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KEYme: Multifunctional Smart Toy for Children with Autism Spectrum Disorder

Raquel Cañete, Sonia López and M. Estela Peralta *

Department of Design Engineering, Higher Polytechnic School, University of Seville, 41011 Seville, Spain; raqcanyaq@alum.us.es (R.C.); sonlopgar@alum.us.es (S.L.)
* Correspondence: mperalta1@us.es; Tel.: +34-954552827

Abstract: The role that design engineering plays in the quality of life and well-being of people with autism spectrum disorder around the world is extremely relevant; products are highly helpful when used as "intermediaries" in social interactions, as well as in the reinforcement of cognitive, motor and sensory skills. One of the most significant challenges engineers have to face lies in the complexity of defining those functional requirements of objects that will efficiently satisfy the specific needs of children with autism within a single product. Furthermore, despite the growing trends that point toward the integration of new technologies in the creation of toys for typically developing children, the variety of specialized smart products aimed at children with autism spectrum disorder is very limited. Based on this evidence the KEYme project was created, where a multifunctional smart toy is developed as a reinforcement system for multiple needs which is adaptable to different kinds of autism for therapies, educational centers or family environments. This approach involves the knowledge transfer from the latest neuroscience, medicine and psychology contributions to the engineering and industrial design field.

Keywords: social sustainability; smart product; autism spectrum disorder; inclusive design; therapy toys; design for ASD

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1. Introduction

Autism spectrum disorder, henceforth ASD [1], is a complex neurological disorder; it involves different types of needs, which makes it difficult to create product solutions that are adaptable to all of them. ASD presents a set of social restrictions associated with the alteration of social interaction (problems in verbal and non-verbal communication, in social and emotional reciprocity), sensory sensitivity, mental dysfunctions and various behaviors (such as aggressiveness, self-harm, restricted interests, hyperactivity or passivity). These symptoms of autism appear at an early age and remain until adulthood, thus making it difficult for such behaviors to disappear [2,3]. Furthermore, the disorders mentioned above lead to other indirect impacts such as harassment, social exclusion and school dropout.

It is important to highlight that society actively coexists with ASD: one out of every 100 births is diagnosed [4]. However, the availability of products that act as facilitators for the development of the needs of children with ASD is limited; parents, guardians and other professionals involved in therapy and education are forced to use not adapted products. After a market and patent research carried out on more than 1000 products [5], it was concluded that few large companies have adapted products for children with disabilities in their portfolios. Furthermore, research, development and innovation in this type of products do not move forward at the same rate as they do in toys for typically developing children. For this, the current trend is the introduction of new technologies to integrate the property of "smart" in the products.

On the other hand, advances in therapies for children with ASD reflect the importance of having facilitators (many of them technological) that allow enhancing the child's interaction with their outside world; technological products are a means of learning for physical, psychological and social development, and they function as tools that stimulate attention, following orders and socialization [6]. Different studies have demonstrated the role that technological products currently play in therapies; they are generally classified as (1) visual, tactile and auditory stimulation devices, (2) video-based instruction and feedback, (3) computer and ICT-assisted actions and instructions, (4) virtual reality and (5) robotics [7–12]. However, they are in the early research and development phase, meaning that the demand for specialized assistive technology in ASD is not covered by the current supply available in the market.

Therefore, this research introduces the KEYme project, an assistive technology design for ASD. The project uses a specific design framework for adaptive assistive technology that makes it possible to cover the set of needs included in the ASD classification [1]. Using this methodology, a multifunctional toy with interactive and smart properties is developed. The combination of multiple requirements allows the creation of game modes adaptable to different autism pictures and contexts of use (therapy, family, didactic). KEYme can help the child to develop those skills in which he has difficulties (like social communication and interaction challenges, repetitive and restrictive behavior, over or under sensitivity to perceptual factors). In addition, it includes those changes, trends and new concepts that are currently being applied in the market within products for typically developing children.

Lastly, the KEYme project contributes to the improvement of products and their accessibility in the field of human development and social sustainability (equity). It works within the scope of childhood and disability, specifically, the wide range of signs and symptoms of assistive technology ASD. The development of quality assistive technology, its universal design and its accessibility (supply and price) is one of the main research challenges identified by the World Health Organization [13].

To do this, the paper is structured as follows. Section 2 contains the background and the market study that analyzes the current situation of the toy sector dedicated to typically developing children and children with special needs, including assistive technology for ASD, product categories and relevant research. Section 3 exposes the methods used for the development of the KEYme project, which are later applied in Section 4, where the design and development of the proposal are explained. Finally, Section 5 summarizes the results and discussions of this research.

2. Background: Interactive Smart Toys Dedicated to Children with ASD

To date, the known causes, as well as the developmental and behavioral disorders associated with ASD, have not been demonstrated categorically. Scientific evidence establishes different demonstrable hypotheses and in many cases can jointly influence from neurobiological bases (genetic influence), obstetric complications, cerebral and cognitive structural alterations (cerebellum, hippocampus, mirror neurons or mamillary bodies) to the connection to other factors such as education, context and environment [14]. These reasons determine the importance acquired by the integrating initiatives of people with ASD in society.

Currently, there are some solutions that allow those people with ASD to minimize problems and satisfy certain needs that improve their quality of life and independence: didactic, educational, behavioral and occupational therapies. They are usually carried out from the detection of the disorder; the early interventions in children are the ones that most efficiently improve the social, emotional, communication and motor skills. In such interventions, assistive technology (AT) is useful [13]. Its correct configuration provides the scientific and technical basis for the development of smart products specialized in ASD. The AT group includes any device, software or equipment that helps overcome certain challenges, specifically for people who require assistance to carry out activities in their daily lives independently.

In this field, the quality of AT and its universal design are some of the main challenges of the World Health Organization [13]. To design a product as AT, emerging technologies are required (such as ICT, sensors, connectivity or the Internet of Things, among others) to create "smart properties" and incorporate specific functions that improve user connection and interaction, allowing imitative activities, stimulation, recognition and understanding of the environment to be faster and more intuitive.

When AT is intended for children, it usually makes use of game strategies to enhance the interaction between child and playmate. In this way, *AT configured as a toy* makes it possible to improve, develop and work on certain skills of the child while being fun, safe, age-appropriate and attractive. In addition to this, through play time, growth is enhanced from the anthropological, psychological and social points of view.

However, all of the above becomes more complicated when AT must be adapted to children with ASD. The heterogeneous group of signs and symptoms of autism, as well as the wide range of needs grouped in (i) communication and social interaction and (ii) flexibility of thought and behavior, makes it difficult to define and select the functional requirements and design variables suitable for product design. This circumstance makes it necessary to either integrate multifunctionality in products or to make AT adaptive, that is, to adapt flexibly to the specific needs or to the resolution of specific problems of each type of disorder and child. This complexity has had repercussions in recent years resulting in a low supply and availability of AT products for children with ASD in the market.

At the European level, Switzerland and Spain are the first two powers in R&D within the toy sector [15]. On the one hand, the Swedish market has a long tradition and recognition record of its products. Despite the great difficulties caused by the health crisis, sales continue to increase due to the introduction of key trends in their toys [16]. On the other hand, the Spanish market is characterized by a high number of toy companies (most of them micro or small companies) generating an annual turnover of around 1600 million euros [17]. Spanish toys are exported to more than 100 countries (the most important being Germany, France, United Kingdom, Italy and Portugal) although representing only 2% of the international market share [15], led by China in mass production and in exports and followed by the United States [18].

Having analyzed the sales of 2019, we concluded that (i) dolls, soft toys (interactive toys that simulate human interaction and affectivity), (ii) technical toys, educational toys, action toys, (iii) electronic toys and (iv) games, books, learning and experimenting were the best-selling toy categories [19]. On the other hand, the trends of the toy sector for the coming years are highly influenced by the introduction of smart features with seven key development categories: (i) movie industry, advertising and digitization (toys based on television series and movies), (ii) STEAM toys (focused on science, technology, engineering, arts and mathematics), (iii) unboxing (the game begins with packaging), (iv) RC toys (remote-controlled), (v) virtual reality (for a full immersion experience), (vi) toys and unisex gender roles and (vii) intended for kid-adults (new versions of old toys for nostalgic adults).

However, most of the toys on the market are targeted toward typically developing children. Those specialized in ASD imply less variety in shapes, interfaces and features; in addition, their availability is much more limited. On top of that, they do not follow the same trends. In general, they are marketed according to the needs which they are aimed for, thus classified into (1) cause-effect toys, (2) toys that improve gross motor skills, (3) toys that improve fine motor skills, (4) to facilitate language and communication skills and (5) favor symbolic and functional play. Most of the toys available within these five categories do not use technology and cannot be considered high-level AT, despite the fact that their benefits as a means of learning for physical, psychological and social development have been evaluated and demonstrated in different studies [6–12]. In particular, the use of SARs (socially assistive robotics) as collaborators has beneficial effects on the development of social skills in children with ASD, especially in areas where they present the most difficulties [20], such as attention, verbal communication or **imitation**, as well as in reducing stereotypic behaviors, where they present an immediate positive effect. Some of the most famous robots on the market are Kaspar Robot [21], Robota [22] or Sprite [23]; among the newly developed ones, we can mention Keepon [24], Nao [25] and Leka [26].

Most of these high-level AT products are off the market; many of them are just projects from research centers and the academic field. On the contrary, the ones that are being commercialized are neither affordable nor universally available because of their high price [27]. Finally, analyzing the design variables used in these products, there is a wide margin for improvement compared to existing toys for typically developing children. In addition to this, each available toy is adapted to a very specific need, so that the same child with ASD requires a large variety of products to meet his/her set of special needs.

As a result of this research, the KEYme project has the main goal of solving these problems through the design of assistive technology based on game strategies. Moreover, KEYme (1) follows current market trends in the toy sector (with smart properties), (2) can be adapted to different special needs and, finally, (3) makes use of affordable and open-source resources to promote universal design.

3. Methods

The design and development of adaptive and specialized assistive technology in special populations is a challenge. The design requirements must comply with a universal and adaptative design as a principle, facilitating **physical accessibility** (adapted mobility characteristics), **cognitive accessibility** (adapted processing, understanding, learning and decision-making characteristics in the task) and **sensory accessibility** (characteristics that assure the correct perception of environmental factors and information about the environment).

