressing the intergenerational environmental knowledge gap identified by Liu et al. (2007).

The findings of this study corroborate the transdisciplinary knowledge integration model (Pohl & Hadorn, 2007). In fact, ergonomically designed environmental dashboards function as boundary objects (Star & Griesemer, 1989), facilitating knowledge sharing across age and disciplinary divides—increasingly critical as environmental management requires integrated responses across ecological, policy, economic, and technological domains.

A three-dimensional model explains design impact on cross-generational environmental decision-making effectiveness. First, perceptual accessibility emerges as interface configuration providing contrast enhancement for age-related visual processing modifications (Owsley, 2011) results in 24% increased decision accuracy in the 56+ group ($p < 0.01$), extending research on age-related interface design by demonstrating perceptual accessibility's direct impact on environmental decision quality. Second, cognitive load management proves critical as platforms implementing cognitive load management principles (Sweller, 2011) through progressive disclosure patterns show reduced decision latencies across age demographics and substantially reduce the age-performance relationship for decision-making tasks (from $r = 0.72$ to $r = 0.31$, $p < 0.01$). Third, interaction paradigm flexibility enhances cross-generational performance, with dashboards supporting varied interaction paradigms demonstrating improved outcomes. In-

terfaces incorporating natural mappings—intuitive correspondences between control actions and system responses—reduce age cohort performance differences by 47% in environmental decision tasks (Norman, 2013). The aforementioned research indicates that interfaces which accommodate diverse mental models have the capacity to improve environmental control across various age demographics.

Dashboard Ergonomics as Climate Resilience Infrastructure

Interface ergonomics consistently influences three resilience dimensions (Folke et al., 2010). First, enhanced response capability emerges as organizations using ergonomic platforms exhibit 37% reduced response time to simulated environmental anomalies compared to less ergonomic alternatives (mean difference = 18.3 minutes, $p < 0.01$), extending resilience theory by demonstrating information ergonomics' direct impact on absorptive capacity. Second, predictive integration enhancement occurs when information visualization follows perceptual processing principles (Ware, 2012), enabling stakeholders to demonstrate 42% higher accuracy in recognizing patterns in three-year climate projection datasets, thereby enhancing anticipatory adaptation capacity. Finally, multi-stakeholder coordination improves significantly, as organizations using platforms with high WCAG 2.2 compliance demonstrate 29% enhanced cross-departmental coordination during simulated environmental crises. This finding is consistent with the adaptive co-management framework, which asserts a direct correlation between enhanced information accessibility and increased institutional capacity (Berkes, 2009).

Design Guidelines for Age-Inclusive Environmental Dashboards

The proposed structured design guidelines for age-inclusive environmental dashboards are intended to enhance climate resilience capabilities across generational divides, as illustrated in Table 5.

These recommendations extend Multiple Resource Theory (Wickens, 2008) to address specific challenges of environmental data visualization across the adult lifespan, providing actionable implementation strategies for organizations seeking enhanced climate resilience through age-inclusive dashboard ergonomics.

Design Category	Guideline	Description	Exemplar Implementation & Evidence
Perceptual Accessibility Guidelines	Color	Implement redundant color coding with minimum 3:1 contrast ratio for critical information (WCAG 2.2 AA compliance)	AQI.in successfully employed complementary visual encodings (position, color, label) that accommodated age-related changes in color perception
	Typography Hierarchy	Utilize minimum 16px base font size with clearly differentiated heading scales (1.5:1 ratio) and weight differentiation	ReefCloud demonstrated effective typographic scaling that accommodated presbyopia in older users without compromising information density
	Visual Element Sizing	Critical interactive elements should maintain minimum 44px touch targets with sufficient spacing (minimum 8px)	Dashboards with larger interaction targets showed 37% reduced error rates among users 56+
Cognitive Load Management Guidelines	Progressive Information Disclosure	Implement layered information architecture revealing complexity progressively on demand	Top-performing dashboards (SUS>80) utilized 3-tier information architecture (overview → category exploration → detailed analysis)
	Attention Guidance Mechanisms	Use visual prominence hierarchies to direct attention to critical information first	Successful dashboards employed preattentive visual attributes (size, orientation, color) to create effective attentional guidance paths
	Chunking Strategies	Group related information into perceptual units of 4:1 elements	ReefCloud's implementation of spatial chunking principles reduced working memory demands for all age groups
Mental Model Accommodation Guidelines	Interaction Consistency	Maintain consistent interaction patterns throughout the interface	Dashboards with high scores on Few's Principles demonstrated interaction consistency that supported development of stable mental models across age groups
	Metaphorical Mappings	Utilize familiar real-world analogies for complex data structures	Global Forest Watch effectively employed map-based spatial metaphors that provided consistent mental models across age cohorts
	Feedback Mechanisms	Provide immediate, clear feedback for all user actions	Dashboards with explicit system state feedback demonstrated 28% improved task completion rates among older users
Collaborative Sense-Making Guidelines	Annotation Capabilities	Support collaborative knowledge construction through shared annotation mechanisms	Platforms with annotation features demonstrated 46% higher knowledge transfer between age groups
	View Persistence	Enable saving and sharing specific dashboard states to support asynchronous collaboration	Platforms with state-sharing features showed 33% improved cross-generational knowledge transfer
	Expertise Adaptation	Provide interface adaptations based on domain expertise and technological literacy	Adaptive interfaces reduced age-performance correlation by 62% in complex data interpretation tasks

Table 5. Age-Inclusive Environmental Dashboard Design Guidelines.

Advancing Ergonomic Interfaces for Intergenerational Context

This research establishes foundational understanding of how ergonomic design principles bridge generational divides in environmental monitoring systems. In fact, thoughtfully designed interfaces serve as critical infrastructure for climate resilience and intergenerational knowledge transfer. The comprehensive analysis of twelve environmental dashboards demonstrates that optimal ergonomic design can dramatically reduce age-related performance disparities, transform-

ing the correlation between age and task performance from substantial $r=0.67$ to negligible $r=0.23$ through strategic application of progressive disclosure principles, cognitive load management, and perceptual accessibility enhancements.

The findings illuminate three interconnected dimensions where dashboard ergonomics directly influences environmental stewardship effectiveness. First, interface complexity creates systematic barriers to cross-generational collaboration, with older professionals experiencing disproportionate cognitive demands when confronting poorly designed environmental data systems. Second, ergonomically optimized dashboards function as boundary objects, facilitating knowledge transfer across both age and disciplinary boundaries through culturally adaptive interfaces accommodating diverse cognitive processing styles and technological literacies. Third, dashboard ergonomics directly impacts organizational climate resilience, with institutions using ergonomically superior platforms demonstrating 37% faster response times to environmental anomalies and 42% higher accuracy in pattern recognition across climate projection datasets. The age-inclusive design guidelines developed through this research extend beyond accessibility compliance to encompass strategic organizational capabilities for environmental management. Platforms exemplifying optimal ergonomic design demonstrate that thoughtful interface design can simultaneously serve diverse user needs without compromising functionality or information integrity.

However, the research exposes significant limitations in current environmental dashboard development approaches. The geographic bias toward Western-developed platforms and English-language constraints limit generalizability to global environmental monitoring contexts. Moreover, the temporal snapshot methodology cannot capture dynamic evolution of both user adaptation patterns and technological capabilities over time.

The implications extend beyond individual interface optimization to encompass systemic transformation of environmental governance structures. As climate change accelerates and demographic aging intensifies, the capacity to effectively translate environmental information into actionable intelligence becomes increasingly critical for societal adaptation. This research suggests that ergonomic design principles should be recognized as essential components of climate adaptation infrastructure.

Future research should address integration of adaptive interface

technologies that can dynamically adjust to individual cognitive capabilities while maintaining collaborative functionality across diverse user groups. The potential for machine learning algorithms to personalize information presentation patterns based on user behavior analytics represents a promising frontier for age-inclusive environmental monitoring systems.

The convergence of demographic aging and climate change presents unprecedented challenges requiring innovative sociotechnical solutions. This research demonstrates that ergonomic design principles offer a powerful lever for enhancing collective environmental intelligence across generational boundaries. By recognizing dashboard interfaces as critical infrastructure for climate resilience and investing in age-inclusive design approaches, environmental organizations can unlock the full potential of their human capital while building adaptive capacity for an uncertain future.

Author Contributions

The present document is the result of a joint reflection by the authors. However, sections Abstract, 1 and 2 (including their respective sub-paragraphs) were authored by M. F. Ucchiello, while sections 3, 4, 5 and 6 (including their respective sub-paragraphs) were authored by A. Caccamo.

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The gestalt of the wheelchair.

Social and technological perspectives of the symbol of disability in the digital era



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Abstract

Mobility represents a fundamental right closely related to autonomy, dignity, and full participation in social life. The paper analyses historical and contemporary developments related to technological, typological, and semiotic innovations of the "product-symbol" of motor disability: the wheelchair. Over time, technical and material innovations have solved functions in increasingly optimized and effective ways. However, the only technical solution of functionality fails to untangle these orthoses (Andrich, 1996) from their exclusionary and stigmatizing dimension, making the design issue particularly challenging. The research aims to depict how syncretically digital manufacturing processes, socio-cultural evolutions, and some media trends can now work together toward

increasing customizability thresholds and a broad normalization of wheelchair use to finally break them free from being the metaphors of vulnerability, disadvantage, and weakness. Specifically, 3D scanners and printers and parametric morphogenesis and AI technologies are now pioneering advanced models, customization, and adaptation of prostheses and orthoses to human variability, conditions, and evolving needs. Digital technologies' "promise" is to create on-demand, increasingly rapid and cost-efficient, adaptive, tailor-made, non-repulsive products and, therefore, devices that can be genuinely responsive to emerging expectations and lifestyles.

Such goals give back to the design discipline the possibility of leading complex design processes that aim to overcome cultural and perception limits and that, beyond fulfilling objective functions, propose radical shifts in meaning by making the wheelchair a "hinge tool" between people, technologies, and environments and a renewed symbol of inclusiveness, independence, and strength.

Introduction

Today, the wheelchair is no longer configured exclusively as a technologically advanced aid but as a meaningful artifact, capable of conveying values such as identity, autonomy, and well-being, orienting itself to a diversified user base and a multiplicity of use scenarios. This change results from the complex intersection of multiple research disciplines, from ergonomics to engineering, from product design to user experience to the most recent applications of rapid manufacturing and artificial intelligence, contributing on defining new design paradigms. The case studies analyzed through a design-oriented perspective, which can be traced more or less explicitly to different areas of innovation: technological, morphological, and typological, share a standard conceptual matrix, namely triggering a radical change in the collective perception of the wheelchair, transforming it from a ghettoizing object, a reason for social exclusion, to a symbol of inclusion. Moreover, in socio-demographic contexts marked by an aging population and the increase in needs related to assisted mobility, the wheelchair is no longer understood exclusively as an aid for compensating a motor deficit but rather as an "active interface" between body and space, a vehicle for mobility, as well as an expressive and identity object, capable of offering support to all those who, permanently or temporarily, experience a

reduced ability to move.

The research recognizes the need to scale up its production, thus transforming it into a truly industrial product, as a key event in the evolution of this particular artifact. Thus, we move from pieces originally adapted from wooden chairs or charriots, intended only for wealthy consumers, to mechanical chairs engineered for mass production. This phenomenology can be reconstructed through the collection and analysis of patents, organized by chronology and typology. Design culture then implements these technological advancements with "innovations of meaning" thus creating specialized, customizable, high-performance products capable of truly adapting inclusively to the evolving needs of a broad and diverse user base. Thanks also to the new capabilities of digital technologies, these designs are helping to redefine uses, roles, and "cultural implications" of wheelchairs, which are finally freeing themselves from being merely a pictogram of the concept itself of disability.

Patented wheelchairs. From the upholsterer to the engineer

Renato De Fusco, taking from Giedion the binomial "upholsterer's furniture-engineer's furniture" (Giedion, 1967, p. 320), describes the historical phenomenon that involves the introduction of mechanized production processes, the invention of metal furniture with changeable or even transformable configurations. According to De Fusco: "The origin of mechanical furniture is to be found in eighteenth-century Europe, in the experimentation going from inventive automatons to the first automatic machines, which led to the construction of furniture such as lits de voyage or other extremely manageable, light and foldable pieces of furniture (...), but it is in America from 1850 onwards that this type of furniture finds its greatest design effort, its most extensive production, sale and consumption." (De Fusco, 1985, p. 66)

They are autonomous furniture, i.e. released from furniture systems and styles, mechanically discontinuous, composed by component articulation, replacing wood with metals, craftsmanship with mechanized production, and introducing and experimenting with new models of comfort and adaptability to the user's body. The following is part of this utilitarian and dynamic furniture: barber chairs, sanitary and surgical furnishings, folding chairs and beds, early office chairs, transformable railroad car fittings, strollers, seats, and

wheelchairs for people with disabilities.

One of the first images depicting a mechanical seat explicitly designed for limited mobility needs is a 1595 engraving representing King Philip of Spain on its “invalid’s chair”. The chair was designed especially for him, equipped with a footrest and a reclining backrest. The chair, equipped with spherical feet, was pushed by a servant to enable the king to move indoors. The modern evolution of this seat can be understood thanks to the documentary study of historical patents as a continuous search for balance between strictly functional needs, technological transfers, and gradual recognition of the right to autonomy that, over time, has expanded the categories of users, redefining the relationship between the individual, the community and the built space by promoting, practices of inclusion, empowerment, and self-representation (Stewart & Watson, 2020).

One of the first truly innovative models is the chair, designed in 1655 by Stephan Farffler. The German watchmaker invented the first model of a self-propelled wheelchair (which, at least in the designer’s intentions, did not need to be pushed by another person). Farffler’s chair features a wooden frame with two fixed wheels at the rear and one at the front equipped with push handles on either side of the case that conceal the gear. Such a model marked a crucial epistemological shift: mobility is no longer just a biomechanical function but is configured as a “tool of self-determination” (Wolfson, 2014).

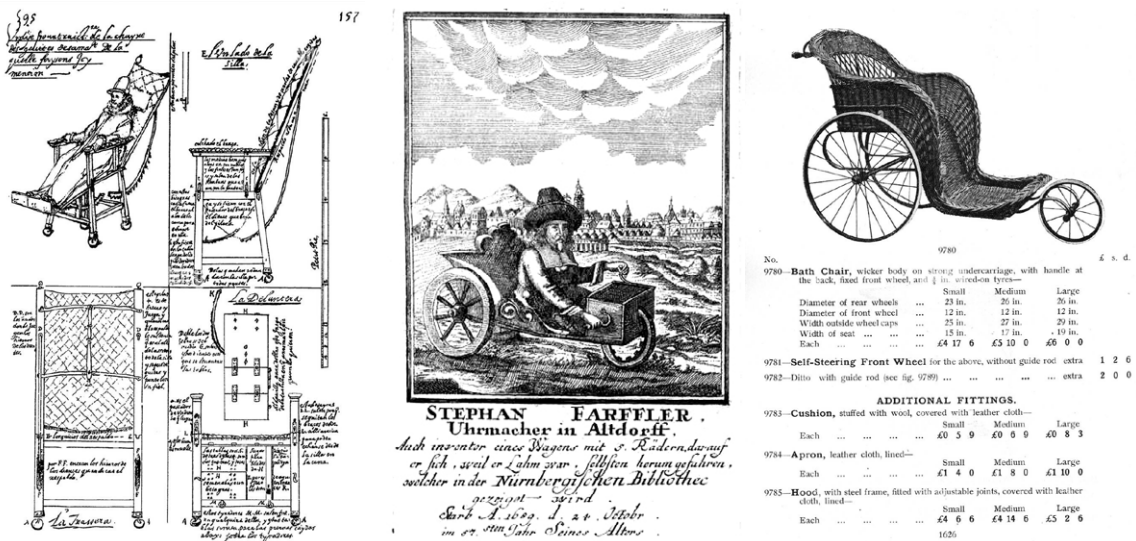


Figure 1. Invalid chair for King Phillip II of Spain, 1595 – 2. Hand-propelled wheelchair, Stephan Farffler, 1655 – 3. Bath chair, John Dawson, 1782.

In 1782, John Dawson developed, by lightening Farffler's chair, a model with a woven wicker seat, with two large metal wheels at the rear and a small front one that could be directed. The so-called "Bath chair," despite being expensive and heavy, became the gold standard in Europe and the United States and was marketed at the high end of the market. Then, in 1846, Scotsman Robert William Thomson patented the application of elastic supports around the wheels to lessen the strain on the arms and dampen vibrations.

With the industrial age and the increase in the number of young amputees on a social scale after World War I, radical changes occurred in the 1920s and 1930s in the choice of materials, production processes, and design approaches. The introduction of light metal and rubber tires enabled the production of wheelchairs that were stronger, easier to handle, and cheaper.

The first tubular steel folding wheelchair was designed in 1932 (patented in 1937). Harry C. Jennings Sr. designed it for his friend Herbert A. Everest, who later founded the company Everest&Jennings, specializing precisely in the manufacture and marketing of wheelchairs and orthopedic devices. After World War II, the electric wheelchair designed by George Klein was made and popularized. In addition to wartime or post-war fields of application, sports fields of application are also often places for experimentation with increasingly performative materials.

Since the 1960s, this industry has experienced an innovative acceleration, particularly in complementary assistive devices that can be applied to existing wheelchairs. The increase in registrations with central international patent offices -including WIPO, USPTO, and EPO- reflects this dynamism. Since the 1980s, there has been significant growth in patented technology solutions integrating electronic components, sensors, intelligent actuators, neural interfaces, and artificial intelligence algorithms.

Some prevailing design directions emerge in this scenario, including manual, electric, all-terrain, extendable, stand-up, lightweight, and sports wheelchairs [Fig.2].

Current experimentation includes highly customized devices designed to meet increasingly complex needs: hybrid-assisted propulsion systems, automated postural adjustment, autonomous driving, biometric monitoring, and gestural or brain controls for users with multiple disabilities (Fouad et al., 2025).

