An Affordable Wearable Immersive Virtual Reality Framework for Children with Neurodevelopmental Disorder

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Abstract

This work presents the design and evaluation of Wildcard, a novel affordable WIVR framework designed and evaluated in cooperation with specialists in Neurodevelopmental Disorders (NDDs), and explores the potential of Wearable Immersive Virtual Reality (WIVR) as a learning tool for children with disability, particularly those with NDDs. In Wildcard, virtual environments are displayed on a smartphone placed inside a commercial low-cost VR viewer and, while children interact within the virtual world through gaze focus and direction, the system automatically tracks their attention levels. Two studies performed at a care center shed a light on the behaviors of children with NDDs in wearable immersive virtual reality environments and show the learning potential and portability of this framework.

Introduction

Wearable Immersive Virtual Reality (WIVR) enables users to experience 3D virtual spaces using Head Mounted Displays (HMDs) while having the impression of "being physically in". Although this technology has been around for some time, its popularity is a recent phenomenon, mostly triggered by the relatively low cost of many HMDs available on the market and by advances in virtual reality development tools, opening new opportunities to create and experiment with new WIVR applications in different domains. Our research explores the use of WIVR as a learning framework for children with disability, particularly with NDD. NDD is a group of conditions with onset in the developmental period characterized by often severe deficits in the cognitive, communicative, emotional, and motor areas, producing severe impairments of personal, social, academic, or occupational functioning. ID (Intellectual Disability), ADHD (Attention Deficit Hyperactivity Disorder), Down Syndrome, and ASD (Autistic Spectrum Disorder) are all classified as forms of NDD [2]. WIVR applications for this target group are very few, and empirical evaluations are limited and offer only preliminary results. Little is known about how this technology works for children with NDD and how WIVR applications can be designed for these persons.

This work offers several contributions. The first section surveys the literature and gives a comprehensive overview of virtual reality technologies for subjects with NDD, explaining the relevant issues in this field. We then describe a novel WIVR framework named Wildcard that aims at complementing traditional educational interventions, facilitating therapists in the creation of the activities, and addressing the attentional skills of NDD children. In Wildcard, virtual environments are displayed on a smartphone placed inside a commercial low-cost VR viewer and, while children interact within the virtual world through gaze focus and direction, the system automatically tracks their attention levels. Wildcard has evolved through progressive prototypes, co-designed with 10 NDD specialists. Two studies have been performed at a therapeutic center involving 16 children with NDD and 10 therapists in total, over a period of 4 months. An exploratory study analyzed the acceptability of WIVR and the usability of Wildcard, followed by an evaluative study that investigated the potential of Wildcard in promoting attention skills – an aspect that, to our knowledge, has never been addressed by prior studies in WIVR. The results shed light on the benefits and drawbacks of using WIVR with children on the NDD spectrum. The lessons learned from this research improve our understanding of how these children behave when they experience WIVR, and suggest the need for further research, with the possibility of eventual adoption of WIVR in home settings.

Related Work

Several studies highlight the potential of interactive technologies for children with NDD, and the importance of introducing them in regular educational or therapeutic practices at school or care centers [1][11][15][17][30]. Most subjects with NDD are visual learners and many traditional learning approaches use visual (often paper-based) supports [12][18]. VR contents are centered on visual representations and therefore capitalize on these visual skills [27]. In addition, the action-feedback mechanism of interactivity enforces simple cause-effect understanding and promotes a sense of purpose and active control over the stimulation. In VR environments, behaviors and responses can be practiced in a safe and repeatable environment and built-upon in a visual context that shares some similarities with the real world. Immersion induces the feeling of being in the environment - a concept referred to as "presence". Presence is thought to stimulate imagination and to promote generalization [25][26]. Inside the immersive digital space, the user is required to build and process a representation of the virtual environment "as a location" to successfully navigate it while, outside the virtual experience, the user is expected to capitalize on this construct, linking the representation of the virtual environment to the real world and therefore generalizing some skills learned in the virtual space [3][14]. According to some studies, presence is also perceived by subjects with NDD and would bring similar benefits. As an example, in a controlled study by Strickland et al. [28] ASD children used an immersive system to learn fire safety skills and manifested similar levels of presence as a typically developing group. Other authors found a positive correlation between presence and social, practical and real-life skills (e.g. crossing the road [16]) in low-medium functioning ASD children [5][8][13][29].