If we analyze the frameworks, methodologies and tools that are currently available and specify design principles and fundamentals, it is possible to conclude that the bibliography is very limited. There are general frameworks for applying universal design [28] or design processes for people with special needs [29]; there is also a set of tools focused on participatory and collaborative design to involve children with ASD and their families in the design process [30–34]. However, there is no exclusive agreed methodology for designing assistive technology specialized in ASD, and not all of the available ones can be applied to intelligent and multifunctional products. For this reason, in this research, the USERfit tool within user-centered design [35] was used in the first place. It is oriented to the system and promotes interactive design. Its objective is to facilitate the definition of the best product development framework by integrating various techniques adapted to the problem. This methodology is appropriate and has been applied in successful assistive technology projects, such as [36–38].

Specifically, USERfit is a user-centered design methodology applied to assistive technology. It is based on a design philosophy that can be described as user-centered, system-oriented and promoting interactive design. This approach to design implies a greater commitment to user requirements. The objective is to learn how to use certain design guidelines in order to determine whether or not they are suitable for our product dedicated to a user with specific needs. To get there, this methodology provides a framework divided into four phases: (1) check if the guidelines are relevant and appropriate for our product, (2) choose those guidelines that best suit our situation, (3) check if the guidelines are consistent with each other and (4) be able to manage a high number of guidelines [35]. These steps allow one to define which principles and design guides are relevant for our target user, in this case, the child with ASD.

Its application in the KEYme project starts with the identification of special needs of the user; through an iterative process (Figure 1), different methods were analyzed, selected and integrated: conventional design (like the Functional Analysis Screening Tool (FAST), Quality Function Deployment (QFD), Analytic Hierarchy Process (AHP) and Hierarchical Task Analysis (HTA), among others), specialized guidelines in universal design [28] and inclusive design [39], participatory design [40], collaborative design [41] or design methodologies for people with special needs [29] as well as smart toy design guidelines [42], concluding in the definition of the design methodology for the KEYme project.

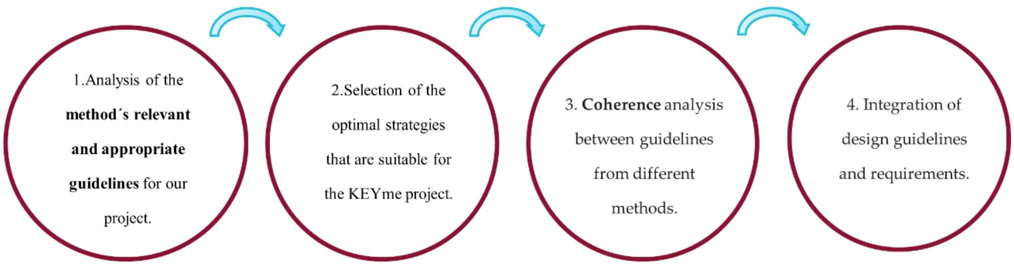


Figure 1. Application of USERfit in design project planning.

In this way, a specific design framework is defined for adaptive AT. It would make it possible to cover the set of disorders included in the ASD classification [1] and would help in making decisions about functional requirements (FRs) and their adequate translation to design variables (DVs) to be included in an interactive and intelligent product. Figure 2 shows the methodology proposed in the KEYme project for product design, which will be applied later in Section 4.

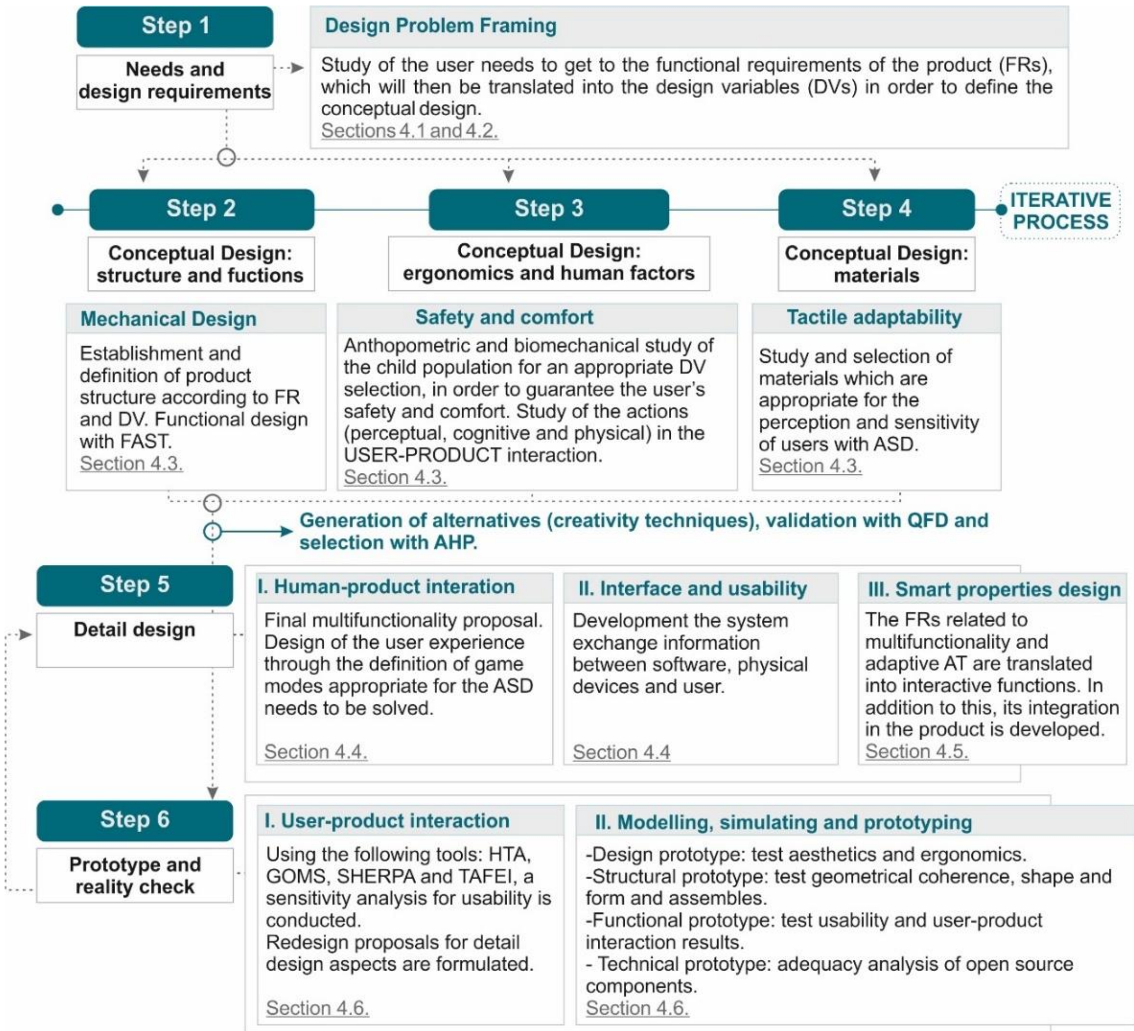


Figure 2. Product design methodology.

4. KEYme: Design and Development

This section covers the development of adaptive assistive technology for ASD. Following the design model of the applied methodology (Figure 2), this section analyzes the design problem, describes the development of the concept and synthesizes the detailed design of the proposal.

4.1. Design Problem Analysis

The design problem, which is our starting point of the KEYme project, raises the need to develop AT configured as a toy adaptable to any user and context of use (therapy, family, didactic environment). This device helps the child with ASD to develop those skills in which he/she has more difficulties; on top of this, it includes the changes, trends and new concepts that we are seeing in toys targeted at typically developing children. To make AT adaptive, first, it must be multifunctional, interactive, and smart; this allows for different game modalities to be included in the same object that would be able to cover a wide range of ASD needs grouped in (i) communication and social interaction and (ii) flexibility of thought and behavior. Moreover, and in order to make this AT universal and accessible to everyone, it must make use of affordable, open-source resources, as well as simple development and manufacturing processes.

Therefore, the project focused on the following design objectives:

1. Design a product as game-based assistive technology. It should enhance and work on different skills of children with autism while being fun, safe, age-appropriate and attractive. Target market and user group: children aged 3–12 years old with ASD and potential playmates (parents, guardians, therapists, teachers or typically developing children).
2. Develop a multifunctional toy, including in the same product the satisfaction of various needs of ASD grouped in (i) communication and social interaction and (ii) flexibility of thought and behavior. This will allow the product to be flexibly adapted to solve specific problems of each type of disorder and child, or what is the same, it can be used by users of different ages and degrees of autism [1].
3. Develop an interactive and smart product that allows for mutual interaction between object and users (children with ASD and potential playmates—parents, guardians, therapists, teachers or typically developing children) and encourages purposeful tasks. The product must be self-contained, as it embeds the interactions within the physical structure, creating an interactive environment of its own.
4. Develop game sequences that integrate sensory, motor (sensory-motor stage) and cognitive activities (preoperational and concrete operation stages) in the same device. The objective is to work on different skills, specifically, to improve non-verbal (sensory-motor stage) and verbal language through social and symbolic imitative play (preoperational stage), improve social interaction (preoperational and concrete operations stages), to work on emotional reciprocity and flexibility in routines (concrete operations stage) and to reduce frustration due to failure during the game.
5. Prioritize the use of imitation in play sequences to improve the interaction between the child with ASD and the playmate.
6. Develop a collaborative product to be used as a facilitator of social interaction and to improve the cognitive, motor and sensory skills of children with special needs.
7. Develop an adaptable product to different contexts of use: indoor (game rooms, home or school) and outdoor environments.

4.2. Needs and Functions Definition

As a result from the analysis of the ASD disorder according to its description in the DSM-V by the American Psychiatric Association [1] and within the heterogeneous group of signs and symptoms, a broad-spectrum set of primary needs was selected:

1. Improve playmate-child with ASD relationships (N1).
2. Sensory stimulation (N2).

3. Improve gross and fine motor skills (N3).
4. Promote shared actions linked to feelings of enjoyment, interest and common goals (N4).
5. Reduce levels of frustration in the game (N5).
6. Increase emotional and social reciprocity (N6).
7. Facilitate learning about changes in game turns (N7).