The historical evolution of the wheelchair is proof of a crucial tran-

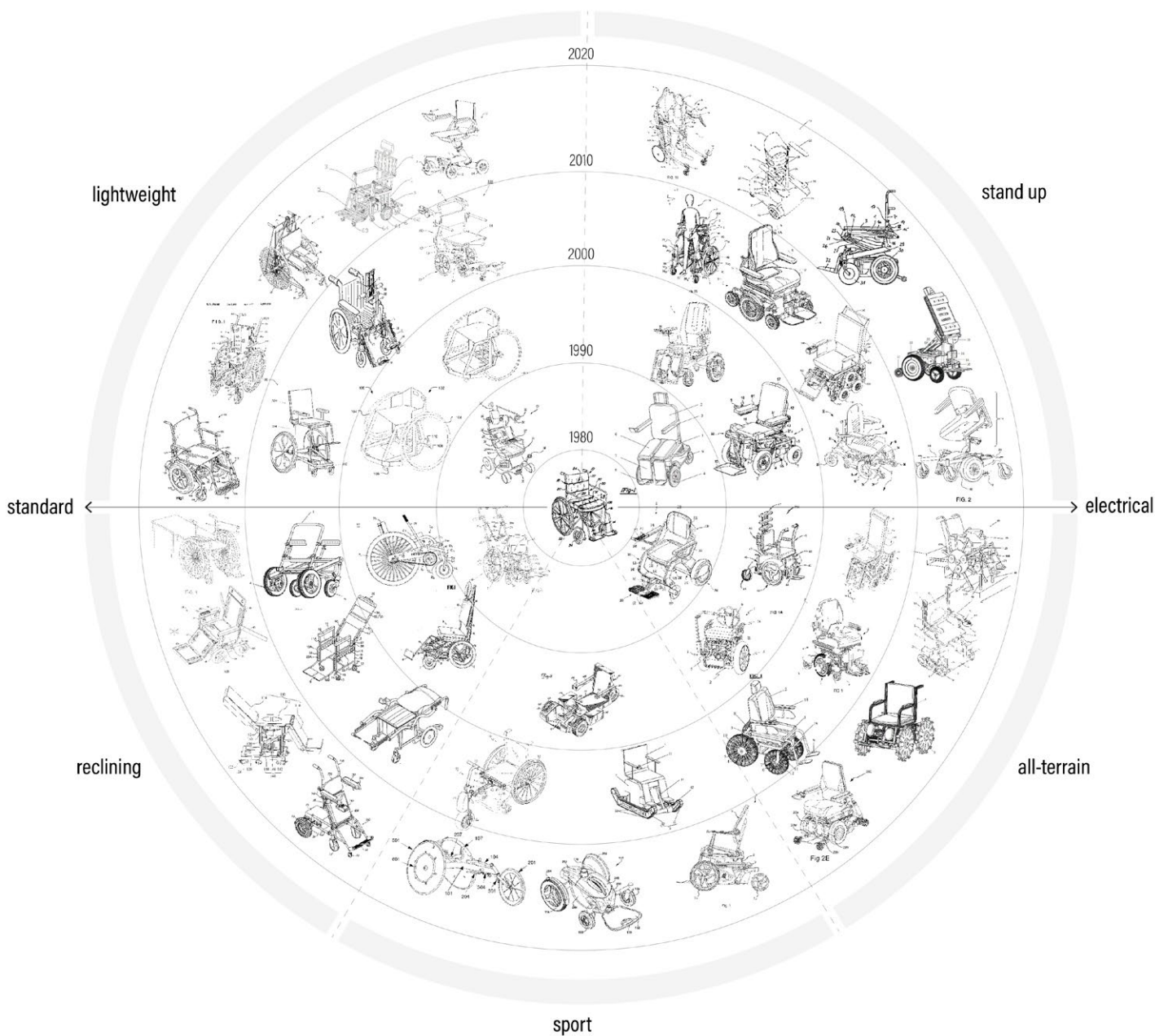


Figure 2. Data map of the evolutions of patented wheelchairs from 1970 to 2020. Elaboration of the authors.

sition from a simple transportation tool to a complex system of interaction between human beings and their context (Nias, 2019). This path is thus marked by phases in which the technique is called upon to adapt to the market's and society's changing needs. In early models, the focus was mainly on status representation, function, and security. After the Industrial Revolution and the two world wars, the focus shifted toward ergonomics, the evolution of mass production systems, and material experimentation. Then, with digital technologies, unprecedented possibilities for customization are introduced, making the device more effective and adherent to the increasingly complex evolutions of its users' needs, semantics and expectations. This narrative is intertwined with the ergonomic dimension and the emotional aspect of the relationship between the device and its user, a bond that, over the centuries, has transformed the wheelchair into a kind of "external technological prosthesis" capable of recovering, supplementing or, even, enhancing the human body's ability to move.

Contemporary wheelchairs. From the engineer to the designer

Traditionally, wheelchairs have always been associated with stigmatizing imagery, which has limited their social and cultural acceptability. In this context, the current design approach, inspired by contemporary design principles, is oriented toward redefining the wheelchair as a desirable object, conceived not only as a functional tool but also as an expressive and customizable artifact. In this sense, the design challenge is structured on a twofold level: on the one hand, it involves the development of ergonomically evolved solutions that can be effectively adapted to a plurality of contexts of use; on the other hand, it aims at a de medicalization of its aesthetics, to transform it into an inclusive, appealing object, capable of joining the vocabulary of contemporary design, treating it as an object of personal use. In recent decades, the collective perception of the wheelchair has undergone a progressive transformation, evolving from a strictly functional and medical device to an object of design experimentation in contemporary design. This evolution is characterized by increasing formal, technological and typological complexity, but especially by the desire to redefine its cultural and symbolic meaning. From this perspective, the design-driven innovation process differs from engineering innovation as it aims to solve problems and generate new meanings. Market competition is

increasingly driven by "why" people need a product rather than by "what" it can do. Indeed, consumption choices are based on deep, often latent reasons that integrate functional needs with symbolic and emotional components. In this context, design assumes the role of a key tool since its essence is precisely in its ability to "make sense of things" (Verganti, 2009).

Materials and Technologies

Technological innovation has been a key contributor in redefining the role of the wheelchair within everyday life, transforming it into a complex and multifunctional device. In this context, the main design challenge is to broaden the range of actions made possible and easy by these devices, making them accessible to users with heterogeneous needs and abilities in different contexts, from the home environment to hospitals to sports and urban settings. Among the most significant examples of the semantic and material redesign of the wheelchair is Kazuo Kawasaki's Carna Folding Wheelchair (1989). The project aims to transform the wheelchair into a desirable object comparable in aesthetics and feels of use to a new pair of sneakers. The Carna is distinguished by a high-tech style, essential lines, and customizable, vibrant color finishes that help overcome traditional medical imagery, restoring a positive, contemporary identity to the object. The polymer, titanium, and aluminum frame is separable and foldable in an optimized manner. Electric motor evolution, the development of user-friendly control systems, and the integration of AI software have led to a significant advancement in wheelchair design, making them increasingly similar to vehicles. In this perspective, wheelchairs also assume a strategic role within active-aging policies, supporting the functional autonomy of older people and promoting their full inclusion in social and home life.



Figure 3. i-REAL, Toyota, 2009.

In cutting-edge technological experimentation, the Toyota i-REAL "Personal Mobility Concept" project (2007) represents an outstanding case of the convergence of robotics, ergonomics, and smart mobility. The project is based on a radically innovative vision: to overcome the dichotomy between vehicle and aid, envisioning a personal means of transportation suitable for users with reduced mobility but potentially extendable to a much broader user base in a universal design perspective. Toyota i-REAL is designed to move easily in indoor and urban environments, thanks to a motorized tri-wheel system that adapts to speed and environmental conditions and perimeter monitoring sensors that can detect possible collisions with people and objects through the emission of sounds and vibrations¹.

¹ Media Toyota. *i-REAL Concept (2007)*. Retrieved May 2025, from <https://media.toyota.co.uk/vehicles/i-real/>

Adopting peer-to-peer, on-demand, and open manufacturing processes enables a high morphological and ergonomic customization level. The tailor-made approach, focused on adapting devices to the actual bodily and behavioral specificities of the user, directly addresses the need to promote functional efficiency and the psychophysical well-being of the individual, emphasizing uniqueness and subjective needs. An example of adaptive design is represented by Aria Wheels (2015). Each chair is developed based on individual anthropometric measurements, considering variables such as posture, level of physical activity, daily habits and aesthetic preferences. The product, which can be customized in size to accommodate different user needs, can be adjusted to six different dimensional parameters: backrest angle to wheel camber and center of gravity position.

3D printing in orthopedics allows the creation of customized models of prostheses or orthoses that mold perfectly to the patient (Ten Kate et al., 2017 - Kim & Jeong, 2015). "It is, therefore, a field of particular research interest as shown by the numerous experiences conducted by different companies and research centers" (Langella&Pontillo, 2023, p. 67). The GO wheelchair designed in 2016 by Benjamin Hubert's Layer Studio is the result of a user-centered research process based on digital manufacturing and parametric modeling, which allows the chair's structure to be adapted to the specific anthropometric measurements of the individual².

² Layer Design. *Go wheelchair*. Retrieved May 2025, from <https://layerdesign.com/project/go/>



Figure 4. 1. Carna folding wheelchair, Kazuo Kawasaki, 1989 – 2. Aria 1.0, Aria Wheels, 2015 – 3. Go chair, Benjamin Hubert - Layer, Materialise, 2016.

Typological specialisations

The contemporary market presents many wheelchairs, primarily distinguishing between manual and motorized. This initial typological classification identifies further functional segmentations that respond to specific contexts of use and user needs. Manual wheelchairs are designed for active use and target those with some motor autonomy of the upper limbs. In this category, in addition to the more common type of domestic use, are hospital wheelchairs and competition sports wheelchairs. Wheelchairs for hospital use are intended primarily for temporary, assisted use in health care settings. Such devices are designed to maximize usability by healthcare staff, emphasizing maneuverability, wear resistance, and compatibility with other hospital systems. The structural configuration is often basic and standardized but oriented toward safety and durability. Sports wheelchairs represent a highly specialized category designed to optimize physical performance. The design of such products focuses on lightweight and aerodynamics. Frames are made of high-performance materials, and the geometries are calibrated to ensure maximum control, quick direction changes, and stability. They are often designed collaboratively (including designers, engineers, doctors, technologists, athletes, and sometimes even the regulatory bodies that define sports regulations in the development processes). They are custom-made, taking into account the morpho-

logical characteristics of the athlete and the specifics of the discipline: basketball, tennis, running, etc.

They are no longer just tools for mobility but become expressions of cutting-edge technology and personal empowerment, capable of conveying an image of strength and determination. One example is the BMW Racing Wheelchair (2016), designed by Designworks USA in collaboration with the U.S. Paralympic team. Made of carbon fiber, this chair features a frame designed through 3D scans to optimize the athlete's posture and reduce air resistance. Used by athletes such as Tatyana McFadden, it has helped improve performance and set new Paralympic records.



Figure 5. 1. BMW Racing Wheelchair, 2016 – 2. Ziesel Mattro, 2013.

As previously mentioned, the introduction of the electric motor marked a radical shift in the evolution of this object. Motorized wheelchairs today increasingly represent real vehicles equipped with electronic guidance systems, user-friendly interfaces, and autonomous functions. In addition to the standard types for everyday use, all-terrain types and those with verticalization functions fall into this category. All-terrain wheelchairs can cope with different terrain, from beach to snow to uneven terrain. Often equipped with tracks, oversized wheels, and enhanced suspension, they are designed to ensure use in otherwise inaccessible natural settings, significantly expanding the possibilities for active participation in outdoor life even by users with reduced mobility. The Ziesel project (2013) by the company Mattro fits into this framework. Ziesel is designed as a high-performance all-terrain vehicle, equipped with

rubber tracks suitable for all seasons, is capable of tackling a wide range of terrain. Control is via a high-precision joystick, and the steel frame defines a racing-derived safety anti-tip structure. Although designed for people with specific mobility needs, it is conceived as a "hybrid" device capable of attracting non-disabled users as well. Other specific electric wheelchairs are those equipped with upright functions. They allow the user to assume the upright position and represent a highly technological typology aimed at ensuring greater autonomy in movement and significant physiological benefits, such as stimulating circulation and reducing the risk of sores. They are configured as valid biomechanical extensions of the body, up to the size of true robotic exoskeletons. A historical example is the Standing wheelchair prototype (1968) developed in the United States by Peter W. Bressler. Within this framework, today, hybrid solutions are multiplying, designed not only for the motor disabled but also for older people with reduced walking ability, people facing temporary rehabilitation paths, and urban users seeking sustainable mobility alternatives. This approach broadens the field of wheelchair design and redefines the concept of "end user," paving the way for truly inclusive and universal design. In this process, design plays a crucial role in creating a new conscious imaginary through a meaning-oriented design language, envisioning these devices as true enablers of social participation.

Social perception of the wheelchair

The iconography related to the wheelchair has slowly but significantly transformed over time. Traditionally, the collective imaginary associates this object exclusively with a condition of disability and limitation, thus symbolizing marginality and fragility and evoking pity and unease feelings. For this reason, especially in contexts related to power and economic or social success, it was necessary to show oneself as more "able-bodied" than one truly was, hiding or minimizing the use of the wheelchair. In recent years, this representation is gradually becoming replaced by a more complex view of the experience of disability. Prominent personalities from the institutional and entertainment worlds are transforming the wheelchair tool into an emblematic object of inclusion, power and visibility. Thus, the concept of "chairwear" (Pullin, 2020) is established, claiming for the wheelchair a role of self-representation, allowing people with disabilities to assert their aesthetics and identity. In this perspective, the chair

and clothing express personal values and social belonging, overcoming stereotypes of homogeneity and anonymity. The wheelchair thus becomes a standard tool that, while maintaining its primary aid function, has wholly joined the contemporary cultural debate, becoming an indicator of social, aesthetic and symbolic transformations. Disability Studies have made a decisive contribution to deconstructing dominant ability narratives, promoting instead a critical perspective that values bodily and cognitive diversity as a resource for the entire social fabric. Here, the wheelchair takes on a new centrality: it does not isolate but connects, becoming an expression of rights and possibilities and intersecting with other forms of oppression and revolutionary responses (Goodley, 2024).

Power/weakness

Historically, figures related to power and institutions have carefully tried to hide the use of wheelchairs. A striking example is the case of the British monarchy, which, according to some revelations by royal correspondent Robert Jobson, tried hard to hide the late Queen Elizabeth II's use of the wheelchair. A military-style drill was set up to bring her to her last public appearance, Philip's memorial celebration held in 2022 at Buckingham Palace. This episode, emblematic in its spectacularization of invisibility, shows the extent to which the disabled body is, in some traditionalist contexts, still perceived as an element to be concealed to preserve an idealized public image consistent with the classical canon of sovereignty. Long before her, another exemplary case was US President Roosevelt, who was forced to use a wheelchair because of a severe form of polio that struck him at a young age. Fearing that his disability would discredit him in the eyes of the public, he tried to minimize it in every way, learning to stand upright through the application of two metal braces to his legs, always carefully concealed. Ironically, he has then become a symbol of inclusion, and his memorial in Washington D.C. is not only one of the first areas designed to be accessible to people with disabilities but inside it hosts a statue created by sculptor Neil Estern that marks the first depiction of a president in a wheelchair. Pope Francis led a historic media breakthrough. His appearances in a wheelchair have not been hidden, but rather have acquired a deep symbolic meaning: the Pope, representative of a secular institution traditionally linked to models of strength and authority, is shown to be both vulnerable and authoritative, thus helping to dismantle the idea that disability equals

weakness or inability.

Hyper-aestheticization of the wheelchair

Over the past decade, within the showbiz world, the evolution of wheelchair-bound imagery has taken complex and sometimes controversial forms, swinging between aesthetic provocation, symbolic appropriation, and critical reflection. Famous is the case of singer Lady Gaga, who in 2013 appeared in public in a Louis Vuitton-branded wheelchair, triggering numerous controversies. The object, transformed into a luxury accessory, is perceived as an act of disrespectful appropriation of disability. The artist's intent, however, is to implement a performative strategy that would interrogate the boundaries between glamour and fragility, visibility and vulnerability, bringing a device often relegated to invisibility to the center of attention. In recent months, the artist herself created, in collaboration with Mastercard, the fan edit video of her latest single, *Abracadabra*, released in February 2025. The video clip depicts the wheelchair within hyper-anesthetized pop imagery, in which the object merges with fantasy and technological elements, becoming part of a narrative of visual empowerment. In this context, the wheelchair becomes a vehicle of power and individuality, reframed in contemporary aesthetic and narrative terms. While this type of representation risks aestheticizing disability to the point of making it abstract, it also enables new forms of identification, imagination, and representation in entertainment and cultural consumption. This ambivalence has been effectively thematized through the numerous photographs of David LaChapelle [Fig.5]. Who photographed the artist herself with a wheelchair in 2009. In *Taking Mummy for a Walk* (1998), the photographer uses the wheelchair as a semantically dense device capable of interrogating and subverting visual conventions, cultural codes, and disability-related stereotypes. The work sits at the crossroads of photographic art, social criticism and media production, exploiting the hyperrealist and theatrical visual style that characterizes the artist's entire output. The image stages two female figures: a young, glamorous, faceless woman pushing a wheelchair occupied by a plastered, hooded figure. The alienating effect of the composition is a critique of how contemporary society filters disability through the prism of aestheticization and performance, sometimes emptying it of its authentic existential dimension. The title of the work *Taking Mummy for a Walk* introduces a double level of linguistic reading: mummy means both mummy and mom, and the semantic ambi-

guity activates a reflection on care and dependence, but also on the nullification of personal identity. LaChapelle does not intend to make a moralistic representation but wants to take to extremes the assimilation of disability into the mechanisms of pop culture, thus revealing its fictional and problematic nature. His work is part of a larger context of representations of the wheelchair in the art world and media, where the object progressively takes on new meanings: from clinical sign to cultural symbol, from the emblem of marginality to postmodern icon. The image, suspended between oneiricism and social satire, problematizes the relationship between visibility and spectacle, suggesting that disability can be as inclusive as it is consumed within the representation system.



Figure 6. 1. *Taking Mummy For A Walk*, David LaChapelle, 1998 – 2. *Lady Gaga*, David LaChapelle, 2009.

The changing imagery of the wheelchair reflects a still unresolved tension between recognition and hiding, between integration and spectacle. While design attention is growing toward inclusive design that intends to conceive no longer as a ghettoizing tool but as a desirable chair for all, cultural and infrastructural barriers that prevent complete emancipation remain. The real challenge is not only technical but deeply cultural: it is necessary to deconstruct the idea of an ideal body (Caspanello, Falsone, 2015). In this complex scenario, future challenges concern rediscovering the collective imaginary in a genuinely inclusive perspective. It is a matter of promoting a culture that does not simply tolerate disability but assumes it as an integral part of the human and social landscape. From this perspective, the wheelchair becomes a key to critically reading the contemporary contra-

dictions and, at the same time, imagining new forms of cohabitation, representation and dignity.

Conclusions

The evolution of the wheelchair represents an emblematic example in the field of assistive design, in which the progressive convergence of technological innovation, shifting cultural paradigms, and assertion of rights has transformed a strictly utilitarian device into a powerful vector of inclusion and representation and a design issue of complex experimentation. From its origin as an elite tool to a medical complement to its current configuration as a highly customizable and symbolically charged object, the wheelchair represents a design issue where design culture can become an expert mediator between individual needs and collective demands. The rise of interdisciplinary and participatory design practices, such as co-design and open-source, is democratizing design access and introducing new educational and production models that can radically redefine the relationship between user, technology, and society. Digital technologies and composite materials have led to the emergence of intelligent wheelchairs, capable of integrating into the urban fabric and responding dynamically to evolving contemporary needs. Open-access platforms and digital manufacturing labs foster processes of self-construction, advanced customization, and bottom-up supply chains, enabling users, practitioners, and designers to share designs and adaptations, thus triggering collaborative learning processes and knowledge sharing. While offering new potential, these innovations introduce an unprecedented set of critical issues. Contemporary wheelchairs are no longer located only within the human-machine relationship but are embedded in a complex sociotechnical and environmental ecosystem in which climatic, urban, digital, and regulatory variables interact (Roulstone, 2016). Ergonomic design is therefore faced with the increasing heterogeneity of users, enhancing the interaction between different types of wheelchairs, even when originally designed for divergent purposes. When guided by Design culture, these complexities can lead to the definition of new possible semantics of the "assistive device" (ISO, 2016). They can define new meanings, new social roles, and new languages that influence widespread media imagery capable of contributing significantly to normalizing the use of aid that, for too long, has symbolized disability and the impossibility of inclusion in many human and social activities.

