HoloLearn: Wearable Mixed Reality for People with Neurodevelopmental Disorders (NDD)

Beatrice Aruanno (1) **Franca Garzotto** (2) **Emanuele Torelli** (2) **Francesco Vona** (2)

(1) Department of Mechanical Engineering - Politecnico di Milano - Milano - Italy
beatrice.aruanno@polimi.it
(2) i3lab - Department of Electronics, Information, and Bioengineering - Politecnico di Milano - Milano - Italy
franca.garzotto@polimi.it; emanuele1.torelli@mail.polimi.it; francesco.vona@mail.polimi.it

ABSTRACT
Our research explores the potential of wearable Mixed Reality (MR) for people with Neuro-Developmental Disorders (NDD). The paper presents HoloLearn, a MR application designed in cooperation with NDD experts and implemented using HoloLens technology. The goal of HoloLearn is to help people with NDD learn how to perform simple everyday tasks in domestic environments and improve autonomy. An original feature of the system is the presence of a virtual assistant devoted to capture the user's attention and to give her/him hints during task execution in the MR environment. We performed an exploratory study involving 20 subjects with NDD to investigate the acceptability and usability of HoloLearn and its potential as a therapeutic tool. HoloLearn was well-accepted by the participants and the activities in the MR space were perceived as enjoyable, despite some usability problems associated to HoloLens interaction mechanism. More extensive and long term empirical research is needed to validate these early results, but our study suggests that HoloLearn could be adopted as a complement to more traditional interventions. Our work, and the lessons we learned, may help designers and developers of future MR applications devoted to people with NDD and to other people with similar needs.

AUTHOR KEYWORDS
Augmented Reality; Mixed Reality; HoloLens; Holograms; Neuro-developmental Disorders; Virtual assistant.

ASSETS '18, October 22–24, 2018, Galway, Ireland
© 2018 Association for Computing Machinery.
ACM ISBN 978-1-4503-5650-3/18/10…$15.00
https://doi.org/10.1145/3234695.3236351

INTRODUCTION
The goal of our research is to investigate the potential of *wearable Mixed Reality* (MR) applications, particularly those based on HoloLens technology, to offer new forms of interventions for people with *Neuro-Developmental Disorders*.

Neurodevelopmental Disorders (NDD) is an umbrella term that comprises various forms of disability ascribed primarily to the functioning of the neurological system and the brain. Included in NDD we find for example Attention-Deficit/Hyperactivity Disorder (ADHD), Autism, Learning Disabilities, and Intellectual Disability. Most individuals with NDD experience various and often co-occurring difficulties in different areas, such as language and speech, memory, learning, social behavior, and motor skills [42]. The occurrence of some disorders in the NDD spectrum, specifically Autism and ADHD, has been increasing over the last four decades [42]. The treatment of NDD involves a combination of professional therapy, pharmaceuticals, home-based and school-based programs. Better results are achieved when interventions start in childhood, but some studies show that therapies can also be beneficial to adults [14].

Mixed Reality (MR) is the richest form of Augmented Reality (AR). AR experiences take place in a real-world environment whose elements are "augmented" by computer-generated overlaid information (e.g. visual and auditory). In AR, the user sees what is in front of him but with an added virtual layer on top of it, which adds new elements to the natural environment or masks portions of it. MR provides a stronger merging of real and virtual reality. Instead of just seeing a set of digital elements overlaid on the view of the physical world, in MR the user can interact with an artificial environment where the surrounding physical space, realistic renderings of physical materials, and digital objects, all co-exist and communicate in real time [13]. In *wearable* Mixed Reality, the real-virtual environment is experienced through a head mounted display (Figure 1).

This paper presents *HoloLearn*, an application for Microsoft HoloLens [27] - the most recent and advanced example of commercial wearable MR technology. HoloLearn addresses young adults with NDD and has been designed in cooperation with psychologists and therapists. The goal of HoloLearn is to promote the understanding of some basic tasks that are typical of domestic routines (e.g. table setting and garbage collection) and to help these people improve autonomy in everyday life.

The paper describes the design rationale of HoloLearn and its technical implementation. We then report an exploratory empirical study that involved 20 people with various forms of NDD, who used HoloLearn at a care center under the supervision of their caregivers. The study results highlight the limitations as well as the potential of HoloLens technology for this target group. We also discuss the main lessons learned during this project, which could benefit designers and developers of future wearable Mixed Reality applications for people with NDD and similar target groups.

Figure 1: Example of Mixed Reality with Microsoft HoloLens; on the background, what the user sees on the head-mounted device.

STATE OF THE ART

Virtual, Augmented, and Mixed Reality for People with NDD

Several studies explore the use of virtual worlds in interventions for people with NDD, particularly those with Autism [4, 6, 7, 8, 10, 11, 43]. Compared to traditional therapeutic or educational materials, VR contents offer safe environments for learning that can be customized to the specific needs of each individual [37, 38]. VR has the potential of stimulating the imagination and promoting generalization [23, 24]; several studies report successful transfer from the skills learned in VR to real life situations [25]. When the virtual world is displayed on a wearable device, the entire user's field of view is "embedded" in the artificial environment; this immersion effect removes the distractions from the external world and helps individuals to remain focused on the assigned task [15, 38].

The first generation of VR headsets had some technological weaknesses, e.g. poor viewing angles, high latency, and weight [38]. Current Head-Mounted Displays (HMDs) are much more comfortable [36], and wearable VR experiences are starting to be experimented in the treatment of NDD [16, 17, 20, 39], especially for children. The *Wilcard* project [21], for example, transforms the stories of some children's books that are used in NDD therapy into immersive VR contents enriched with interactive affordances and simple gamification features. These VR experiences require only a smartphone mounted on a low-cost VR viewer (Google cardboard). In [22], the authors exploit a similar approach, using contents inspired by "Social Stories", i.e. short narratives describing everyday life situations that are widely used as a therapeutic method among people with Autism.

