Design and Development of One-Switch Video Games for Children with Severe Motor Disabilities

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Video games are not just played for fun, they have become a handy instrument for the cognitive, emotional and social development of children. However, several barriers prevent many children with disabilities from playing action-oriented video games, alone or with their peers. In particular, children with severe motor disabilities, who rely on one-switch interaction for accessing electronic devices, find fast-paced games, that require rapid decision-making and timely responses, completely unplayable. This paper contributes to lowering such barriers by presenting *GNomon*, a software framework that allows the creation of action-oriented single switch video games. The paper reports the results of two studies that evaluate the playability and rehabilitation-suitability of GNomon-based video games. The *playability* of GNomon-based games is evaluated by assessing their learnability, effectiveness, errors, satisfaction, memorability and enjoyability, with a group of 8 children with severe motor disabilities. The *suitability for pediatric rehabilitation* is determined by means of a focus group with a team of speech therapists, physiotherapists, and psychologists from a Local Health Agency in Turin, Italy. The results of the playability study are positive: all children had fun playing GNomon-based video games, and 7 out of 8 were able to interact and play autonomously. The results of the rehabilitation-suitability study also entail that GNomon-based games can be exploited in training hand-eye coordination and maintenance of selective attention over time. The paper finally offers critical hindsight and reflections, and shows possible new future game concepts.

CCS Concepts: • **Human-centered computing → Accessibility design and evaluation methods**; Graphical user interfaces; • **Applied computing → Computer games**;

Additional Key Words and Phrases: Accessible Games, Children with Disabilities, One-Switch Interaction, Single Switch Selection, Action-Oriented Games

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1 INTRODUCTION

Playing games is an essential skill during childhood [50] as it promotes the development of cognitive, motivational, emotional, and social competence. In recent years, video games have become the most popular type of games (see the United States [23] and Europe [33] statistics, respectively) and they are already an integral part of contemporary culture. In fact, as pointed out in [15], every

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single child was born into a world where video games are simply a fact of life. Modern video games offer interactive and engaging experiences through sophisticated interfaces and game mechanics mainly designed for entertainment, but they also have the potential to support healthcare related processes (e.g., rehabilitation) or educational activities, as reported in [43].

However, many children with disabilities[1] do not have the sensory, cognitive, or motor skills for accessing most off-the-shelf video games. These children experience several barriers that prevent them from having fun in their free time, learning in more stimulating ways, or participating in interactive rehabilitation therapies. Providing suitable educational and entertaining activities is part of the goals of the *pedagogical rehabilitation* process [14] (also known as rehabilitation for children). In particular, children with motor disabilities often lack the ability to use standard input devices such as keyboard, mouse, or game controllers, and thus they are usually impeded from playing the same video games their peers use. Moreover, children with *severe* motor disabilities that rely just on the use of single switches for interacting with electronic devices, find *action* video games[2] completely unplayable.

The interaction offered by a single switch (a.k.a. one-switch interaction) is not suitable for playing action-based games because they are fast-paced games that require rapid decision-making and timely responses to provide a satisfying experience. On the contrary, common one-switch interaction methods, such as *scanning*, are very slow [39] as they are not intended for time-dependent tasks or rapid decision-making processes. In particular, scanning is not suitable for interacting with action video games as it requires the selectable elements to be stationary in rigid layouts, it takes time to be operated, and it defines a fixed scanning order that cannot change automatically (i.e., without the user awareness), as will be detailed in Section 2. On the other hand, action games are characterized by the presence of elements that can move across the screen and offer complex and fast changing visual scenes. As a result, one-switch users have been traditionally limited to static, time independent, and barely interactive games.

The target of the studies presented in this paper are children with *severe* motor disabilities, typically affected by cognitive disabilities too, that can only rely on the use of a single switch to operate a computer. To exemplify, the target population is children with cerebral palsy, classified as level III-V in the Gross Motor Function Classification System (GMFCS) [25], or with Spinal Muscular Atrophy. They present motor impairments, often accompanied by cognitive and communication difficulties, e.g., they are non-verbal children. Their legitimate wish for fully-playable action-oriented video games is still unmet. In fact, not only they do want to play games similar to those played by their peers without disabilities, as found by Hernandez *et al.* in a year-long participatory study [28]; but it has also been shown (e.g., [24] or [7]) that complex training environments such as video games, and specifically action ones, produce learning that transfers well beyond the training task. In the following, we will use 'action' and 'action-oriented' games interchangeably, according to the definition given in [28]. Similarly, we will use 'dynamic game mechanics' to indicate the game mechanics typically employed in action-oriented games.

The objective of this paper is to investigate the feasibility of one-switch video games that are playable and also suitable to be used in speech therapy with children with severe motor and cognitive disabilities. For this purpose, research structured in four phases was conducted, as illustrated in Figure 1. First, the authors designed and developed GNomon: a software framework, based on

[1]Living with disabilities is a complex multidimensional experience difficult to evaluate or to measure. UNICEF [45] estimates that the 5.1% and 0.7% of children (aged 0 to 14) worldwide live with "moderate to severe disabilities" and "severe disabilities", respectively.

[2]Action games [4] include, for example, car-racing games, first-person shooters, sports games, dancing games, and platformer games.

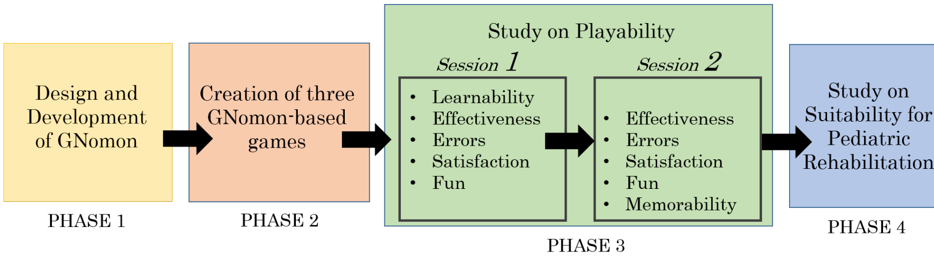

Fig. 1. Organization of the research

the NOMON [13] mode of interaction, that allows the creation of action-oriented single switch video games. Second, three one-switch video games with different levels of difficulty were created, based on GNomon. Third, the authors conducted a study for evaluating the *playability* of GNomon-based games. The study was designed to assess the following properties: *learnability*, *effectiveness*, *satisfaction*, *errors*, *memorability*, and perceived *fun*, by means of a two-session evaluation. Finally, in the fourth phase of the research, the authors carried out a study for evaluating the suitability of the GNomon-based games as useful tools in pediatric rehabilitation and speech therapy, by means of a focus group conducted with a team of speech therapists, physiotherapists, and psychologists from one of the Local Health Agencies in Turin, Italy.

This article is a totally rewritten and significantly extended version of the paper “Playable One-Switch Video Games for Children with Severe Motor Disabilities” [2], presented at the 7th International Conference on Intelligent Technologies for Interactive Entertainment. The new material presented here includes a significantly improved Related Work section (Section 2), a new introduction to NOMON (Section 3), a deeper explanation of GNomon and the GNomon-based video games design (within Section 4), and the second session of the playability study (within Section 5), which enabled us to assess the property of *memorability* of the GNomon-based games, as well as to reinforce the assessments of the other playability properties with new data. The fourth phase of the study (suitability for pedagogical rehabilitation, Section 6) is entirely new. Furthermore, the overall discussions on GNomon and on the two presented studies have been improved. Critical reflections, limitations of the approach, lesson learned, and a brief presentation of other action-oriented GNomon-based video games have been added as well (Sections 7 and 8).

The remainder of the article is organized as follows: Section 2 presents a review of the literature regarding common one-switch interfaces as well as a review about accessible and one-switch video games. Section 3 briefly introduces NOMON, the interaction method that is the basis of the present work. The design and development of GNomon and the three GNomon-based video games (phase 1 and phase 2 of the research, respectively) are described in Section 4. Section 5 presents the playability study (phase 3 of the research). The study on pedagogical rehabilitation suitability (phase 4 of the research) is reported on Section 6. Section 7 discusses the limitations of GNomon, the lesson learned, and the results from both studies with a critical approach. Section 8 describes current and future work and explains how researchers and practitioners can use the results of this work; additionally, it briefly introduces three other action-oriented GNomon-based video games. Finally, Section 9 draws conclusions.

2 RELATED WORK

Before discussing the design and development of accessible and action-oriented video games for children with severe disabilities, it is important to establish the state of the art of accessible interfaces as well as to be aware of the types of accessible games that are already available. This section reports the main findings of a literature review, conducted with a two-fold objective: 1) to define the current situation of accessible video gaming, including available games and evaluations of such games with real users; and 2) to understand the types of interaction modalities that are used nowadays to allow players with disabilities to interact with video games.

The inclusion criteria (inclusive OR) for the reported related works are the following:

- Documents that present useful guidelines for the design and development of accessible interfaces for people with severe motor and cognitive disabilities.
- Documents related to accessible games for people with severe disabilities.
- Documents that describe accessible games design.
- Documents that summarize available interactive technologies related to accessible gaming and entertainment.
- Documents that report evaluation of accessible games with real users.

Additional sources of information, useful during the development of this work, were some game accessibility guidelines such as "Includification: a practical guide to game accessibility" by the AbleGamers foundation [6]. This report advises developers on how to improve the accessibility of their games. Similarly, the International Game Developers Association (IGDA) published a list of guidelines [32], inspired by the Special Effect's Game Accessibility Wish List [40], that suggests ten easy-to-implement steps for making almost any video game more accessible. Even Microsoft, with its accessible technology group, addressed accessible games through the online article "Making Video Games Accessible: Business Justifications and Design Considerations" [35], which explains to developers who want to reach the accessibility community market how to design basic accessibility features for people with vision, hearing, speech, mobility, and cognitive impairments.

In the literature, in guidelines, and in actual video games, the accessibility features of a video game are usually categorized according to the three main classifications of disabilities: physical, sensorial, and cognitive. Therefore, the literature review was limited to the material concerning people who live with severe motor disabilities caused by traumatic injuries (e.g., spinal cord injury), diseases (e.g., Lou Gehrig's disease) or congenital conditions (e.g., Cerebral Palsy or Spinal Muscular Atrophy), that usually interact with computers using two main strategies: assisted direct selection or scanning interfaces.

On the one hand, *assisted direct selection* refers to the action of somehow pointing (e.g., with the head or with the gaze) or naming (e.g., voice-based selection) any desired item for selecting it. This is important for users with disabilities, as they can interact with electronic devices hands-free, and have the opportunity to successfully communicate, read, or play.

Playing, which is one of the most important activities for a child, can be done through eye-gaze interaction or voice-based commands, depending on the residual capabilities of each player. Eye-gaze interfaces support levels of interaction similar to those required by traditional action video games, according to the study presented by Vickers *et al.* [48], in which the results obtained with a group of young people with cerebral palsy and muscular dystrophy showed that eye-gaze interfaces help players to significantly improve their control of in-game characters. Similarly, this kind of interaction supports other playful activities enjoyed by children (besides game playing), such as drawing. Hornof and Cavender present EyeDraw [30], a software program that allows children with severe motor impairments to draw with their eyes. Likewise, van der Kamp and Sundstedt [47] propose a combination of gaze and voice commands for interacting with a paint style program. In their proposed application, voice commands are used to activate drawing, while gaze is used to move the cursor. Applications that employ voice input to control the cursor movement for navigation and selection, i.e., two fundamental tasks for playing video games, are proved to be

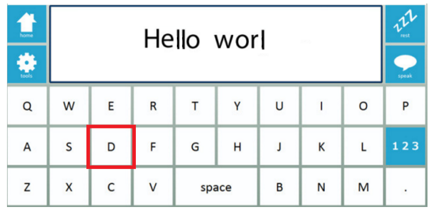

Fig. 2. A scanning interface for writing with the letter *"D"* highlighted as the current possible selection. If the user activates the switch, she will select it, otherwise the scanning indicator will shortly move to the next letter (*"F"*).
Image modified from a screenshot of The Grid software (Smartbox Assistive Technology). Reprinted with permission.

a powerful alternative for persons with motor impairments that still can speak out loud. Harada *et al.* [26] report the encouraging results of a longitudinal study in which 5 people with motor disabilities learned to use a vocal joystick efficiently after just 2.5 weeks: the vocal joystick can be used for playing or for general communication purposes.

On the other hand, *scanning interfaces* allow the indirect selection of one element at a time from the screen. The desired element can be selected by activating a switch when an indicator highlights it (for a short amount of time), and before it highlights the next element in a predefined sequence. Figure 2 illustrates a very simple scanning-based interface for writing. A red square indicator signals to the user that if she activates the switch in that moment, the selection will be the the letter *"D"*.