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Investigating consumer preferences in choosing garments: An approach on Origami based design



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Abstract

The aim of this study is to determine how origami affects consumer's satisfaction in garments selection. This descriptive study identifies some factors that influence on user preferences during their clothing selection. When consumers encounter a product, they initially experience emotions and compare it with their own previous experiences of buying similar products. Ultimately, they develop an attitude bias, which positively affects their decision to buy the product. Origami, as a form of artistic expression, holds potential benefits within the realm of cognitive ergonomics. An elevated level of cognitive engagement among consumers can enhance psychological perception, thereby contributing to greater overall satisfaction. This study assessed the relationship between origami-designed garments and user's satisfaction. The conducted research investigates the attitude bias of participants by measuring their inclination and preferences towards origami designs in

clothing selection. The results show the positive effect combining these two mentioned components on the consumer, which influences their valuation, demand, and inclination to reuse that product.

Introduction

Today, Consumer satisfaction is a crucial prerequisite for competing in the global market. Aesthetics quality plays an important role in enhancing customer satisfaction and has a positive impact on the user (Chen & Chuang, 2008). The mental quality of aesthetics is a crucial in attracting and determining the level of preference and consumer satisfaction (Sung H Han, 2015). One of the main objectives of product configuration is to improve customer satisfaction, which can be achieved by incorporating customer feedback into the process. (Cheng, Yu, Chu, Fan, & Hu, 2022). One of the classifications that most products fall into is clothing and some consumers prefer fashionable clothing styles that are recognized and admired (Naderi, 2013). The way consumers perceive the aesthetics of a product plays a significant role in determining their response towards it (Chen & Chuang, 2008). Origami is a type of paper art that originated in Japan after the introduction of papermaking (Lyu & Zhang, 2023). By exploring the relationship between origami designs and consumer preferences in clothing purchases, this research can address many challenges and opportunities.

Consumer's satisfaction

Consumer satisfaction refers to the level of satisfaction and enjoyment a product brings to its consumer. If user satisfaction is divided into different categories, the first category is the initial feeling, which includes color, texture, shape, and light. The second one is the description of images based on consumers' experiences, and the third category is the attitude based on the judgment, evaluation, and overall preference of the consumer for the (Han & Hong, 2003). Consumer buying behavior is influenced by individual differences such as personality and gender, which can impact purchasing decisions and time spent shopping (Workman & Cho, 2013). The fashion market has three main features that influence the decisions and preferences of consumers, namely, product lifecycle, demand fluctuations, and motivation. From an emotional perspective, satisfaction results from varying intensities of emotional feelings, and consumers understand during

product usage and experience (Antonio Marín-García, 2021). Product design can be broken down into various design features and each of these features can have an impact on user satisfaction (Han & Hong, 2003).

Cognitive ergonomics and satisfaction

Cognitive level is an evaluation state of a consumer's subjective psychological perceptions after utilizing a service. The higher the consumer's cognitive level, the more the consumer's psychological perceptions match the offered features. There is a reasonable relation between perceived value and satisfaction (Jia & Wang, 2016). Origami is considered as one of the artistic activities that can offer benefits for cognitive abilities or emotional well-being (Martinčević & Vranić, 2025).

Aesthetics

Consumer satisfaction increases with aesthetically pleasing qualities, which include authenticity, unity, completeness, form satisfaction, simplicity, and pleasure (Chen & Chuang, 2008) Beauty is a suitable criterion for understanding product satisfaction because it correlates with repeated use (Hassenzahl, 2004). The quality of aesthetics and design has a positive influence on consumers (Chen & Chuang, 2008).

Fashion

The desire to be fashionable has become a significant preoccupation for the consumer society. The theory of collective choice is a social theory based on the positive impact of fashion and trends on consumer preferences (Oran, 2019). In the fashion cycle, consumer preferences are determined intrinsically, relying on the consumer's previous experience, both personally and from other consumers (Di Giovinazzo & Naimzada, 2015).

Origami in Fashion

The art of origami is a traditional technique associated with Japanese culture, which refers to folding (Hongrattanavorakit & Chantakul, 2021) (Morris, McAdams, & Malak, 2016). In recent years, origami has been increasingly applied in various fields such as fashion, clothing and furniture design (Wang, Yang, Li, & Zhu, 2022) (Hongrattanavorakit & Chantakul, 2021) (Newton, 2011). The art of origami in fashion

design summarizes the expression through studying external characteristics, origami shaping, fabric features, experimental confirmation, and practical techniques (Wang, Yang, Li, & Zhu, 2022). When incorporating origami techniques into clothing design modeling, we need to comprehensively consider the relationship between origami techniques, clothing fabrics, patterns, structures, and use innovative thinking to make structural changes and creative designs (Wang, Yang, Li, & Zhu, 2022).



Figure 1. Origami in fashion.

This study aims to investigate consumer preferences in selecting garments designed using origami-based techniques. Accordingly, the main question of this study is: What influences consumer preferences when choosing garments designed with origami-based design principles?

Methodology

This descriptive-cross-sectional article utilizes library, documentary, and field research methods. The primary aim was to investigate consumer preferences regarding garments featuring origami-based design elements. Data is collected through questionnaires, and samples are selected via non-probabilistic voluntary sampling. In this study, 24 images depicting explicit origami forms were chosen from 3 designers identified through various fashion design websites. These images were presented to skilled designers, and 9 of these images were se-

lected for this study. A 5-point Likert scale questionnaire was distributed among design students via online platforms. The questionnaire was divided into two sections. The first section gathered demographic information, while the second section focused on many participants' preferences, such as influence on future purchase decisions, positive impact on consumer perception, contribution to enhanced creativity, evoking a sense of specialness for the user, and willingness to pay a premium price. The sampling method was non-probabilistic voluntary sampling, focusing on participants with at least foundational design education. A total of 135 individuals (94 females, 39 males and 2 invalid data; Age mean=24.56 years) participated in this phase. The average age of the participants was about 24, and the necessary data were extracted from their responses. Data was analyzed in SPSSWin 23. Descriptive statistics (means, frequencies, standard deviations) were used to summarize preferences, while inferential statistics were employed to explore associations between variables. This approach allows us to move beyond surface-level trends and evaluate the strength and direction of consumer responses in relation to origami-based design aesthetics. The findings are then interpreted in relation to the study's research questions and theoretical framework, with the goal of identifying whether origami-inspired garments influence consumer perceptions in meaningful and market-relevant ways.

Results

After using SPSS software to analyze the total population responses, two invalid responses were removed. Additionally, Cronbach's alpha was used to confirm the questionnaire's reliability with a coefficient of 0.885 (Tab. 1, Tab. 2).

Cases	Valid	133	98.5	Cronbach's Alpha	N of Items
	Excluded ^a	2	1.5		
	Total	135	100.0	.885	12

Table 1-2.

Each question on the Likert scale questionnaire was analyzed in the one-sample t-test. It was found that out of the 12 variables in the second section of the questionnaire, the first 10 questions have a significant relationship with origami. However, the significance of the last two questions, which were related to paying extra costs and using them in different situations, could not be conclusively judged. The one-sample t-test confirmed the hypothesis, indicating a significant relationship between origami and consumer preference. By examining the data and descriptive statistics, the greatest and least discrepancies among respondents in this section were investigated (Tab. 3).

		Gender	Age	Visual Appeal	Unique and Interest	perception of attractiveness	Attracting More Attention	Feeling of creativity and innovation	Future clothing purchases	Overall beauty enhancements	Differentiation in selection	Reflective of Modern Style	Recommendation to others	ore cost	Use in various situations
N	Valid	133	133	133	133	133	133	133	133	133	133	133	133	133	133
	Missing	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Mean		1.29	24.56	4.09	4.04	3.59	3.50	3.91	3.49	3.63	3.88	3.83	3.20	2.83	3.15
Median		1.00	24.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	3.00	3.00	3.00
Mode		1	23	4	4	3	4	4	4	4	4	4	3	3	4
Std. Deviation		.457	4.008	.783	.839	.913	1.049	.900	.989	.857	.905	.996	.957	1.060	.996
Variance		.209	16.067	.613	.703	.834	1.100	.810	.979	.734	.819	.993	.916	1.124	.992
Minimum		1	19	2	1	1	1	1	1	1	1	1	1	1	1
Maximum		2	40	5	5	5	5	5	5	5	5	5	5	5	5

Table 3.

The significant relationship of each question with the two variables of age and gender was measured by Pearson correlation test. After analyzing the correlation between attractiveness of origami designs and their proximity to modern style, a significant relationship was observed between participants' responses and their gender (Tab. 4, Tab. 5).

		Gender	Reflective of Modern Style
Gender	Pearson Correlation	1	-.171*
	Sig. (2-tailed)		.050
	N	133	133
Reflective of Modern Style	Pearson Correlation	-.171*	1
	Sig. (2-tailed)	.050	
	N	133	133

*. Correlation is significant at the 0.05 level (2-tailed).

		Gender	perception of attractiveness
Gender	Pearson Correlation	1	-.203*
	Sig. (2-tailed)		.019
	N	133	133
perception of attractiveness	Pearson Correlation	-.203*	1
	Sig. (2-tailed)	.019	
	N	133	133

*. Correlation is significant at the 0.05 level (2-tailed).

Table 4-5.

Upon examining the Pearson correlation table between the age variable and the data, it was found that only one question had a significant correlation with age, and even that correlation was very weak. Considering the negative slope of the corresponding graph, it can be concluded that as users' age increases, their inclination towards this variable decreases (Tab. 6).

		Age	Attracting More Attention
Age	Pearson Correlation	1	-.186*
	Sig. (2-tailed)		.032
	N	133	133
Attracting More Attention	Pearson Correlation	-.186*	1
	Sig. (2-tailed)	.032	
	N	133	133

*. Correlation is significant at the 0.05 level (2-tailed).

Table 6.

Discussion

To ensure higher accuracy and validity of the research, the participants were classified into four age groups. The first group includes individuals aged 19 to 22 years, accounting for approximately 24.1% of the sample population. The second group consists of only those aged 23 years, representing approximately 21.1% of the sample. The third group comprises individuals aged 24 and 25 years, making up about 32.3% of the sample population. Finally, the fourth group encompasses individuals aged 26 and above, constituting approximately 22.5% of the population. The attempt was made to have a similar sample size for each group. In this section, analyzing the table can reveal opportunities and challenges within the data. We examined items with the highest scores and lowest variances among females and males. The variables are as follows. The first variable was the visual appeal of clothes with origami designs, with Group 3 females and Group 1 males showing the highest inclination.

The highest inclination for second variable which is unique and attractive origami designs was exhibited by females in Group 3 and males in Group 1. The third variable, which was the perception of attractiveness, was the most popular among females in Group 2 and males in Group 1. The fourth variable, proximity to modern style, received the highest average score among females in Group 2 and males in Group 1. The fifth variable, which was attracting more attention to origami designs on clothing, was preferred by females in Group 2 and males in Group 1. Lastly, the use of clothing with origami designs in different situations was favored by females in Groups 1 and 3, as well as males in Group 1. In the challenges section, there are variables that warrant further discussion, as users showed the least inclination towards them and had the lowest average scores. These variables include a willingness to pay more for purchasing clothes with origami designs among Group 1 females and Group 2 males. In the next variable which is "attracting more attention", a high variance was observed, which indicates a large difference of opinion among people. In this variable, group 4 women and group 2 have shown the least desire. Lastly, the use of clothing with origami designs in various situations in group 4 of women and group 3 of men has the lowest score.

Conclusion

This study's findings are specific to its defined scope and the attri-

butes of the selected participants. The sample was gathered through voluntary, non-probabilistic methods, focusing on individuals with a basic background in design. Within these boundaries, Participants in this sample showed a relatively high level of interest in clothing styles influenced by origami aesthetics. The results showed that participants had the least difference of opinion when it came to the visual appeal of the clothing, with a variance of 0.613. However, the largest difference of opinion among respondents was in regards to the willingness to pay extra for clothing featuring an origami design, with a variance of 1.124. After analyzing the data, it was found that the variable with the highest score was visual appeal, implying that most participants were more inclined towards this aspect. It is noteworthy that no participants in this sample selected the strongest level of disagreement with the options provided, indicating that the respondents were less inclined towards paying extra costs. According to the scores, respondents' average opinion regarding the visual appeal was slightly higher than agree, while their average opinion in the question of paying extra costs was lower than neutral and slightly towards disagree. By focusing on enhancing the beauty and attractiveness of origami-inspired fashion, these findings may help inform design directions that align with the preferences observed in this sample. The data indicates that respondents showed a much higher inclination towards origami fashion compared to other aspects, suggesting that this should be a key focus area for future developments in the fashion domain. Because the sample included more female participants, the findings related to females reflect the responses of a larger subgroup within this particular sample. However, in terms of distinguishing origami from other designs, males had a higher average. In other words, to put it simply, the male participants in the study showed a preference for origami clothes over other types of clothing. Additionally, the male participants tended to rate their willingness to pay more for origami-designed clothes and use them in various situations higher than the female participants did. In this sample it appears that male participants showed a higher average willingness to spend money on origami-designed clothing and wear them in different situations. Furthermore, the average ratings for the distinctiveness and appeal of origami-designed clothing were almost identical between females and males, implying that both groups have a mutual agreement on this matter.



Figure 3-4.

According to the data collected from participants, the most enthusiasm was observed among males aged 19 to 22 and females aged 23 to 25 within this study group. This subgroup may represent a demographic that is more open to experimental fashion concepts or could drive emerging trends in the industry. It is important to note that there is a notable challenge regarding respondents' reluctance to pay more for clothing with origami designs. Interestingly, there is a significant difference of opinion among different groups on the matter. Specifically, Group 2 males and Group 1 females showed the least willingness to pay more for such clothing. It is worth noting that in this research, male participants showed a higher average willingness to pay for clothing items with attention-seeking features compared to females, regardless of age. As females age, their inclination towards the consumption and selection of such clothing items decreases. According to the data from this study, females aged 26 and above (Group 4) showed the lowest tendency to draw attention to themselves within the sample, which is consistent with the previously mentioned observation. On analyzing the average ratings provided in the survey, it can be inferred that women in this sample group have a higher inclination towards utilizing apparel with origami designs. Within

this study group, female participants rated origami designs slightly higher in preference for clothing with origami designs compared to men. However, they are not willing to pay as much as men for such designs. Based on the findings of this study, additional investigations with comparable or larger samples may provide deeper insights into this phenomenon. Building on the findings of this study, future research would benefit from including larger and more diverse participant groups to improve how well the results apply to broader populations. Using different data collection approaches could also offer deeper and more detailed insights into consumer behavior. Moreover, exploring how consumer preferences relate to cognitive ergonomics might help develop more effective and tailored design strategies. Finally, creating and testing real-world prototypes of origami-inspired clothing and gathering feedback from users would be a valuable next step toward enhancing ergonomic benefits and driving better, more widely accepted designs in this area.

Limitations

Despite providing valuable insights into users' preferences for origami-inspired fashion, this study has several limitations. First, the sample size was relatively small and limited to a narrow age range of young adults, which may reduce the generalizability of the findings to a broader population. Additionally, the gender distribution was uneven, with a considerably higher number of female participants, which could introduce bias in interpreting gender-related results. Another limitation is that participants' real-life exposure to origami fashion was neither controlled nor measured, which likely led their responses to be based more on perceptions and assumptions rather than actual experience.

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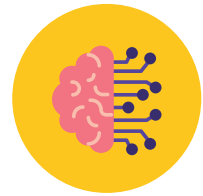
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Disconnection and belonging in full remote teams: a case study on a participatory activation intervention for organizational wellbeing



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Keywords: organizational ergonomics, full remote team, facilitation, wellbeing, technostress

Abstract

The widespread adoption of full remote work has intensified phenomena of relational disconnection, loss of shared meaning, and weakening of bonds within professional contexts. This article presents a case study of a light, self-organized ergonomic intervention, initiated bottom-up in response to signs of fragmentation within a digital team. The initiative involved 12 professionals divided into three thematic micro-groups with weekly non-directive facilitated meetings.

The results show strong initial engagement and the reactivation of collaborative and identity-based dynamics. However, the lack of formal recognition by the organization, the absence of continuity spaces, and difficulties in aligning the initiative with operational logics limited its long-term impact, at times generating frustration and disillusionment.

The article offers a reflection on the sustainability of participatory practices in digital contexts: when not legitimized and integrated into corporate systems, even valuable experiences risk producing effects different from those desired. Organizational ergonomics can offer effective tools to redesign relational environments in full remote and distributed systems, but it requires a concrete alliance between bottom-up initiative and systemic vision.

Introduction

In recent years, digital transformation and the widespread adoption of remote work have profoundly reshaped the ways people collaborate, build relationships, and assign meaning to work. While this modality has introduced benefits in terms of flexibility, autonomy, and operational continuity, several studies have also highlighted its psychosocial drawbacks. The *Smart Working Observatory Report* by the Politecnico di Milano (2021) identifies key risks such as relational isolation, loss of a sense of belonging, difficulty disconnecting due to the overlap between personal and professional life, and a general weakening of informal interactions—all of which negatively impact well-being and organizational cohesion. In response to these risks, the literature on organizational ergonomics emphasizes the importance of interventions that can reactivate participation and strengthen relational networks. As noted by Boerchi (2024), for work to be sustainable over time, it must consider not only productive dimensions, but also relational, motivational, and identity-related aspects. From this perspective, participation is not an accessory element but a central factor in organizational health, capable of fostering belonging, engagement, and well-being. At the same time, attention is growing around the psychological effects of intensive digitalization. Bernardelli (2022) introduces the concept of *technopathologies*, describing how unregulated use of technology can lead to loneliness, hyperactivation, stimulus dependence, and an erosion of relational thinking. In this context, remote work risks being implemented solely as a tool of efficiency, while neglecting its impacts on professional identity and mental health.

Added to this is the rising incidence of *technostress* (Tarafdar et al., 2015), a cognitive and relational overload resulting from constant exposure to digital tools and the lack of clear boundaries between work and personal life. In this context, facilitation emerges as a strategic organizational competence to support professional teams un-

dergoing transformation. Expert facilitation (De Sario, 2013), transformative coaching (Whitmore, 2006; Hawkins, 2021), and process consulting (Schein, 2001) offer practical tools to foster dialogue, sustain mutual listening, and create shared learning spaces—even in virtual environments.

Additional studies demonstrate that coaching in digitalized contexts enhances learning, engagement, and well-being, confirming its effectiveness even at a distance (Jones et al., 2016; Ellis-Brush, n.d.; Isaacson, 2021).

Digital coaching is now an expanding field, with the potential to positively influence adaptation to change and group climate (Schermyly et al., 2022), particularly in distributed teams where transformational leadership requires new forms of connection and support (Bagga et al., 2023).

The initiative presented in this case study fits into this scenario as a participatory, self-organized intervention aimed at activating dynamics of collaboration, exchange, and cohesion within a fragmented team.

The aim of this study is to explore the potential of organizational ergonomics in designing replicable interventions for participatory activation and the promotion of well-being in full-remote professional groups that lack structural cohesion but share a common organizational affiliation.

Through this case study, the article seeks to propose an initial methodological foundation for light, scalable, and adaptable interventions capable of strengthening belonging, motivation, and engagement even in fragmented work contexts.

Context

The intervention took place within Conflux s.r.l., a company specialized in user experience (UX) design, employing between 50 and 60 people, including permanent staff and long-term freelance collaborators. The organization operates entirely remotely, providing consulting services on complex projects for national and international clients across various sectors.