Subsequently, these needs, as well as the way of working with them, were evaluated in detail; they were subdivided and defined by analyzing early intervention therapies, specifically, applied behavior analysis [43], Denver [44], pivotal response treatment [45], sensory integration [46], physical therapy [47], auditory integration [48], music therapy [49] and use of high assistive technology [50]; other techniques to improve attention with imitation tasks and environmental resources were also analyzed and considered; their efficiency is contrasted with the neural activation of the subject [51–55]. Due to the heterogeneous group of signs and symptoms linked to sub-needs, it was necessary to direct the design of assistive technology toward multifunctionality; this implies including in the same product the satisfaction of various needs, making it possible for it to adapt to the disorder in a flexible way and therefore being adequate for a greater number of users (different ages and degrees of autism [1]). This exhaustive research study on psychological, physiological and neuronal factors resulted in conclusions on the most suitable design variables (motor, visual, auditory, tactile, olfactory, imitation, interaction, context, cognitive and temporal) contrasted by their relationship with (1) neuronal activity, (2) the subject's adequate and comfortable reaction to environmental stimuli and (3) the use of imitation tasks to improve the child's attention. In addition, the most appropriate functions and design variables were defined (see synthesis in Table 1), since the relationships between the need and the design variables were evaluated as "excellent, medium, low or null", and only those relationships rated as "excellent" were taken into account in the conceptual design.

It must be taken into account that, unlike typically developing children, a user with ASD may present deficiencies in social interaction, communication, behavior or executive function. This implies that the execution of tasks while using the product implies an added difficulty when having to pay attention to the object, to other people or to the actions that they carry out. To improve usability, comfort, reduce frustration and minimize errors, the toy should have motivational and behavioral elements or facilitators as secondary functional requirements. They will make the product adapt to the user in three dimensions:

(1) Physical accessibility: it includes all anthropometric adaptations (static or dimensional and dynamic or mobility).
(2) Cognitive accessibility: functions and elements of the product are adapted to the processing, understanding, semiotics, learning and decision-making of a user with ASD.
(3) Sensory accessibility: it assures that the perception of the product is comfortable, intuitive and adapted to the perceptual peculiarities of a user with ASD.

Table 2 details and classifies the set of functional requirements necessary to improve the accessibility of the product; they are derived from the general requirements defined in Table 1 (numbered from 1 to 10). These allowed to carry out the conceptual design in the project were defined.

Table 1. Analysis of needs and functional requirements.

Functional Requirements			Needs							Smart Product
Major	**Secondary**	**Num**	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	
STRUCTURE should allow	Your own mobility and displacement.	1			X					The child must be able to change the environment/modality based on his/her wishes.
	User movements on it (swing, tunnel, climbing) with the aim of improving gross motor skills.	2			X					Feedback from the toy should be clear, explicit and easily understood by the child.
	Included components should allow for multiple movements to improve fine motor skills.	3			X					
MATERIALS	Stimulate the perceptual system with different textures adapted to hyper and hypo sensitivity.	4		X	X		X			Visual design according to the content, objectives and goals.
GAME MODES should include	Collaborative, aimlessness, not-sexist and not-violent.	5	X	X	X	X	X	X	X	Optimal number of game modes: too many variations affect attention and concentration. Toys should allow children to play collaboratively.
	Cooperative sequences for problem resolution.	6	X	X	X		X	X	X	The child must be aware of the results obtained from the toy. Avoid dead time; reduces concentration.
User-product INTERACTION INTERFACE Information should be reinforced simultaneously by visual and auditory stimuli	Safe and comfortable stimuli adapted to the child's perceptual characteristics.	7					X			Feedback given by the toy should be clear, explicit and easily understood by children.
	Musical sounds and lights combined with body movements and force generation (key pressure) to reinforce imitation tasks.	8	X	X	X	X	X	X	X	Background music can optionally be used to attract attention. Show dynamic content. "Help" screen before starting to play. The virtual environment must be interactive, and children must be able to change the environment based on their wishes. It must be easily controlled. There must be immediate feedback from the toy.
	Informative and intuitive interface.	9		X				X	X	
	Reinforcement stimuli for the performance of tasks.	10				X	X	X		

Table 2. Detail of functional and technical requirements for adaptability.

General Requirements	Specific Requirements
Physical accessibility (adapted mobility characteristics) ① ② ③ ⑩	Comfort and ergonomic adaptability for an age range 3–12 years old through a variety of body positions and ranges in the use of the product (crawling, sitting, standing, sliding or kneeling).
	Simple instructions on information exchange.
	The interface should include control elements grouped according to function, easily distinguishable by shape, color, size and movement (press, turn or slide).
	Safety: the dimensions and shapes of the product allow balancing actions while preventing tipping. The structure of the product ensures a non-slip grip to the ground and compressive strength. The surface of the product does not pose a risk of shocks, cuts or other damages.
Sensory accessibility (characteristics that assure the correct perception of environmental factors and information about the environment) ④ ⑦ ⑨ ⑩	Tactile, visual, auditory and proprioceptive stimulation through a variety of elements of different sizes, shapes and materials.
	Comfortable, safe stimulation adapted to hyper-hypo sensitivity.
	Improve attention processes through keyboard-guided imitation tasks (with mirrored keys).
	Reinforcement of the action sequence on the keys through pressure, auditory and visual stimuli.
Cognitive accessibility (adapted processing, understanding, learning and decision-making characteristics in the task) ⑤ ⑥ ⑦ ⑧ ⑨ ⑩	Adaptation to different ages according to learning level and degrees of autism with game modes I to IV.
	Custom game modes designed for ASD (I to IV).
	Reinforcement of information processing (success in tasks) with an automatic response from the product to user failures.
	Facilitate the game sequence with an automatic response from the product for each change in game turns.
	Facilitate the interpretation of the game through multisensoriality.
	Automatic collection of relevant data from the game experience.
Technical and economic feasibility	Affordable product.
	Low cost of electronic platform.
	Free-use electronic platform.
	Reduced manufacturing costs and times.
	Affordable product.

4.3. Conceptual and Detail Design

In design engineering, the basic stages to achieve an optimal result are [56] the generation of candidate design alternatives and selection of the most optimal one (through a prior quantitative evaluation). The generation of alternatives is carried out with the conceptualization of the system, that is, recognizing viable solutions for the target user. In this project, three different alternatives destined to satisfy the needs of Table 1 (and requirements of Table 2) were created (Figure 3); they were developed using creative methods (brainstorming and mind map) and the quality of the solutions was validated with QFD [57]. Specifically, QFD allowed us to transform qualitative user demands into quantitative parameters, that is, translate the needs and demands of the users (child with ASD, typically developing children, adult playmates such as parents, guardians or therapists) to the product specifications (definition of functions and selection of design parameters).

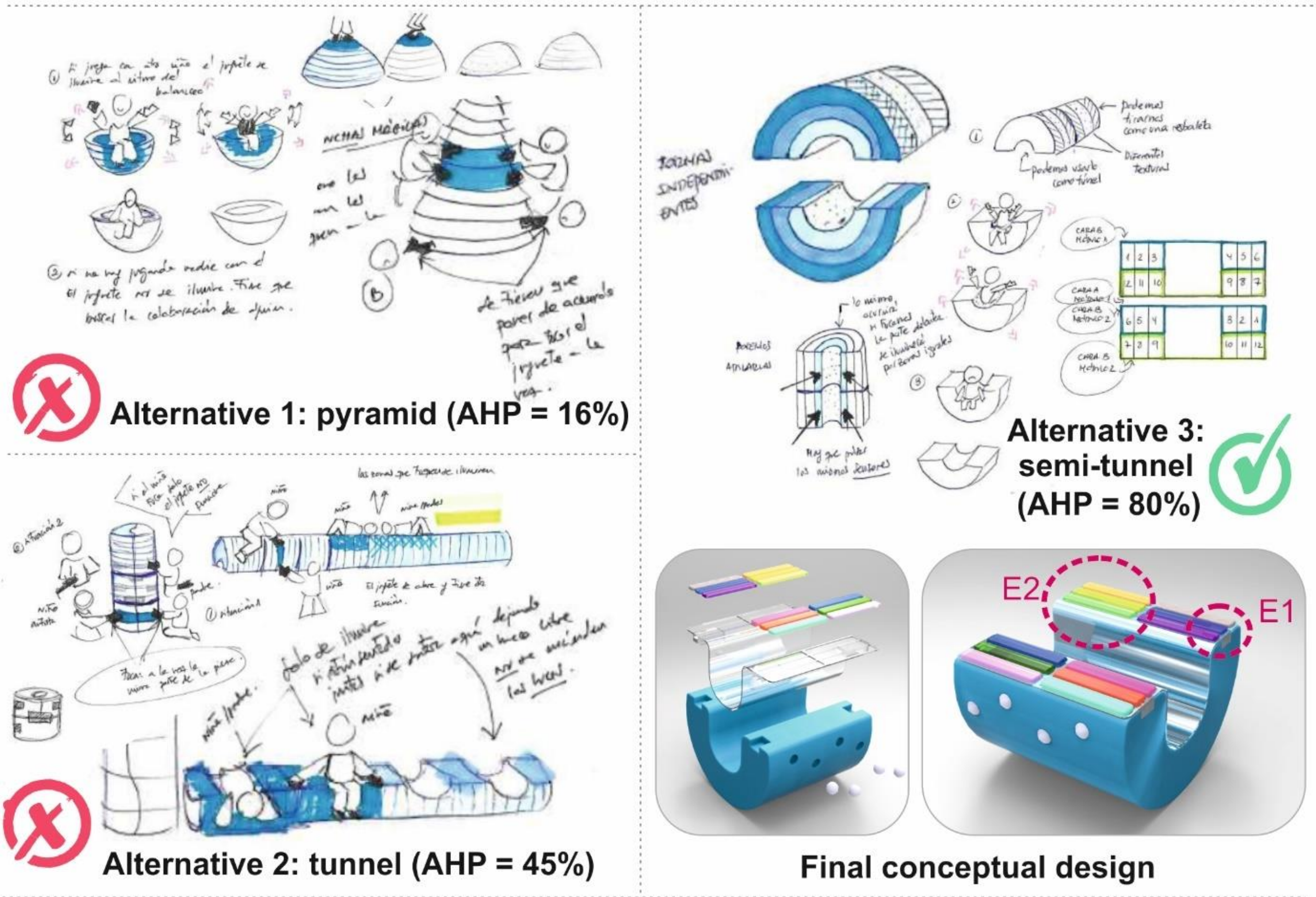


Figure 3. Generation and selection of design alternatives.