There are several scanning *patterns* and several scanning *control* techniques. Patterns refer to the layouts in which the selectable elements are arranged to be sequentially highlighted (in a predictable way) for selection; these can be linear, by blocks, or hierarchical. Scanning control techniques refer to the mode in which an indicator highlights the different choices. The most popular one-switch control technique is *automatic*[3], in which the indicator moves automatically, highlighting the selectable elements and waiting for a short time (i.e., the scanning delay) on each of them for an input to occur. Such an input is usually the activation of a single switch, which consists of just a "click" with timing information (i.e., the instant of the click, and not its duration). The selected element is the one currently highlighted when the input event occurs. A second scanning technique is *inverse*: the selectable elements are highlighted while the user holds down the switch, and the selection takes place when the switch is released. A third scanning mode, namely *step scanning*, is not considered here since it requires the usage of two switches: one for advancing the selection indicator, and the other to confirm the intended selection.

Although scanning is considered slower and more cognitively demanding than direct selection, it generally consists of a much simpler and inexpensive set up and it requires considerably less motor control to be used efficiently (see [5] for more details about scanning as an interaction method). Moreover, some direct selection technologies cannot be used by some people with severe disabilities. For example, vocal joysticks are not usable by non-verbal persons, while eye-trackers require the person not to move her head and to maintain focused attention for long periods of time, and thus are not accessible by people with uncontrolled movements. For all these reasons, scanning interfaces operated through single switches are very popular among children with severe disabilities, especially for communication purposes.

Over the years, research efforts concentrated on improving one-switch selection mechanisms for enhancing the interaction capabilities of individuals with severe motor disabilities of all ages. In

[3]Throughout this paper, 'scanning' and 'automatic scanning' will be interchangeable concepts.

the book of Beukelman and Mirenda [9], the authors discuss diverse alternative access options to address complex communication needs, such as different scanning control techniques. Angelo [5], instead, systematically compares three basic modes of scanning (i.e., automatic, inverse, and step) for supporting one-switch interaction of people with cerebral palsy. The results of her study show that a "preferred" mode of scanning does not exist, and that the scanning strategy must be tried and chosen individually, considering also the specific type of cerebral palsy. Other studies, such as [42] and [19], focus on designing entire systems to provide one-switch users with access to computer applications, which is essential for participating in modern information society.

In Human Computer Interaction, recent related work delved into universal accessible interfaces. The early study by Stephanidis *et al.* [41] presents a preliminary collection of design-oriented guidelines and development requirements for accessibility and universal design in human-computer interaction, by analyzing various international normatives as well as design practices. In particular, research on universally accessible games (a concept formally introduced by Grammenos, Savidis and Stephanidis [22]) has improved the quality of life of many children with several types of disabilities that experience social isolation, by supporting their participation in education and entertainment along with their typically developing peers. The survey presented by Yuan *et al.* [51] reports a large number of accessible games at the state-of-the-art in research and practice. The survey covers accessible games separately for different types of impairments (i.e., visual, hearing, motor, and cognitive) and across 8 specific game genres. For each type of disability, the authors extract specific strategies for game designers to inform their work (e.g., reducing the amount of stimuli, for cognitively impaired players). Interestingly, the authors find that very few games are developed for players with cognitive disabilities, that popular game genres (mostly action-oriented) are not yet available for severely motor impaired players, and that the distilled strategies often need some tradeoffs to avoid "ending off with a game that is not fun to play".

Grammenos, Savidis and Stephanidis [22] focus on universally accessible games and present a structured design method for realizing such games. They demonstrate the application of such a methodology mainly in the design and implementation of two accessible games: a) *UA-Chess*, a universally accessible chess game, illustrated in Figure 3; b) *Access Invaders*, a universally accessible multiplayer version of Space Invaders, shown in Figure 4.

Both UA-Chess and Access Invaders can be played with a single switch through scanning. In the single switch mode, UA-Chess [21] can be considered a "classical" scanning-based game, since it is not fast-paced nor does it present dynamic game mechanisms.

Access Invaders, instead, is more interesting since it is conceived as an action-oriented game. However, in the single switch mode (depicted in Figure 4), the game loses most of its functions and the interactivity is reduced: the player can control only the spaceship's movement direction (i.e., she toggles it), while the spaceship moves and fires automatically at a predefined speed, without any personalization possibility for the single switch player (see [31] for more details). Moreover, to activate the in-game menu or to pause the game, the player must keep the switch pressed for at least 5 seconds, thus requiring a precision for playing the entire game that is not always reachable by children with severe disabilities. A consequence of this choice is that the player can toggle the spaceship's movement direction only if she presses the switch for *less than* 5 seconds.

3D virtual worlds, multiplayer environments used for gaming or leisure, have also received some interest from the accessibility community. In particular, the works of Trewin *et al.* [44] and Folmer *et al.* [18] are of particular relevance for single switch users. The former paper [44] explores the necessary features for making virtual worlds usable by people with visual or dexterity impairments. To demonstrate this, the authors built a multiplayer 3D virtual world game, called *PowerUp*, designed to teach middle school students how to use science and math concepts to solve

Fig. 3. UA-Chess main user interface
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Fig. 4. Access Invaders in the single switch profile
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critical environmental problems with renewable, alternative energy sources. PowerUp has several accessibility features (e.g., font customization, text-to-speech output, keyboard-only navigation, etc.) for people with visual or dexterity impairments, well described and easily extensible to similar virtual words. Instead of building a new accessible virtual world, the latter paper [18] focuses on the one-switch navigation of a 3D avatar in Second Life, by targeting people with severe motor disabilities (such as quadriplegics). The authors explicitly target "*the most extreme user*" when developing an efficient scanning method that provides continuous and mixed input by using the smallest amount of input possible, i.e., a binary switch. In this sense, their work is similar to the one presented in this paper, since both works concentrate on "extreme" users and the usage of a single binary switch. They propose and describe *hold-and-release*, a novel scanning control method for 3D navigation that is able to provide continuous and mixed inputs using a single switch. The control method for navigating the 3D world is specifically trained thanks to other Second Life users, but the usage of hold-and-release was simulated without real users.

Multiplayer games that balance differences in player ability levels proved their effectiveness in fostering social interaction of children with disabilities. On this topic, Hernandez *et al.* [27] present encouraging results of a ten-week home-based study with children with cerebral palsy playing the multiplayer game *Liberi*, while the novel augmented reality computer game *Powerball* [11] was designed to bring together children with and without disabilities.

In the last decade, alternative input methods for empowering users with disabilities to interact with electronic devices, such as brain computer interfaces (BCI) [38] and inexpensive eye-tracking interfaces (e.g., CameraMouse [8][4]) have been explored. Unfortunately, it is known that BCIs may be less accurate (as any other interaction modality based on physiological signals) than switch interfaces.

Eye-tracking interfaces may require long times to be operated successfully, which is acceptable for navigation, text entry or menu selection, contexts in which 1) selection sets are large and the occurrence of having to repeat an input is low, 2) selection sets are known and static, 3) single elements can be arranged in fixed positions to enhance selection speed and effectiveness, 4) each element has a computable probability of being the next to be selected, given the previous selections.

Consequently, when the alternative input methods or the traditional one-switch selection mechanisms are utilized to enable children to interact with video games, the resulting experience is often frustrating, trivial, or static.

This situation is well illustrated in the following review of several free games (listed in the popular non-profit website "OneSwitch.org.uk" [17], mainly). The criteria for including the games in the review was that they can be freely played with just an affordable two-state single switch (without the need of holding it down). We identified three major disjoint categories of one-switch video games and the main barriers that prevent children from enjoying them:

(1) *Cause/Effect games.* The goal on these simple games is to press the switch to obtain some effects (e.g., when the switch is pressed, a football player kicks a ball). These games are used for teaching children how to use the switch and to associate it to a trigger for different actions. The downside of many cause/effect games is the *lack of interactivity* for children due to the fact that they cannot make any decision to affect the outcome of the game, as the effect of pressing the switch at any time is completely random. Figure 5 shows the "Penalty Game" [49] before the switch is activated, during the activation action, and at the end of the associated reaction. The lack of interactivity is evident: every time the player presses the switch, the ball is kicked without any control or insight upon the chance of scoring a goal.
(2) *Scanning based games.* Most of the available one switch games (e.g., chess, memory game, battleship, etc.) fall under this category. These are usually more complex and more interactive than cause/effect games, since scanning allows selecting more than one element (or action) from a set of options. However, it is not possible to interact with video games that do not have a *static* pattern of selectable elements, a fixed scanning order, and suitable game mechanics to allow enough time to make any selection even after a complete scan. Figure 6 shows the "Crazy Chicken" [34] game, in which the players have to drop eggs into

[4] a free program that allows the control of the mouse pointer by moving the head

Fig. 5. Cause/Effect game: "Penalty Game"
Image copyright by David Vincent (Specialbites). Reprinted with permission.

a basket when a chicken (the highlighting indicator of the scanning) passes above it, while moving across different positions (selectable elements of the scanning).

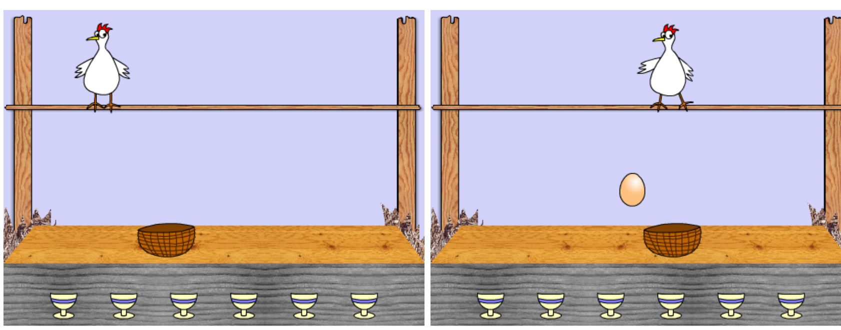

Fig. 6. Scanning game: Crazy Chicken
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(3) *Click timing games.* This category of one switch games includes those in which the player has to press the switch with high precision to perform an action in a very specific moment. It includes some action-oriented games, differently from the previous two categories. These games are, typically, interactive and with dynamic game mechanisms. However, the problem with many of these games, such as Poto & Cabenga [29] and Strange Attractors [37], is that they are not fully accessible to children with severe disabilities because such games require *speed and precision* levels that these children often lack. Figure 7 illustrates the Poto & Cabenga game in which the player controls a running character which has to jump in precise moments to score points and to avoid being eaten by a monster. With the GNomon framework, we would like to allow the creation of *interactive* games, with *dynamic* game mechanisms, but without the "inaccessible" characteristics present in this category.

An alternative classification of accessible games, complementary to the one presented in this section, is reported in the survey of Yuan *et al.* [51]: it identifies a subset of specific and "standard" game genres (i.e., first-person shooter, strategy games, sport games, etc.), and analyzes them according to various type of impairments, separately. This paper, instead, focuses on single-switch games only, independently from the specific game genre, and suitable for children with severe motor disabilities that are typically affected by cognitive impairments too. Obviously, the two classifications share the analysis of various games. For example, *Strange Attractors* is considered a "one-switch puzzle game for people with motor impairments", while in our classification it is a "click timing game".

Fig. 7. Click timing game: Poto & Cabenga.
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3 NOMON IN A NUTSHELL

This section briefly describes the NOMON one-switch mode of interaction, originally presented by Tamara Broderick and David MacKay [13]. The GNomon framework (Section 4.1) is based on NOMON and its operation directly derives from it.

NOMON is a one-switch mode of interaction that allows the selection of one element from a set of elements without specific extra hardware (e.g., expensive eye trackers) and without the need of using static or pre-ordered element arrangements. It is characterized by a set of widgets in the form of small *clocks*, each one associated to a selectable element. Figure 8 shows a series of NOMON clocks associated to numbered options all over the screen. Every clock widget has two clock hands: one red, fixed at noon and another black hand, which rotates with the same constant angular speed in all the clocks, but with a different phase. From the user point of view, in order to select an element, she has to look at the clock associated to the element and try to press (click) the switch when the black hand is crossing the red hand (at noon), as precisely as possible. At this point, all the moving clock hands will reset to their initial positions (determined by their initial phases with respect to noon). The user repeats these actions until her desired element is shown to be selected.

In more detail, after a click from the user, NOMON calculates for each clock the probability of being the intended selection, given the sequence of clicks thus far. To avoid ambiguity, if the difference of probability between the two clocks with the highest probability of being the intended selection does not reach a predefined threshold, a selection will not be performed, yet. Instead, the calculated probabilities accumulate for each clock and the clocks with a sufficiently high probability (but not enough to be selected) turn yellow. Finally, when the difference of accumulated probability between the two clocks with the highest accumulated probability is large enough, the clock with the highest probability of being the intended selection turns green and its associated element gets selected. As the number of clicks required to make a selection is variable and depends on how precisely the user clicks and on how many selectable elements are available, the original NOMON mechanism *adapts* to the user performance. In this manner, NOMON allows precise users to click just once or very few times to make a selection, while it tolerates more errors from less-precise users without affecting the final selection result. The rotation period of the clock hands can be calibrated by the user.