In the years following the systematic adoption of remote work—initially introduced during the pandemic and maintained as a permanent organizational model—recurring signs of relational fragmentation, progressive demotivation, and weakening of collective identity began to emerge. Although several initiatives had been introduced to foster

connection among colleagues, over time these opportunities became increasingly less attended—partly due to their voluntary nature—and gradually turned into predominantly operational or informational meetings, which proved insufficient in sustaining authentic and lasting professional bonds.

For organizational purposes, the company's workforce is divided into three main working groups, each coordinated by a team leader. Within one of these teams, progressive signs of disengagement and declining motivation were informally observed. During weekly meetings with her group, the team leader identified these signals and independently decided to launch an experimental initiative.

It is important to clarify that the intervention was not initiated by explicit organizational mandate, nor was it formalized as a corporate project. However, it was made possible by a pre-existing condition: the team leader had been granted a dedicated half-hour each week to manage, among other tasks, team climate and cohesion.

The meetings were held regularly within this allocated time slot, which participants then voluntarily extended by starting their workday 30 minutes earlier. This allowed the initiative to proceed without disrupting operational activities. Participation was entirely voluntary.

The company was not selected a priori as a research setting; rather, the case emerged internally from the observation of a real situation, in line with an action research approach, in which the intervention arises and develops within the very context it aims to transform (Lewin, 1946; Zuber-Skerritt, 2021).

Objective of the Intervention

The initiative—internally called “UX Sparks”—was launched with the aim of creating new opportunities for peer-to-peer learning and fostering a team culture grounded in curiosity and collaboration.

The main goals of the initiative were to:

- create horizontal spaces for discussion among people who usually do not work together;
- activate small collaborative projects on thematic topics, free from operational or production-related pressure;
- support motivation and a sense of belonging through informal interaction and experimentation.

The intervention was entirely developed using internal resources and tools, with no formalization or direct investment from the company. The team leader acted as promoter and facilitator with the purpose of

empirically testing whether it was possible to stimulate a more positive team climate and engagement without relying on formal or top-down mechanisms.

Participants

The presentation of the initiative led to the participation of 12 out of 15 team members—a significant number when compared to the usual average of 5 attendees at weekly team meetings.

All participants were professionals working in UX, UI, or Service Design, who were not used to collaborating with each other, as they were assigned to different projects and clients, and held no coordination or organizational responsibility within the company. Participants were between 24 and 37 years old, with a balanced distribution in terms of seniority (junior, mid-level, senior), and a male majority (9 men and 3 women).

Participation was entirely voluntary, not tied to any operational goal or individual performance evaluation system, and did not involve any formal obligations or commitments.

Structure of the Intervention

The intervention was structured into four main phases:

A. Presentation and Activation

The proposal involved launching micro-working groups around an initial set of suggested topics. Participants were free to choose which group to join based on their interests.

B. Implementation of the “Spark Teams” Activities

Following the initial activation phase, three thematic groups were established, with each participant joining only one group:

- AI Spark – focused on the exploration and application of artificial intelligence in everyday work processes (5 participants);
- Spark Academy – centered on the development and sharing of transversal professional skills (3 participants);
- Spark People – aimed at fostering active participation and listening within the internal company community (4 participants).

Each team self-organized, defining its goals, working methods, and tools. Groups met once a week for one hour over an eight-week period. The only requirement was to present their work to the other groups at the end of the experience.

The team lead took on the role of a non-directive facilitator: she sup-

ported the initial formation of the groups by offering methodological guidance and remained available afterward in case of difficulties or the need for support.

C. Feedback Survey

At the end of the experience, a survey was distributed to all participants to gather feedback on satisfaction levels, perceived usefulness, and suggestions for improvement. The results were later shared with the entire group during a final event.

D. Final Presentation

The closing phase of the intervention involved an in-person feedback event—an option strongly desired by the Spark Team participants. The event served a threefold purpose: to present the initiative for the first time to the entire company (as other colleagues were not previously aware of it), to share the outcomes of the first team (AI Spark), and to create a concrete opportunity for physical meeting and team bonding.

The initiative was highly appreciated by both colleagues and company leadership, which in turn encouraged the remaining two Spark Teams to organize their own in-office presentation sessions. On each occasion, the teams showcased their work, shared the ideas that had emerged, presented the materials they had produced, and outlined potential avenues for future development, with the aim of assessing the feasibility of continuing the proposed project.

In the final event, the results of the previously distributed survey were also shared.

Data Collection methods

To assess the effectiveness of the intervention, two main tools were used:

A. Participatory Qualitative Observation

The facilitator conducted participant observation throughout the entire duration of the intervention. The approach adopted was unstructured and non-intrusive, in order to respect the autonomy of the groups and avoid influencing their dynamics. The observation focused on relational and behavioral aspects, including:

- signs of engagement (e.g., punctuality, consistent participation, contributions during meetings);
- cooperation dynamics (e.g., role-taking, spontaneous peer support, mutual listening);
- signals of difficulty or disorientation (e.g., declining participation,

requests for help);

- prevalent modes of interaction (e.g., communication patterns, dominance).

Observations were noted informally at the end of each session, without the use of a predefined framework. The observation was also discontinuous, as the groups met simultaneously and the facilitator alternated her presence across the three.

B. Post-intervention Feedback Survey

At the end of the eight-week period, an anonymous online questionnaire was administered to all participants via Google Forms. The tool included:

- 5 closed-ended questions using a 5-point Likert scale (from 1 = not at all to 5 = very much), with a follow-up request for clarification in the case of scores 1 or 2, aimed at evaluating:
 1. the participant's level of personal engagement;
 2. satisfaction with the project developed by their group;
 3. satisfaction with the final output;
 4. the overall assessment of the experience;
 5. the perceived importance of continuing the initiative within the company.
- 6 multiple-choice questions, with the option to select "Other" and specify, addressing:
 - compatibility between Spark and daily work activities;
 - the amount of time available for the initiative;
 - the main value attributed to the experience;
 - perceived strengths and critical issues.
- 1 open-ended question, aimed at collecting suggestions, feedback, and proposals for improvement.

The survey was intentionally designed to be lightweight, agile, and coherent with the intervention's overall philosophy.

Results

Team participation remained consistent and active throughout the duration of the intervention. The groups met every week, even in minimal conditions.

Over time, each team experienced changes in composition:

- In AI Spark, one participant dropped out due to increasing workload.
- In Spark Academy, one participant left due to a lack of organizational recognition and was replaced by a new freelance collabora-

tor joining the company.

- In Spark People, a participant withdrew to focus on onboarding, having recently joined the company. She maintained occasional involvement, while an intern joined and became an active contributor.

For new team members, the initiative represented a valuable opportunity to connect with colleagues in an informal, safe, and participatory setting. The experience also fostered contact between senior professionals and newer colleagues, generating a climate of horizontal trust. Another notable aspect was the participants' autonomous decision to start meetings earlier, moving the time from 9:30 to 9:00 a.m., in order not to interfere with client work. This reflects a clear sense of ownership and personal investment in the initiative.

The final survey gathered 10 responses out of 12 participants.

Quantitative data were collected using a 5-point Likert scale (1 = not at all, 5 = very much), and yielded the following average scores for each indicator:

- Perceived level of engagement: 4.2/5
- Satisfaction with the project developed by one's group: 3.2/5
- Satisfaction with the group's output: 3.6/5
- Overall evaluation of the initiative: 3.8/5
- Perceived importance of continuing the initiative within the company: 4.2/5

According to the final survey, participants identified the value of the activities carried out within the working groups as follows:

- the opportunity to work on concrete solutions to respond to company-related challenges (60%);
- the freedom to explore new ideas unconstrained by operational pressures (40%);
- the possibility of developing a project outside client-imposed boundaries (40%);
- the chance to engage with and learn from peers (30%).

The critical issues identified fell into two main categories: the difficulty of making time for the initiative alongside daily work tasks; and the lack of formal recognition from the organization, which led the activity to be perceived as extra-curricular and, in some cases, less legitimate.

A thematic analysis of open-ended responses regarding suggestions and future perspectives identified three recurring themes:

1. Greater formalization and organizational recognition;
2. In-person meetings as energy catalysts;
3. Improvements related to format, output, and expectations.

Among other observed results, the in-office presentation events—never held before in the company’s history—were widely attended and led to the emergence of new, self-organized in-office gatherings, always on a voluntary basis.

Finally, as noted in qualitative observations, the workload was not evenly distributed: in each team, two individuals took on leading roles, while others contributed more passively. However, consistent presence and the willingness to attend—even just to listen—were interpreted as legitimate forms of participation.

Discussion

The results indicate that a light, self-organized intervention based on participatory dynamics can foster engagement, belonging, motivation, and perceived well-being—even in fragmented, fully remote contexts. Participants’ consistent involvement, the spontaneous emergence of follow-up initiatives, and the desire to expand the model suggest that the Spark Teams addressed a real need for connection, internal visibility, and cultural identity. The initiative was experienced as a meaningful and safe space for collaboration and self-expression. This is especially significant in UX consultancy settings, often marked by distributed teams, isolated projects, and weak group identity.

However, several critical issues limited the intervention’s impact. The one-hour weekly time slot, carved out from already compressed schedules, proved insufficient, leading to fragmented work and a natural tendency to prioritize client demands. The lack of formal recognition—such as protected time or visibility—created friction between personal motivation and business priorities.

This tension was also reflected in lower satisfaction with team outputs, largely due to time and resource constraints. Furthermore, despite strong appreciation from colleagues and leadership, no structural follow-up occurred on the projects initiated. Participants had hoped that key themes—AI integration, internal training, and participatory practices—would be taken up, but this did not happen.

This gap between perceived value and organizational response led, in some cases, to disillusionment. Without legitimization and continuity, such initiatives risk becoming missed opportunities, potentially discouraging future participation.

Still, the fact that participants were motivated by the idea of contributing to the organization—without being asked—underscores a key insight: in distributed contexts, engagement can arise without formal prompts, but it must be seen, supported, and translated into concrete action to be sustained.

Study Limitations

The case study presented, which is exploratory and qualitative in nature, has several limitations:

- Small and non-generalizable sample: The intervention involved only one team within a specific company, characterized by unique organizational features.
- Self-selection of participants: Voluntary participation may have attracted individuals who were already motivated, potentially providing a partial view of the overall team climate.
- Lack of structured pre-post data: No validated tools or longitudinal measurements were used—only self-reported data gathered through surveys and participant observation.
- Facilitator bias: The fact that the facilitator was also the team leader may have influenced participation or responses, although her role was intentionally kept discreet and non-directive.

Future developments

Despite its limitations, the intervention offers useful insights for designing sustainable organizational practices in remote and fragmented contexts, even when few resources are available.

The main implications that can be drawn from this pilot include:

- Invest in non-instrumental relational spaces: Even without budget or formal mandates, creating opportunities for informal collaboration generates value.
- Promote self-organized models enabled by facilitation: It is essential to have a figure who supports the process without directing it, preserving lightness and autonomy.
- Integrate organizational recognition: One of the main limitations reported by participants was that the Spark Teams were not officially recognized. Including them in calendars or organizational processes could enhance their impact without compromising their nature.
- Experiment with small-scale formats in similar contexts: Agencies, consulting teams, and cognitively intense environments

could benefit from similar interventions, tailored to their specific settings.

UX Sparks represents a lightweight, scalable, and adaptable model based on self-organization, non-directive facilitation, and voluntary participation. Its replicability depends on two key conditions:

1. The existence of a minimal relational context (a baseline culture that does not hinder self-activation);
2. Formal recognition of bottom-up initiatives, at least in terms of time and visibility.

The intervention reflects a view of organizational ergonomics as an internal capability—one that enables people to observe and respond to weak signals within the system, activating meaningful spaces for connection.

Conclusions

The experience of the Spark Teams demonstrates that even low-structure interventions can activate meaningful dynamics of participation, motivation, and a sense of belonging. However, for these effects to consolidate and translate into real and lasting change, they must be recognized, welcomed, and supported by the organization.

Without a process of institutional legitimation and continuity, such experiences risk remaining confined to the realm of individual initiative. In this scenario, what begins as a generative gesture can gradually become a missed opportunity: rather than reinforcing organizational attachment, it may instead foster detachment.

For this reason, such interventions are effective—but they work only if they are seen. Seen in their transformative value, seen in the questions they raise, seen as early signals of an organizational culture that is capable of evolving from the bottom up.

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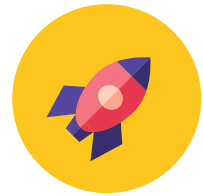
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New technologies for space perception: haptic space and visual impairment



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Keywords: visual impairment, technologies, haptic spaces, design for all, multisensoriality

Abstract

The purpose of this article is to delve into the potential of cutting-edge technologies in improving spatial perception for those living with visual impairment. It aims to investigate alternative ways of using space. These ways do not rely on sight. It does this by analysing case studies. These case studies involve innovative technologies. The notion of space can prove to be a considerable challenge for those suffering from visual impairment. The concept of space is a very complex one for a visually impaired person, who may struggle to navigate their environment and access information. The division of space is usually based on things like how close or far away it is, whether it is fixed or moving, if it is empty or full, and so on. The adoption of assistive devices for daily living is a fundamental element in achieving full personal autonomy, which is why it is so important. Opportunities presented by multisensoriality

and innovative new technologies mean that research into including people with visual impairment is vital. Using assistive devices in your daily life is an important step towards being completely independent. There are opportunities presented by multisensoriality. New technologies are innovative. In consideration of the prospects engendered by multisensoriality and the pioneering instruments proffered by contemporary technologies, it is paramount that research is initiated with a view to incorporating individuals with visual impairment.

Introduction

The Charter of Fundamental Rights of the European Union, which was adopted in 2000, recognises the rights of persons living with disabilities to avail themselves of all measures that have the potential to increase autonomy, social and professional inclusion, and participation in community life (EU, article 26, 2000) The integration of individuals with disabilities are integrated into cultural and social settings can be regarded as a key barometer of their societal inclusion. As indicated by the relevant documentation, (Giaconi et al, 2021). It is evident that access to information and social integration can facilitate the realisation of the right to self-determination. Furthermore, it has been demonstrated that such integration can enhance opportunities for individuals with disabilities to participate in community activities. It is essential to consider the importance of accessibility in order to facilitate the autonomy of individuals with disabilities and enable their full participation in society. This form of involvement has been shown to engender greater self-determination and to facilitate the acquisition of the necessary agency over their lives. It is crucial to recognise that this objective must be realised through a dynamic and continuous approach, based on gradual changes and progress that empower communities and foster the creation of systems that promote inclusion and the dissemination of participatory values (Shogren & Raley ,2022). It is imperative to acknowledge that communities to which people with disabilities belong, including those under consideration, those with visual impairments, strive for the right to full and effective participation in life, on equal terms with people without disabilities. The promotion of collaboration and the sharing of cultural interests, recreational activities, entertainment, tourism and the attendance of cultural institutions such as libraries and museums has been identified as a key strategy in the fight for this right. Recognising the in-

terdependence between social and cultural integration is imperative for the facilitation of comprehensive societal cohesion (Booth & Ainscow, 2011). According to estimates made by the World Health Organisation (WHO), visual impairment affects approximately 2.2 billion people on a global scale. Current estimates suggest that in 2023, the number of individuals in Italy experiencing total or partial blindness will amount to approximately 220,000, with a further estimated 1.5 million being visually impaired (WHO, 2019). Of these, it is estimated that approximately 110,000 will be residing in the Campania region, with more than half of these individuals located within the metropolitan area of Naples. (Istat, 2019) In 2010, Oliver and Barnes advanced the thesis that the difficulties experienced by people with disabilities are not a consequence of their disability, but rather are caused by the discrimination and external barriers they encounter during ordinary daily activities, including cultural and social activities (Oliver & Barnes, 2010). The objective of this article is to discuss the role of advanced technologies in facilitating the perception of space in individuals with visual impairments. The present contribution is based on an analysis of case studies using innovative technologies, with the aim of investigating non-visual ways of using space. The objective is to formulate guidelines for the design of products that maximise the accessibility and autonomy of people with visual impairments in the environment.

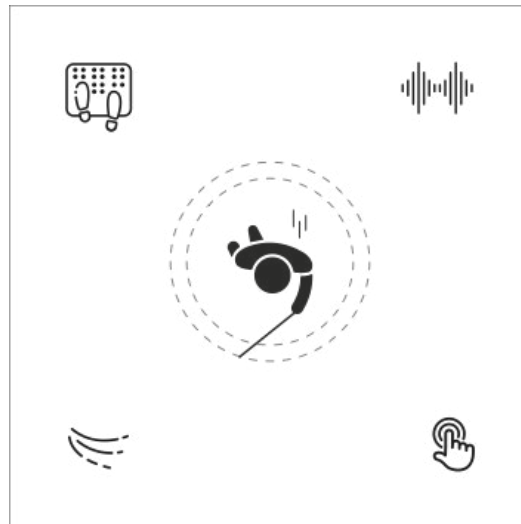
Visual impairment

The term "blindness" is commonly employed in everyday discourse with the connotation of an objectively verifiable physical and sensory disability characterised by the complete absence of sight. () Individuals living with visual impairment possess the capacity to perceive light, even if this ability is not necessarily associated with their visual abilities. In contrast, the term "low vision" is open to different interpretations since it does not specify the extent of residual vision. The term "severe visual impairment" is used as a more precise term to indicate a severe impairment of visual capacity that cannot be corrected by lenses, surgery or drug therapies. (Fiocco, 2006) Blindness is defined as the total or partial loss of vision, irrespective of its origin (i.e. congenital or acquired). The ability to interact with one's environment through the execution of complex motor patterns is a defining characteristic of this condition. Examples of such motor patterns include walking and writing patterns, as well as gestures, which are

rarely if ever overlooked. It is evident that educational and rehabilitation interventions can be planned and implemented according to well-defined criteria. (Caldin, 2006) The condition of low vision, characterised by impaired visual capacity, can present as a heterogeneous condition, with varying degrees of impairment, and may even conflict with other conditions. This heterogeneity renders it impossible to establish standardised educational and rehabilitation pathways. The quality of visual perception and the overall well-being of individuals with low vision can undergo significant alterations in response to a range of physiological and environmental conditions, refractive defects, and brightness levels.

Space in visual impairment: the concept of haptic space

The division of space is typically undertaken based on various criteria, including proximity or distance, static or dynamic, empty or full, and so forth. The term "surrounding space" is defined as the environment surrounding the human body, and therefore the individual perceives it as his or her centre of reference (Cavazza). The conception of space is a notion of considerable complexity, which makes it difficult to synthesise and define for a visually impaired individual. However, it is important to emphasise that a blind person's perception and characterisation of tangible space can be achieved through the tactile examination of objects or through sensory emission, which must be localised in space; an example of the latter would be sound (Virga,2000). As demonstrated by numerous studies in the domain of ergonomics, the incorporation of sensory faculties in the analysis of the immediate environment has been shown to result in the development of the concept of "haptic space" (Fig. 1). However, it is imperative to acknowledge the limited influence of this space, as it exclusively encompasses that which can be examined. A considerable number of scholars have examined the relationship between the various perceptual fields and their laws. Visual perception occurs instantaneously; in contrast, tactile perception necessitates a phase of discrimination of the constituent parts of the different elements, which are subsequently integrated in a process of synthesis of the object's form. It is therefore observed that the use of sensory organs for spatial perception originates "haptic space", although the intrinsic limitations of this concept must be highlighted, as it only includes that which is susceptible to examination. In this perspective, it is noted that the visual sense is

*Figure 1.*

predominantly oriented towards the perception of forms, while the haptic sense is directed towards the recognition of the structure of objects. The process under scrutiny is governed by a set of principles that pertain to tactile perception and shape identification. As Villey observed, blind individuals have been shown to develop a mental process of spatial synthesis for the construction of mental images (Banchetti, 1981). Sensory abilities have been shown to contribute to the progressive broadening of the conception of extension, with this development occurring through a process of inductive synthesis rather than deductive synthesis. In this sense, the visual sense is primarily oriented towards the perception of forms, while the haptic sense is directed towards the recognition of the structure of objects. The processes of tactile perception and shape identification are governed by specific principles. In the absence of direct vision of the object, the manipulation process will not be limited to a mere tactile action, but will be accompanied by the acquisition of information aimed at understanding the characteristics of the object itself. In accordance with Révész's theory, this approach facilitates the implementation of the stereoplastic principle. This modality enables the acquisition of a range of information pertaining to the materiality of the object, including its volume, hardness and the impression of its plastic strength (Révész, 1950). However, it should be noted that the issue of form has not yet been addressed. The following essay will provide a comparative summary of models of visual and haptic cognition.