As shown in Figure 3, three alternatives were developed that combine *gross motor skills, fine motor skills and sensory stimulation*. Alternative 1 is a pyramidal structure, made up of stackable components; alternative 2 is a modular tunnel that can be used horizontally and vertically; and alternative 3 is a semi-tunnel formed by a single module. All the alternatives have an interactive interface that combines sensory stimuli (motor, tactile, visual and auditory).

Subsequently, the most suitable one was selected with the AHP method (analytic hierarchy process) [58], which assesses each alternative according to the fulfillment of different criteria and sub-criteria. In this case, the AHP hierarchy was structured modeling the evaluation with (1) the design goals 1 to 7, (2) alternatives 1, 2 and 3 for reaching the goals and (3) a group of criteria and sub-criteria that relate the alternatives and goals: (i) suitability for sensory stimulation (somatic, vestibular, visual, auditory, tactile, cognitive, motor and language); (ii) formal design (structure, materials, innovation, environmental impact and integration in space); (iii) safety and comfort (stability, toxicity, anthropometry and biomechanics) and (iv) usability (affordance, visibility, mapping and feedback). After carrying out the pair-wise ranking, calculating the *numerical dominance matrix, obtaining priority concepts and checking the consistency of the priority concepts*, the scope of the design objectives for each alternative was quantified: 16%, 45% and 80% for alternatives 1, 2 and 3, respectively.

Consequently, alternative 3 of the semi-tunnel obtained better results in all the analysis criteria. Specifically, it presents better sensory stimulation by focusing the user's attention on the objective of the game and making the sequence of tasks more intuitive; this is because alternative 3 combines different stimuli (motor, tactile, visual and auditory) in the interface feedback, compared to alternative 1 (visual, motor and auditory) or alternative 2 (visual and tactile). In addition, due to the design of the structure, alternative 3 combines different components with concave and convex shapes, the possibility of turning, interchangeable components and keyboard, allowing to exercise gross and fine motor skills in a more complete way: crawl, climb, swing, squeezing, pressing, pushing, grasping and pinching, compared to alternative 1 (climb, squeezing, pressing and pushing) and alternative 2 (crawl, pressing, pushing and grasping). On the other hand, the distribution of the elements and controllers (interface) of alternative 3 makes the players face the front, a more ideal position for observing and repeating their partner's actions in real time (compared to alternative 1, in a circle, or alternative 2, side to side). In terms of safety and comfort in the use of the product, alternative 3 presented better results. The manipulation of alternatives 1 or 2 is more complicated since to activate the different game modes it is necessary to stack several modules and build pyramidal (alternative 1) or tubular (alternative 2) structures. In contrast, alternative 3 has a single module that integrates all the game modes in the same structure. Although alternatives 1 and 2 are suitable for outdoor environments, the size of alternative 3 is the most suitable for indoor environments.

Despite the positive results compared to alternatives 1 and 2, alternative 3 showed signs of deficiencies in (ii) formal design, specifically, the structure of the basic module was not adequate (see Figure 3, E1) since the keys came into contact with the ground when the product was turned over, which could cause premature deterioration of the keyboard and damage to the circuit if the user left the toy on; and (iv) usability, specifically, in the chromatic selection of the keyboard (Figure 3, see E2) that presented similar colors in keys with close locations, which could generate confusion, errors in the game and therefore increase the frustration of the child [59].

After the final adjustments, the detailed design of alternative 3 was subsequently carried out. To meet the requirements defined in Table 2, this alternative includes four game modes that, as will be explained later in Section 4.3, convert the KEYme into adaptive AT:

- Mode I: Seesaw.
- Mode II: Multikey. Keyboard games with visual and auditory reinforcement, making use of colored lights and musical sounds:
    - Submodality I: sequence and simultaneous pressing game, where one player imitates another by pressing keys of the same color.
    - Submodality II: turn-based sequence and memory game.
    - Submodality III: musical game, each key produces a sound.
- Mode III: Tunnel with visual reinforcement.
- Mode IV: mobility enhanced with stimulation using touch spheres of different textures.

The basic principles of toy design were applied to design game-based assistive technology. These principles guide the design of play sequences that (1) allow the acquisition or exercise of certain skills of the child and (2) are fun, safe, age-appropriate and attractive. For this, all KEYme game sequences are collaborative "aimlessness", between equals, non-sexist and non-violent. In particular, the different primary modes (from I to IV) were configured so that the user experience was linked to (1) promoting cooperation, that is, promoting from an early age the enjoyment of sharing interests in free and equal spaces; (2) replace competitive interaction strategies—rivalry—with cooperation between equals to achieve a common goal (that is, "aimlessness" where the focus is on the process and on the interest in the user's activity and not on a final result of the winner); and (3) develop feelings and affections with the playmate, work on emotions and tackle challenges in a constructive and creative way. Usability and user experience are described in detail in Section 4.3.

To integrate these game modes, the structure of the product is made up of a single module with the components shown in Table 3; these components were designed according to the functional requirements established in the design problem (Tables 1 and 2). Figure 4 shows a simplified exploded view.

Table 3. Product structure.

Component and Number (See Figure 4)	Units	Material	Function
Base module (1)	1	HDPE. PVC-coated foam	Main structure.
Support module (2)	1	HDPE	Covers tunnel wiring; keyboard structural element and trim.
Keys: structure (3) and cover (4)	18 18	PET PET	Mirrored according to color. Structural element for the led strip and push buttons.
Safety cover for battery (5)	1	HDPE	Allows access to battery.
Spheres (6) interchangeable sets according to type of sensitivity	8	Nylon, cotton velvet, beechwood, cork, artificial grass, silicone, leather, felt, polyurethane foam	Tactile stimulation; support elements for climbing and sliding.
Countersunk screw M6, 12	58	Steel	Joining elements.
LED strips: 25 cm (7)	20	-	Light actuators activated with buttons (9); light up: keyboard in mode 2 and sides in sub-game 2.2.
LED strips: 1 m (8)	2	-	Light actuators: they are activated when the product is turned over and when the photoresistor (7) registers a light intensity lower than the set value.
Buttons on keys (9)	18	-	Touch sensors located under the keys (4); activate the LEDs (7) and passive buzzer (12).
On/off button (10)	1	-	Turns the product on and off. Input touch sensor. The ON position activates the rest of the sensors (9, 11, 13, 14).
Game selection switch (11)	1	-	Game selection in mode 2.
Passive buzzer (12)	1	-	Sound actuator. Loudspeaker that plays the tunes on, off and melodies from game mode 2.
Light sensor: fotorresistor (13)	1	-	Analog input light sensor; detects incident light intensity on the surface of the legs; when the product is turned over, it sends a signal to activate the tunnel LEDs (8) in mode 3.
ESP32 board (14)	1	-	Board for programming the toy. Requires programming software.
Stabilizing feet (15)	4	HDPE	Anti-tip and anti-slip stabilizing feet.

Table 3 lists the materials that were selected during the components development according to their suitability to the design of toys [60]. The following technical conditions were taken into account: suitability to create hollow structures, impact resistance, suitability for additive manufacturing, resistance to environmental conditions in outdoor contexts, low toxicity and compatibility with the sensitivity of children with ASD. Additive manufacturing allows fast and economical reproduction of any geometry, custom parts, easy maintenance, short series manufacturing and more environmentally sustainable results (reducing raw material by up to 40% compared to conventional processes). Using 3D printing and open-source electronic platforms allows AT to be affordable and replicable in an agile way; this is a great advantage for users (associations, training centers, therapy centers, etc.), as they have completely personalized and adapted products at their fingertips.

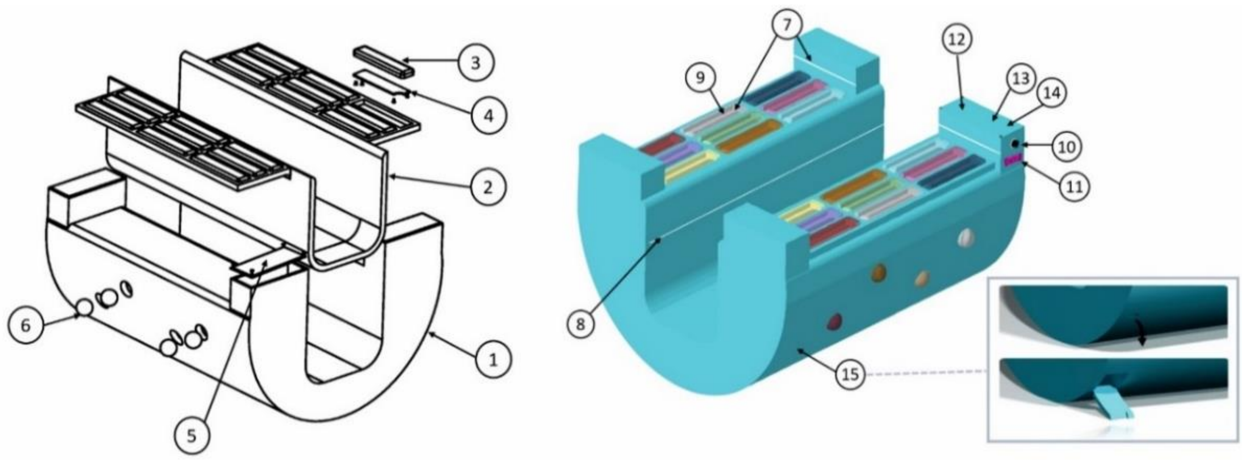


Figure 4. Product Structure.