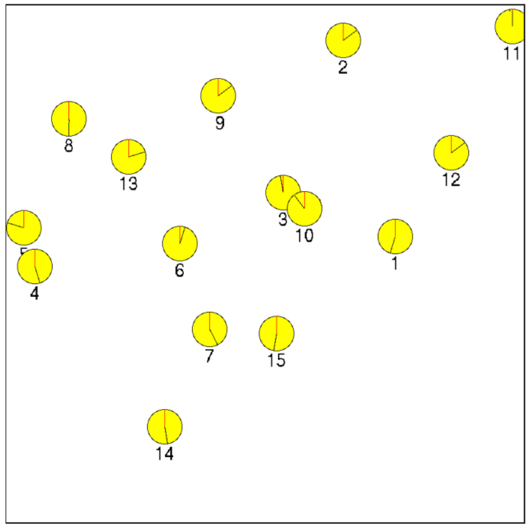

Fig. 8. 15 NOMON clocks associated to numbered options. These clocks can be as well associated to any other form of graphical element on the screen, even if it moves. This flexibility is leveraged by the GNomon framework, which associates the selection clocks to selectable game objects.
Image reprinted from [13] under an Open Access license.

3.1 Statistical model

NOMON works on the basis of a statistical model elegantly explained in [13], which calculates for each clock the probability of being the user intended selection, given a series of clicks in time. The model allows setting *prior probabilities* (indicated by $p(c)$) to the selectable elements on the screen, a very useful feature in contexts in which some options are more likely to be selected than others. For instance, in a writing application, some letters are more likely than others. In contexts such as games, this feature could be used to tune the difficulty of the game by making some elements more easily selectable than others (e.g., in a shooting game, it could be easier to shoot some enemies than others).

The statistical model also assumes that the probability distribution of the user's r^{th} click time t_r around noon, $p(t_r|c)$, is known. Such a probability distribution, which is modeled as a normal distribution, depends on the chosen clock, the rotation period of the clock hand and of course the user clicking capabilities; thus, each user should spend some time generating enough data for determining such a distribution. However, the original NOMON implementation skips such a time-consuming and boring task and lets the user start using the interface right away, assuming an initial distribution slightly offset from zero and learning for each click of the user in order to update the model online (see [13] for the complete click distribution study).

Figure 9 shows a hypothetical clicktime probability distribution around noon approximated to a normal distribution with $\mu = 0$ and $\sigma = 1$. For non-novice users, the starting click distribution of the original NOMON implementation is modeled by the normal distribution $N(0.05T, (0.14T)^2)$ and the default rotation period is $T = 2s$.

After the R^{th} click of the user, NOMON calculates the *posterior probability* that each clock has of being the intended selection, given the clicks thus far, using Bayes' theorem. In the original NOMON model, the *weak* source of information provided by the times in which the user did not click were ignored. Therefore, given a series of R clicks, the resulting posterior probability of a

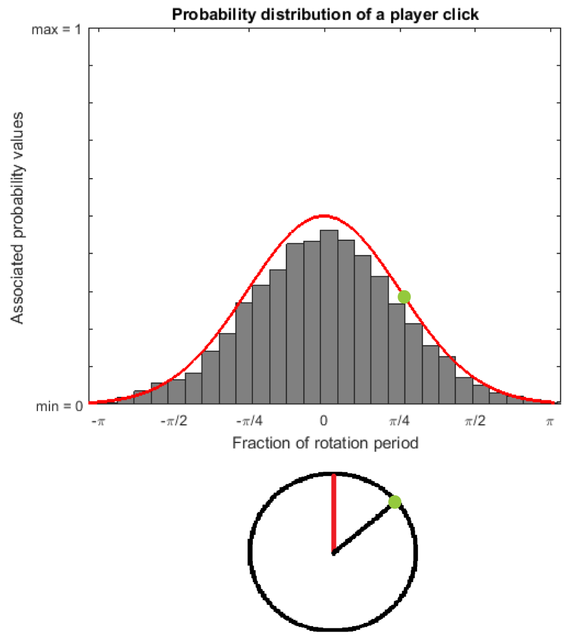

Fig. 9. The figure shows the relation between the click times t (representing different fractions of the clock rotation times) and the probability associated to them $p(t|c)$.

clock c of being the user intended selection is:

$$p_{c,R} = p(c|t_{1:R}) = p(c)\prod_{r=1}^{R} p(t_r|c)$$

The clock c (and, by extension, the selectable element associated to it) is declared as the selected one if its posterior probability is higher than $1 - p_{error}$, where p_{error} is a pre-defined but configurable error rate.

In practice, NOMON uses an approximate evaluation for declaring a clock (c) as the selected one (see [12] for a more detailed explanation): after the clocks are sorted by their posterior probabilities, the most probable clock is considered as selected when its posterior probability is higher than the posterior probability of the second most probable clock by at least a factor of α:

$$p_{(C),R} > \alpha p_{(C-1),R}$$

If no clock is chosen after a click, NOMON sets a new selection round by resetting all the clocks. However, NOMON chooses new relative clock hand offsets (with respect to noon) according to an heuristic, in order to help the two most probable clocks ($p_{(C),R}$ and $p_{(C-1),R}$) to diverge and satisfy the error criterion as quickly as possible in order to have a winner. The heuristic makes the most probable and the second most probable clocks start with a phase difference of 180°. The next two most probable clocks start at 90° and 270° relative to the most probable clock, then the next four at 45°, 135°, 225° and 315°, and so on. In such a way, the chances of ambiguity between the group of most probable clocks in the new selection round are reduced.

4 GNOMON: FRAMEWORK AND GAMES DESIGN

This section presents the development of GNomon and the accessible one-switch video games, designed for children with severe motor disabilities that use this framework: One Switch Demo, One Switch Ladybugs, and One Switch Invaders. The main goal of the GNomon framework is to provide the functionality necessary for the creation of action-oriented video games, which support dynamic and/or time-dependent game mechanics, through the use of just a single switch. Similarly, the design features of the GNomon-based games aim at going beyond the limitations of currently available one-switch games (as described at the end of Section 2).

4.1 GNomon

GNomon (**G**aming **NOMON**) is a software framework that enables the creation of accessible and action-oriented one-switch video games (the original idea was included in a poster presented by Aced López *et al.* [1]). It is based on the NOMON [13] one-switch mode of interaction that allows the selection of one out of many elements on the screen with a single switch.

GNomon leverages the original operation principles of the NOMON selection mechanism as illustrated in Figure 10 and summarized below:

- GNomon associates a small widget in the form of a clock to each selectable element on the screen.
- Each clock widget has two clock hands: one red hand fixed at noon and another black hand that rotates with the same speed in all the clocks, but with a different phase.
- To select an element, the user has to look at the clock associated to the element and try to press (click) the switch, as precisely as possible, when the black hand is crossing the red hand (at noon). Then, for each clock GNomon calculates the probability of being the intended selection, given the sequence of clicks so far.
- If the difference of probability between the two most probable clocks exceeds a predefined threshold, the clock with the highest probability turns green and its associated element is selected.
- Otherwise, if the difference of probability between the two most probable clocks does not reach the predefined threshold, there is not a selection and the clocks with a sufficiently high probability turn yellow. Selection probabilities are recomputed, and as a consequence these clocks are given new and well-separated phases; the user may easily disambiguate with a new click.

The framework, differently from NOMON, provides functions for creating sets of selectable game objects with associated clock widgets, to enable dynamic point-and-click game mechanics that work with a single switch. These sets can be resized at any time by adding or removing elements: this is necessary for supporting common dynamic game actions such as the creation of new items or the destruction of elements. Moreover, the results in [2] demonstrate that the framework is also very useful to realize "static" games (like cause/effect games) that are challenging because they allow selectable elements to be displayed without layout restrictions.

A participatory approach was adopted for eliciting the features and accessibility guidelines of GNomon, thus the authors worked in close collaboration with a team of speech therapists, physiotherapists, and psychologists from one of the Local Health Agencies in Turin, Italy. They actively supported the project by guiding important design choices and by proposing features on behalf of the children assisted by them. In total, five meetings were conducted with the experts for testing and collecting suggestions to improve the framework. Thus, several features of GNomon, mainly related to specific accessibility issues, were adapted to follow their valuable recommendations. The recommendations are the following:

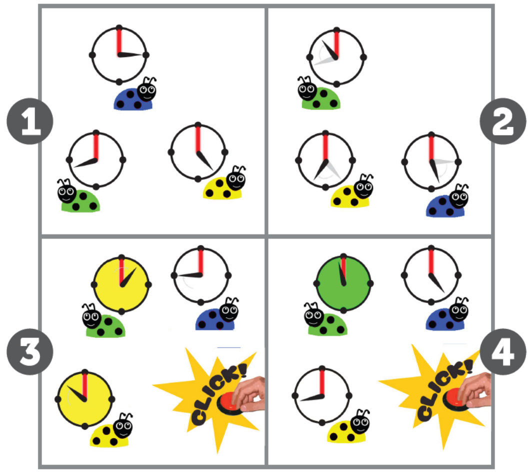

Fig. 10. The operation of GNomon. 1) First, every element has an associated clock widget. 2) All the clock hands rotate at the same speed and with different phase. 3) The user activates the button and the probability of being the selection is calculated for each clock; those with the highest probability turn yellow. If there is not a winner, a new round starts again and clocks with similar probability of being the selection are assigned new and very different phases. 4) Eventually, the difference of probability between the two most probable clocks becomes large enough to declare a winner, that turns green.

(1) Provide additional indicators for easier interaction. In particular, four circular marks were placed in the clock quarters (three o'clock, six o'clock and nine o'clock) to facilitate the interaction of children with long muscular latent periods (i.e., the time between the movement command and the muscle movement) by helping them with clues about when to start "preparing" themselves for pressing the switch.
(2) Make the clocks more eye-catching. Action-oriented game objects are usually attractive, colorful and animated, hence they tend to concentrate the attention of children. Moreover, as the clocks are just the means for selecting game objects, it is normal that the former are less striking than the latter. However, the clocks' appearance was redesigned to be as eye-catching as possible (while keeping its simplicity) to prevent the less attentive children from ignoring the clocks. In particular, the clocks were enlarged, the colors were made brighter and more contrasting, the lines were thickened and the moving clock hand was made pointier. Figure 11 shows a comparison between the classical NOMON clock and the new appearance of the clocks. The experts recommended "embedding" the clocks into the game objects themselves. However, this recommendation was not adopted in the final design as it heavily limits the looks and appearance of the game objects.
(3) Reduce the average speed of rotation of the moving clock hands and making it customizable. The rotation period of the clock hands ranges from 1 to 10 seconds, to allow children with long muscular latent periods to enjoy GNomon-based games. The rotation speed can be set and changed easily by their parents or caregivers.
(4) Give visual feedback when a clock is selected. Besides the specific feedback and the actions triggered in each game when a clock is selected (e.g., the death of a character, or a jump of victory), the clock itself changes color.

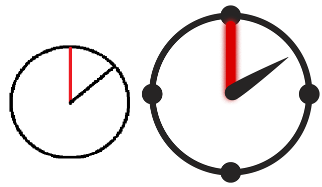

Fig. 11. Clocks used by GNomon for selecting game objects (right) and the original NOMON clock (left). The appearance of the new GNomon clock is based on the original design but with the important modifications suggested by the experts: enlarging the clock, thickening all clock lines, placing marks at clock quarters, rendering more eye-catching the red noon hand and making the moving clock hand pointier (image originally appeared in [2] under a Creative Commons Attribution license).

The final implementation of the GNomon framework incorporates custom extended C# versions of the original NOMON Python libraries into a Unity 2D plugin [46]. As explained in Section 8, the software will be available in Open Source format for other developers and researchers.

4.2 The Games

In collaboration with the Local Health Agency, the authors designed three mini games with different degrees of difficulty that are fully playable with just one switch, and presented them as prototypes [2]. This paper presents their final versions, freely available for download at http://elite.polito.it/gnomon-games.

One Switch Demo. The first game is One Switch Demo, a cause/effect video game that allows children to make a ladybug jump when they select the clock associated to it. When the ladybug is correctly selected and it jumps, it also produces an auditory feedback to increase the child's reward. There are no scores or time constraints of any kind because the game has been designed mainly to explain how the clock selection works. The aesthetics, as well as the objective of the game, are very simple to help the children with visual and attention difficulties to stay focused on the game mechanics. Figure 12 shows a screenshot of the game.