As the HMD removes the distractions of the outside world it maximizes the immersion effect [9] and therefore, in principle, would improve the learning potential of these technologies especially for children with NDD, who often have severe attention deficits. In the past, the technological weaknesses of first generation VR headsets (e.g., poor viewing angles, high latency, and weight) and their high cost prevented the adoption of WIVR in educational programs for children with NDD. The study performed by Strickland et al. in 1996 [27] described the HMD as "heavy and awkward"; eventually the children accepted it, but manifested dizziness and eye fatigue during the experience. HMDs today are more comfortable and some of them (e.g., Samsung Gear VR and Google Cardboard) are commercially available at an affordable cost, triggering an increasing attention to WIVR by research and industry. In the educational arena, "immersive" learning has been introduced as a mean to keep the learners active and engaged and to convey knowledge that might be hard to grasp through conventional media [6][10][19][29].

Few studies to date investigate the use of new WIVR devices among subjects with NDD. Most of these studies explore the questions raised by Strickland et al. [27] surrounding acceptability and willingness to engage with VR viewers [9][21] but only few of them further analyze learning outcomes.

Co-design and Research

The design process included 10 NDD specialists (1 neuropsychiatric doctor, 7 special educators, 1 speech therapist, 1 psycho-motor therapist) from a care center specialized in children with NDD. Initially, the developer participated as an observer during 10 regular learning sessions at the care center. Observing children's activities in their normal context enabled the developer to understand what happens in the real-life context and where the opportunity lies for WIVR technology. During follow-up workshops, the specialists were familiarized with WIVR technology, trying Google Cardboard and interacting with VR contents (360° videos) retrieved from the web, to identify together the main learning goals that this technology can address. We agreed to design WIVR experiences that promote not only cause-effect understanding and sense of agency as in most interactive applications, but also, and mainly, attention skills, a prerequisite in many real-life situations. Considering the attention impairments of children with NDD and their difficulty of staying focused on an assigned task, we hoped to capitalize on the capability of WIVR to isolate the child from external visual stimuli.

After a broad overview of low-cost viewers, the specialists opted for Google Cardboard because it is available in different shapes, colors, and materials (plastic or cardboard), so that they can select one which is appropriate for each child. Educators also asked to be always in control of the activity by seeing the same contents the child was looking at so to be able to intervene, providing real-time suggestions and feedback as well as maintaining the child's link to the real world. The specialists also suggested that we create virtual worlds that evoke the visual contents of story books used in regular interventions, because familiar contents could mitigate the potential distress that unpredictability and the unknown often causes. The specialists provided 2 storybooks ("Suzy and The Wave" and "Giulio the Rabbit") that they used weekly as learning material. Both books have a simple plot, a clear distinction between the main character and the subsidiary elements, and appropriate graphics (simple shapes, clear lines and colors). For each storybook, Wildcard offers three interaction modalities: Story360, Research360 and Exploration.

- *Story 360*. Story360 task take places in a 3D virtual environment populated with the pictures of the main character from the book, alongside 6 other elements of the story. The goal is to explore the space "together with" the main character and "collect" the items encountered along the way. The main character is initially placed at the center of the user's field of view while the other elements are distributed in the entire 360° environment at equal distance from one another. When the child focuses her gaze on the main character, the character starts moving forward, making the user feel like she is dragging the character. When the child loses the focus, the character stops walking.
- *Research360*. In Research360, three items are randomly positioned in the 360° world. The child, by following the directions of her therapist, has to find and collect the items. Each item fades out when the child focuses for at least 3 seconds. Unlike the Story360 mode there is no protagonist to look at. Therapist predefines the order of the objects to collect so the system can automatically track and fade the right items at the right times.
- *Exploration*. In the exploration task, the virtual environment is shaped as a zig-zag 3D path (hereinafter referred to as "labyrinth") that requires several changes of gaze direction to be traversed. The goal is to reach the "exit" of this non-linear space. Images related to a theme are placed on the labyrinth walls close to the turning points indicating the direction to follow. If the child stops looking at the image, she stops moving in the virtual space until her gaze focus returns to the image.

Figure 1. From left to right: WIVR technology, Unfolded view of *Story360*, Unfolded view of *Research360*, Top and inside view of *Exploration*

Study 1 - Exploratory study

The exploratory study was devoted to gain an initial understanding of the acceptability and usability of the viewer, and to uncover any problems that may limit the adoption of this technology in therapeutic or educational contexts. We operationalized acceptability in terms of the main parameters adopted in the current literature on WIVR for subjects with NDD (e.g., [27][21]): children's willingness to use the visor, motion-sickness, double vision and digital eye strain [24]. The usability of Wildcard was measured in terms of "task accomplishment" (number of completed tasks) and "support from caregiver" (number of times the caregiver provided prompts, i.e., helped the child to interact and to move body or head properly).