Finally, KEYme is an interactive smart toy that allows for an autonomous interaction between the user and the product. For the implementation of the functions related to the smart object, the product's structure integrates (i) a set of sensors that capture the child's actions in the game and the information from the environment (Table 3: 9, 10, 11, 13 elements); and (ii) a set of actuators that provide the autonomous response from the product (Table 3: 7, 8, 12 items). The joint action of these elements closes the information loop in user-product interaction.

The dimensioning of the toy was established according to the defined user target: child population aged between 3 and 12 years. The selection of this wide age range is due to the fact that the goal of the project was to create adaptive AT for different users, and therefore one of the strategies used was to organize the game modes by age: (i) modes I, III and IV suitable for younger children (3–7 years), and (ii) mode II adapted to older children (7–12 years). In addition to this, the product as a whole must allow the user to stand and sit while playing, perform movements on it (slide, climb, crawl) and allow for smaller comfortable movements (grasp, press, pinch, squeeze, etc.) with adequate access and visibility of the interface.

With these requirements, an anthropometric study of the child population was carried out, and the product was sized according to each anthropometric variable (Figure 5):

1. Height: the keyboard games are played standing or sitting; the product must allow players to reach the keyboard. The 5th percentile of girls was selected.
2. Hip width, buttock-popliteal length and shoulder width: since the seesaw and tunnel are intended for younger children, maximum measurements were selected for 7 years, in this case, the 95th percentile of girls.
3. Weight: older children must be able to sit or climb on the toy; moreover, the product must also support older playmates. The 50th percentile of weight was selected for 12-year-old children.

4.4. Interface Design, Human-Product Interaction and Usability

The interface design is the main priority to produce high-quality AT. With the functional requirements described in Table 1, the KEYme interface consists of a keyboard made up of two mirror groups of 9 colored keys arranged, an ON and OFF button, a game selection switch and different elements that provide information about the implementation of the game (visual, auditive, tactile and proprioceptive stimuli). These elements improve the user's attention and focus and adapt the environment to the special needs of the child with ASD. Figure 6, as well as Tables 4 and 5, describes in detail the elements of the interface and analyzes the usability of the game modes.

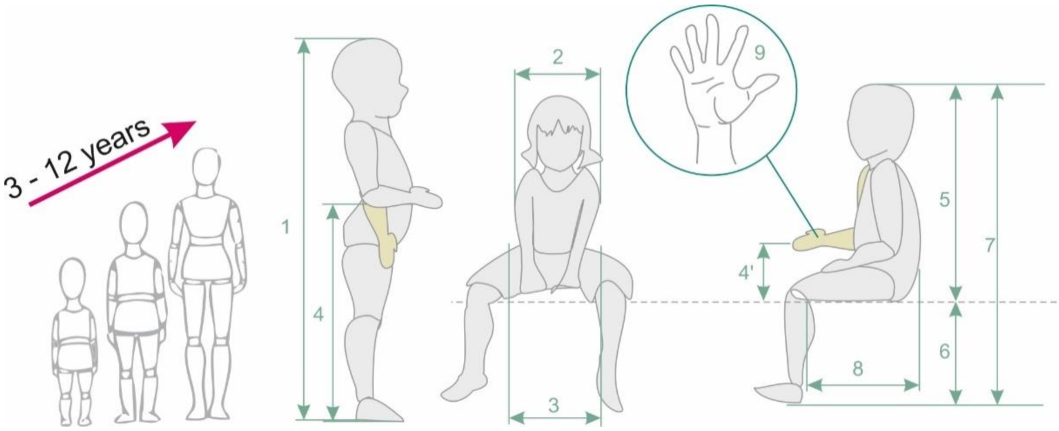


Figure 5. Anthropometric requirements: (**1**) stature (body height); (**2**) shoulder (bideltoid) breadth; (**3**) hip breadth, sitting; (**4**) elbow height, erect and sitting; (**5**) sitting height (erect); (**6**) lower leg length (popliteal height); (**7**) body height, sitting; (**8**) buttock-popliteal length; (**9**) hand measurement (circumferences, breadths, palm length, middle finger length, proximal phalanx length of middle finger, finger grip and hand grasp); and body mass (weight).

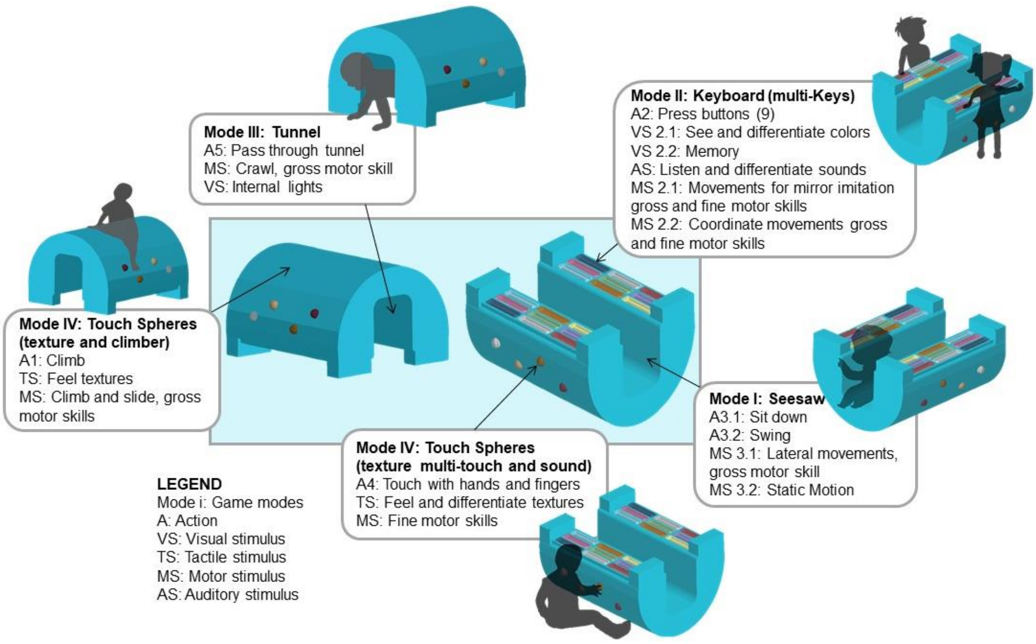


Figure 6. Interface components and usability analysis of the different game modes.

Table 4. Game mode description (part 1).

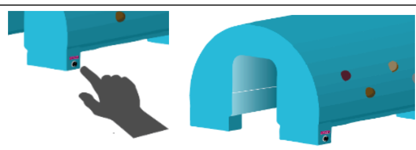
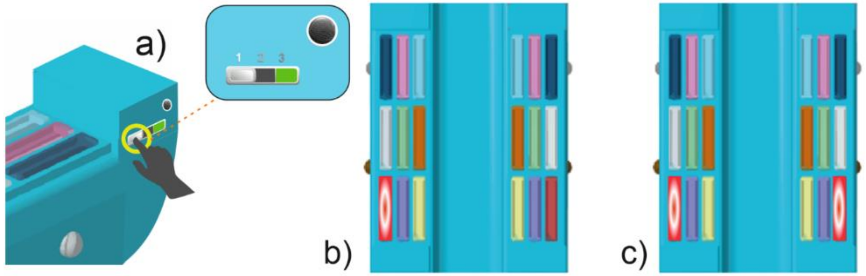
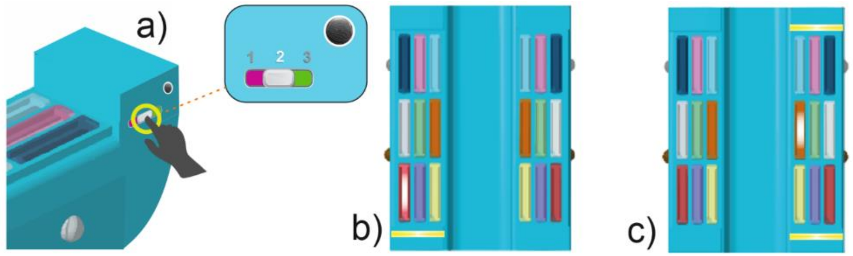
Mode	Objective	
Mode I. Seesaw	The child sits on the module with the keys facing up and swings side to side. This mode will favor gross motor skills.	
Mode III. Tunnel	Turning the toy over and pressing the on/off button will turn the inside lights on. As long as the module is in this position, the rest of the modes are automatically off.	
Mode IV. Touch Spheres	Two interchangeable sets of spheres according to the type of sensitivity (hypo or hyper) for sensory stimulation and development of fine motor skills. In addition to this, the spheres allow easy climbing and sliding on the base module structure.	

Table 5. Game mode description (part 2).

Sub-Game Modes	Interaction with Smart Product
Simultaneous sequence (position 1 on the interface). A child plays the leading role, and the partner must imitate him/her. It enhances the understanding of role changes in the game, among others.	The user selects option 1 on the interface (a). One of the players presses a key (b), while the partner imitates those moves. In case of a hit (both players press the same color and position), both keys will light up and a melody will be played (c); in case of failure, the melody changes, and there will be no visual reinforcement. 
Sequence and memory (position 2 on the interface). The two playmates will sequentially press different keys that they must remember in their next turns, creating a sequence of keystrokes that will become more complex as the game moves forward. It helps to identify shared feelings of enjoyment, interest and goals.	The user selects option 2 on the interface (a). The turns are identified by tuning on lights on the side of each player's interface (b). In turns, each playmate presses a key (which activates lighting and a musical sound). In the following turns, each player must remember the sequence and add a new key (c). If the sequence is incorrect, a melody will be played, and the player will have a number of chances to get it right. The game ends with the restart or change of mode. 
Musical (position 3 on the interface). Turns the toy into a musical and light keyboard. It favors the ability to improvise, among others.	The user selects option 3 on the interface. The keyboard produces musical sounds and with each keystroke, the key lights up. This mode can be individual or collaborative; there are no turns, and players can use the keyboards simultaneously if they wish.
4 non-slip and anti-tip feet can be set up by releasing the snap-fit. These elements ensure that the structure does not move during mode II.	