	VISUAL COGNITION	HAPTIC COGNITION
Nature of space	The term 'optical' refers visually to the concept of space, and is frequently described as allocentric (body-independent). (Török, A. et al, 2014).	The concept of haptic space is predicated on the notion of space being constructed through direct bodily interaction, which is initially egocentric in nature. (Kappers, A. ,2007).
Primary mode of space exploration	The faculty of sight is defined by the capacity to perceive objects from a distance, and by the simultaneous organisation of these sensory impressions into a coherent perceptual whole. (Wagemans, J et al, 2012).	The exploration of space is characterised by both sequential and active processes, which are facilitated by touch and proprioception. (Rincon-Gonzalez, L et al, 2011).
Organisation of space	The theory is based on allocentric coordinates, which refer to the environmental factors that surround the individual. (Ekstrom, A. D., et al,2014).	It has been demonstrated that, in many cases, the system in question is based on egocentric coordinates. These egocentric coordinates refer, of course, to the body. However, it has been demonstrated that, with experience, the system can become allocentric. (Volcic, R., et al, 2008).
Construction of Mental Representations	The concept is conveyed by means of visual imagery and spatial maps that are centred on the visual. (Guelton B. ,2023).	The process under investigation involves manual exploration, the creation of tactile and motor cognitive maps, and the use of these to facilitate the understanding of the subject. (Tonelli, A., et al, 2016).
Spatial construction modes	The phenomenon of distal, simultaneous, perspective- and distance-based vision has been observed. (Erkelens C. J.,2017).	The concept of touch and movement is examined through the framework of sequential construction, integrating the principles of proprioception. (Cordo, P., et al, 1995).
Neurocognitive development	Dominance of the visual cortex and hierarchical development of visual modules are two key concepts in this field. (Murakami, T.,et all, 2022).	The phenomenon of cortical plasticity is demonstrated by the reuse of the visual cortex for haptic and tactile processing. (Sathian, K., et all ,2007).
Cognitive efficiency	The ability to access a large volume of information in a rapid and concurrent manner. (Hasan M. K,2024).	The rate of execution is reduced, yet the result is one of enhanced precision and richness of tactile detail. (Wuang, Y. P., et all, 2022).
Brain plasticity	The process of specialisation in the visual cortex is characterised by stability. Wandell, B. A., et all, 2009).	The phenomenon of high cross-modal neuroplasticity is characterised by the reconversion of visual areas for the purpose of touch and hearing. (Glick, H., & Sharma, A,2017).

Table 1. comparative summary of concurrent condition for space cognition in visual and haptic terms.

New approaches and best practices

The advent of modern technologies has had a profound impact on human interaction with the environment, leading to a radical transformation in our modes of interaction with our surroundings. This tendency is especially evident in the domain of integration of people

with disabilities. The risk of failure in everyday activities is increasing, with origins primarily in the educational context, from which it subsequently disseminates to the social and employment contexts. (Emedea, 2013) The adoption of assistive devices for daily living is a fundamental element for achieving full personal autonomy. In view of the opportunities offered by multisensoriality and the innovative tools introduced by new technologies, it is necessary to initiate research aimed at the inclusion of people with visual impairments. In the following, a number of case studies selected on the basis of innovative characteristics related to the usability of spaces for individuals with visual impairment were examined.

The following case studies will be divided into thematic subcategories in order to facilitate understanding.

The technologies that form the focus of this study can be categorised as follows: audio-optical technologies, wearable devices, VR/AR platforms, and assistive digital apps.

AUDIO-APTICAL TECHNOLOGIES:

ARENA2D is a recently developed device that provides auditory feedback. The proposed technological solution signifies a substantial innovation within the domain of sound reproduction, as it facilitates the serial emission of spatialised sounds. The hardware development was conducted by the Electronic Design Laboratory (EDL) unit of the Italian Institute of Technology (IIT) in Genoa. ARENA2D constitutes a vertical array of 25 haptic blocks arranged in a matrix (50 x 50 x 10 cm). Each block, measuring 5 x 5 cm, consists of a 4 x 4 array of haptic sensors or pads (2 x 2 cm each) with a speaker in the centre. A salient feature of this device is its modularity. The constituent components are interconnected via USB cables, with a maximum separation distance of 20 centimetres. Furthermore, each block can be programmed independently, thus enabling the user to set separate sounds for each block (Setti et al, 2022). (Fig. 2)



Figure 2. Arena 2D.

The "ABBI" project involved the development of the innovative ABBI-K portable system, consisting of a case equipped with a set of customised loudspeakers, controlled by a dedicated Android application via a Wi-Fi connection and two ABBI devices. The project was developed with the primary objective of providing a more accessible and intuitive tool for the simplification of testing procedures. ABBI-K aims to achieve substantial progress, beyond the limitations found in existing experimental models, in assessing the spatial and motor skills of visually impaired children and adults engaged in rehabilitation programmes using ABBI. Furthermore, the system incorporates ten independent Wi-Fi speakers and a mobile device equipped with the Android application "ABBI-K". The device is also equipped with two 7-port USB hubs, accompanied by the necessary power supplies to facilitate the concurrent charging of multiple devices. Additionally, it contains two ABBI devices, contributing to its multifaceted functionality. The device is not fit for purpose in relation to the basic functions of telephony, sending text messages and connecting to mobile data networks. It is only suitable for experimental applications. In light of this, the company's technical infrastructure has replaced a personal computer with a mobile phone equipped with a user-friendly application (Finocchietti et al, 2017). (Fig. 3)

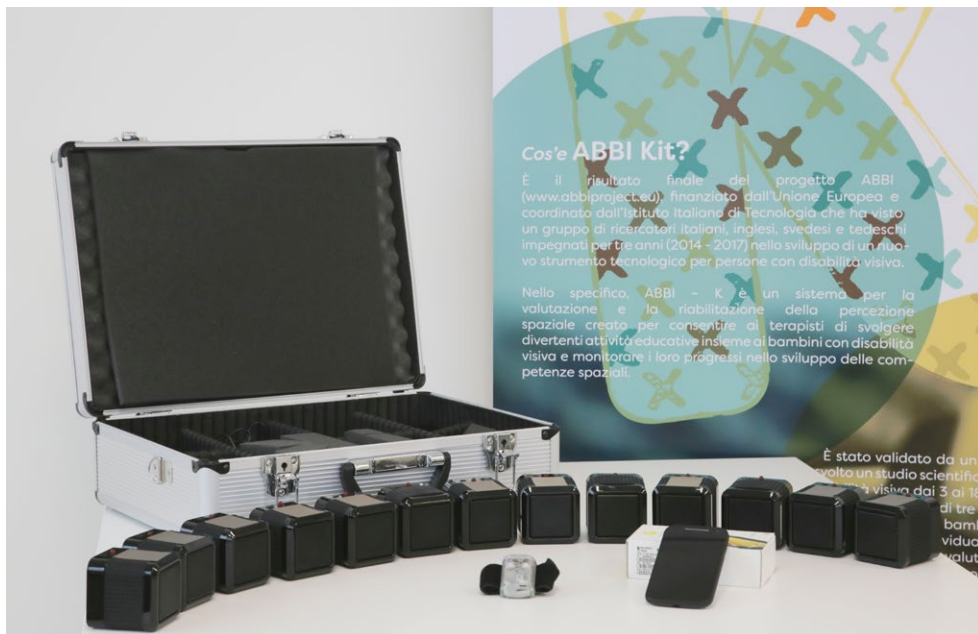


Figure 3. The ABBI project.

The Rotational-Translational Chair (RT-Chair) constitutes a motion platform that facilitates action on two degrees of freedom. The device under scrutiny is capable of analysing the vestibular system, which is responsible for the perception of angular and linear acceleration of the head in space. This device provides information on body movement in the absence of external signals such as sight or hearing. The RT-Chair has been designed to possess the following functionalities: unlimited rotations of 360° along the vertical earth axis and linear translations of up to 200 cm. Furthermore, it has the capacity to execute both types of movement concurrently. The device under scrutiny in this study was conceived with an innovative approach that not only facilitates neuroscientific investigations but also boasts extensive application potential. In synergy with virtual reality (VR), this technology has the capacity to enhance the VR experience, ensuring smooth and vibration-free movements, and reducing the sense of discomfort associated with cybersickness. It is suggested that further applications of interest exist in the domain of research facilities and hospitals, where the technology could be employed to perform evaluations and rehabilitation treatments for patients suffering from vestibular disorders (Cuturi et al, 2020). (Fig. 4)



Figure 4. The Rotational-Translational Chair (RT-Chair).

RoMAT signifies a novel robotic platform for the analysis of the perception process in multisensory movement tasks, involving individuals with and without sensory and motor disabilities. The system facilitates the analysis of the integration process of multisensory signals, incorporating the velocity and direction of the stimuli. The robotic platform under discussion consists of two rotatable plates, mounted on a visual and tactile wheel that, once positioned under the finger of the participants, allows them to observe the elements of the device. The development of such a device would constitute a system for designing, screening and rehabilitation protocols based on neuroscientific findings. The intended application of this system is for individuals with visual and motor disabilities (Gori et al,2021). (Fig. 5)



Figure 5. RoMAT.

WEARABLE DEVICES:

AudioBrush is a portable device, measuring 35x35 centimetres, which has been designed for the playback of spatialised audio content. The

tablet is composed of 576 capacitive sensors. The audio files are characterised by a fixed format, with 8 bits per sample, a frequency of 22050 Hz and a mono mode. The system is comprised of six TAT1 and TAT2 boards, which are managed locally by a Raspberry board running a Linux operating system. In addition, the system is connected to a PC or smartphone via WiFi. The Raspberry device is capable of identifying available WiFi networks and, in this particular instance, has been configured to connect to the network named "AudioBrush" (Setti et al, 2022). (Fig. 6)

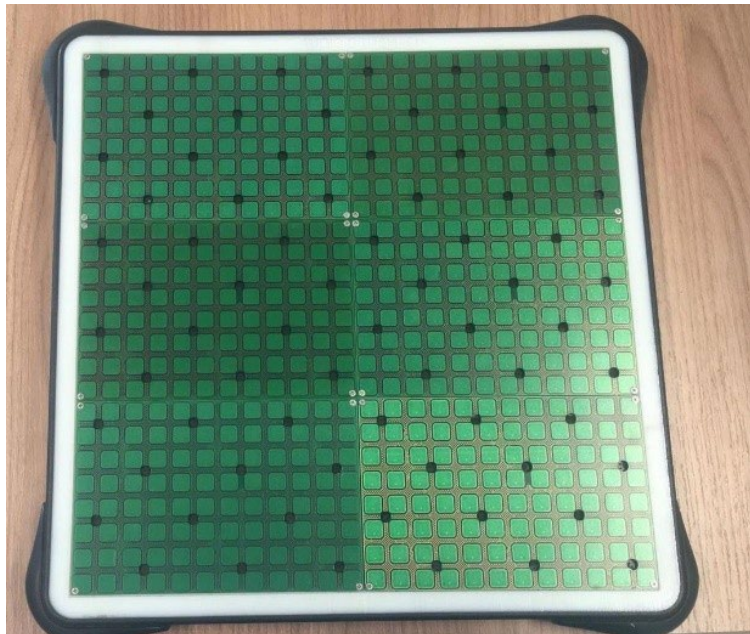


Figure 6. AudioBrush.

Caterpillars are notable for their ability to function as multisensory systems, incorporating visual, auditory and tactile stimuli. The utilisation of such devices facilitates the examination of the multisensory integration process by considering the spatial and temporal properties of the stimulus. These aspects, which include both extrapersonal and bodily space, are examined in the context of the analysis in order to facilitate a comprehensive understanding of the underlying processes (Gori et al, 2019). (Fig. 7)

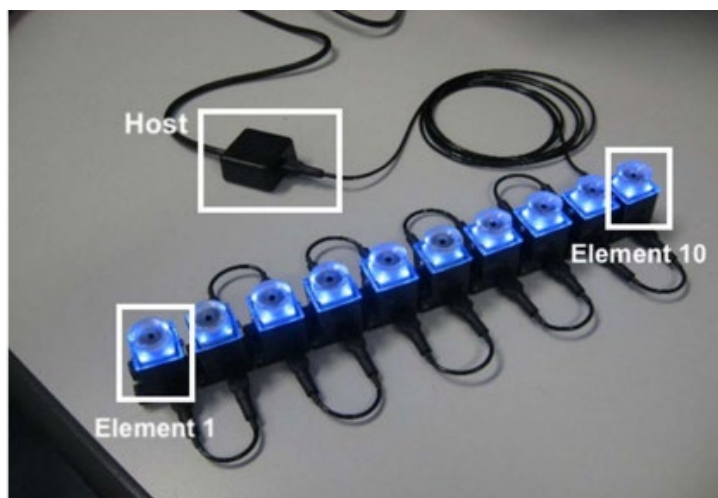


Figure 7. Caterpillars.

VR/AR PLATFORMS:

SALLO is an open source suite of tools that has been developed to facilitate the process of creating psychophysical experiments, with a particular focus on spatial orientation as it pertains to Unity projects. The psychophysical method finds application in a variety of approaches involving both psychological and physical spheres, with the goal of measuring perceptual experiences. Therefore, SALLO comprises model game objects and fundamental components, encompassing every sub-element of the psychophysical experiment (Esposito et al, 2024). (Fig. 8)



Figure 8. Sallo.

The primary objective of the MULTITOUCH project is to provide high-quality education for a new generation of Early Stage Researchers (ESR) working in the multidisciplinary field of haptics. This objective will be accomplished through a combination of practical training, collaboration between academic and industrial researchers, the acquisition of the requisite academic knowledge and transversal skills, and the successful navigation of research challenges in diverse domains including neuroscience, computing, rehabilitation, human-computer interfaces, multisensory haptic displays and virtual reality. This study explores the potential for integrating haptic feedback with auditory and visual feedback in the context of next-generation multisensory human-computer interfaces (HCIs). Such interfaces combine haptic, auditory and visual feedback, including multisensory haptic displays (TD) and multisensory virtual reality (VR) configurations. The objective is to enhance the user experience. During the course of the project, the DRS aims to expand current knowledge on how the sensation of touch is integrated with the other senses under active touch conditions. That is to say, the project aims to investigate how tactile information is derived from active contact with the surrounding environment (Brahimaj et al, 2024). (Fig. 9)



Figure 9. Multitouch.

ACOUSTIC VIRTUAL SIMULATION: The system under consideration facilitates the emission of spatialised sounds through the use of ear-phones, in addition to the capacity for the recording of perceived positions utilising an Arduino Uno-based keyboard. The user can listen to spatialised acoustic stimuli by means of an open source library for spatialising audio and simulating hearing loss and hearing aids. The keyboard, conceived through the utilisation of AutoCAD software, was materialised through the employment of a laser-cut wooden box, which exhibited an array of buttons on its upper surface (Zanchi et al, 2021). (Fig. 10)

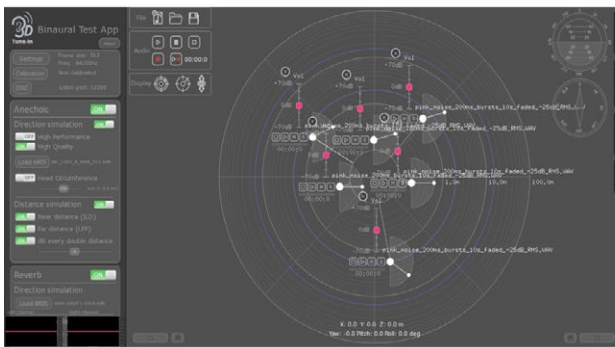


Figure 10. Acoustic virtual simulation.

VRCR constitutes a platform of serious games based on virtual reality, utilised for the evaluation of head-trunk motor coordination, sensitivity to altered head-trunk sensory-motor contingencies (perception-action associations), and asymmetries of spatial perception. It is generally acknowledged that the discipline under consideration comprises a series of recreational shooting activities, customised according to arrow guidance techniques that make use of the head, trunk or, in some cases, a combination of the two. Consequently, the athlete is capable of manipulating the weapon through the utilisation of diverse anatomical regions. Presently, two distinct versions of the platform are being maintained: a visual-only version and an acoustic-only version (Esposito et al, 2021). (Fig. 11)



Figure 11. VR CR.

ASSISTIVE DIGITAL APPS:

In recent years, there has been a significant increase in the development of applications capable of recognising objects. The technology in question is founded upon the principles of Artificial Intelligence. The automatic recognition of an object or the reading of text is achieved by framing the object or text, respectively. By listening and reading enlarged, high-contrast text, the user is able to recognise texts and objects, even in cases of low vision.

Be My Eyes is an application designed to offer assistance to people with visual impairment, whether total or partial. The utilisation of remote communication technology, such as video calling, has the potential to provide significant assistance to individuals requiring guidance in performing fundamental daily activities. The device's utilisation is characterised by an exceptionally high level of intuitiveness. The application is initiated by a blind or visually impaired person who requests assistance from Be My Eyes. In response, Be My Eyes initiates a video call with other users who are registered as visually impaired. The individual who first accesses the conversation and interacts with the initiator is responsible for processing the questions in order to fully understand the nature of the problem and offering appropriate support (Avila et al, 2016). (Fig. 12)



Figure 12. Be My Eyes.

The Aipoly Vision application constitutes an assistive technology that facilitates the recognition of objects and colours, thereby contributing to the mobility and independence of people with visual impairments. The application functions by utilising the mobile device's camera to identify the object of interest and subsequently activating one of the recognition buttons located at the bottom of the screen. This initiates the AI system, which then proceeds to vocalise the list of recognised objects. It is possible to identify 1,000 basic objects free of charge, with thousands more available to subscribers. Aipoly exhibits the capacity to differentiate between 1,400 colour tones or more, a feat that signifies a substantial enhancement over the capabilities of conventional devices (Şen & Akbay, 2023). (Fig. 13)



Figure 13. The Aipoly Vision app.

Drishti is a mobile application designed to assist individuals with visual impairments. It was developed by the Accenture Lab in Bangalore in collaboration with the National Association for the Blind in India. The term "Drishti" is a Sanskrit word that signifies "vision" and is also used to denote "Disambiguating Real Time Intelligence". This concept has been translated as the ability to make acquired information coherent. Drishti employs advanced technologies, including artificial intelligence, facial recognition and natural language generation, to gather information, process it and provide real-time voice guidance that is beneficial in enhancing the quality of life of people with visual impairments (Limaye, 2012).