Fig. 12. A red ladybug and its associated clock during a One Switch Demo game (image originally appeared in [2] under a Creative Commons Attribution license).

One Switch Ladybugs. The second game is One Switch Ladybugs, another mini game that allows children to make one of four ladybugs jump. This game can be considered similar to currently available scanning-based games. Each ladybug has a different color (red, green, blue, or yellow) and provides a unique auditory and visual feedback when it is successfully selected. There are no scores or time constraints of any kind, but unlike the first game the aesthetics are richer and there is background music playing in a loop. The objective of the game is the same as the previous game (i.e., to make a ladybug jump), but now the child may choose which one. Figure 13 shows a screenshot of the game.

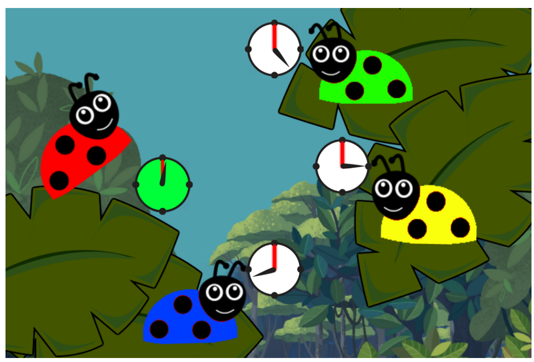

Fig. 13. The selection of the red ladybug (top left) during a One Switch Ladybugs game (image originally appeared in [2] under a Creative Commons Attribution license).

One Switch Invaders. The third game is definitely more complex than the first two and is called One Switch Invaders (Figure 14). It is an engaging *action-oriented* one-switch game that does not require accurate timing nor clicking precision to be played. The game has not a fixed layout: in fact, multiple selectable elements (aliens), moving around the screen, have to be selected with time constraints. The implementation of One Switch Invaders is not feasible by applying scanning control techniques because the elements are not static in predefined patterns and it is not possible to establish a scanning order without negatively affecting the game mechanics. The game objective is to score points by eliminating the aliens before three of them touch ground. There are aliens of five different colors (red, green, blue, yellow, and purple) which constantly fall down the screen at a bounded random speed. Each alien is associated to a clock for enabling its selection and is generated in a random horizontal position at the top of the screen.

4.3 Design Considerations

The design of the mini games (specially One Switch Ladybugs and One Switch Invaders) takes into account some of the valuable design recommendations by Hernandez *et al.* [28] for playable action-oriented video games for children with cerebral palsy:

(1) *Simplify level flow, reducing the number of decisions players need to make and reducing the demands on visual-spatial reasoning*. In One Switch Ladybugs, this is taken into account by presenting only four ladybugs that can perform just one action (jump). In One Switch Invaders, where the player has many aliens to eliminate, we decided to let them fall at the same constant speed; with such constraint, the decision of which alien to eliminate first is simple: the one closest to the ground.

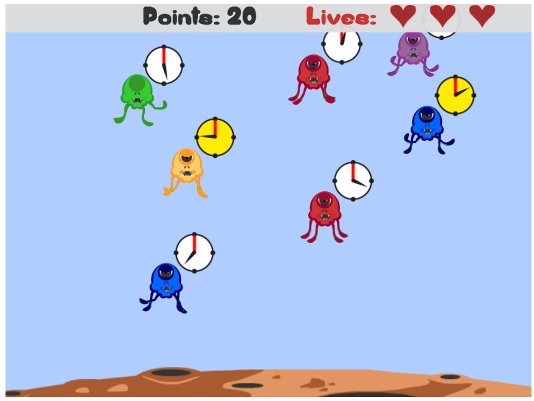

Fig. 14. Seven aliens falling down the screen while two of them are in the selection process during a game of One Switch Invaders.

(2) *Reduce consequences of errors, ensuring that errors due to difficulties completing rapid or time-sensitive actions do not impair fun.* While in One Switch Ladybugs there is no error penalty at all, in One Switch Invaders the players have three lives before they lose the game. Moreover, if a player misses the selection of an alien, she has more opportunities to kill it as its falling time is enough for allowing several clock hand revolutions before the alien touches the ground.
(3) *Limit available actions, reducing the number of decisions players need to make, and enabling a simpler control scheme.* The control scheme of GNomon-based games consists of just one action: to press the switch. The only decisions that the players have to make, besides *when* to press the switch for selecting the desired clock, are: which ladybug jumps in One Switch Ladybugs and which alien is better to eliminate in One Switch Invaders.
(4) *Remove the need for precise positioning and aiming, reducing the demands on manual ability and visual-motor integration.* This is part of the selection process itself. The player does not have to press the switch precisely when the clock hands are together for the interface to work. Moreover, if there is ambiguity between two or more elements, their associated clocks turn yellow to indicate it and the player gets another chance to select the desired element.
(5) *Make the game state visible, reducing the need for attention to gameplay, and reducing the need for visual spatial reasoning to deduce game state.* The information of which alien the player needs to select is loosely included in the gameplay: one of the aliens present in the lower part of the screen, near the surface of the planet. Therefore, the player needs to concentrate on the lower part of the screen, only. The specific alien to be selected is left to the player, to avoid reducing the fun of the gameplay. Moreover, when an alien reaches the ground, the player loses a life and the game background becomes temporary red, to give an immediate feedback on the new game state.

Here, we summarize the main recommendations made by the Local Health Agency experts regarding the prototype games, which were also taken into account during the design phase of the final versions:

- The appearance of each game object (ladybugs or aliens) must be unique. This helps the children to remember the game object that they are trying to select if they lose track of it.

For the ladybugs, this was achieved by assigning them four different colors and placing them in the four quadrants of the screen. However, in the case of the aliens this was not possible because there is not a predefined number of aliens that can be on the screen at the same time. Therefore, the solution adopted in the second game was to choose five colors to be sequentially assigned to each new alien. In this way, children who lose track of their game object can retrieve it without being confused with another close object with a similar look.

- Different game objects have to produce different visual and/or acoustical feedback when selected. This was easily achieved by changing the animations and sounds produced by different characters when selected (e.g., each ladybug jumps in a unique manner and produce a different sound).
- Although aliens could fall with different speeds, the maximum falling speed has to be bounded by a maximum value set by the player or a caregiver. However, for evaluation purposes, in this version all aliens fall at the same constant speed.
- In the One Switch Invaders game, at game start-up, the aliens await the first "click" before they start to fall down. In this way, the player can observe the clocks and familiarize with the speed of rotation of the clock hands before trying to select one of them.

5 PLAYABILITY STUDY

The Phase 3 of this research (Figure 1) consisted of the evaluation of the three GNomon-based mini games. In particular, this phase aims at answering the question of whether the developed GNomon-based video games are *playable* by children with severe motor disabilities, typically affected by cognitive disabilities too, that rely just on the use of single switches for interacting with electronic devices. Therefore, a study was conducted with 8 children, where six main properties of playability were assessed (based on the concept and characteristics of playability presented by González Sánchez *et al.* [20]):

(1) *Learnability:* How easy is it for children to understand and successfully start to play the GNomon-based games after they have been explained?
(2) *Effectiveness:* How much time and resources do children need while playing the GNomon-based games for achieving the various goals of the games?
(3) *Errors:* How many times, during the game, does it happen that the selected elements do not match with the element that the players wanted to select?
(4) *Satisfaction:* Do children like to play video games with a GNomon-based interface?
(5) *Memorability:* How easy are the games to remember after a substantial time-lapse between play sessions?
(6) *Fun:* How much fun do children have while playing GNomon-based games?

The study was divided in two sessions, with a one-month pause between them. The first session assessed all the playability properties except memorability. The second session, instead, mainly assessed the *memorability* of the games and reinforced the other properties by means of the additional data collected, with the exception of *learnability*. Learnability was evaluated only when the children learned for the first time how to play the games, namely in the first session. The methods and the rationale behind them are reported in the remainder of this section.

5.1 Methods

The two-session study was conducted in Italian with children between 4 and 14 years old with severe motor disabilities who consistently use one-switch interfaces as the main or only input device to interact with a computer. For the study, the three mini games were played in sequence, both with specific goals (i.e., tasks) and freely. After each game and at the end of each session, a short interview was performed to collect data for assessing the six main properties of playability. The sessions were carried out at the Health Agency facility, a familiar environment for the children, to avoid anxiety problems for some children.

A speech therapist (tester) held the sessions and two observers carefully took notes of the sessions. The choice to have a speech therapist to play the role of the tester was particularly important both to avoid making some children uncomfortable or anxious and to present information and questions in the most suitable way. Before the study, the speech therapist was carefully instructed and trained. Only two observers were present during the tests (one expert from the Health Agency and one HCI researcher), to prevent some children from being distracted and being uncomfortable in the presence of many people. Moreover, all the tests were video recorded hiding the children's faces, with the authorization of the children's parents, for further analysis.

The study did not undergo a formal ethical approval, since the formal approval was considered unnecessary by the board of the Local Health Agency facility, that discussed and officially approved the experimentation. However, ethical procedures were followed (as reported in the remainder of the section), e.g., parents were informed and gave consent for the participation of their children, children could stop the evaluation at any time, risks have been minimized, and privacy and confidentiality of the participants were considered and respected during the entire study.

5.1.1 Set-up and Materials. Each child played the games on a laptop connected to a 21" screen, operated with a Big Red 5-inch mechanical switch activated with the hand or with the head, depending on the capabilities of each child. The interface between the switch and a laptop was a Helpibox 16. In the case of non-verbal children, it was also necessary to use Alternative and Augmentative Communication (AAC) tables to allow them to answer the tester's questions; in particular these tables contained the colors of ladybugs, the yes/no answers and the faces to indicate "like" or "dislike". Table 1 summarizes the materials used for carrying out the study.

Table 1. Materials used for carrying out the study

Materials
Intel i7 laptop with 8GB of RAM running 64-bit Windows 7
21" VGA monitor
One Switch Demo game
One Switch Ladybugs game
One Switch Invaders game
Helpibox 16 interface
Big Red 5-inch switch
Logitech Orbit webcam with microphone
Adjustable school table
Alternative and Augmentative Communication (AAC) tables

5.1.2 Participants. The participants of this study were 8 children, 7 boys and 1 girl, with severe motor disabilities. All of them were between 4 and 14 years old and relied on the use of single switch interfaces to access electronic devices. P1 and P2 were the only children who activated the switch with their heads, while the others did it with their upper limbs. The severe motor impairments of the children had different causes, which in most cases entailed cognitive disabilities as well (as in the case of some children with cerebral palsy). In fact, with the exception of participants

P5 and P8 who were affected by spinal muscular atrophy (which did not compromise cognitive capabilities), the participants had a mental age between 3 and 5 years. Instead, P5 and P8 had mental ages that approximately matched their chronological age. Table 2 reports a detailed summary of the participants.

The recruitment of the participants was straightforward since the Health Agency proposed and contacted the children, and helped to fix the appointments for the study. The criteria for selecting the participants was that they had to be children who use a single switch as the main or only modality for accessing electronic devices. Participants were not paid or otherwise compensated for their participation.

Table 2. Participants with details about age, impairments, and diagnosis

Participant	Age (years)	Impairments	Diagnosis
P1	4	Non-verbal with spastic quadriplegia with dystonia	Cerebral Palsy
P2	4	Non-verbal with postural hypotonia	Aicardi-Goutières syndrome (AGS)
P3	4	Spastic quadriplegia, cognitive and communication difficulties	Cerebral Palsy
P4	6	Spastic quadriplegia, strabismus and cognitive difficulties	Cerebral Palsy
P5	7	Muscular dystrophy	Spinal Muscular Atrophy (SMA)
P6	7	Moderate cognitive difficulties	Down syndrome with right-side hemiparesis
P7	8	Cognitive, visual and coordination difficulties. Spastic quadriplegia.	Cerebral Palsy
P8	14	Muscular dystrophy	Spinal Muscular Atrophy (SMA)

Given the fact that the participants were children who have special communication needs due to their disabilities, it was not possible for the tester to conduct the study exactly in the same way for every child. Inevitably, for some children, the tester had to explain the requested tasks in more detail and to avoid asking open questions for the final questionnaire. Nevertheless, the results are completely acceptable as the contents of the information provided (and requested) by the tester to (and from) the participants was essentially the same. Only the explanations of the games were adapted to better suit the capabilities of each child.

5.1.3 Procedure. Each of the two sessions was conducted and video recorded at the Local Health Agency facility, in Turin, by a speech therapist with two observers: another therapist and a HCI researcher. Before each session, the parents of the selected children were informed by the team of caregivers of the Health Agency together with the researchers, who explained the aim of the evaluation, its procedure, and what will be done with its data. Then they were asked to sign an informed consent form regarding the study and privacy issues. The children could stop the study or withdraw from the evaluation at any moment.