Participants. For this exploratory nature of this first study we included children with different levels of skills and functional levels, help us understand how subjects with different capabilities would respond to the use of WIVR.

ID	Age	Diagnosis
C1	6	ASD (Autism Spectrum Disorder)
C2	7	ASD
C3	8	ASD
C4	10	SLD (Specific Learning Disorder)
C5	8	Motor disorder

Table 1. Study 1 - Participants' profile.

Figure 2. Moments during the exploratory study.

ID	Age	Diagnosis
C1	8	ASD (Autism Spectrum Disorder)
C2	7	ASD
C3	7	Sotos Syndrome / Intellectual Disorder (ID)
C4	9	Motor Disorder
C5	9	SLD (Specific Learning Disorder)
C6	7	ADHD (Attention Deficit Hyperactivity Disorder)
C7	9	ASD
C8	7	Motor Disorder
C9	6	Communication Disorder
C10	8	Down Syndrome + Intellectual Disorder
C11	10	Psychomotor Disorder

Table 2. Study 2 - Participants' profile

The study involved 5 young boys with NDD and their 4 therapists (Table 1). The children were aged 6-10 and attended the center on a regular basis. According to the preliminary medical assessment, they had mild or moderate severity level and intellectual functioning level. The evaluation took place in the room at the care center which is normally used for game-based activities, which was well-known to the participants and associated with pleasant experiences. The room setting remained the same for the entire period of the study. The child was sitting on a rotating chair with the caregiver sitting aside. A video camera was placed on the wall that recorded the child's movements, the external display, and therapist's interventions.

At the beginning of each session PCSs (Picture Communication Symbols) [12] were used to introduce the experience with Wildcard to the child by showing a sheet containing the visual instructions of the task that will be performed during the session. The two books that inspired Wildcard contents were shown to the child inviting her to choose the character he liked most and the activity was presented as a new game. All children used Wildcard in 2 individual sessions, once per week. Each session lasted for approximately 7 minutes. In each session, the child was asked to experience Story360 tasks first and to continue with Exploration. Caregivers asked frequent questions, to learn if the child was understanding what she was requested to do and how she felt, monitoring whether she was experiencing tiredness, distress, motion-sickness, double vision or digital eye strain.

The data about acceptability and "support from caregiver" were extracted from the video analysis performed by therapists who knew the children and attended the workshops but did not participate in the sessions. The coding scheme was defined according to the definition of these variables: willingness to use the visor, motion-sickness, double vision, digital eye strain, and prompts. The information about all the other variables were extracted from the interaction logs. Concerning acceptability, C1 and C2 had an initial resistance to wear the visor, but only in the first session. They accepted it after the therapists wore it, invited them to manipulate it, and showed to the child what he could see inside. C3 was immediately attracted and excited at using the viewer. C4 and C5 did not express any concern at all. Concerning usability, the comparison of the number of prompts in the 2 sessions showed a reduction of the need for therapist's support in the second session.

Study 2 - Evaluation Study

Study 2 involved a wider number of children (11) and 5 therapists for a longer period (2 months). The goal of the study was twofold: i) to evaluate acceptability, and understand whether some improvements identified in Study 1 (described below) mitigated the acceptability problems; ii) to investigate the learning processes that took place during a relatively prolonged use of Wildcard. We recruited 11 medium-low functioning children that had not been engaged in the pilot study, had never used an HMD before, who attended the center once a week, for 1.5 hours. Out of the 11 children, 9 were males, 2 females, all aged 6-10 years.

In response to Study 1, therapists decided to setup a preliminary two-weeks phase in which Study 2 participants experienced a "familiarization" period: they started getting used to the VR viewer by hand-crafting and wearing cardboard-based masks in a playful setting. Then, they invented a game where children had to point with a torch light book-based images on the walls of a dark room to exercise immersion and attention focus. Moreover, they created their own activities, still based on their storybooks, using a simple web-based authoring tool developed for them.

The setting of the room remained the same as in Study 1 for the whole period of the experimentation. Children used Wildcard along a 2-months period participating in average to 5 individual sessions. Each session lasted approximately 9 minutes, although the average time the children wore the device in a session was 5 minutes. In order to evaluate research goals from automatic logs we structured our research variables into: *Performance variables* - measuring how satisfactorily the child completes a specific task divided in Productivity (Prod) and Accomplishment Time (AT) - and *Attention variables* – analyzing the attention switch events using two variables: #FC and SA.