The following essay will provide a comparative summary of the strengths and limitations inherent in each case study analysed.

	STRENGTHS	LIMITATIONS
ARENA2D	<p>The system exhibits high modularity, with each constituent element being capable of independent programming.</p> <p>The process under discussion enables the spatialisation of sound in a serial and precise form.</p> <p>The apparatus under consideration is notable for its compact, well-integrated design, which facilitates multi-sensory testing.</p>	<p>Physical limitations in the distance between blocks (maximum 20 cm).</p> <p>Complexity in initial configuration and management of USB connections.</p>
AUDIOBRUSH	<p>Portable and compact design.</p> <p>High touch resolution (576 sensors).</p> <p>Wireless management via Raspberry and WiFi.</p>	<p>Fixed, low quality audio format (8 bit, 22050 Hz, mono).</p> <p>Specific technical requirements for interfacing.</p>
ABBI-K	<p>Portable system for motor/spatial testing of the blind.</p> <p>Use of independent WiFi speakers for spatial freedom.</p> <p>User interface via Android, easy to use.</p>	<p>Not suitable for mobile communication (phone calls, messages).</p> <p>Specifically designed for experimental use, not versatile.</p>
ACOUSTIC VIRTUAL SIMULATION	<p>Inexpensive, open source system for spatialised audio testing.</p> <p>Customisation via Arduino.</p>	<p>Limited accuracy in sound localisation.</p> <p>Homemade solution, less robust for large-scale clinical applications.</p>
RT-CHAIR	<p>Combined rotational and translational movement.</p> <p>Applicable in VR and neuroscientific studies.</p> <p>Useful in vestibular rehabilitation.</p>	<p>Cumbersome and expensive.</p> <p>Relevant only for specialist studies, not versatile for everyday use.</p>

ROMAT	Specifically designed for analysing multi-sensory motion tasks. Detailed and adaptable haptic interface.	Application limited to laboratory tests. Low portability.
CATERPILLARS	Multisensory: integrates visual, tactile and auditory stimuli. Suitable for sensory integration studies.	Not very detailed in technical specifications. Little information on usability and portability.
SALLO	Open-source and easily integrated with Unity. Excellent for creating customised psychophysical experiments.	Requires high technical skills (programming, Unity). Not a physical device: only software environment.
MULTITOUCH PROJECT	Wide scope of application: haptics, VR, neuroscience. Educational project for researchers, with practical and theoretical components.	It is more of a research infrastructure than a ready-to-use product. Long implementation time and complex practical transferability.
VRCR	Accurate assessment of head-trunk coordination. Two modes (visual and acoustic), customisable by disability.	Limited to rehabilitation or research contexts. High requirements for VR equipment.
BE MY EYES	Real-time support via video call. Easy to use and free of charge.	Depends on availability of a volunteer. Requires stable Internet connection.
AIPOLY VISION	Instant recognition of objects and colours, even shades. Works offline in part (for basic objects). Extensive AI database, updatable.	Limited access to free version. Possible recognition errors in unfavourable light/scene conditions.
DRISHT	Combines advanced AI, facial recognition and voice guidance. Designed for urban navigation and interaction. Multilingual and culturally adapted (India).	Not yet deployed globally. Dependent on AI cloud and connectivity.

Table 2. Comparative summary of the strengths and limitations of each case studies

Results and conclusions

An analysis of the extant literature reveals a lack of formal standardisation that could serve as "general principles of action". In this regard, the proposal being presented has been developed in order to address the identified limitations and to facilitate the creation of tools that will enable blind individuals to more effectively utilise space. The

bibliographic production was analysed to highlight the centrality of integrating different sensory stimuli in the context of overcoming visual limitations, resulting in increased accessibility for visually impaired persons. The analysis of the case studies provided a fundamental contribution to the drafting of a preliminary set of guidelines. The objective of the guidelines is to design a device to facilitate access to a space for people with visual impairments.

Consequently, the design of the device must take the following characteristics into consideration:

- The utilisation of multisensoriality to stimulate alternate senses and mitigate the impact of visual impairment is an innovative and promising approach.
- There is a necessity to equip devices with voice commands that facilitate seamless communication, thereby eliminating the requirement for visual interfaces or manual controls, thus ensuring intuitive interaction with the user.
- The integration of advanced technologies into analogue devices represents an opportunity to extend the functionality of visits, for example through the use of Near Field Communication (NFC) or tactile vibrations to provide new information.
- The integration of orientation and navigation systems, based on Global Positioning Systems (GPS) or internal sensors such as Bluetooth, has the potential to facilitate the mobility of visually impaired persons within new and unfamiliar spaces.
- It is imperative that such systems possess the capability to detect the user's position and provide voice prompts to facilitate spatial orientation.
- In order to overcome the limitations of Braille and enlarged characters, tactile maps, audio-guided routes and ground signalling strips, there is a need to diversify and broaden the offer.
- It is imperative that the device is equipped with an intuitive and accessible mode of operation, thereby ensuring ease of use for the user, thus eliminating the necessity for external assistance.
- It is imperative that the device be capable of providing support to both visitors and staff, with a view to enhancing the visitor experience.

The synergy between these functions facilitates the development of devices that not only facilitate access to the surrounding environment, but also provide a profound and gratifying experience for blind people, allowing them to explore and acquire knowledge in an auto-

nomous and stimulating manner. The present research endeavours to achieve a dual objective: firstly, to enhance the usability of space and, secondly, to implement the use of other senses in the absence of sight through the utilisation of novel technologies or their implementation, with a view to enhancing the quality of life and the usability of spaces for blind individuals, thereby ensuring full participation in social life. While the present state of affairs does not permit the provision in question, its incorporation in forthcoming developmental projects is regarded as imperative. In this regard, the subsequent potential directions can be suggested. The integration of artificial intelligence with the objective of personalising haptic feedback represents a substantial advancement within the domain of assistive technology. The importance of conducting pilot tests in authentic public settings, such as educational and cultural institutions, cannot be overstated. Furthermore, the proposed solutions are subject to a cross-cultural validation process. In order to achieve a comprehensive understanding of the observed phenomena, it is imperative that interviews and tests are utilised as a means of investigation. The utilisation of these instruments as fundamental tools in the design and implementation phase of the study is of paramount importance. Engagement with the expertise of professionals operating within the context of associations for individuals living with visual impairments is imperative in order to address the complex needs of this vulnerable demographic.

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*It is important to note that the images in this collection are the intellectual property of the respective individual projects.

DANIELE DE PASCALE

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Designing the future of workwear. Smart solutions for thermal safety in the climate change era



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Keywords: climate change, workers, safety, health, wearable technology, smart clothing

Abstract

In contemporary times, the rise in the Earth's surface temperature has been largely attributed to anthropogenic causes. The increasing intensity of extreme weather events and prolonged heat waves has significantly impacted work and production activities, leading to widespread thermal discomfort and elevated heat stress. Construction and road workers are particularly exposed to health and occupational safety issues in this context, as they face heightened workplace risks and an increased risk of developing short- and long-term occupational diseases. A study of existing literature reveals that personal protective equipment designed for thermal mitigation remains underutilised, largely due to ergonomic limitations, high production costs, inadequate integration into daily workflows, and cultural resistance. In response, wearable technologies have emerged as a promising avenue for counteracting heat-related

risks. Thermoregulation systems that can detect, respond to and adapt to thermal stimuli show significant potential for protecting the most exposed workers. This paper provides a synthesis of existing wearable thermoregulation systems, identifies key gaps in their ergonomic implementation, and outlines future directions for interdisciplinary research and design innovation.

Introduction

Since the earliest stages of human history, individuals have been exposed to environmental and physiological risks associated with occupational activities. Notably, as early as the Roman era, Pliny the Elder documented the implementation of rudimentary preventive measures by craftsmen working with cinnabar: a mineral employed to produce a distinctive red pigment. «Persons polishing cinnabar in workshops tie on their face loose masks of bladder-skin, to prevent their inhaling the dust in breathing, which is very pernicious, and nevertheless to allow them to see over the bladders» (Pliny the Elder, ca. 77–79 C.E., p. 95, trans. by Rackham). In the 17th century, Bernardino Ramazzini, considered the father of occupational medicine, asserted the correlation between occupational exposures and the onset of specific diseases in his work *De Morbis Artificum Diatriba* (1700) (Spaterna, 2022), thereby anticipating the modern concept of ‘cumulative trauma disorders’ (Franco & Franco, 2001). Subsequently, inspection reports from the Industrial Revolution documented frequent episodes of heat collapse and impaired vigilance—phenomena now recognised as early indicators of ‘occupational heat stress’ (Ogden, 2023). These historical accounts establish a clear thread linking past occupational hazards to contemporary challenges posed by Climate Change (CC). Global warming, accelerated by anthropogenic CC, is leading to an increase in the frequency and intensity of heatwaves, with direct consequences for public health and worker safety (ILO, 2024). This highlights the need to address ‘old’ risks from new ergonomic and preventive perspectives. According to current climate projections (IPCC, 2023), continued greenhouse gas emissions are likely to push global warming beyond the 1.5°C threshold in the near future. Furthermore, it is estimated that the highest summer temperatures recorded between 1950 and 1979 will occur at least 70% of the time between 2035 and 2064 (NCA, 2014). In the coming decades, this will increase the incidence of heat-related illnesses, poor air and water quality, declining food resources, and a subsequent decrease in labor productivity (ISS, 2009).

Considering these premises, it is clear that the risk of heat exposure for humans will become increasingly critical shortly. This concern is especially pertinent for outdoor workers, such as those in the agricultural and construction sectors. Accordingly, this paper concentrates on the occupational hazards posed by heat waves. The study begins with an analysis of the literature and explores the consequences of prolonged heat exposure in work environments. Focus is directed toward emerging advancements in monitoring physiological parameters and preventing heat stress through wearable technologies. Finally, the paper offers a discussion on potential interdisciplinary approaches to effectively address these emerging challenges.

Methodology

This contribution is structured along two main thematic lines: (i) the correlation between CC and its impacts on human health; (ii) the evolution of prevention strategies, with particular attention to regulatory frameworks and wearable technologies for monitoring heat stress. The aim is to offer an updated synthesis of recent scientific and institutional contributions, in order to recontextualise historically known occupational risks in light of contemporary environmental, technological, and social transformations. Sources were selected through consultation of scientific databases and institutional websites, including those of the World Health Organization (WHO), the National Institute for Insurance against Workplace Accidents (INAIL), and the European Agency for Safety and Health at Work (EU-OSHA). Although the study is not structured as a systematic review, it adopts a qualitative, narrative synthesis approach, prioritising sources based on their relevance, recency, and representativeness in the international debate. The literature search was guided by keywords such as 'climate change', 'heat stress', 'human health', 'wearable technologies', and 'smart garments'. Alongside technical and scientific data, the paper also integrates historical and cultural insights—for instance, traditional adaptation strategies of desert nomadic populations—which exemplify embodied resilience in extreme environments. In the following sections, we explore the physiological, occupational, and regulatory dimensions of heat stress, beginning with a general overview of climate-health interactions.

Living and working in extremes

Global surface temperatures have risen by approximately 1°C above

pre-industrial levels (IPCC, 2023), with 0.8°C of this increase occurring since the 1970s (NASA Earth Observatory, n.d.). Although data remain somewhat fragmented and geographically heterogeneous, evidence from the past two decades confirms that health risks arise from the interaction between climate-related hazards (both acute events and long-term trends) and the vulnerability and exposure of human and natural systems (IPCC, 2014). The primary pathways through which CC affects health are: i) direct impacts, such as exposure to high temperatures, storms, floods and air pollution; ii) effects mediated by natural systems, such as vector-borne diseases (e.g. malaria, dengue fever and Lyme disease); iii) indirect impacts, such as food security and water scarcity (WHO, 2021; FAO, 2016). These pathways reveal a systemic cascade wherein CC and health risks are interlinked, with each effect potentially amplifying or triggering others (Haines et al., 2019; Campbell-Lendrum et al., 2023). A significant study estimates that anthropogenic CC accounts for approximately 37.0% (range: 20.5% to 76.3%) of heat-related deaths during the warm season (Vicedo-Cabrera et al., 2021). The WHO has identified climate change (CC) mitigation and the management of its health impacts as priority actions within the Global Public Health Agenda (WHO, 2021). Exposure to extreme heat for a prolonged time, without the ability to dissipate it effectively, can trigger a chain reaction of physiological dysfunctions across multiple organ systems (McKeever, 2021). Figure 1 outlines the multifactorial pathways through which CC impacts human health, with particular emphasis on thermal stress resulting from both extreme heat and cold. CC is shown as a central driver that increases the frequency and severity of both heat waves and cold spells. These exposures lead to direct health effects—such as heatstroke, dehydration, cardiovascular and respiratory complications—as well as indirect effects, including reduced labor productivity, increased healthcare demand, and socio-economic vulnerabilities. Particularly at risk are outdoor workers, the elderly, children, and individuals with pre-existing health conditions (Acharya et al., 2018; Commissione Europea, n.d.). This paper focuses on the impact of extreme heat on outdoor workers and the potential of wearable technologies to increase thermal comfort.

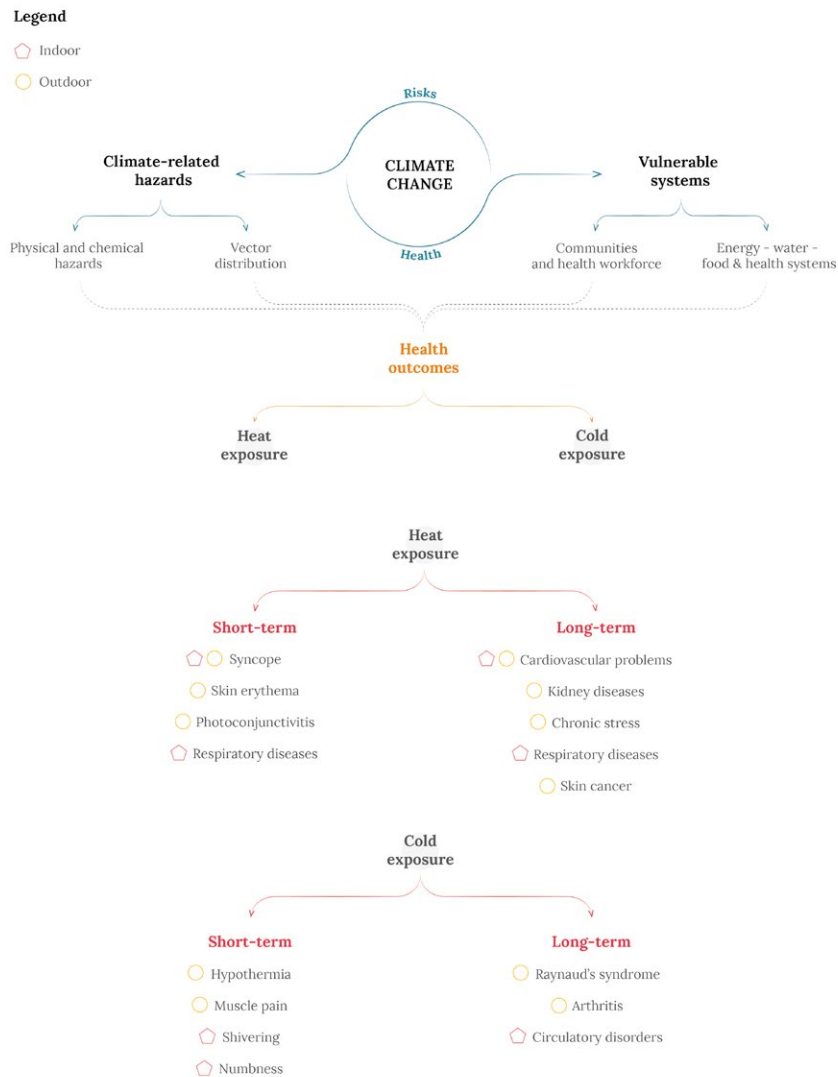


Figure 1. An overview of the impact of Climate Change (CC) on human health.

Heat exchange in the human body

The human body consists of a heat-generating core containing vital organs, surrounded by an external layer of tissues that insulate it from the environment. Although temporary conditions such as physical activity can cause fluctuations, body temperature typically remains at around 37°C (Bevilacqua & Piccioni, 2022). As homeothermic organi-

sms, humans maintain a stable internal temperature through biological thermoregulation, which is controlled by the hypothalamus. In hot conditions, effective thermoregulation via sweating and evaporation is essential to preserve alertness and prevent accidents. (Bevilacqua & Piccioni, 2022). An unsatisfactory bodily reaction can result in serious conditions like heat exhaustion or heat stroke in tough work settings marked by extreme temperatures and ongoing heat exposure. Epidemiological studies conducted in several countries (Martínez-Solanas et al., 2018; Varghese et al., 2019; Marinaccio et al., 2019; Spector et al., 2019; Lee et al., 2019; Gariazzo et al., 2023; Di Biasi et al., 2023) have documented these effects. In addition to physiological effects, prolonged exposure to heat stress impacts cognitive and psychological functions. Specifically, research has shown impairments in reaction time, alertness and decision-making ability among workers (Mazloumi et al., 2014; Dutta et al., 2015; Rastegar et al., 2021). From a cognitive ergonomics perspective, these effects translate into an increased risk of human error, particularly when performing complex tasks.

The working population, particularly those in occupations that require protective clothing, is more susceptible to heat stress than the general public. This clothing often lacks breathability, trapping heat and humidity inside and impeding sweat evaporation, which significantly reduces the body's natural cooling mechanisms. As sweat accumulates without evaporating, core body temperature rises, increasing workers' vulnerability to heat-related strain (Amodu et al., 2023). Amodu et al. identify several occupational and individual risk factors that contribute to heat-related illnesses and their associated health outcomes. It emphasises the heightened vulnerability of specific groups—such as migrant workers, especially those employed in agriculture or other physically demanding outdoor jobs—who are disproportionately exposed to heat stress due to intense workloads and limited access to protective measures. It illustrates the main adaptation strategies adopted to date. These include hydration practices, resting in shaded or cooled areas and adjusting work schedules—none of which address the limitations posed by protective clothing. Ongoing anthropogenic global warming will substantially reduce physical work capacity (Ioannou et al., 2022). Therefore, preventive and adaptive strategies are essential for protecting worker health and maintaining productivity.

Heat stress in outdoor workers: risks and mitigation strategies

The relationship between CC and occupational heat strain among outdoor workers is well established, with the most probable physiological pathway involving progressive dehydration, physical fatigue, dizziness, cognitive impairment, reduced concentration, and general discomfort (Habibi et al., 2021). A recent review indicates that migrant and ethnic minority outdoor workers are disproportionately affected by occupational heat stress (Sharma & Anikeeva, 2025), due to multiple overlapping vulnerabilities, including precarious employment conditions, language and cultural barriers, limited access to health services, and inadequate living and working environments (van Selm et al., 2025). These findings underscore the need for tailored interventions and policies to address heat-related risks in vulnerable worker groups. Among these, construction workers are particularly vulnerable, as they almost always work outdoors—often during the hottest months—exposed to humidity, solar radiation, and intense physical exertion (Acharya et al., 2018). This combination of heat, humidity, solar radiation, and physical exertion hinders the body's ability to dissipate heat effectively by reducing sweat evaporation, leading to impaired thermoregulation and an increased risk of heat-related illnesses. Several studies have shown that solar ultraviolet rays are a key risk factor for skin cancer, specifically among outdoor workers (Slavinsky et al., 2024; Wittlich, 2022; Cherrie & Cherrie, 2022). Among that, Vernez et al. (2015) analyzed a sample of 889 individuals, considering two common postural scenarios in outdoor work: standing upright and bending the torso forward. The study identified the body areas most exposed to solar radiation and demonstrated how working posture can influence exposure levels. Graphs a, b and c (Figure 2) particularly confirm these findings, showing that the neck and upper shoulder areas are especially vulnerable among construction and road workers. Graph d shows the estimated average UV dose on different body parts across seasons, compared to UV radiation measured at ground level. While the ground consistently receives the full amount of incident solar radiation, the human body—being three-dimensional and in motion—exhibits variable exposure levels depending on the angle of solar incidence and the worker's posture.