The study was held in Italian and lasted between 7 and 18 minutes for the first session and between 8 and 15 minutes for the second session, depending on various factors such as the cognitive or visual difficulties of the children taking the test, their fatigue and how much they wanted to play each game. The sessions, although in a flexible way, were structured in three parts, one dedicated to each game:

(1) In the first part of the first session, the tester explained the scope of the One Switch Demo game (i.e., to make the ladybug jump) and how to accomplish it. The tester demonstrated twice the selection mechanism by making the ladybug jump. Then, the child tried to make the ladybug jump one time and could freely play for 2 minutes maximum.
(2) In the second part of the first session, the speech therapist presented the One Switch Ladybugs game to the child by saying that she could play in the same way as before, but explaining that this time it was necessary to identify which of the four ladybugs should jump and to focus on the clock next to it. As before, the tester gave demonstrations with two examples. Then, she asked the child to make a different ladybug jump following a standard sequence 1) green, 2) red, 3) yellow, and 4) blue. Finally, the child was asked to choose a ladybug to make it jump and to say it out loud (the non-verbal participants used an AAC table for this task) before selecting it. At the end of this part of the study, the child could play freely for 3 minutes maximum, if she wanted.
(3) The last part of each session, which consisted in playing the One Switch Invaders game, was carried out only with participants P5, P6, and P8. This part of the study was *not proposed* to the other participants because during the preparation of the evaluation phase, the experts considered that it would be above their cognitive or visual-attentive capabilities, and therefore no reliable results could be expected from them. However, when this part of the study was conducted, it followed a similar scheme: the objective of the game was explained to the child, then the tester demonstrated twice how to kill the aliens, and finally the child could play freely for 5 minutes maximum, if she wanted.

At the end of each part, three questions were asked to the participants:

(1) Did you like the game?
(2) Which aspect of the game did you like the most?
(3) Which aspect of the game did you not like?

At the end of the entire session, the children were also asked the following questions:

(1) Did you remember how to select the elements while you were playing?
(2) Was it difficult to select the elements?
(3) Did you have fun?

Although these questions were not neutral, they were chosen because they are simpler and more straightforward to reply to for the cognitive and communication capabilities of the participants. The tester was particularly careful not to push positive or negative responses in posing or explaining the questions.

One month after the first session, the children were asked to play the games again, but this time without any explanation or indication of what to do or how to do it. Before starting the second session, two questions were asked to the participants:

(1) Do you remember the game with the ladybugs and the clocks?
(2) Do you want to play it?

Before starting each game (but with the game already on screen) the participants were also asked:

(1) Do you remember *this* game?
(2) Do you know how to play *this* game?

Memorability, one of the main heuristics for usability [36], is especially important for children with cognitive impairments since they can be more subject to forgetting new information that they do not use frequently.

5.1.4 Measures. At the end of both the first and the second sessions, the recordings were carefully transcribed for further analysis, combined with the observation notes taken by the observers. From them, in particular, we extracted the number of games played and the session duration for each participants. Similarly, all the responses to the questionnaires were collected and analyzed.

Moreover, several data were logged from each session. More specifically, the logs collected information about the chosen rotation speed of the clocks, the falling speed of the aliens (in the One Switch Invaders game, only), the number of clicks performed and the time of each click, the selection of a ladybug in the One Switch Ladybugs game, and the final score in the One Switch Invaders game. From the log data, we calculated the error ratio for the One Switch Ladybugs game (i.e., the number of selections that were not the intended selection by the participant vs. the total number of selections) and the click effectiveness for the One Switch Demo game (i.e., the number of clicks that result in a selection vs. the total number of clicks).

All these measures were then used to assess the six playability properties.

5.1.5 Observations. Before discussing the obtained data, some general observations are presented, to provide contextual information useful for understanding the results and the subsequent discussion.

During the first session, there were minor difficulties while evaluating the games with the children mainly related to the children's mood. In general, the youngest children with cognitive and attention difficulties (P1 and P3) became tired by the end of the first game (i.e., the one with a single ladybug) and faced the rest of the study with unfavorable attitude. In particular, P1 (who is a non-verbal child) started to stare at the door when the tester asked him for the fourth (and last) time to select a ladybug during the second game, indicating that he wanted to leave the room. After that, P1 did not want to freely play the second game and he decided to stop the study. He agreed to reply to the final three questions, however. Similarly, P3 at the end of the second game, did not want to freely play as he wanted at the end of the first game. Nevertheless, the experts who regularly assist these children agreed that it was normal that they were tired after trying new experiences that require their attention and concentration.

Another slightly problematic situation happened at the first session with P2, a 4-years-old girl, as she was not being cooperative because she wanted her mother in the room. The tester and the observers decided to call in the mother to calm the child, before considering the possibility to withdraw her from the study. However, although the child calmed down, she was sometimes distracted by looking at her mother. It is to be noticed that the tester and the observers decided not to stop the session since (1) this behavior is quite typical for P2, according to the experts who weekly meet the child and who often call in the mother during their own therapy sessions, (2) when the child calmed down, the tester asked her whether she wanted to continue or not and the child replied "yes".

The second session ran more smoothly as it lasted less time (in average) and the children had the right amount of challenges but without being frustrated or tired. Moreover, given that the conditions were as similar as possible to those of the first session, the children found themselves in a more familiar environment: they knew the protocol, the researchers, and the procedure (i.e., playtime followed by some questions).

5.2 Results and Discussion

This section presents the data and information collected during the playability study, along with their analysis and the corresponding research findings. First, the qualitative observations made during the first and the second session of the study are presented and discussed; Tables 3, 4, and 5 summarize the collected quantitative measures. Later, the *learnability*, *effectiveness*, *errors*, *satisfaction*, *memorability*, and *fun* of the games are assessed thanks to the analysis of the aforementioned Tables and the video recordings of each session.

5.2.1 First session. The first session lasted on average 13.13 minutes (SD = 3.52) and all participants, except P7, played at least the first two games (One Switch Demo and One Switch Ladybugs). P7 could not make the single ladybug jump in the One Switch Demo because he was very distracted by watching the clock hand rotating or looking at the table, and given his lack of cooperation the tester decided to stop the study. On the other hand, P5, P6, and P8 were able to play satisfactorily all the games, including One Switch Invaders.

The error rate was higher in the case of children with cognitive or attention impairments than in the case of children with motor disabilities only. In particular, P3 and P4 were facilitated by hiding two of the four ladybugs in an initial phase. In such a way, the tester limited the visible options at the beginning of the free selection phase during the One Switch Ladybugs game, to help the children to concentrate on the ladybug they wanted. On the contrary, P5 and P8 made no errors when they tested all three mini games, and moreover they asked to play One Switch Invaders again but with a faster falling speed.

All participants with the exception of P1 answered that they enjoyed and had fun playing the mini games. However, the negative answer of P1 to the question *Did you have fun?* seems to be not completely reliable because it was at the end of the study when he was very tired, and it is in contrast with the notes taken by one of the observers, which reported that the participant was "continuously smiling" while he was playing.

The clock rotation speed may be set in an absolutely straightforward way, with a horizontal slider in the first screen of each game. However, the procedure to choose the most suitable value for each child was based on an "educated guess", according to the attentive and cognitive capabilities of each participant. The rotation speed of the clock hands, in fact, was initially determined by the tester on the basis of the previous knowledge that she had about each child. However, in one case, the rotation speed was modified after the first mini game. The rotation speed is expressed as an integer in the linear interval [1-20], where 1 represents a rotation period of 10 seconds and 20 represents a rotation period of 1 second. Determining the right rotation speed is a sensitive task, especially when the participants had attention difficulties, because setting a faster speed increases the difficulty of successfully selecting the intended ladybug, while a slower speed gave some participants enough time to be distracted and forget about the selection task. Typically, for first-time users, the tester selected a speed in the low end of the range (i.e., around 4-8) for children with cognitive impairments, while she choose a speed of around 10-12 for participants without cognitive difficulties. During the development and test phases of the games, expert users of GNomon without cognitive impairments tended to settle around a rotation speed of 15-17.

Table 3 summarizes information regarding the following aspects: the number of games actually played by each participant, the error ratio during the One Switch Ladybugs game (i.e., the number of selections that were not the intended selection by the participant vs. the total number of selections), clock hand rotation speed, overall duration of the session and the answer of each participant to the final question *Did you have fun?*. The error ratio has been computed only for the controlled part of the game; the lower the error ratio is, the better.

Table 3. First session details

Participant	Games played	Session duration	Error ratio	Rotation speed	Had fun?
P1	2	14 min	55%	5	No
P2	2	15 min	50%	7	Yes
P3	2	18 min	53%	8	Yes
P4	2	11 min	62%	6	Yes
P5	3	10 min	0%	10	Yes
P6	3	15 min	29%	8	Yes
P7	1	7 min	-	6	Yes
P8	3	15 min	0%	10	Yes

Table 4. One Switch Demo details

Participant	Click effectiveness	Number of “clicks”	Rotation speed
P1	56%	41	5
P2	78%	9	8
P3	68%	31	8
P4	80%	15	6
P5	100%	9	10
P6	56%	36	8
P7	56%	18	6
P8	100%	18	10

Finally, Table 4 focuses on the first mini game (One Switch Demo) and presents the click effectiveness (i.e., the number of clicks that result in a selection vs. the total number of clicks), the total number of times the button was pressed (number of “clicks”), and the rotation speed initially selected for each participant. For this game, we cannot compute an error ratio like for the One Switch Ladybugs since there is only one ladybug that can be selected. The higher the click effectiveness is, the better; the total number of “clicks” is different between each participants because they were allowed to play freely for maximum 2 minutes.

5.2.2 Second session. The main goal of the second session was to evaluate the *memorability* of the GNomon-based games, as well as to track the individual improvements for the other playability properties. This session was carried out with the same group of experts and in the same conditions of the previous session. Nevertheless, there was an unexpected problem, as participant P5 left the Local Health Agency facility, thus he could not take part in this session.

The second session lasted on average 10.86 minutes (SD = 1.86) and this time all participants were able to play the first two mini games (One Switch Demo and One Switch Ladybugs). The same participants who successfully played One Switch Invaders in the first session (P6 and P8) were the only ones who could play it during the second session.

Similarly to the previous results, the error rate during the second session was higher in the case of children with cognitive or attention impairments than in the case of children with motor disabilities only. This time all the children, with the exception of participant P6, reduced their error rate. In particular, participant P2 decreased her error rate from 50% to 33% and participant P7, who did not have an associated error rate for not being able to play One Switch Ladybugs during the first session, was able to play it getting an error rate of 55%, a result that is in line with the error ratio of the novice players in the first session.

During the second session there was no need to facilitate the tasks to any participant by hiding any of the ladybugs in the One Switch Ladybugs game, as it was the case in the first session with participants P3 and P4. Moreover, participants P1, P2, P4, P6, P7, and P8 played with a higher clock hand rotation speed than the one set for the first session. This resulted in a more engaging and fun game but somewhat influenced the error ratio, thus making it difficult to perform a comparison between the error ratios of the two sessions. Participant P3 played with the same speed in both sessions. Notably, participant P8 was able to score 17 points at One Switch Invaders with a rotation speed of 19 (almost the double of his first session's rotation speed).

Again, all the participants with the exception of P1 answered that they enjoyed and had fun playing with the mini games. However, this time the negative answer of P1 to the question *Did you have fun?* was in line with the attitude he showed while playing: he was very nervous and angry, and he took more time to complete the tasks in this session than he did in the first one.

Finally, the memorability of the GNomon-based games was better than expected: 5 children out of 7 answered affirmatively to the question "Do you remember the game with the ladybugs and the clocks?" and described correctly how they had to play the games. One of the participants (P7) answered that he remembered the games but he did not actually remember how to play them. Participants P6 and P8 who were the only children who played the third game (One Switch Invaders), remembered it very well and P8 described without hesitation not only how to eliminate the aliens but also a strategy to win the game: "you just have to eliminate the aliens as soon as they appear on the top, do not give them the chance to move".

Table 5 summarizes information regarding the following aspects evaluated during the second session of the tests: the number of games actually played by each participant, the error ratio in the One Switch Ladybugs game, clock hand rotation speed, overall duration of the session, the answer of each participant to the final question *Did you have fun?* and the answer of each participant to the question *Do you remember the game with the ladybugs and the clocks?*.

Table 5. Second session observations. P5 did not take part to this session.