Modes I, III and IV work on motor skills with different game sequences (Table 4). Each of them has elements that allow the user to perform various motor tasks: crawl, climb, swing, squeezing, pressing, pushing, grasping, and pinching. The combination of movements with sensory stimulation (visual, auditory and tactile) improves coordination, attention to the task, mood, relaxation and social interaction. The modes are adapted to the needs of sensory seeking and both hyper-sensitivities (over-responsiveness) and hypo-sensitivities (under-responsiveness). Mode I is meant for the user to use the toy as a seesaw, allowing the child to swing to the sides. The players must place the module with their concave part facing upward, like an armchair, to sit down and begin with the lateral movements. Mode III converts the toy into a tunnel. The child can turn the toy upside down so that the lights inside the tunnel light on. In this way, the child can use the toy as a tunnel and crawl inside it. On the other hand, mode III allows you to create a safe space to be alone. Mode IV is meant for the child to interact with the sets of touch spheres. All the spheres are made with different textures, including hard and soft material; the spheres have the function of facilitating the child's climb to the highest part of the module and being able to slide back down.

Mode II is based on imitation and sensory stimulation tasks. It includes 3 submodalities (sequence, memory and musical), which collaboratively and individually work on all the needs described in the analysis of the design problem. Due to the complexity of the game's implementation, it integrates most of KEYme's smart properties. In addition, it is designed to collect interesting data from the gaming experience, such as the number of hits/misses, playing time or sustaining attention.

As stated in Tables 3 and 4, all the modalities make use of visual, proprioceptive and auditory stimuli to improve user-product interaction. Regarding visual stimuli, the following specific considerations related to ASD needs were taken into account: (1) use geometric shapes, (2) use neutral or pastel colors, (3) use striking colors, but not excessively bright (optimal luminosity) and (4) easily distinguishable colors. Figure 7 shows the color selection for the product, as well as the final visual result.

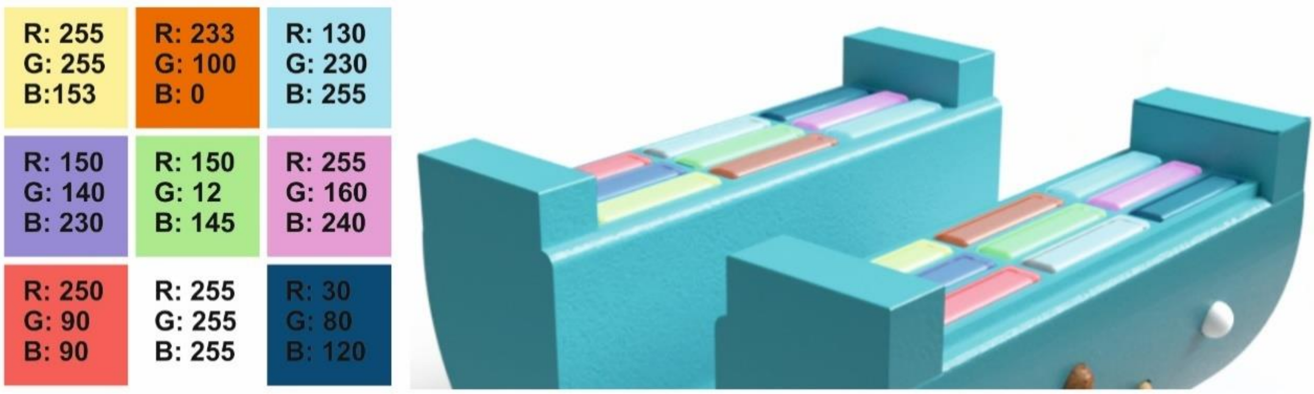


Figure 7. Color Selection.

On the other hand, regarding auditory stimuli, it must be taken into account that the majority of children with ASD present auditory hypersensitivity [61]. This means that, whereas for a typically developing peer the comfort limit is 70–80 dB, for a child with autism it will be 40 dB [62]. Moreover, strident sounds are especially annoying, the most appropriate being the use of musical instruments that emit natural sounds (wood, string or wind) such as piano, violin, flute, guitar and bongos. Lastly, children with ASD have difficulty hearing frequencies of 1–2 kHz; therefore, the notes and frequencies selected ranged from Do_3/C_3 (261.626 Hz) to Do_4/C_4 (523.251 Hz).

Finally, Table 6 summarizes the user-product interaction. The primary and secondary functions (subfunctions) derived from the requirements defined in the analysis of the design problem are listed (Table 1). The functions and the states of the product will be activated or modified with different actions of the user (child with ASD or playmate). The type of user activity will depend on the stage in the game sequence and the objective to be achieved, defining (1) motor actions to change the status of the product or function; (2) retrieval, that is, reading and interpretation of information of the user on the function and status of the product; (3) communication of information to the product by the user for the change of a function or status of the device; (4) checking or verification of a task or a status of the product; and (5) selection of options and alternatives between various functions or product states. All these user activities involve cognitive processing and are omitted for brevity (see legend Table 6).

4.5. Smart Product

According to its characteristics and functionalities, KEYme can be considered (1) an interactive and (2) a smart toy. First, as stated by Moggridge [63], interaction design is concerned with subjective and qualitative values and "would start from the needs and desires of the people who use a product or service, and strive to create designs that would give aesthetic pleasure as well as lasting satisfaction and enjoyment". By taking a closer look at the roles of interactivity in products stated by Clint Heyer, an interactive product focuses on controlling or accessing something unavailable, providing sensuous experience and pleasure and allowing for expression and communication. KEYme project emphasizes this last two roles of interactivity, which are being addressed following dialogue: (1) it works in a conversation-like way as the user and product wait for the next inputs; and (2) implicit styles of interaction: the product reacts to human and other phenomena, for example, the light that the photoresistor detects [64]. Second, as stated by Kara et al. [42], the concept of a "smart toy refers to a technologically developed physical toy constructed with a meaningful purpose". This concept is further explained by Cagiltay et al. in *Smart Toy Based Learning*, in which it is argued that "smart toys are new forms of toys that incorporate tangible objects and electronic chips to provide two-way interactions leading to purposeful tasks with behavioral or cognitive merit" [65] and they allow for an interactive environment to develop cognitive, social and behavioral abilities by means of the toys' dynamic structure. Following this definition, KEYme's different game modalities allow for a very dynamic play that would be mostly focused on improving the child's cognitive, social and behavioral skills. Every game mode is focused on specific needs and is destined for a specific set of skills. Game mode and its consequent actions have a very clear purpose (as explained in Section 4.4). On top of this, these smart toys can be categorized based on the kinds of tasks initiated (behavioral or cognitive tasks), which in the case of KEYme's game modes would be divided into (1) behavioral tasks (Mode I: Seesaw, Mode III: Tunnel and Mode IV: Touch spheres) and (2) cognitive tasks (Mode II: Keyboard games).

Another essential characteristic of smart toys according to Cagiltay is that smart toys should raise the awareness of children about their activities. Building on this statement, KEYme requires the child's full attention to play the different sub-games of the game Mode II. The lights and sounds given by the object help the child understand their performance in the game.

- Submodality I: sequence and simultaneous pressing game, where one player imitates another by pressing keys of the same color: being a game based on empathy, the child must be fully aware of his actions as well as his playmate's to be able to press the same color at the same time.
- Submodality II: turn-based sequence and memory game: the child must again not only be fully aware of his own moves but also his playmate's. The awareness is achieved through memory.
- Submodality III: musical game, each key produces a sound: different sounds are used together with lights responding to keystrokes. This helps the child become aware of their actions.

Table 6. Product functions and user activities relationships.

Product Functions			User Activities
Functions		**Subfunctions/Functional Requirement (Table 1)**	
Turn toy ON		Toy ON/③⑨	Press ON/OFF button 🟦
		"Hello" melody sounds ⑦⑨	Check if toy is ON 🟩
Game selection		Game mode selection	Choose game mode 🟩🟥
		Sub-game selection ③⑨	Choose sub-game using the switch 🟦🟪🟥
Game Mode I: Seesaw		Allows for sitting ①⑨	Sit down 🟦 Check posture 🟩
		Allows for swing ①②⑨	Swing 🟦
Game Mode II: Keyboard Games	Sub-Game 1: Simultaneous sequence.	Allows for keystrokes ①③④⑨	Stand up 🟦 Verify posture 🟩 Decide on roles 🟩 Press key 🟦🟪🟥
		Recognizes if players press at the same time ⑤⑥	Imitate playmates' moves 🟦🟩 Check if we are pressing the correct key 🟩
		Two keys of the same color light up ⑦⑧⑨⑩	If both players press at the same time
		"Correct" melody sounds ⑦⑧⑨⑩	
		"Miss" melody sounds ⑦⑧⑨⑩	I players don't press at the same time
	Sub-Game 2: Memory game	Turn LEDs light up ⑤⑥⑦⑨	Check whose turn it is 🟩 Wait for playmate to press a key 🟩
		Allows for Keystrokes ①③④⑨	Stand up 🟦 Verify posture 🟩 Press key 🟦🟪🟥
		Memorizes the sequence ⑤⑥	Remember sequence 🟩
		Key lights up ⑦⑧⑨⑩	If sequence was correctly entered
		"Correct" melody sounds ⑦⑧⑨⑩	
		"Miss" melody sounds ⑦⑧⑨⑩	If sequence was wrongly entered

Table 6. *Cont.*

Product Functions			User Activities
Functions		**Subfunctions/Functional Requirement (Table 1)**	
	Sub-Game 3: Musical	Allows for Keystrokes ①③④⑨	Stand up 🟦 Verify posture 🟩 Decide which key to press 🟪 Press key 🟦🟪🟥
		Key lights up ⑦⑨	
		A music note sounds ⑦⑨	
Game Mode III: Tunnel		Allows for turning toy upside down ①⑨	Turn toy upside down 🟦
		Recognizes when the toy is upside down through incident light	Check position 🟨🟩
		Tunnel lights up ⑦⑨	Check lights 🟩
		Allows for crawling inside ①②⑨	Verify posture 🟩 Crawl 🟦
		Recognizes when the toy is facing up through incident light	Check position 🟨🟩
		Tunnel lights off ⑨	Check lights 🟩
Game Mode IV: Touch Spheres		Allows for the child to feel different textures ①③④⑦⑨	Touch spheres with hands and fingers (squeezing, pressing, pushing and grasping) 🟦🟪
		Allows for climbing ①②⑨	Climb 🟦
		Allows for sliding down ①②⑨	Slide down 🟦
Turn toy OFF		Turn OFF manually ③	Push ON/OFF button 🟦
		Turns off automatically after 15 min	Wait for toy to turn off 🟩
		"Goodbye" melody sounds ⑦	Check toy is OFF 🟦

LEGEND Categorization of User Activities	
Action: include attention, perception, decision making and action	🟦
Checking: include attention, perception and evaluation of own task and product state	🟩
Retrieval information of product: include attention, perception, decode information and interpretation	🟨
Communication (with product): include attention, perception, decision making and data communication	🟥
Selection: include attention, perception and decision making between two or more options	🟪

In smart toys, child–toy interaction is not only important to raise awareness of children about their actions but also in terms of technological components and instructional activities. In this way, KEYme has different modalities of interaction depending on the game mode: (1) *Child-Child interaction*: Mode II—Submodality I and II; (2) *Child-toy interaction*: Mode I; Mode II—Submodality III; Mode III; and Mode IV. It also counts with different types of feedback (light, movement and sound) to guide the child along the games.