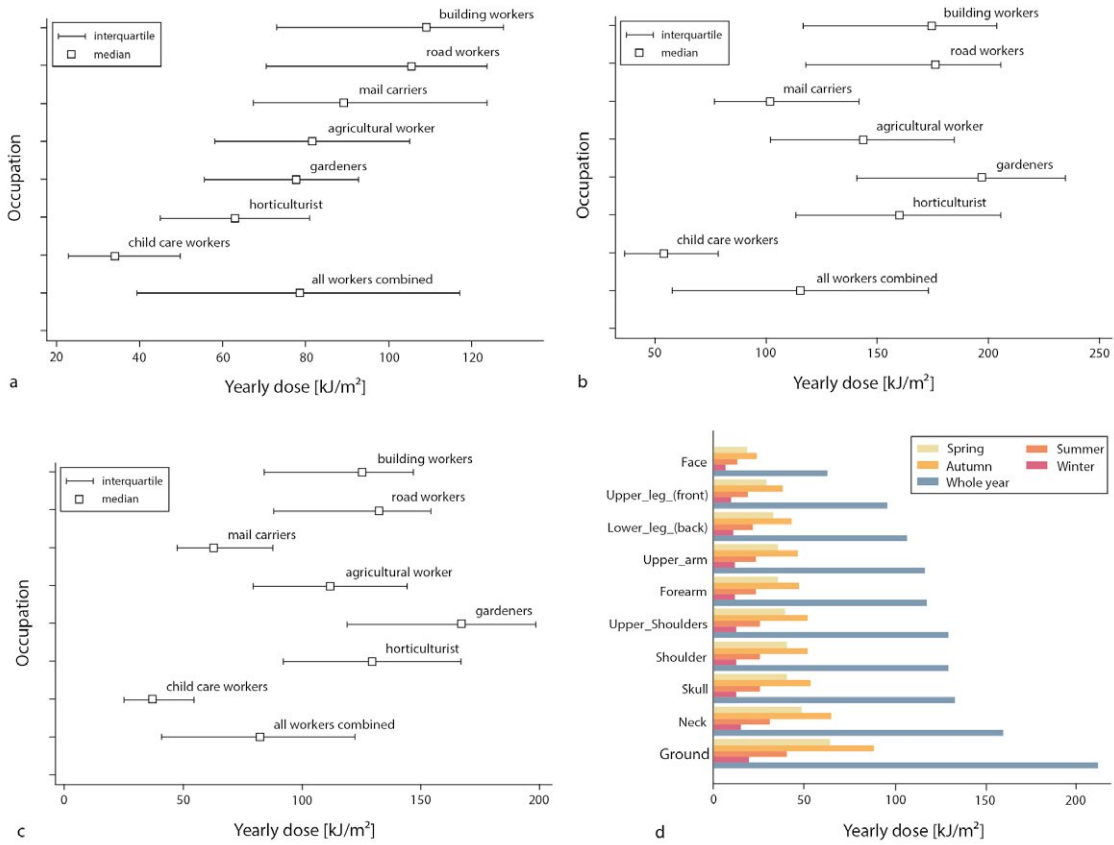


Figure 2. Estimated erythemal ultraviolet (UV) dose, expressed as yearly dose (in kJ/m^2) [median (interquartile range)], by occupation and body site: (a) face, (b) neck, (c) top of shoulders. (d) Variation in estimated erythemal UV dose across different body sites, stratified by season and year. Source: Vernez et al., 2015.

These considerations highlight the importance of preventative strategies and the promotion of effective work practices to manage heat-related thermal stress. Occupational heat stress is addressed by international standards such as ISO 7243:2017, which provides a method for assessing environmental heat exposure using the WBGT index, and ISO 7933:2004, which estimates physiological strain through the Predicted Heat Strain (PHS) model. While ISO 7243 is based solely on environmental parameters, ISO 7933 incorporates individual factors such as metabolic rate and clothing insulation. Despite their technical relevance, the application and regulatory enforcement of these

standards vary considerably across countries and industrial sectors (Al-Bouwarthan et al., 2019).

In Italy, the reduction in productivity due to the need to limit heat exposure is estimated at an average of 6.5%, with peaks reaching up to 80% for physically demanding activities (Grifoni et al., 2021). In 2023, the National Research Council's Institute of BioEconomy (IBE) launched the Workclimate 2.0 project, supported by INAIL and other entities, to study the impact of extreme temperatures on workers' health and quantify the social costs of injuries. A web platform using the MOLOCH meteorological model was developed to provide personalised forecasts that support heat-related prevention strategies. Construction and infrastructure workers emerge as among the most at-risk categories, alongside agricultural workers and personnel in logistics and transportation (Beheshti et al., 2017; Del Ferraro et al., 2021; Grifoni et al., 2021). It is only through a process of acclimatisation that the human body can develop the capacity to tolerate tasks performed at elevated temperatures. While Personal Protective Equipment is essential for safety, it can impair the body's ability to cool itself by restricting airflow and trapping heat and moisture, thereby increasing the risk of heat stress. Regulatory frameworks, such as Italy's LD 81/2008, generally lack specific measures and offer only broad recommendations for heat exposure management. These include wearing lightweight, breathable, and light-colored clothing, using a hat with a visor and/or UV-filtering sunglasses, and applying high-protection sunscreen to exposed skin. Regulatory gaps highlight the need for more targeted guidelines. Moreover, common assumptions about clothing in hot climates are challenged by traditional desert attire. Though it may seem trivial, a study conducted as early as 1980 on Bedouins (Shkolnik et al.) reminds us that loose black garments can enhance thermal comfort by promoting airflow between fabric layers, thereby aiding heat dissipation. Although dark colours absorb more solar radiation than light ones, it is important to bear in mind that material, fit, and ventilation play a more significant role in cooling.

New frontiers for personal thermal management

The literature shows growing interest in innovative technologies and materials to protect workers from heat in high-risk environments. Wearable Technologies (WT) are particularly effective due to

their ability to monitor physiological and environmental parameters in real time (Bernasconi et al., 2022) and support the management of work-rest cycles and workloads, enhancing both well-being and productivity in high-temperature professional environments (Kato et al., 2025). They enable early detection of heat stress and the activation of preventive measures. By acting on the body, WT can provide localized and personalized cooling, as well as skin protection from UV radiation. Integrated into workwear through intelligent garments and smart textiles, WT help ensure comfort, breathability, and freedom of movement without compromising safety (Chan, Guo & Wong, 2015). The interaction between embedded sensors, actuators, and alert systems also allows for timely warnings to workers or safety personnel in case of risk, thereby preventing heat-related illnesses and injuries. In this field, Smart Clothing (SC) plays a central role, representing the convergence of materials science, electronic engineering, and design. The literature identifies three key evolutionary trajectories: the degree of smartness, the level of technological integration, and the degree of energy autonomy. In terms of smartness, textiles are categorised as passive, active, or very smart based on their ability to sense, respond to, and adapt to external stimuli. Passive textiles do not autonomously respond to stimuli—their function is limited to sensing only. Active textiles are capable of detecting changes in body or environmental temperature and responding through integrated mechanisms such as controlled heating or cooling. Very smart textiles not only detect and respond, but also learn and dynamically adapt to body and environmental conditions, thanks to integrated sensors, actuators, microcontrollers, and adaptive logic. The level of integration has evolved across three generations: (i) electronic components externally applied to the fabric; (ii) components embedded within the textile structure; and (iii) electronic functionalities integrated into the fibers, enhancing comfort and aesthetic quality (Xiaopei and Li, 2019). This classification is relevant from an ergonomic perspective, influencing perceived comfort—defined as the absence of physiological, psychological, or physical discomfort (Kamalha et al., 2013)—as well as breathability, freedom of movement—dynamic wearability (Gemperle et al., 1998)—and long-term usability. SC and textiles for personal thermoregulation are not new to research. Over the past years, a growing number of studies have explored a variety of strategies and applications aimed at maintaining thermal comfort. Wu, Chen and Hsu (2023) provided a review in which four levels of personalised thermoregulation (PT) are identi-

fied: static, passively adaptive, actively adaptive and active (Figure 3). According to them, systems in the active category “rely on external work to enhance heat transfer, such as thermoelectric device (TED), liquid cooling circulation, and air ventilation”. Although these systems are capable of providing greater cooling capacity, they are now outdated and still consume a high amount of energy. While the proposed framework helps categorize existing solutions, it does not sufficiently address the trade-offs between thermal efficiency and wearability in real-world occupational settings.

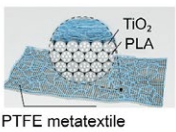
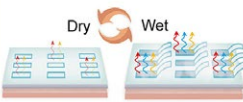
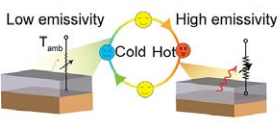
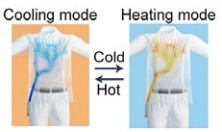
	Static	Passively adaptive	Actively adaptive	Active
Wearable thermo-regulation				
Energy consumption	Zero	Zero	Low	High
Cooling power	Middle	High	High	Very high
Sensor compatibility	No	No	Yes	Yes
Manufacturability	Easy	Moderate	Difficult	Difficult

Figure 3. Estimated erythemal ultraviolet (UV) dose, expressed as yearly dose (in kJ/m²) [median (interquartile range)], by occupation and body site: (a) face, (b) neck, (c) top of shoulders. (d) Variation in estimated erythemal UV dose across different body sites, stratified by season and year. Source: Vernez et al., 2015.

In the same year, Lei et al. (2023) offered a review of the recent advances in PT clothing, focusing on enhancing heat dissipation control between the skin and the immediate environment (garments that regulate thermal exchange through radiation¹ and conduction mechanisms). The review by Sajjad et al. (2023) addresses instead the growing need for energy-efficient personal thermal management devices, especially for individuals exposed to harsh or hot environments who require portable cooling solutions. It consolidates various cooling strategies, including active cooled garments (air, liquid, evaporative, micro fan ventilation, thermoelectric, vapor compression)², passive cooled garments (phase change materials, shape memory alloys), in-

1 Thermal radiation is a process of heat transfer through electromagnetic waves (infrared) emitted by any body with a temperature above absolute zero. In the case of the human body, the skin naturally emits heat in the form of infrared radiation toward

the surrounding environment. Garments for personal thermal management regulate this heat flow by mediating between the body and environment: they facilitate heat dissipation with infrared-transparent or reflective fabrics in hot conditions, limit heat loss with reflective materials in cold conditions, and dynamically adjust their thermal properties to optimize comfort based on environmental or physiological changes.

²*However, these solutions have been adopted for decades and generally suffer from low reliability relative to the operating times of individual systems. In particular, vapor compression refers to a cooling method that uses a refrigerant circulating through a closed loop, where the refrigerant absorbs heat by evaporating at low pressure and temperature, then releases heat when compressed and condensed at higher pressure. This process, commonly used in refrigerators and air conditioners, enables effective*

telligent textiles, and hybrid cooling systems.

Each category's concepts, designs, applications, benefits, and limitations are discussed, along with radiative³ and conductive cooling textiles. Despite the broad range of identified strategies, the actual long-term impact of each system on worker productivity and comfort remains unclear, an essential factor for large-scale industrial adoption. More recently, Zhang et al. (2024) provided a critical analysis of the strengths, limitations and ongoing challenges in SC designed for enhanced personal thermal management. Still, in 2024, Ma et al. provided a review of smart thermal management fabrics, distinguishing between passive and active systems based on their energy consumption (the presence or absence of external energy input) and by examining their mechanisms, research developments, advantages, and limitations. They highlighted the evolving role of e-textiles in health monitoring and energy harvesting, emphasizing the importance of maintaining wearing comfort in multifunctional applications.

Energy harvesting plays a crucial role in powering self-sustaining WT, meaning those capable of collecting energy from the surrounding environment without the need for an external power source. Among the different energy sources (heat from human body, light, vibrations, radio frequency) wearable thermoelectric generators (W-TEGs) stand out as a promising solution because they can produce hundreds of microwatts, which are sufficient to power different electronic sensors, such as electrocardiograph and pulse oximeters (Pang et al., 2023). Nevertheless, the reliability of energy harvesting under varying environmental and physiological conditions remains a key issue to address to ensure uninterrupted functionality.

As per product development, a smart cooling vest designed to reduce heat stress among construction workers was studied by Hossain et al. (2024). Focusing on active cooling mechanisms (Peltier fans⁴) and ergonomics, the research evaluates the vest's effectiveness in regulating body temperature and enhancing worker comfort and safety. A recent example of the integration of cooling fans was presented at Osaka Expo 2025 Designing future society for our lives (Fig. 4b), a jacket with built-in electric fans designed by Anrealage. In Japan's summer months, fan-equipped jackets have become a common sight among blue-collar workers. The technology, introduced in 2004 by former Sony engineer Hiroshi Ichigaya, founder of Kuchofuku, works by circulating air through the garment via two small fans at the waist, enhancing sweat evaporation and regulating body temperature. Now

widely adopted by construction workers, traffic controllers, and other laborers in Japan—and increasingly entering markets such as China and the U.S.—this type of climate-responsive clothing has yet to see widespread use among the general public (Ogawa Clarke, 2024). This indicates that, beyond technical functionality, cultural and aesthetic factors still significantly influence the mainstream adoption of thermoregulatory clothing.

It is indeed a clear attempt to balance aesthetics with the ergonomic constraints of bulky ventilation components, reflecting ongoing efforts to improve thermoregulation without compromising comfort or mobility. An effort also evident in the Biosuit by Dainese and MIT (Figure 4a), designed to enable freedom of movement while maintaining safety and physiological stability of the astronaut, through body-mapped materials and tension lines that mirror muscular and skeletal anatomy. However, the design complexity and high cost of such systems pose major challenges for their translation into less extreme and more cost-sensitive contexts like construction or manufacturing.

A comparable design focus can also be found in the Liquid Cooling and Ventilation Garment (LCVG), an underlayer worn by astronauts. While the outer spacesuit provides insulation and helps retain body heat—except in areas exposed to extreme cold—active cooling is essential to prevent overheating. The LCVG meets this need by circulating water through a network of flexible tubes embedded in the garment, effectively dissipating excess heat. For the system to function properly, continuous and unobstructed water flow through inlet and return lines is critical. In both cases, the garments exemplify the complex interplay between technological performance and the human body in extreme environments (Smithsonian National Air and Space Museum, 2012).



cooling but requires complex components like compressors and condensers, which can limit durability and portability in wearable applications.

³ *Radiative cooling is a passive process where materials emit infrared radiation to dissipate heat without energy use. In clothing, radiative cooling textiles maximize body heat emission while minimizing sunlight absorption, helping wearers stay cooler in sunlight. These fabrics use coatings or fiber structures that reflect visible light but emit strongly in the infrared, offering an energy-free way to regulate body temperature. A comprehensive review on this topic is provided in the paper "Recent advancements in radiative cooling textiles for personal thermal management" by Jiang et al. (2024).*

⁴ *A Peltier fan uses the thermoelectric effect to create cooling on one side of the garment while a built-in fan dissipates heat from the other side, enabling efficient temperature regulation.*

Figure 4a. Biosuit by Dainese and MIT. Source: Newman, 2012; **Figure 4b.** A jacket with built-in electric fans designed by Anrealage, Osaka Expo 2025. Source: Burgos, 2025



Figure 5. Liquid Cooling and Ventilation Garment (LCVG). Source: Smithsonian National Air and Space Museum, 2012

⁵In thermodynamics, the Coefficient of Performance (COP) is an index used to evaluate the efficiency of a thermal system, such as a heat pump, refrigerator, or air conditioner. It expresses the ratio between the useful energy produced (transferred heat or cooling) and the electrical energy consumed to obtain it (Çengel & Boles, 2014).

Similar, but different in the technological approach, is the study by Hong et al. (2019) that demonstrated a W-TEG that can deliver more than 10°C cooling effect with a high coefficient of performance⁵ (COP > 1.5). It was the first to achieve long-term active cooling with high flexibility, due to a novel design of double elastomer layers and high-ZT rigid TE pillars⁶. In line with these developments, the study by Catarinucci et al. (2022) presented a preliminary validation of the software and sensor functionalities of a smart IoT system designed to improve workers' thermal comfort. It integrates customized, energy-efficient wireless sensors into graphene-based textiles, enabling optimal heat exchange and real-time monitoring of physiological parameters to detect signs of thermal stress. It features sensors, alert mechanisms for workers, and analytical tools for safety personnel to monitor and assess the collected data.

Regarding passive cooling systems, an Anti-Heat Stress Uniform for construction workers in hot and humid weather was first developed

by Chan et al. (2015) and subsequently adopted in Hong Kong's Construction Industry Council guidelines. In 2015, Tong et al. introduced a personal cooling technology based on an infrared-transparent yet visible-opaque fabric, enabling passive body cooling by allowing thermal radiation emitted by the human body to pass directly into the environment while maintaining a conventional textiles appearance. Made from synthetic polymer fibers engineered to maximize infrared transmittance (that refers to the ability of the fabric to allow infrared radiation—heat energy emitted by the human body—to pass through it) and minimize reflectance (which is the fabric's ability to reflect infrared radiation back toward the body), the fabric achieves high thermal efficiency. Although these materials show promising lab results, their long-term durability and effectiveness under dynamic and prolonged usage scenarios remain to be validated.

In 2019, Zang et al. developed an infrared-adaptive textile made of polymer fibers coated with carbon nanotubes. The yarns dynamically expanded and contracted in response to heat and humidity, altering fiber spacing. This adjustment improved breathability and modified the textile's infrared emissivity, enhancing heat exchange under hot and humid conditions. The self-adjusting emissivity offers promising potential for wearable thermal management. A similar concept is that of the Biologic Suit, developed by MIT's Tangible Media Group, which uses biohybrid fabrics with moisture-reactive bacterial cells that expand and contract in response to body heat and sweat, enabling dynamic ventilation and passive thermal regulation (Wang et al. 2017). More recently, the Central Leather Research Institute and the Desert Research Center in Cairo have developed a cooler leather (Tejonmayam, 2025) made by applying a coating of chemicals derived from paraffin and Porous Activated Carbon (PAC) to the outer surface. It can maintain a surface temperature at least three degrees lower than leather coated with only PAC. The key lies in the phase-change materials in the coating, containing substances that absorb and release heat during phase transitions, such as melting and solidifying.