- #FC: Number of Focus Changes, the event where the eyesight diverges from an object of interest to a non-relevant item and vice versa. #FC is the sum of all those attention-switch events.
- SA: Sustained Attention: the percentage of the summation of all "attentive" periods within the total gameplay time (AT). Sustained attention is a relevant measure but may hide the number of Focus Changes, so it is critical to consider both of them while analyzing the data.

Table 3 summarizes the definition of the research variables introduced earlier and shows which activity each variable applies to.

Domain	Variable	Definition	Story360	Research360	Exploration
Performance	Prod	$\sum completed\ activities / \sum sessions$	×	×	×
Performance	AT	actual time of "gameplay"	✓	✓	✓
Attention	#FC	sum of attention-switch events	✓	✓	×
Attention	SA	$\sum t_1 / AT * 100$	✓	×	×

Table 3. Research variables and the interaction modes [✓=the variable applies, ×=the variable does not apply]

Results and discussion

The data gathered automatically, along with therapists' notes and focus groups resulted in a wide set of observations and empirical results. Quantitative data are shown in the following tables. For each activity, we analyzed only those children that performed at least 3 sessions with that activity, and in at least 2 consecutive sessions, so that we could be confident the child had a chance to be familiar with the activity. In the following tables, dark grey boxes mean the child was absent and light grey ones refer to children who were present but did not play with that activity in that session.

AT	S1	S2	S3	S4	S5	S6	S7	S8	#FC	S1	S2	S3	S4	S5	S6	S7	S8	SA	S1	S2	S3	S4	S5	S6	S7	S8
C2	549	204	151		87	83		103	C2	172	47	35		17	17		40	C2	35%	70%	86%		87%	88%		78%
C5				136	117			108	C5				57	37			28	C5				62%	60%			65%
C6				229	234	170		137	C6				45	61	47		54	C6				52%	33%	57%		54%
C8				112	119			128	C8				22	48			42	C8				70%	71%			66%
C9			280		148	181		146	C9			73	43	25	51		50	C9			49%	50%	53%	51%		62%

Table 4. Story360 Results – from left to right: Accomplishment Time (AT), Focus Change Number (#FC), Sustained Attention (SA)

In *Story360*, all children show a marked improvement in SA and inversely in reducing AT. Both C2 and C8 drastically bettered their attention in S6 compared to the first sessions but, after 2 weeks (S7 is null), they were less concentrated (SA). Logs clarify that C8 improved a lot in Session 8 too accounting for 83% of SA in the first half of the activity but then drastically reduced her attention in the second half (32%). By carefully analyzing logs we also found that C6, who decreased his SA in S5, focused less on the protagonist but 4 times more on protagonist-related objects which should be considered for future variables definition.

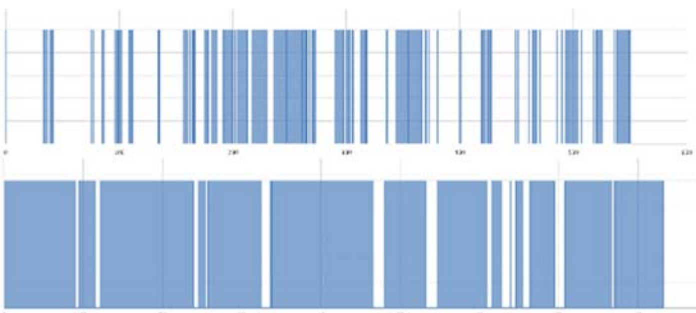
R360 AT	S1	S2	S3	S4	S5	S6	S7	S8
C2	174	88	58		69	70		71
C4			49	45	76	88		
C5				83	69	61		
C6			94	99	100	71		105
C8			157	79	71			57
C10		137	226	163				148
C11		156	86	62	59			104

R360 #FC	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**
C2	93	37	31		27	32		40
C4			19	25	34	49		
C5				29	31	31		
C6			49	40	62	18		57
C8			82	30	32			27
C10		93	188	99				95
C11		65	56	20	33			68

AT	S1	S2	S3	S4	S5	S6	S7	S8
C1			199	142		200		145
C2			273		116	133		122
C3			212	133				128
C4			261	115				135
C5			171	136	127	127		118
C6			383		202	519		298
C7			430	159				169
C8			251	139	277			142
C9			744		223	269		159
C10				442	183			313
C11		329	175	259				193