Participant	Remembered?	Games played	Session duration	Error ratio	Rotation speed	Had fun?
P1	Yes	2	15 min	50%	8	No
P2	No	2	10 min	33%	10	Yes
P3	Yes	2	10 min	38%	8	Yes
P4	Yes	2	11 min	62%	6	Yes
P6	Yes	3	10 min	25%	10	Yes
P7	No	2	10 min	55%	8	Yes
P8	Yes	3	10 min	0%	19	Yes

5.2.3 Playability Assessment. From the results of the playability study, it is possible to give a positive answer to the research question of whether it is possible to make *playable* one-switch video games based on GNomon. The playability, assessed through the properties of *learnability*, *effectiveness*, *errors*, *satisfaction*, *memorability*, and *fun* of the GNomon-based games is adequate and promising. In particular, all the children who played the games learned and were able to use both the GNomon-based interface and the selection mechanism to play the games, and had fun.

Moreover, the participants who tried One Switch Invaders (3 out of 8) indicated that it was the funniest of the three video games, and that they had never played anything similar. At the end, participant P8 asked if he could have the One Switch Invaders game for playing it again at home.

The research findings regarding the playability properties are reported in detail below:

(1) *Learnability*

It took, on average, two activations of the switch for the children to understand the mechanism and to be able to consistently make the single ladybug jump (on the One Switch Demo game). There were cases (P5 and P8) in which the participants understood and were able to use the GNomon selection mechanism immediately, but in other cases (P7) it was unclear if the mechanism was even understood.

Two of the questions at the end of the first session helped us to determine if the selection mechanism was difficult to grasp: *Did you remember how to select the elements while you were playing?* and *Was it difficult to select the elements?*. Not all the children were able to answer the first question because it was very difficult for their cognitive and communicative skills, but all of them (of those who played at least two games during the session) agreed that it was not difficult to select the elements. Even P4 said that it was easy to select the single ladybug, but he emphasized that selecting one of four ladybugs was not an easy task. Moreover, the observers agreed that, in general, the children understood how the selection mechanism worked, even though some of them had trouble operating it by themselves.

The results presented here suggest that a game with a GNomon-based interface is learnable by children with severe motor disabilities, especially if they do not have additional cognitive or visual impairments.

(2) *Effectiveness*

The evidence suggests that using the GNomon-based mechanism is effective, since it was certainly possible for 7 out of the 8 participants to play and complete the tasks of the first session in less than 20 minutes, despite the high number of errors for half of them (discussed below).

Moreover, during the second session in which the participants were already familiar with GNomon, all of them were able to play satisfactorily (even participant P7, who could play only the first game during the first session).

(3) *Errors*

In the first session, the error ratio was 49.8% (SD = 12.4%) on average, excluding the two outlier cases (P5 and P8). This significant error ratio can be explained by the additional cognitive impairments that the participants had, with the exception of P5 and P8. In fact, those two outlier cases, which had a 0% error ratio, do not encounter the difficulties that some participants have to *plan* the movement, as both of them have latent periods of typically-developing children (i.e., the time elapsed between the movement command and the muscle movement).

However, it is worth noticing that during the second session, despite the increase in the rotation speed of the clocks, the average error ratio decreased to 43.8% (SD = 14.1%), excluding the outlier cases as before (i.e., they still have 0% error ratio).

The worst results, in first sessions, were obtained by children with cognitive and communicative difficulties (P1-P4), with error ratios equal or higher than 50%. Moreover, the same four participants did not play with the action-oriented game. Apparently, this is a problematic issue for the effectiveness of GNomon and its games. However, in the second session, the same four participants *lowered* their error ratios: among them, only P4 remained with an error ratio higher than 50%, without showing any improvement. The other three participants, instead, increased their performance, immediately after their first usage of GNomon. In particular, P3 maintained the same rotation speed during both sessions and lowered his error ratio by 15% (from 53% to 38%). P1 increased the rotation speed (from 5 to 8) but lowered his error ratio by 5% (from 55% to 50%). P2 increased the rotation speed of the clock hands, reaching the exact value of the two participants without any cognitive impairments (rotation speed of 10), and lowered her error ratio by 17%, reaching an excellent result. This a promising progression and may indicate that performance over time can be improved with training. However, further research needs to be conducted for verification.

(4) *Satisfaction* and *fun*

The children who were able to answer the question *What did you like the most?* in the first session (P5, P6 and P8) said that they liked how the ladybugs jump and also the ladybug moving around. For the One Switch Invaders game, they answered that they liked the falling aliens and to be able to kill them. These answers suggest that the dynamism of the games, in particular in the case of the last game (the only action-oriented game), was really appreciated by the players as something new that they were able to try. In the second session, participants P6 and P8 answered this same question by referring almost exclusively to the One Switch Invaders game.

Moreover, at the end of the second session, P8 (the oldest participant, a 14 years old boy) was very excited and wanted to talk more about the games: he explained better that One Switch Invaders gives him the *emotion* of having to score points knowing that he could lose at any time. He said "*In this game I do not know how many points I will score, while in the other games I can play I know that I can't fail and there is no emotion there*". He also recognized that many times the games he plays are those he can control, and are not necessarily the ones that he would be interested in. As an example he showed the researchers an online scanning-based game for making cakes in which he picks up ingredients and places them in predefined positions on the cake base. He explained: "*This game is ok but not like killing the aliens; however, I can play it and it is entertaining*". It is clear that games with dynamic mechanics facilitated by GNomon are not only satisfactory, but an exciting new alternative for children who cannot freely choose what they want to play, but are forced to play what they can operate with their single switch.

Finally, other children expressed their satisfaction while playing the games in diverse ways that were noticed by the observers. This is the case of participant P3, who yelled "*More, more*" when the tester announced to him that the time for freely playing One Switch Ladybugs, in the first session, was over. Similarly, participant P2 indicated through an AAC table that she wanted to continue playing the second game when the tester gave her the chance to stop due to her apparent lack of interest. P5 and P8 also asked, on their own initiative, if they could play more at the One Switch Invaders game after finishing the first session, which indicates that they enjoyed playing the game.

Consequently, it seems that engaging in the GNomon-based games was not only considered satisfactory but also fun by the children during the study. Moreover, the children who had the cognitive and visual capabilities to play an action-oriented game such as One Switch Invaders indicated that was the one they liked the most.

(5) *Memorability*

All but two participants (P2 and P7) answered that they remembered the games. However, the two participants who answered negatively to the questions related to the memorability of the games were the most distracted during the first session: P2 was constantly looking for her mother, ignoring sometimes what was happening around her; P7 was so distracted during the first session that the tester decided not to present him the second game (One Switch Ladybugs) and he only played the One Switch Demo game. Therefore, it is understandable that after one month they did not recall the GNomon mini games.

Nevertheless, in the second session, everyone was able to select the game elements using the clocks without any additional explanation or demonstration. This suggests that even if the specific games are not remembered, the operation of the GNomon selection is memorable.

6 SUITABILITY FOR PEDIATRIC REHABILITATION STUDY

In Phase 4 of this research (Figure 1), we conducted a second study to assess the suitability of the GNomon-based games as a useful tool in pediatric rehabilitation. The notion of rehabilitation, in the case of children and of the pediatric age in general, is different from rehabilitation for adults, where it aims at recovering a lost functionality. 'Rehabilitation for children' or 'pediatric rehabilitation,' instead, includes all the services delivered to minors, from infants to teenagers. It includes all the services required to foster social participation of the children, and not solely to specialized interventions [14]. Therefore, the goal of pediatric rehabilitation interventions is to alleviate the effects of impaired body structures and systems; or to foster the development of children's capacities and their participation in various activities.

Pediatric rehabilitation interventions cover different activities, ranging from the ones dedicated to physical movements to speech and languages exercises. Moreover, the therapies differ according to the specific impairment and diagnosis of the children. For a child with cerebral palsy, for example, physical therapy may help in developing coordination (e.g., hand-eye coordination), building strength, maintaining flexibility, improving posture, etc. This can be realized with physical exercises or through gaming: moving an object from one area to another to "win" something, sorting objects from the largest to the smallest, grabbing or pushing a portion of a toy to have some feedback, etc. Speech and language therapy, instead, focuses on word formation, pronunciation, listening, language and vocabulary development, word-object association, maintaining attention over time, etc. For non-verbal children, speech therapy may teach how to communicate with gestures, symbols, picture boards, and so on.

In this phase, the interest is mainly focused in answering the research question of whether the game mechanics and the control interfaces based on GNomon (more than the individual games themselves) are suitable to be exploited by the healthcare experts that work with our target children everyday, within their therapies, and for their rehabilitation goals.

6.1 Method

To answer the research question, a semi structured interview was conducted, in the form of a focus group with two speech therapists and a physiotherapist who already collaborated throughout the GNomon design and playability study. The three experts work on a periodic basis with children with severe motor disabilities, typically affected by cognitive disabilities too, that can only rely on the use of a single switch to interact with a computer. The focus group lasted 40 minutes and the audio was recorded for later analysis. Two HCI researchers participated in the interview: one as the moderator, proposing the questions and guiding the conversation, while the other carefully taking notes to be integrated with the recorded audio. The actual questions, the answers, and the conversations between participants and the moderator interventions were in Italian; afterward, all the material was translated into English. The issues discussed during the interview are the following:

- How important is it for children to play *action-oriented* video games?
- What other types of video games do children with severe motor disabilities play?
- What about non-digital games? Do children play them? Are these games “static”?
- For children with severe motor disabilities, what are the rehabilitative, educational or leisure benefits of playing action-oriented video games?
- For which kind of games are GNomon-based game mechanics suitable? What benefits can derive from playing GNomon-based games?
- What are the reasons for the errors made by the children while playing the GNomon-based games?
- Stemming from this experience, what would you change or improve about GNomon or about the games?

The focus group was fully transcribed and analyzed through inductive thematic analysis [10]. Two researchers were involved in this, while the coding was performed by one of them. The analysis started by categorizing the material at the sentence level through open codes. Initially, 27 open codes were used, later grouped in four broader themes.

6.2 Findings

The thematic analysis revealed four key themes: (1) usage of games in pediatric rehabilitation, (2) limitations and workarounds of current games, (3) GNomon usage for rehabilitation, (4) limitations and possible improvements of GNomon.

The four themes revealed by the thematic analysis are presented and discussed in the following. In excerpts, “M” identifies the moderator, while “E1”, “E2”, and “E3” represent the three experts involved in the focus group.

6.2.1 Usage of games in pediatric rehabilitation. Currently, children who can interact with a computer by means of a single switch play a lot during rehabilitative sessions. For them, video games are not just a pastime and playing is never wasted time. Playing with video games is a therapeutic resource. Their parents and school teachers do it rarely at home or school, and always with a clear objective.

In the rehabilitation sessions, the gaming moment is split between digital and non-digital games. The latter games are the most problematic: toys need to be adapted or a “facilitator” has to be present during the entire gameplay to ensure a smooth experience. Video games, instead, present less problems, but they are typically “static” and repetitive. Available computer games are mostly based on scanning so that children can play by themselves. In the last few years, some children started playing with tablets, even if not everyone is able to autonomously play the available games for these platforms. Children, however, do not play nor continue the rehabilitation process at home, as stated by **E3**: “there are some parents that have the time and disposition to play with them, but often what they do, with their best intentions of course, is to guide the hands to touch the tablet so the children are not independent in the game”.

During the focus group, action-oriented video games and their usage in rehabilitation with children were discussed. The healthcare assistants perceived this category of games as particularly important:

E1: “I think that action-oriented games allow children to have a transferred experience of movement… I am thinking that, especially for those kids that cannot move at all, the fact of being able to participate in a dynamic experience is something big! The possibility of accessing a video game through a PC or a tablet in which it is possible to regulate times, distances, and speeds is also a good attention exercise… like a training!”

Moreover, when the children see an action-oriented video game (maybe on the tablet), they always express the desire to play with it. However, very often, they are not able to "access" those games.

6.2.2 Limitations and workarounds of current games. The three healthcare experts commented about the limitations that they face, and the workarounds that they employ, with current videogames during the rehabilitation sessions.

First of all, children cannot play autonomously with most current videogames: they need a "facilitator" or a different version of the game, adapted to their needs and possibilities. In some cases, this prevents children from continuing rehabilitation or educational activities at home, and constrains the rehabilitative action to the weekly session with speech therapists and physiotherapists. For example, this is a workaround that a speech therapist uses when playing with a tablet game:

E1: "A way of playing is for example by "borrowing my finger": she [the child] sees where she want to go and indicates it with her gaze and I place my finger there [on the tablet screen]".

Another relevant aspect in this theme is that children's performance or success with specific games varies a lot according to the specific disability. Moreover, even considering a single child, her "gaming experience" is strongly related to the activities that she performed before the rehabilitation and to the specific game. For instance, one healthcare expert stated during the focus group:

E2: "For some children, when they are excited to do something new or fun, dyskinesia kicks in. That is why sometimes we have to restrain them to contain their involuntary movements".