Discussion

Despite the benefits and the growing diffusion of WTs, several critical factors continue to hinder their widespread adoption and long-term integration in occupational settings. Field observations and direct dialogue with workers reveal a substantial cultural and informational gap: many users are unaware of existing wearable technologies (WTs)

⁶High-ZT rigid TE pillars are solid columns made of high-performance thermoelectric materials, designed to maximize the conversion of heat into electricity (or vice versa) while maintaining mechanical rigidity. They are used, for example, in thermoelectric generators, cooling devices, or sensors.

and express skepticism or discomfort toward unfamiliar devices. This perceived disconnect is often exacerbated by limited training and unclear added value, which together contribute to a widespread reluctance to adopt new solutions. Such attitudes highlight a systemic failure in participatory design processes, where experiential knowledge from end-users is insufficiently integrated. These cultural and cognitive barriers are compounded by unresolved technical challenges. From an ergonomics perspective, thermal comfort is frequently compromised by suboptimal materials and limited adaptability to individual variability. For instance, Phase Change Materials (PCMs), while effective under controlled conditions, have been associated with skin irritation when placed in high-contact areas such as the chest and back, suggesting a significant gap between laboratory testing and real-world usability. Air-based cooling systems present additional contextual limitations. When relying on ambient air, fluctuations in temperature, humidity, and purity may compromise effectiveness and limit scalability across different environments. Internal air circulation offers more consistent performance but tends to increase bulk and energy consumption. Current fan integrations remain largely external and cumbersome, limiting mobility and comfort. Similarly, liquid-based cooling systems, despite their heat dissipation capacity, raise concerns about added weight, potential leakage risks and chemical safety concerns, and maintenance complexity. These layered limitations (technical, ergonomic, and socio-cultural) underscore the need for an iterative, user-centered design methodology that balances thermoregulatory performance with wearability, simplicity, and trust. Finally, environmental sustainability remains a critical dimension in the development of wearable technologies (WTs). According to the Global E-waste Monitor (2022), the amount of electronic waste generated globally continues to rise, raising concerns about the long-term impact of all technology-intensive solutions, including WTs. Although many of the thermoregulatory systems discussed in this article (such as PCM-based garments, air-cooled vests, and liquid circulation devices) are not inherently electronic, their effective implementation increasingly relies on active components (fans, sensors, control units, batteries). If these elements are not designed for disassembly or reuse they may contribute to e-waste accumulation over time. Innovation in this domain must therefore be critically evaluated not only in terms of performance, but also of durability and sustainability across the entire product life cycle.

Conclusions

CC is reshaping the historical link between human labor and exposure to extreme environments. Higher and more unpredictable temperatures require an integrated approach to the prevention of thermal risks. In this context, WT and smart textiles offer new opportunities due to their ability to monitor and actively intervene in thermoregulation. Nevertheless, transitioning from experimental solutions to widely adopted and effective tools requires addressing key challenges, including device miniaturization, energy efficiency, ergonomic integration and scientific validation. In particular, future developments should aim to combine multiple thermal regulation mechanisms within a single fabric to enable broader industrial and everyday applications. Only through an interdisciplinary synergy between materials science, occupational medicine, engineering and public policies will it be possible to translate these innovations into concrete responses to the changed climate scenario, helping to protect the health and productivity of exposed people. Addressing these complexities will be essential for translating smart workwear from experimental prototypes into scalable, effective solutions for protecting vulnerable workers in an increasingly hostile climate.

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An ergonomic approach to the inclusive design of industrial cobots for older workers



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Keywords: Psychophysical well-being; Collaborative robots; Ergonomics; Multidisciplinary design approach; Older workers

Abstract

Occupational well-being is a complex concept that includes physical, psychological and social health. Collaborative robots (cobots) have been introduced to support operators in their tasks, enhancing their capabilities and reducing the burden of strenuous tasks. However, technical regulations, such as the Machinery Directive, focus mainly on safety features, neglecting ergonomic aspects. Therefore, it is essential to also consider physical and cognitive ergonomics to ensure the psychophysical well-being of operators, influenced by personal and social factors. In particular, older operators, due to age-related functional decline, need more support. While cobots can offer significant benefits in this regard, they must be designed with specific ergonomic needs in mind.

It is crucial that the interaction between cobots and operators is pleasant, intuitive and fluid. The incorporation of social robotics

knowledge can improve the acceptance of cobots by designing them as safe, reliable and useful. In an increasingly heterogeneous work environment, an ethical and multidisciplinary design approach is crucial to maximise benefits and minimise risks, ensuring inclusivity and well-being, especially for older workers.

Introduction: toward human-centered automation in Industry 5.0

This article derives from a broader doctoral research project conducted by the author at the IUAV University of Venice, currently under embargo. The study aims to contribute to the growing discourse on the integration of collaborative robotics within the framework of Industry 5.0, with a particular focus on ergonomic design and its implications for aging workers in industrial environments.

Although primarily theoretical, the research is grounded in a systematic review of scholarly literature and regulatory documents. The selection focused on peer-reviewed publications from 2000 onwards that explore intersections between ergonomics, human-robot interaction (HRI), and the aging workforce. In addition, European institutional reports and case studies related to the adoption of collaborative robots (cobots) in industrial environments were considered to ensure conceptual coherence and practical relevance.

From Industry 4.0 to Industry 5.0: a paradigm shift toward inclusivity and human well-being

In recent years, an expanding body of scholarly literature has supported the conceptualization and advancement of the Fifth Industrial Revolution, commonly referred to as Industry 5.0 (Paschek et al., 2019; Demir et al., 2019). This transition, primarily driven by visions of "human-robot collaboration," is widely acknowledged as a transformative innovation with substantial implications for industrial practices and societal development. The paradigm shift embodies a deliberate reorientation toward broader societal objectives that transcend traditional goals of economic growth and employment generation (Xu et al., 2021).

As articulated in recent academic and policy discourse, Industry 5.0 promotes inclusive and resilient forms of prosperity by advocating for production systems that respect ecological boundaries while prioritizing human well-being. Rather than replacing the technological foundations of Industry 4.0, this new industrial vision seeks to expand

and deepen its scope through enhanced research, innovation, and systemic human-machine integration (Breque et al., 2021).

Aligning industrial innovation with societal and environmental values

In this context, the transition to Industry 5.0 is deemed vital to aligning technological innovation with the social and environmental imperatives articulated by the European Union. This transition calls for a paradigmatic shift away from the mere implementation of isolated technological tools and toward a holistic approach that accounts for the multifaceted effects of industrial transformation on both individuals and ecosystems. As Breque et al. (2021) emphasize, emerging technologies must be developed in coherence with evolving societal values, especially those concerning the human role in future industrial systems. Supporting this approach, the European Agency for Safety and Health at Work (EU-OSHA, 2023) stresses the primacy of workplace well-being as a determinant of organizational productivity and quality of work life across European industries.

Challenges and opportunities of human-robot collaboration in Italian SMEs

Reflecting these human-centered principles, Industry 5.0 encourages new production paradigms characterized by close cooperation between humans and machines, particularly through the integration of collaborative robots (cobots) (Pizoń & Gola, 2023). In Italy, however, the concept of Human-Robot Collaboration (HRC) remains relatively underexplored, particularly in small- and medium-sized enterprises (SMEs), where the adoption of collaborative technologies is still nascent (Paschek et al., 2019).

Although cobots are engineered to enable intuitive and user-centered interactions that enhance operator well-being, their successful deployment necessitates an in-depth understanding of the dynamic interplay among human, machine, and environmental factors. As noted by Buti (2008), designers and practitioners must possess the analytical tools to interpret and anticipate the complex, multifactorial needs that arise from these human-machine-environment configurations. Consequently, collaborative robotic systems must be designed to accommodate a wide spectrum of psychophysical characteristics, especially those associated with aging workers. Achieving such adaptability requires the application of rigorous methodological frameworks. In

this regard, two disciplines—HRC and Ergonomics for Design—emerge as pivotal. While HRC focuses on interactional processes between humans and robots, Ergonomics for Design emphasizes the alignment of technological systems with the comprehensive well-being of human users (Tosi, 2016; Buti, 2008).

Despite this recognition, the current research landscape reveals a disproportionate emphasis on safety, often at the expense of ergonomics. A systematic review by Gualtieri et al. (2021) highlights this imbalance, noting that while safety dominates scholarly and technical discourse, ergonomic dimensions—including cognitive workload, physical comfort, and task engagement—remain insufficiently explored. This gap underscores the need for a more integrated research strategy that gives equal priority to both safety and ergonomics.

Toward holistic ergonomics: integrating physical, cognitive, and psychosocial dimensions

From a design perspective, incorporating ergonomic principles into collaborative robotic systems enhances not only operational safety but also user comfort and system effectiveness. This is particularly important given the complexity of cobots, which frequently operate in proximity to human workers and without the conventional barriers that separate human and machine operations (Colgate et al., 1996).

Ergonomic design, however, must go beyond superficial considerations of ease-of-use. It requires a sophisticated understanding of diverse variables, including the user's physiological and cognitive profile, organizational culture, and environmental context (Buti, 2008). The integration of physical, cognitive, and psychosocial ergonomics into cobot design is essential for developing systems that are simultaneously safe, effective, and conducive to user well-being.

Expanding regulatory frameworks: from safety compliance to ergonomic integration

Current regulatory standards—such as the Machinery Directive (MD 2006/42/EC) and ISO technical norms (ISO 10218-1/2; ISO/TS 15066)—continue to focus heavily on physical safety, offering prescriptive guidelines for minimizing mechanical hazards. While these frameworks are vital, they tend to marginalize ergonomic considerations such as repetitive strain, attentional fatigue, and emotional stress. Thus, a broader and more inclusive regulatory and design philosophy

is warranted. This argument is reinforced by the work of Calitz et al. (2017), who emphasize that real-world implementation of collaborative robotics must extend beyond injury prevention to encompass the optimization of cognitive and ergonomic interfaces. Similarly, Hart and Staveland's (1988) NASA-TLX model illustrates the importance of cognitive load measurement in the evaluation of system usability. To realize the full potential of HRC, collaborative systems must be developed through integrative design strategies that harmonize technical, ergonomic, and organizational perspectives. Such approaches support sustainable human-robot interaction by mitigating risks associated with both physical and psychological stressors.

Beyond physical safety: addressing psychosocial risks and ethical dimensions

Emerging empirical evidence points to the relevance of this approach. Maharana et al. (2024) report that prolonged interaction with cobots may lead to psychological phenomena such as robophobia or behavioral dependency. These findings emphasize the importance of deploying ergonomic strategies not only for physical safety, but also for safeguarding the mental and emotional health of operators.

The psychosocial implications of robotic interaction extend beyond industrial applications. As global demographics shift toward aging populations (United Nations, 2015), robots are increasingly being integrated into eldercare and domestic assistance settings. In these contexts, socially interactive robots have demonstrated positive effects in reducing loneliness and improving user engagement (Van Maris et al., 2021; Sharkey & Sharkey, 2020). Similar effects have been observed among children, who often perceive robots as socially intelligent agents (Piçarra & Giger, 2018; Maharana et al., 2024).

These observations support the notion that human-robot interaction is inherently social and must be designed accordingly. Ethical concerns also emerge, particularly around user autonomy, infantilization, and identity misalignment in robot design. Frennert and Östlund (2014) and Van Maris et al. (2021) highlight the need for participatory design practices to ensure that robot morphology and behavior align with users' values and self-conceptions.

Trust, transparency, and the needs of aging workers

In industrial settings, similar issues of trust, transparency, and com-

municative clarity are equally critical. Effective collaboration depends on intuitive interfaces and real-time feedback mechanisms that allow workers to interpret robot behavior with minimal cognitive effort (Ferraguti et al., 2019; Shirzad & Van der Loos, 2016). These elements are particularly important for older workers, who may face greater barriers in adapting to new technological systems (Villani et al., 2018; Rossato et al., 2021).

The integration of social robotics insights into industrial HRC research can inform more nuanced and inclusive design strategies. For instance, social robots have been shown to foster social cohesion among users and reduce isolation, suggesting that similarly designed cobots could promote teamwork and communication on factory floors (Van Maris et al., 2021).

From social robotics to ethical industrial design

Furthermore, widespread media narratives often distort public perceptions of robotics, amplifying fears and resistance (Huang et al., 2022; Martynov et al., 2019; Paschek et al., 2022). Addressing these perceptual biases is crucial for fostering a supportive environment for technological innovation.

Finally, the growing cobot market—projected to reach \$649 million in 2019 with an annual growth rate of 45% through 2025 (Bi et al., 2021; Maharana et al., 2024)—highlights the urgency of embedding ergonomic and ethical principles into system design. The long-term viability of these technologies hinges on their ability to support inclusive, adaptive, and human-centered work environments.

In summary, collaborative robots—when designed with ergonomic, psychological, and ethical considerations—offer transformative potential in creating safe and inclusive industrial environments. For older workers in particular, cobots represent a critical tool for sustaining work performance, mitigating strain, and promoting engagement. However, realizing this potential requires an interdisciplinary, human-centric approach aligned with the foundational principles of Industry 5.0 (Breque et al., 2021; Cusano, 2022; Mobed et al., 2024). Only through such a framework can the deployment of collaborative robotics foster genuinely resilient, equitable, and sustainable work systems for present and future generations.

Ethical issues raised in caregiving contexts—such as the loss of autonomy or infantilization—are not solely confined to social domains but

are becoming increasingly relevant in industrial settings as well. In particular, the design of collaborative robots intended for older workers must account for these dimensions in order to prevent perceived marginalization or resistance linked to professional self-perception. Explicitly integrating such ethical considerations into the design and deployment phases of cobots constitutes a critical step toward the development of genuinely inclusive systems.

User acceptance as a pillar of sustainable human–robot collaboration

Thus, while social robots and industrial collaborative robots operate in distinct application domains and engage with user populations exhibiting differing needs and expectations, both categories give rise to fundamental questions regarding user acceptance, system integration, and their broader societal impact. Research in social robotics offers valuable insights that can substantially inform the enhancement of human–robot collaboration (HRC) in industrial environments. A shared critical factor in both domains is end-user acceptance, which significantly affects the efficacy and long-term sustainability of both social and industrial robotic systems (Van Maris et al., 2021).

Social robotics literature emphasizes the importance of designing robots perceived as safe, reliable, and functionally beneficial by users. These principles apply equally to industrial contexts, where the success of cobot integration is mediated not solely by technical capabilities but also by workers' readiness to engage with these systems. Such engagement is influenced by individual differences, prior experience, and the availability of structured training programs aimed at easing the transition toward new interaction paradigms (Van Maris et al., 2021).

Evidence from social robotics also suggests that, while robot use may decrease direct human contact in some scenarios, it can simultaneously enhance perceptions of connectedness and social presence. For example, studies have shown that social robots can reduce feelings of isolation and stimulate interaction, both with the robot and among users (Sharkey & Sharkey, 2010; Van Maris et al., 2021). Translating these findings to the industrial sphere suggests that collaborative robots—when designed with sensitivity to social and psychological dimensions—could foster similarly enriched, communicative, and inclusive work environments.

Ethical design and human autonomy: addressing risks of infantilization

However, the deployment of robotic systems—whether in caregiving or industrial roles—inevitably raises ethical issues. A salient concern involves the potential loss of autonomy or feelings of infantilization, particularly among older users engaging with robots that adopt overly playful or reductive aesthetic cues. This perception may undermine user dignity and self-image unless mitigated through thoughtful design and the direct involvement of users in the co-creation process (Frennert & Östlund, 2014; Van Maris et al., 2021).

Comparable concerns are emerging in industrial settings, where the evolving human–robot relationship necessitates robust systems of trust, transparency, and interpretability. Collaborative robots must be capable of clearly communicating their operational states, constraints, and intentions. Achieving this requires the incorporation of intuitive user interfaces and real-time feedback mechanisms to minimize cognitive load and avoid operator frustration or safety risks. Such communication clarity is vital to fostering trust and ensuring safe and effective interaction.

Individual differences, User Experience, and inclusive interaction

Accordingly, interdisciplinary research and sustained ethical reflection are indispensable in shaping the design and implementation of both social and industrial robotic systems. These endeavors are critical not only to optimize technical integration but also to support the psychophysical well-being of users. The overarching objective must be to maximize the benefits of robotic technologies while minimizing unintended negative outcomes, discomfort, or ethical compromises.

The convergence of social robotics and industrial HRC research also reflects a growing recognition of the evolving nature of user perceptions as robotic interaction becomes more frequent and complex. As users accumulate experience, their expectations and attitudes are likely to change, necessitating longitudinal, interdisciplinary studies that examine cognitive, emotional, and social dimensions of human–robot interaction over time (Maharana et al., 2024).

Collaborative robots possess specific attributes that render them especially valuable for supporting aging workers. These systems can offer physical assistance, simplify tasks, and reduce workload, thereby

addressing functional declines typically associated with aging, such as reduced stamina or fine motor control (Van de Perre et al., 2018; Rossato et al., 2021; Müller-Abdelrazeq et al., 2019). However, the realization of these benefits hinges on user perception. Technologies must be seen as accessible, intelligible, and trustworthy—particularly by older employees who may encounter greater technological adaptation challenges (Villani et al., 2018; Wang et al., 2019; Roda-Sanchez et al., 2020; Rossato et al., 2021).

The successful integration of collaborative robots thus depends on a nuanced understanding of how human factors—including age, technological literacy, and individual preferences—interact with system design. By acknowledging and accommodating these individual differences, organizations can improve adoption outcomes, support inclusion, and cultivate more equitable and sustainable workplace environments.

Resistance to robotic systems may also stem from negative predispositions, which can act as barriers even when the technologies in question are demonstrably beneficial and tailored to specific tasks (Davis, 1989; Park et al., 2013; Rossato et al., 2021). As a result, fostering positive user experiences is paramount. This necessitates a rigorous application of user experience (UX) and usability principles during the design phase—paralleling best practices in the broader field of digital technology design (Pluchino et al., 2019; Rossato et al., 2021).

Designing for seamless, multimodal, and cognitive-friendly interaction

Effective interaction should be intuitive, engaging, and seamless across modalities, whether through physical commands, touchscreens, voice inputs, or gesture recognition (Wang et al., 2019; Ferraguti et al., 2019; Rossato et al., 2021). Interfaces must remain accessible and cognitively manageable, supporting users of varying levels of skill and familiarity with technology (Shirzad & Van der Loos, 2016; Ferraguti et al., 2019; Rossato et al., 2021). Well-conceived interaction paradigms serve not only operational goals but also enhance user satisfaction and trust, paving the way for the integration of collaborative robots into daily industrial workflows.

Conclusion: toward inclusive, ethical, and adaptive robotics in Industry 5.0

In conclusion, collaborative robots, when designed and implemented

with intentionality and scientific rigor, hold the potential to address both traditional ergonomic challenges and emergent psychosocial risks within industrial contexts. Their utility in empowering aging workers positions them as essential tools for cultivating inclusive and adaptive workplaces. However, fully unlocking this potential demands an integrated approach that transcends narrow conceptions of technical safety.

Instead, collaborative robotics must align with the foundational principles of Industry 5.0, emphasizing sustainability, resilience, and human-centeredness (Breque et al., 2021; Cusano, 2022; Mobed et al., 2024). Only through such a multidimensional framework can these technologies truly contribute to the development of equitable, advanced, and socially responsible industrial systems.

To translate the principles of Industry 5.0 into practical actions, the adoption of participatory design practices is proposed—such as workshops with older workers—where interfaces and modes of interaction can be co-designed to address their specific needs. Furthermore, the integration of adaptive UX systems—capable of dynamically adjusting interaction complexity based on detected cognitive load—may offer an additional pathway to support technological inclusion. These hybrid approaches, which combine physical, cognitive, and social ergonomics, not only help mitigate psychosocial risks but also foster long-term user engagement and trust in collaborative systems.

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