According to Cagiltay [65], "the relationship between the characteristics of smart toys and the developmental stages of children needs to be analyzed to develop effective smart toy learning environments". In this way, it is important that smart toys are created according to the different developmental stages in children:

- Sensory-motor stage: In this first stage, simple reflexes, actions and movements are the main activities of children. Language is yet not present, and object permanence is not developed. KEYme's game modes that belong to this stage are Mode I and Mode IV.
- Preoperational stage: Symbolic functioning and language acquisition are the main characteristics. Therefore, cognitive processes are mostly emphasized, though behavioral processes can also play an important role at first. In this stage, creativity and imagination should also be emphasized for children. Using smart toys for collaborative purposes should be implemented from this stage forward. KEYme's game modes that belong to this stage are Mode II—Submodality III and Mode III.
- Concrete operations stage: The concrete operations developmental stage involves children's ability to engage in calculations, rational relations and numerical activities. This is also the stage at which children become capable of classifying objects according to similarities and differences and serializing according to size and weight. KEYme's game modes that belong to this stage are Mode II—Submodality I and II.

Smart toys must therefore also have specific functions making the toy easy to use for play. In this case, KEYme gives feedback for the child to understand how the toy works and how he/she is doing in the game: (1) sounds to express changes of state in the product; (2) lights and sound to express hits and misses; (3) lights to help the child understand the turns; and (4) tunnel lights to reinforce how the toy must be used.

Finally, as stated by Malone and Lepper [66], learning experiences should be intrinsically motivated and, therefore, define toys as objects guided by the internal goal. In their article, they state which are the main dimensions for intrinsic motivation. In this way, Cagiltay [65] goes further, saying that smart toys must explore the different intrinsic motivation components concerning learning experiences:

- Challenge: Activities should challenge learners in order to motivate them intrinsically [66]. Smart toys that provoke behavioral or cognitive tasks provide possibilities for challenging and motivating children. This dimension is mostly explored in the concrete operations stage, more specifically in Mode II—Submodality I, as it requires higher concentration and coordination from the child, and Submodality II, as it is the one that requires more memory.
- Curiosity: It is the most effective component in motivating learners intrinsically. Several smart toys provide open-ended features that allow children to explore new facets of play and increase curiosity. This dimension is explored in all the different developmental stages through the different activities, thus implemented in every game, as all of these modalities allow for a different result every time they are played, depending on how the game develops.
- Control: Activities should give a powerful sense of control to learners to provide a successful learning experience. Some smart toys allow the child to take control of the toy itself to conduct purposeful tasks [66]. This dimension is mostly explored in the preoperational and concrete operations stages more specifically addressed in Mode II—Submodality I and II, in which the games require the user to make decisions and take the leading role.
- Fantasy: According to Cassell and Ryokai, "Fantasy play allows children to explore different possibilities in their life without the risk of failure and frustration from

unexpected events" [67]. This dimension is mostly explored in the sensory-motor and preoperational stages. In this case, it is explored through the multifunctionality of the product and the multiple positions in which it can be placed, as well as through Mode II—Submodality III, in which the child can improvise.

We could therefore argue that KEYme meets all the above objectives, being a self-contained smart toy, as it embeds the interactions within the physical structure, creating an interactive environment of its own. Table 7 summarizes the different characteristics that have been mentioned and how they are implemented in KEYme.

Table 7. Smart functions and properties of KEYme.

Characteristics of Smart Toys		Functions and Characteristics Embedded in KEYme
Purposeful tasks as the main function.		Multifunctional toy. Focused on cognitive, social and behavioral skills.
Tasks can be categorized	Behavioral	Modes I, III, IV.
	Cognitive	Mode II.
Raise awareness about actions.		Submodality I: empathy and imitation as basis of the game; lights and sounds. Submodality II: memory; lights and sounds. Submodality III: lights and sounds.
Interaction modalities	Child-child interaction	Mode II—Submodality I and II.
	Child-toy interaction	Mode I, III, IV. Mode II—Submodality III.
Reinforce instructions with interactivity.		Feedback: lights, movement and sound to guide the child.
Focus on different developmental stages	Sensory-motor stage	Modes I, IV.
	Preoperational stage	Mode II—Submodality III. Mode III.
	Concrete operations stage	Mode II—Submodalities I, II.
Specific functions: easy to use for play.		(1) Sounds to express changes of state in the product. (2) Lights and sound to express hits and misses. (3) Lights to help the child understand the turns. (4) Tunnel lights to reinforce how the toy must be used.
Intrinsic motivation components	Challenge	Mode II—Submodality I and II: concentration and memory.
	Curiosity	All different modalities: different results every time.
	Control	Mode II—Submodality I, II: make decisions, leading roles.
	Fantasy	Multifunctionality: multiple positions.Mode II—Submodality III: improvisation.

Finally, in smart toy play, learning through interaction can be defined as learning several concepts or skills combined with purposeful tasks that are accomplished by interacting with fun technological and instructional components. This statement clearly summarizes the purpose of the KEYme project, which was created with the goal of supporting children with ASD with specific needs in a fun and enjoyable manner using interactive interfaces. Smart toys should be focused on children's learning and cognition, and in this case, the KEYme project is strictly aimed toward the learning process of the child with ASD. The aim is to help children with those skills that can become more difficult. It is worth noting that smart toys provide children with richer experiences by combining physical and digital elements. KEYme is an attractive physical product enhanced with electronic components to achieve interactivity through a reality environment. The different game modes encourage the child to pay attention to both, the physical elements (object, playmate) and the digital elements. In this case, technology is used to reinforce and guide the physical actions of the child.

4.6. Design Verification

The aim of the last phase of the KEYme project development process was to verify the design concept. First, a prototype was manufactured at 1:6 scale that integrated the following scopes: (1) design to validate aesthetic and ergonomic aspects, (2) structural to verify geometric consistency, shape and assemblies between components, (3) functional to verify the detail design and the results of use and interaction and (4) technical to verify the suitability of the smart features of the product and its adequacy to the game modes and interface. The prototype was manufactured using 3D printing, PLA plastic and the Ultimaker Cura 4.5 software, with which adjustments were made to the final design in order to optimize material, time and manufacturing costs. Figure 8 includes some images of the prototype that show details such as the integration of the electronic circuit, the touch spheres or the keys. The next stage, included in the future lines of work, will be focused on the validation of the design. A working full-scale prototype will be tested on a group of target users.

Figure 8. KEYme validation prototype.

As an example, and to illustrate the implementation of the smart properties in the prototype, Figure 9 shows the sub-game 2.1. with the schematics and wiring diagrams for all components. The Arduino IDE software was used to make the programming code for the prototype. Sub-game 2.1. was selected to verify the detailed design and the results of use and interaction in the functional prototype. The developed code was entered on the selected board (ESP32). Since the loudspeaker that was implemented had difficulty reproducing the frequencies of the real design (too low), in the functional prototype all the notes were raised one octave, the following being the frequencies implemented: C [C: 523,251; Mi: 659,255; Sol: 783,991; Do: 1046.50]; C # [C #: 554,365; Fa: 698,456; Sol #: 830,609; C #: 1046.50]; and Re [Re: 587,330; Fa #: 739,989; A: 880,000: Re: 1174.66], only valid for the prototype because, as stated in Section 4.2., musical sounds should not exceed a frequency of 1 KH for users with ASD. On the other hand, the rest of the game modes that include smart properties in user-product interaction were validated in the technical prototype using Autodesk's Tinkercad software.

Finally, the usability of the product was analyzed in order to validate and optimize the user-centered design. After modeling and simulating human interaction with the tools HTA [68], GOMS [69], Sherpa [70], TAFEI [71] and user experience analysis [11], a set of results was obtained that allowed us to implement different improvements in the final design. Table 8 summarizes the obtained results. The usability requirements of the table (column 1, "basis") correspond to the basic analysis criteria taken into account in the simulation and evaluation of user-product interaction:

- Visibility: the interface elements are visible, recognizable and accessible.
- Feedback: real-time synchronization between user and product; adequate information on the current and future sequences of actions.
- Affordance: perceived and actual properties of an object that give clues to its operation.
- Mapping: clear, obvious and intuitive relationships between controllers and their effect on product performance.
- Constraints: the controllers and interface design reduce error by adequately preventing some movements.

- Consistency: interface guides the learning process with similar operation and use of elements for achieving similar tasks.
- Reinforcements: adequacy of interface feedback stimuli.