Finally, while action-oriented games were considered useful by all the participants at the focus group, they do not employ them in their daily practice since they were not able to find any game fully playable by their assisted children. Most of the action-oriented games, as discussed in Section 2, require a *speed* and *precision* that these children often lack.

6.2.3 GNomon usage for rehabilitation. All three participants in the focus group said that GNomon has great potential for rehabilitation, education, and leisure activities. They recognized that the interface and the selection mechanism are useful for all the three target games.

In particular, GNomon can be useful for educational activities since it involves concepts like time, waiting, attention, etc. For leisure activities, it can allow children to play "without a goal," just for fun, a type of playtime that they do not experience, typically. GNomon may give the feeling that they are are playing games such as those played by their brothers or classmates. However, the available games need more personalization aspects (e.g., the possibility to choose the game character) for better engagement during free time.

Finally, for the rehabilitative aspects:

M: "What benefits exactly do you think GNomon fosters [for rehabilitation]?"

E2: "Well, it trains the children to maintain a selective attention and to hold it over time; it trains the visual scanning between various objects; it strengthens the hand-eye coordination; it supports the learning of concepts such as colors, numbers, letters, depending on the game topic; it supports and develops the autonomy to play, it teaches to wait and to respect time-outs."

6.2.4 Limitations and possible improvements of GNomon. Although the participants recognized great potential in GNomon, they also highlighted some limitations and suggested some enhancements, according to their professional experience and to their involvement in the playability study.

They attributed most of the high error ratio obtained during the previous study by the children with both severe cognitive and motor disabilities to their specific impairments. For them, the problem with every new experience is to understand what is behind it, according to a relatively simple pattern, like "see – wait – touch". There may be attentive difficulties, problems with hand-eye coordination, difficulties in containing emotions and movements, unexpected dyskinesias, etc.

E1: "These [the errors] depend on the condition of each children. For example *participant P8* had no errors at all, while *participant P1* is a kid that, when excited about something, cannot totally control his movements".

They were interested to understand whether these errors may decrease with practice, noticing that in the second session most children improved their performance in the games and with GNomon itself. They suggested "*to make a long-term study to track this*" and confirmed their availability to support such a study.

The experts recognized, however, that these errors are more present with GNomon than with scanning. They attributed the higher ease of use of scanning to the fact that scanning has less elements to "control":

E3: "But it is true that the less elements you have, the less problems. Each element can be a problem source, and maybe scanning has less elements than GNomon, but less flexibility… at the end you have to find a trade-off."

Finally, the participants suggested possible improvements for GNomon, especially concerning the widget (i.e., the clock). E2 pointed out a possible problem with the clock itself: planning the action for activating the switch by following the circular movement of the clock hands.

E2: "Maybe it could be useful to explore other graphical elements instead of the clocks as interface elements because some children found it difficult to wait for the clock hands to come together for activating the switch. Maybe something with colors or shapes, easier than the concept of 'clock' and rotation, and angular distance."

During the discussion, they envisioned two alternative concepts and widgets for GNomon:

- A horizontal bar, whose movement (i.e., horizontal filling) may be easier to comprehend than a circular movement.
- A ball that shrinks, grows, and changes color; the children could wait for the ball to grow and change to some defined color to activate the switch.

A suggestion of integrating the GNomon widget inside the game objects has been made, as well. E3 proposes:

E3: "Instead of being next to the game object, they [the widgets] should be inside or at least they should have the same graphical style that as element to which they are associated. During the study we noticed that the clock should draw more children attention, like the game character itself."

6.3 Discussion

The rehabilitation-suitability study suggests that GNomon-based games have the potential of being used within speech therapy, providing a positive response to the initial research question. The experts interviewed in the focus group considered that the kind of interaction supported by GNomon-based games is "very positive" and "valuable". In fact, the speech therapists wanted to extend the use of the GNomon games from the Local Health Agency to one of the children's hospitals in the city, not only for the kids' fun, but for developing and improving several skills within the therapy.

Obviously, GNomon is not able to remove most of the limitations and workarounds currently present in non-GNomon video games used for rehabilitation purposes. However, it should be considered as an additional option, allowing therapists to have more choices and, possibly, more control over the games which may open new possibilities and opportunities to improve the rehabilitative intervention. The possible adoption of GNomon for proposing video games that children can play autonomously, a behavior that currently does not happen with other games, is also interesting.

The research findings of this study are in line with previous findings in the field of game design for rehabilitative therapy. Moreover, the results of this suitability study suggest that GNomon-based games could be exploitable in speech therapy with children with cognitive impairments, or in brain injury (BI) therapy. It was found that the main pediatric rehabilitation aspects of GNomon-based games, identified in the focus group, finely address some of the main goals of BI therapy (according to [16]), such as attention/coordination, processing speed, hand-eye coordination, sequencing and command following, and visual spatial abilities, among others.

The main rehabilitative aspects for which GNomon-based games are suitable to be used in therapy with children with severe motor disabilities are summarized below. Such aspects may be further enhanced, if needed, in the design of novel GNomon-based games or by editing some characteristics of the GNomon way of interaction, like its widget.

(1) *Training the maintenance of selective attention over time:* Children have to maintain their concentration onto a single clock and wait for the adequate moment for making a successful selection with GNomon, ignoring distractions such as other game elements.
(2) *Training the visual scanning between various objects:* Children have to move their gaze to search for the elements they want to select, instead of just waiting for the elements to be automatically highlighted (as in the case of scanning interfaces).
(3) *Strengthening hand-eye coordination:* Children have to coordinate the moment of switch activation with what they are seeing on the screen. Moreover, they have to compensate for their own latent periods and plan the motion accordingly for a successful selection.
(4) *Learning to wait and to respect time-outs:* Children cannot activate the switch any time they want, if they want to successfully select a specific element. Thus, it is important that they wait until the right moment and that they learn to refrain from clicking it in the meantime.
(5) *Supporting the autonomy to play:* Children can play autonomously with the GNomon-based games, they can select the game menu options by themselves and can decide to play the games outside the therapy hours. Moreover, they can feel free to access point-and-click mechanics independently of their caregivers.
(6) *Supporting the interactive learning of concepts such as colors, numbers and letters:* GNomon supports the creation of many different games, with different goals, mechanics and aesthetics. This gives the caregivers the possibility of fully customizing the games that they use in therapy, with learning or rehabilitative objectives specific to each kid, instead of adapting the children's needs to the available options in the market.

The improvements to GNomon suggested during the focus group are an opportunity to enhance the gaming experience with GNomon and to solve some of the problems which arose during the playability study, like the relatively high error ratio obtained by children with both cognitive and motor disabilities. Section 8 briefly reports how some of these suggestions have already been exploited.

7 CRITICAL REFLECTIONS

This section presents the lessons learned during the entire process described in the paper, from the design phase of the GNomon framework to the evaluation phases. It aims at critically discussing the presented results, the encountered issues, and the possible limitations of both GNomon and the two studies.

After the two studies, GNomon – as a framework – can be considered suitable for realizing action-oriented games for single switch players. In particular, children with severe motor disabilities but without cognitive impairments can play the developed games immediately and with no issues. However, children with severe motor *and* cognitive disabilities may experience some difficulties with GNomon-based games. Such difficulties seem to be mitigated with a prolonged usage of the games. However, as outlined in this section and in Section 8, some "tweaks" may help with lowering these barriers.

7.1 Limitations of the studies

The main limitation of the playability study pertains to the selection of the participants, and to the high variability of the "performance" results.

Children were carefully selected in collaboration with the Local Health Agency to be consistent with the target population and around the same mental age: young single-switch users, i.e., children with *severe* motor disabilities, typically affected by cognitive disabilities too, who can only rely on the use of a single switch to interact with a computer. They present motor impairments, often accompanied by cognitive and communication difficulties, e.g., they can be non-verbal children. Even with this careful selection process, study results were highly variable, especially for what concerns the errors made and the numbers of played games. In fact, three children made more than 50% of errors in the first session of the playability study, while the other three children, only, were allowed to play with "One Switch Invaders", the only truly *action-oriented* game in the study. The tester and the experts involved in the study, in fact, decided to avoid proposing the third game to the other children after seeing their test duration and their fatigue. According to this choice, however, it is not known whether these children would have been able to play "One Switch Invaders" (and with which results).

To explain the different "performance" of the 8 participants involved in the playability study, notice that the children without any cognitive impairment made few or no errors in the games. Moreover, they were able to successfully play the third game. Conversely, the children with a higher degree of cognitive disability made most errors.

Given the target population, this fact was almost inevitable. In fact, the involved types of cognitive disabilities present multifactorial aspects and a difficult separation for levels of competencies and capabilities. It is virtually impossible to come up with a uniform population, taking into account the many differentiating impairment factors, the varying age, and the fact that (luckily) such users are a tiny percentage of the general population (the 8 selected children were practically the totality of children that matched the selection criteria, in the territory served by the Local Health Agency).

For example, even if just considering the children diagnosed with Cerebral Palsy (P1, P3, P4, and P7 of the playability study), there are different associated impairments: P1 is a non-verbal child with dystonia, P3 has spastic quadriplegia with cognitive and communicative difficulties, P4 has spastic quadriplegia with cognitive difficulties like P3 but without communicative problems, and P7 has cognitive, visual, and coordination difficulties associated with spastic quadriplegia. Moreover, some children can become excited when experimenting with something new; this joyous feeling may rouse dyskinesia and thus increase the number of errors or problems during an activity. This aspect was also highlighted by the experts involved in the focus group during the second study and it may explain why all children had fun with the games, independently from how many games they played.

However, it seems that a correlation between cognitive impairments and the error ratio exhibited in the GNomon-based games exists. Current and future works aim to discover what are the main causes of this problem in GNomon, and how to solve or minimize them. Section 8 presents some first efforts in this direction.

Finally, a possible limitation of both studies concerns the involved experts. From the beginning of this work, in fact, the team included almost the same experts within one Local Health Agency in Turin. They discussed some design choices of GNomon and its mini-games, some of them conducted the playability study, and they were the participants of the focus group in the second study. This made them quite proficient and "experts" of GNomon, but might have introduced a bias in the results since they were deeply involved in the work. The results of the studies, therefore, should be read with this consideration in mind. Probably, a replication of the playability study could further confirm the outcomes of the study.

7.2 Limitations of GNomon

The GNomon framework described in this article presents some limitations that impact the games realized with the framework itself. Such limitations may be problematic especially in action-oriented games, but most of them can be overcome or made less evident during the design phase of each game. Examples of action-oriented games that deal with and, in some cases, surpass these limitations may be found in Section 8.

Cluttering and immersion issues. The GNomon framework requires enhancing each game element with a dedicated widget (i.e., the clock) to let the player autonomously control the game. When many game elements are "GNomonized", the screen may become cluttered. Cluttering, moreover, is detrimental to immersion in the gameplay. Therefore, during the game design process, two strategies need to be considered to overcome or, at least, minimize these limitations:

- *Control elements* (e.g., the menu buttons) need to be organized in different screens and grouped by functions. With respect to non-GNomon games, this may entail a few more selections to reach an option but it helps in lowering the cluttering in the interface.
- *Game elements* (e.g., game characters) must be realized by considering this problem and to minimize the space used by the dedicated GNomon widgets. For example, the widget can be embedded *inside* the game element or it may *become* the game element itself. As emerged in the focus group and shown in the next Section, it is not mandatory for the GNomon widget to be a clock. Alternative, visually lighter, widget designs may be considered.

In other accessible games, based on scanning for example, these two limitations are absent since the mere highlighting of an element is visually much less obtrusive.

Issues with games not based on selection. Partially linked with the cluttering issue, the realization of video games whose objects are not prevalently selectable may constitute a limitation for the framework. In particular, if we consider those action-oriented games in which the player controls a character (e.g., instead of directly killing aliens falling from the sky), such as platformer games or escape games, we may notice that there is no "object" to attach the clock to. In this case, two strategies may help in minimizing or going over this issue:

- *Create a control pad.* If the player should move a character, a possible solution for this issue is to create a "control pad", maybe around the character itself, to allow its movement. Figure 18 (Section 8) shows an example of this strategy in a platformer game.
- *Find other selectable objects.* If the player should move a character, do not attach a GNomon widget to the character, but put it on the "target" elements. For example, the game designer can decide to put a GNomon widget at the end of each line in a platformer game to move the character in that direction. Figure 19 shows an example of this strategy in a multiplayer game.

These two strategies may be employed in the same way even if the player should shoot an enemy or jump over some obstacles. In adopting these solutions, however, particular attention must be paid to the "cluttering" issue.

Timing issues. After a successful selection, GNomon resets the probability model to be ready for the next selection. This reset affects the visual appearance of the widgets: with the clocks, it means that all the remaining clocks suddenly move their hands. This unpredictable movement may create additional difficulties for single switch players with cognitive impairments.