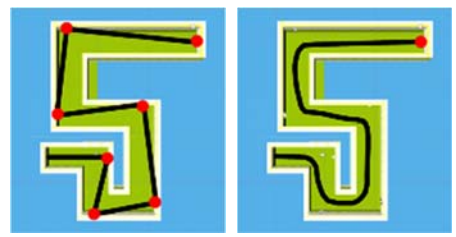
Table 5. Research360 - Accomplishment Time (AT), Focus Change Number (#FC) and Exploration - Accomplishment Time (AT)

Seven children had adequate experience with *Research360.* All children bettered their performance by decreasing their previous AT in most sessions. In S3 of C10 we found that she decided to remove the visor for 40 seconds due to eyesight difficulties. From S4 we solved the problem by adjusting the lenses distance and C10 kept his improvement session by session. In *Exploration*, all children who met the usage requirement demonstrated a sharp decrease in the AT of the Exploration activity through the 8 sessions with an average of 30% improvement between their first and their last session. Due to space constraints, we are not able to show detailed results for each child, but we'd like to show the potential of the framework by showing the detailed graphs of *Story360* attention levels, and the *Exploration* progression pattern for C2, who attended most of the sessions (Figure 3).



C2 is frequently changing focus between the main character and the background ending the activity in about 500 seconds.

C2 is sustaining her attention for most of the time taking around 90 seconds.



Left: the child is hitting the walls at every checkpoint. Right: she is anticipating the maze's turns.

Figure 3. *Story360* attention spans during Session 1 and Session 6 (left). Progression pattern evolution in *Exploration* (right).

As shown in Figure 6, with time, this child started to learn how to move in the maze and looked around the corner to next image, advancing directly towards the next checkpoint without hitting the wall, thus not generating any collisions.

Conclusions and Future work

The promise of Wildcard is to provide a cheap, portable means of experiencing and interacting with immersive virtual environments to exercise some learning goals. The very preliminary results of our evaluations suggest that this promise may become a reality, but they must be taken with caution. As often happens in empirical studies involving subjects with NDD, due to the small size of our sample, the heterogeneous impairments of the subjects, we used a single-subject design to assess individual improvements. The performance and attention variables we analyzed improved for all children, in different degrees. Improvements were small but promising, considering that the experience in the immersive virtual world was very short and the duration of each task, from the first moment to task completion, was in the range of 2 to 5 minutes. In NDD clinical research, micro-behaviors detected in very short times are considered as fundamental indicators of the basic cognitive or perceptual skills development of a child.

We have recently started a more comprehensive and systematic empirical study designed as a controlled experiment that will last for 6 months, and will comprise an extended set of VR stories that the specialists are developing. This study involves a group of 20 ID children with comparable intellectual functional level who are using Wildcard on a biweekly basis, according to a plan of activities defined by the therapists. The long-term effects of this treatment will be measured using both data automatically collected with our system and pre-post standard tests of attention. The latter results will be compared with results from a control group.

In this paper, we presented Wildcard, an affordable framework designed in cooperation with specialists for children with NDD and evaluated in a preliminary exploratory study with 5 children and an evaluation study with 11 children at a care center. The findings are promising, and Wildcard seems to have potential, particularly to improve attention skills. The system was willingly accepted by the children, and allowed them a total engagement in the exercise they were performing. Wildcard was able to track their attention level for a subsequent analysis, and during the therapy it provided continuous feedback to the caregivers, who were indeed able to see the simulated world through the user's eyes. This way therapists supervised seamlessly entire sessions and understood what elements created difficulties in the activity progression. The possibility to personalize each single activity was a key requirement to maintain a high engagement during the therapy.

Wildcard is unique in terms of features it can offer: therapeutic centers have now the possibility to completely define a therapeutic session and tailor the exercise to each child's needs through the personalization component. This means caregivers are not dependent on external developers to make changes in the activities. They can set up and update therapeutic sessions for each child without incurring in delays and costs that may result from requirement gathering and development processes. All the aforementioned features are possible thanks to Wildcard's modular nature. In fact, the usage of an external device such a smartphone enables the installation and update of our framework as an "app" that can be downloaded by masses. Since parents can have the same tool, Wildcard will be able to smoothly migrate from therapeutic centers to children's home. Children will thus exercise on their own devices, after a few supervised sessions, and still benefit from all advantage VR technologies can give.

A video explanation is available at the following link: https://www.youtube.com/watch?v=1t9EasAHRdU

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