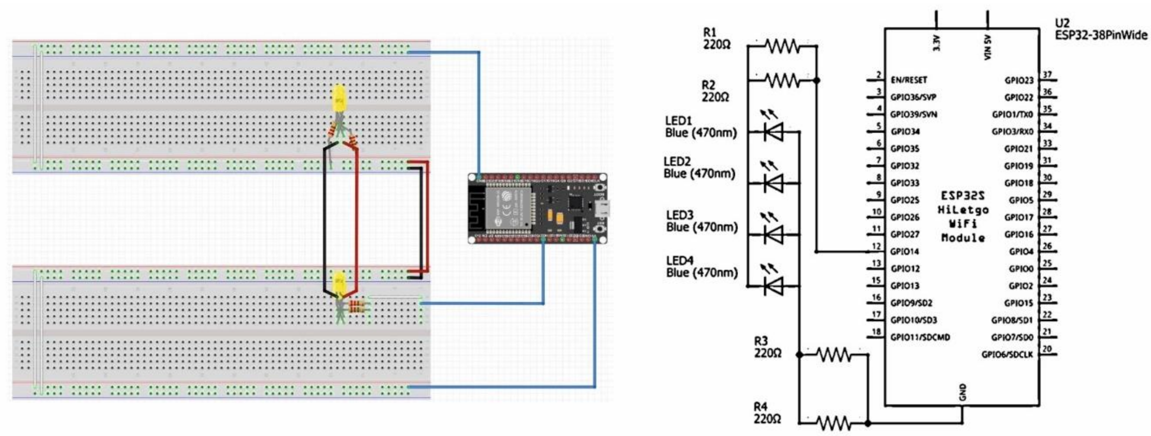


Figure 9. Wiring diagrams for sub-game 2.1.

Table 8. Usability sensitivity analysis and improvements carried out.

Basis	Usability Analysis	Improvements on Final Design
Visibility	All interface elements are visible while the toy is facing up. When turned over, the keys are hidden to prevent them from being pressed in tunnel mode. The design is safe.	
Feedback	It is done with visual, perceptual and proprioceptive stimuli; feedback is correct except for (1) on/off, (2) game turns and (3) game misses.	Add sound and light for power on. LED strip is added as a "shift in turns" indicator. Melodies are added for error identification.
Affordance	All the affordance used has an intuitive meaning that is easy for the user to understand.	
Mapping	(1) There may be errors during turn on and selection of game mode. (2) The action-reaction consistency of musical sounds is not adequate.	(1) A 3-position touch switch is added for game mode II; this is independent of the on/off switch. (2) Pitch rise (musical sound) is set from left to right and bottom to top on the keyboard.
Constraints	Correct. They reduce the probability of human error. The interface helps to focus attention on the tasks and the product with different simultaneous stimuli; it avoids unwanted actions thanks to the design of buttons with mechanical restriction and helps to reduce errors by restricting the type of interactions that the user can carry out.	
Consistency	Aesthetic, functional, internal and external consistency is correct. The grip, movement and stereotype patterns are correct.	
Reinforcements	Correct. Through visual (light and color), auditory (musical sounds) and proprioceptive (textures, movements, grip, pulsation, pressure and force generation) stimulation.	
Working memory use	Game mode II is the most complex and requires user training (sequence, memory and music). As its objective is to improve the capacity of sequential memory (remembering, while imitating and respecting the given order), in this mode short-term memory makes more effort (it stores more information as the game turns progress). For this reason, user-product interaction was reinforced with visual, auditory and proprioceptive stimuli.	
Automatic shutdown	To avoid pressing keys by mistake in mode I, in addition to manual shutdown, the product automatically shuts down as long as no activity is detected.	

5. Discussion

The results of the KEYme are consistent with the development of *a game-based AT* and adaptable to any user and context of use (therapy, family, didactic) that helps children with ASD to develop those skills in which they have difficulties; and, in addition to this, it includes changes, trends and new concepts of toys intended for typically developing children. The properties of multifunctionality, smart features and interactivity allow for different game modes to be included in the same object to cover a wide range of ASD needs grouped in (i) communication and social interaction and (ii) flexibility of thought and behavior.

KEYme is not a toy for individual use; it is a collaborative product to be used as a facilitator of social interaction and to improve cognitive, motor and sensory skills of children with special needs; in particular, seven broad-spectrum needs: (i) playmate-child with ASD relationships, (ii) sensory stimulation, (iii) motor skills, (iv) shared actions related to feelings of enjoyment, interest and common goals, (v) levels of frustration in the game, (vi) emotional and social reciprocity and (vii) learning about changes in game turns.

The balanced implementation of motor, visual, sound and tactile stimuli results in an increase in neuronal activity, which in turn facilitates the achievement of objectives within the aforementioned skills. More specifically, the improvement of psychomotor skills is achieved (referring to the actions and motor skills that involve the movement of the muscles in the body). First, with the development of gross motor skills orienting and guiding the necessary movements (such as crawling, climbing, swaying or maintaining balance) to finish each game sequence; and second, with the development of fine motor skills, thanks to the performance of movements such as *squeezing, pressing, pushing, grasping or pinching (touch spheres)*, all accompanied by visual and auditory stimuli used as reinforcement or positive feedback, which improve hand-eye coordination. It should be noted that the spatial distribution of the interactive functions restricts movements to mirror imitation, which increases neuronal activity four times more compared to anatomical imitation. This type of imitation helps to understand the consequences of each partner's actions, thanks to the experience acquired and the codification of the playmate's intentions.

The improvement of **social behavior** is done through physical contact "child> product> playmate". The motor stimulus has a strong emotional component; it helps to create a bond between playmates increasing the enjoyment of sharing interests. Moreover, during the interaction, the child observes the playmate performing actions in real time; this favors neuronal activity, achieving better results compared to viewing the same actions in videos or images. On the other hand, the frustration of failure during the game is worked through the coordination and synchronization between actions, as well as with the dynamics of the change of roles in mode II, where the two playmates assume an active or passive role in performing imitative tasks (depending on the game turns). In addition to this, sequential memory work contributes to the learning of everyday tasks and independence in daily life. Recalling information while following an order of tasks allows the child to develop skills in everyday tasks (school, didactic and domestic tasks).

Finally, KEYme allows for the interaction between several pairs of players, creating spaces for collaborative play. The structural design of the product makes the result adaptable to different contexts of use. Figure 10 shows the integration of KEYme in indoor (game rooms, home or school) and outdoor environments.

KEYme proposes **inclusive and accessible AT for ASD**. It is an attractive physical product enhanced with electronic components to achieve interactivity through a reality environment. The different game modes encourage the child to pay attention to both the physical elements (object, playmate) and the digital elements. In this case, technology is used to reinforce and guide the physical actions of the child. It is developed with an open-source electronic platform, with versatile and easy-to-use software and hardware. The use of additive manufacturing [72] allows the reproduction of any geometry, the manufacture of completely customized parts in a short period of time and at a low cost, easy product maintenance, as well as more environmentally sustainable results. The integration of additive manufacturing and open-source electronic platforms makes assistive technology affordable, replicable in an agile way and with reduced costs. This is a great advantage for users (associations, families, school environments) since they have at their disposal the possibility of manufacturing fully customized products adapted to different needs.

Figure 10. Integration of KEYme in different contexts of use.

Future developments in this project will focus on transforming the *smart toy* into a *smart toy product-service system* [73]. This involves the KEYme project moving toward interactions with external computers, in order to provide reports of results that would allow for medical monitoring and personalization. The technology used in KEYme makes it possible to configure it for the collection and storage of data, being the most interesting *the number of hits and misses in the game, the reaction time of the child when interacting with his partner or the game time dedicated to each game mode*. The data, collected for further processing, would be sent to therapists and parents for monitoring and observing the child's evolution. On top of this, and to build on the smart characteristics of the design, this information collected and memorized by KEYme could be used for the personalization of the different sub-games, automatically adapting the game's difficulty to the performance of the child. That is, the different game modes would have different levels of play classified by difficulty, using additional feedback (lights, sounds, labels) to help the child in the first stages and removing these reinforcement stimuli as he or she improves those skills. Some of the personalization elements that will be considered in future work are defined in Table 9. Furthermore, the data collected could be used to analyze the user experience and draw conclusions about the child's motivation, attention and interest in the toy, relevant information for future redesigns, integration of new game modes and improvements in the product.

The second major line of future work focuses on the development of a framework for the interactive and intelligent design of assistive technology for children with ASD. This framework will allow for the design of products adapted to the specific needs and problems of each disorder (according to the DSM-V classification [1]). It will take into account the level of neuronal activity (mild, moderate or severe) that different stimuli and imitation actions provoke, which will be directly linked to the design variables to be used in the development of the concept. Directly relating the needs of the child and the design variables (related to sensory activation stimuli) helps in the interpretation of the needs of each disorder and their translation into functional requirements and smart properties of assistive technology.

Table 9. Examples of custom elements.

Game Mode	First Stages	Later Stages
General Mode II	Colors are labeled. 	Labels are removed. 
Mode II, submodality 1: Simultaneous sequence	KEYme chooses a color by lighting up a key that both players must press at the same time.	Players decide the roles they want to take and the color that is going to be pressed at the same time.
Mode II, submodality 2: Sequence and memory	KEYme helps the players to memorize the sequence using light cues.	Players must memorize the sequence without any cues.
Mode III: Luminous tunnel with music touch wall	KEYme detects if the user is moving or still.	If the user stops, KEYme activates calming sounds and multi-colored LED lights when he/she presses the walls. Mode III becomes a luminous tunnel with a musical touch wall.

Finally, the KEYme project contributes to the improvement of products and their accessibility in the field of human development and social sustainability (equity). It works within the scope of childhood and disability, specifically, the wide range of signs and symptoms of assistive technology ASD. The development of quality assistive technology, its universal design and its accessibility (sufficient supply and price) is one of the main research challenges identified by the World Health Organization [25]. This project involves the knowledge transfer from the latest neuroscience, medicine and psychology contributions to the engineering and industrial design field. In addition to this, it takes advantage of new trends in accessible toys and resources (such as additive manufacturing and open-source electronic platforms) to create products available to everyone.

6. Conclusions

This research is an open proposal for the design of products developed as game-based assistive technology. This article presents the design of KEYme, a single and multifunctional module, although the project, the proposed methodology and the design strategy are open to the development of new products, with the aim of contributing to the challenge and need to transform more inclusive, innovative and innovative societies. reflective. Introducing new emerging technologies (related to open source electronic prototypes to create interactive objects, rapid prototyping techniques and 3D printing) into everyday products is of great interest. These solutions can improve the health and social well-being of currently underprivileged groups, helping engineering advance the development of science with and for society. KEYme also aims to drive a shift in the toy industry toward a more inclusive approach; it is important to expand its platforms and portfolios with adapted products that follow the same trends demanded by typically developing children, but integrating the resolution and satisfaction of the needs of special populations.

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