This limitation cannot be overcome since it is strongly connected with how the probabilistic model of GNomon (and NOMON before) works. However, the effect of this issue may be reduced in two complementary ways: a) by rendering the movement associated with the reset more smoothly, e.g., with an animation to slowly moving the clock hands; and b) by providing a "training" mode before the start of the effective game to prepare the player to this effect.

We have to state, however, that we do not have any empirical information about the relevance of this problem nor about the effects of the proposed solutions.

Overlapping widgets. In action-oriented games, it may happen that two GNomon-enhanced game elements are close. This may occur, for example, when a character "enhanced" with a control pad reaches a selectable game element (e.g., a game object to be picked up by the player). When this happens, the GNomon widgets of the two game elements may overlap. This must be avoided to preserve the playability of the game.

In this case, there are no generally valid recommendations to avoid the issue, but a proper game design needs to take into account the overlapping risk, and with a small reorganization of the widgets positions, these scenarios can be avoided in most cases.

7.3 Lessons learned

This section aims at summarizing some lessons learned during the realization of the GNomon framework and its mini-games, during the evaluation, and across the various discussions with the Local Health Agency members, other users and colleagues. Some of these lessons can be also considered as recommendations for researchers and game designers interested in realizing accessible games.

(1) Despite the interest around action-oriented games, both from a leisure [28] and from a rehabilitation point of view [43], very few games exist for children with severe motor disabilities. In particular, children with both cognitive and motor disabilities will benefit the most from these games since, for instance, such games represent a good attention exercise (see Section 6.2 for further details). However, such children are the ones with less access to this game category.
(2) In developing and evaluating games for children with severe disabilities, the real problem is to let them understand the game mechanics through a relatively simple pattern like "*see – wait – move*". Some children have attentive difficulties, others have problems in hand-eye coordination, for some there is a difficulty in containing their emotions and, consequently, their movements, etc. Each child is a world per se, which needs particular and dedicated attention.
(3) In developing games for this audience, it is extremely important to find a balance between the game features and its difficulty. Simple games or scanning-based games have less dynamic game mechanisms, are simpler, and permit fewer errors, but quickly become boring. Action-oriented games have the potential to be more fun and more engaging, but they present more difficulties and may generate more errors. It is important to accept this

challenge and properly balance these aspects, and avoid sacrificing the benefit of more engaging games to avoid errors and problems.

(4) Cognitive disabilities are varied and complex, even inside a specific diagnosis and within well-defined mental ages. Games need to be flexible, and must be tested extensively with this population, due to this great variability.
(5) Do not forget the "fun" part. A lot of available games for one-switch users are not fun (e.g., the "Cause/Effect games" presented in Section 2). Maybe they are useful and educational, but since they target children they should have a component of leisure and fun [51]. Game mechanics and gameplay of action-oriented games are typically well-suited to accomplish this goal.
(6) Give the *right* amount of feedback during a game. In particular for children with cognitive impairments, providing too much feedback during a game may be harmful since it may distract them. No feedback at all may cause the same problem. Similarly to the suggestions of Yuan *et al.* [51], focus on the various types of feedback (visual, vocal, sound, etc.) and exploit them properly and consistently during the entire game.

8 CURRENT AND FUTURE DIRECTIONS

This research opens new lines of work at the intersection between the worlds of video games and accessible technologies.

One of the directions, which has been identified in the focus group (Section 6.2), is the study of new alternative widgets to replace the clocks for improving the performance of players with cognitive difficulties. A first result of this study has been presented by Aced López *et al.* [3], where bars- and balls-based widgets were compared with the default clock (these new widgets are shown in Figures 15 and 16). The initial results of the evaluation of these widgets show that they require fewer cognitive efforts to be understood, and that children prefer the ball widget. The error rates between bars and balls are comparable.

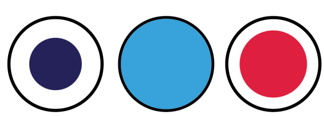

Fig. 15. From left to right: normal ball widget, normal ball widget with reinforcement (i.e., it is time to "click"), and highlighted ball widget (i.e., there is ambiguity between two or more elements).

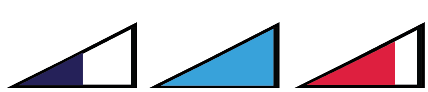

Fig. 16. From left to right: normal bar widget, normal bar widget with reinforcement (i.e., it is time to "click"), and highlighted bar widget (i.e., there is ambiguity between two or more elements).

Moreover, a recent collaboration with the Psychology Department of the University of Torino enabled a new investigation of accessible *multiplayer* games based on GNomon. In this case, the aim is fostering the social inclusion of children with disabilities by allowing them to play and have fun with their typically developing peers. In Section 8.1, a first outcome of such a collaboration will be briefly presented, and in particular the new action-oriented GNomon-based games that were jointly designed.

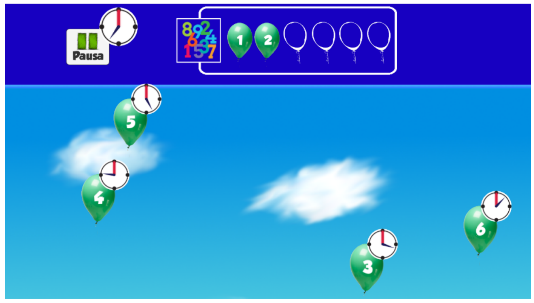

Fig. 17. The educational *Balloons* game in the "numbers" mode.

Other researchers may benefit from the findings, lesson learned, and recommendations presented in this article, as these can be generalized and taken into account for the creation of many kinds of applications for children with severe motor disabilities. Moreover, the GNomon software framework will be released as open source code, including the three GNomon-based mini games. Such games are already publicly and freely available to download at http://elite.polito.it/gnomon-games. This will allow anyone interested in the field of accessible computing to create new one-switch video games and to explore one-switch interaction capabilities with persons with different types of disabilities. Similarly, the games can be downloaded by therapists interested in integrating video games as part of educational or rehabilitative therapies, or simply by anyone who wants to have some fun.

8.1 Other GNomon-based games

This section briefly introduces three *action-oriented* GNomon-based video games. These three games are currently *under development* and they are *not yet evaluated* with children. Consequently, no results or structured insights can be derived from them.

One game focuses on educational aspects, by including educationally-relevant mini-games. The other two, instead, aim at enhancing social inclusion of children with disabilities, by offering multiplayer and multi-input features. The basic idea is that one child uses the single switch (with GNomon), while the other child exploits the keyboard and/or the mouse to play together.

Balloons. This is an educational "multi-game". The goal in the video game is to obtain the maximum score by popping balloons according to the different modes presented in the game. Four modes are currently present in *Balloons*: numbers, colors, words, and dimensions. Each mode has its own objective. For instance, in the "numbers" mode, the player must pop the balloons in ascending numerical order. Similarly, in the "dimensions" mode, the player must pop the balloons in increasing or decreasing order of size. Each mode includes several levels of increasing difficulty.

A screenshot of the game, in the "numbers" mode, is shown in Figure 17. In the game, the balloons float freely in the screen (i.e., they are not fixed in a pre-determined position), bouncing around, thus presenting some dynamism. The game is localized in Italian and it employs GNomon both for controlling the menu and for the actual play, with the possibility to choose which GNomon widget to use. In higher levels of the game, time constraints towards the completion of the level can be added.

The Monster Maze. This is a platformer game, to be played by two children: one player uses the single switch (with GNomon), while the other plays through the arrow keys on a keyboard. During the game, the two players will find themselves inside various mazes. Each player controls and is

Fig. 18. *The Monster Maze* multiplayer game (at level 17). The purple monster is controlled with GNomon, while the green one with the keyboard.

represented by a game character (a monster). The goal of the game is to move the monster so that it can reach a "button" located in a certain point of the maze. Each monster has its own button to reach, and the button has the same color of the character. To reach the button, each monster should overcome some obstacles. Each monster can move in any direction, but will always move until it finds an obstacle, therefore the paths must be planned carefully. The two players may move freely, independently, and do not need to take turns.

The main characteristic of the game is the *collaborative* component. In the game, in fact, the children must play together to win. The players must agree on the movements of each character and, in some cases, elaborate various strategies to complete the level. Currently, 60 levels have been realized, each with its own difficulties, prizes, and obstacles. Some of them are impossible to win without close collaboration of the two monsters. Each level also includes some items (prizes) to collect: depending on the number of collected items, the completion of a level may have a score ranging from one to three stars.

Figure 18 shows a screenshot of the game at level 17. The level has three prizes to be collected (i.e., the three bananas) and two obstacles represented by the "double arrows" (i.e., two conveyor belts, which immediately move a character in the direction indicated by the arrows). The game is localized in Italian and it employs GNomon both for controlling the menu and for the actual play of one of the players, with the possibility to choose which GNomon widget to use.

El GNomo Loco. This is another multiplayer game, developed by one of the authors during a Game Jam in 2015. Similarly to the previous game, *El GNomo Loco* allows collaborative play between children with severe motor disabilities and their typically developing friends.

The two players access the game differently according to their abilities: the controls are standard (keyboard or mouse) for one player, while the other uses the single switch with GNomon. Both players have to collaborate to kill as many aliens as possible, while driving a shared car through a series of randomly generated platforms. One player drives, and the other shoots. However, they have to be careful because the roles can change in the middle of the game (if they step on special platforms): the driver becomes the shooter, and viceversa.

The game is capable of adapting to the different types of interaction according to the current role of each player. In particular, when the player with severe motor disabilities is driving, she can select the next platform where she wants to jump through an associated GNomon clock. On the other hand, the teammate shoots the aliens by using the standard controls (keyboard or mouse).

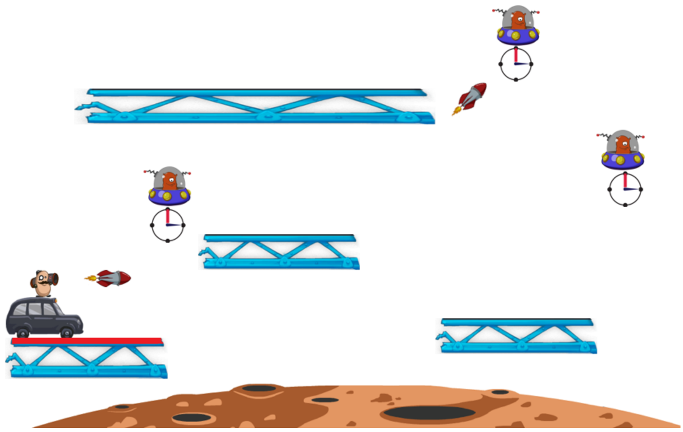

Fig. 19. *El GNomo loco* multiplayer game. The single switch player is in charge to kill the aliens, while the car is controlled by the other player by means of the keyboard.

Differently from the previous game, the GNomon widgets are not "attached" to the car, but are located on the destination platforms.

When the roles of the two players are inverted, the platforms are not longer selectable with GNomon, but reachable by using the keyboard. The aliens, instead, can be eliminated by selecting the GNomon clock associated to them.

The game is depicted in Figure 19. In the screenshot, the single switch player is in charge of shooting the aliens, while the other player controls the car.

9 CONCLUSION

This paper presents the results of a comprehensive research study conducted in close collaboration with a team of speech therapists, physiotherapists, and psychologists from a Local Health Agency in Turin, Italy. Two studies were carried out, aiming at investigating two hypotheses: that it is possible to develop action-oriented video games playable by children who can only use a single switch for operating a computer, and that such games are valuable as educational and rehabilitation instruments.

For tackling this complex challenge the authors developed GNomon, a software framework to enable the creation of action-oriented one-switch video games. The playability of three GNomon-based games has been evaluated with a group of 8 children with severe motor disabilities, typically affected by cognitive disabilities, too. At the end of the playability evaluation, a focus group with the experts of the Local Health Agency assessed the educational and rehabilitative value of the video games.

The results of this work are encouraging and demonstrate that, in fact, it seems possible to develop action-oriented single switch video games playable by children with severe motor disabilities and typically affected by cognitive disabilities. Out of the 8 participants, 7 of them expressed that they had fun playing the GNomon-based mini games, and all of them were able to play One Switch Demo and One Switch Ladybugs autonomously, after two sessions. Three participants also played One Switch Invaders and expressed that it was the game they liked the most. Moreover, two of them wanted to continue playing it after the first study.

Likewise, the potential of GNomon for making educational and/or rehabilitative games emerges from a focus group carried out during the second study. All the experts agreed on the novelty of the interaction but also recognized useful principles that can be exploited to train aspects such as hand-eye coordination, maintenance of selective attention over time and support of autonomous play.

Finally, a critical reflection with the lessons learned as well as some other examples of GNomon-based games are reported, to inform the work of other researchers and accessibility game designers.

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