The benefits of AR among subjects with NDD have been much less explored than VR ones. AR is thought to have the advantage of maintaining a real, familiar environment during the virtual experience. Some AR applications (e.g. *Empower Me* [9] by Brain Power) use Google Glass and aim to teach practical life skills to children and adults with Autism, such as language, emotional understanding, eye contact, conversational skills, and behavior control [5, 26].

Some AR technologies for NDD enable the user to interact with VR contents using body movements [19]. This interaction paradigm is thought to promote embodied learning and to enhance engagement. Examples are *Pictogram Room* [12] and *Shape Game* [19]. These systems provide different game-based activities but share the goal of helping people with Autism to develop their body schema and imitation skills by performing playful tasks based on body postures and movements of legs or arms.

Very little is known on how to exploit MR in general, and HoloLens technology in particular, for people with NDD. To our knowledge, the only HoloLens application that addresses people with cognitive disability is the one reported in [3]. This system addresses people suffering from Alzheimer's disease, it was designed in cooperation with neurologists and geriatric doctors and consists of a set of tasks that aims to improve short-term memory and spatial memory, in an attempt to slow down mental decline.

Microsoft HoloLens

HoloLens - the Microsoft flagship device for wearable MR [27] - is a self-contained, holographic computer mounted on a headset (Figure 2) and is equipped with specialized components, like multiple sensors, advanced optics, and a custom holographic processing unit. HoloLens enables the user to interact with digital contents rendered by holograms that are placed in the real environment where the user is located. Using spatial mapping techniques, the device captures the information about the physical space, identifies planes such as tables, floor, walls, and ceiling [31], and generates a fully realistic rendering of the surrounding environment where interactive holograms representing real objects or other kinds of interactive digital contents can be placed.

HoloLens supports various interaction modes, and visual or audio effects can be associated with interactive items (e.g. hologram animations) and also with the environment as a whole (e.g. spatial sound [32]) as responses to the interaction.

- *Gaze*. By changing gaze direction, the user updates his/her view of the environment. A cursor appears on the gaze focus and follows the gaze movement [28]. Technically, the built-in sensors track only head orientation and movements (i.e. there is no eye tracking). The user's gaze focus is determined by head orientation, the changes of the pointer position and the space view correspond to head movements.

- *Gestures*. Hand gestures are used to interact with holograms in the surrounding physical space. The main gesture is *air-tap* of *thumb and index*. "Instantaneous" air-tap selects and activates the gazed interactive hologram on which the cursor is placed, triggering the associated feedback. "Sustained" air-tap performs drag&drop. In this case, after the initial air-tap on the gazed hologram ("selection"), fingers must be kept close to move the selected item to the desired position and must be opened to "drop" the element there [29].
- *Voice*. Voice commands can be defined to give instructions to the application and interact with interactive items [30].
- *Clicker.* A physical button-shaped controller connected to the headset via Bluetooth can be used in place of air-tap to select and move interactive elements [34].

Figure 2: HoloLens device [27]

HOLOLEARN DESIGN

User Needs and Requirements

The design process of HoloLearn involved two therapists (psychologists) who work at "*Fraternità e Amicizia"*, a care center in Milan that serves over 80 individuals with NDD. Three preliminary focus groups with these specialists were devoted to understand how MR could help these people. The therapists pinpointed that many education activities performed at the center attempt to make these people more autonomous (or at least less dependent on caregivers) and highlighted the need to help these people learn how to perform the basic everyday life tasks.

These considerations informed the definition of the general goals of HoloLearn: to use MR in order to provide virtual environments for people with NDD which are the same as real-life ones and enable them to practice tasks associated with their domestic activities.

As a starting point for the design of HoloLearn, we focused on two activities: *Laying the table* and *garbage collection*.

These activities involve movements in the physical space and the actions of grasping/moving/placing objects and can be simulated using the built-in features of HoloLens technology. The physical space where the MR experience takes place - the one sensed and digitally rendered by the device - should contain the physical elements functional to the designed tasks, for example a table for the "Laying the table" activity. The space view is then enhanced with holograms which represent the other elements needed for the tasks, for example objects that need to be "grasped" and placed in the proper position using gaze focus, gaze movement, and air-tap.

Another requirement indicated by the therapists was to offer additional elements in the MR space that attract the user's attention to objects and target locations, help the user complete the task by providing step-by-step instructions, and promote engagement and fun. To this end, we decided to introduce an animated holographic character into the MR experience which plays the role of a cheerful virtual assistant. According to the therapists, the virtual assistant should evoke something familiar to users, such as a cartoon character. We considered a number of options, and asked the people attending the center to vote their favorite one. The "most popular" turned out to be a *Minion* (from the movie *Despicable Me*); therefore, we decided to model the shape of the virtual assistant on this.

Finally, the therapists pinpointed the importance of making the application as customizable as possible, to enable them to address the different and evolving needs of each person with NDD. For each activity, we designed different configurations corresponding to different levels of task complexity which the therapist can choose before a session by setting some features of the activity, such as the presence or absence of the virtual assistant, the number of interactive digital objects in the MR space, and their visual characteristics.

"Laying the table" activity

The purpose of this activity is to teach the user to lay a real table by placing various objects (e.g. virtual glasses, plates, cutlery, or bottles) on it, in the proper position.

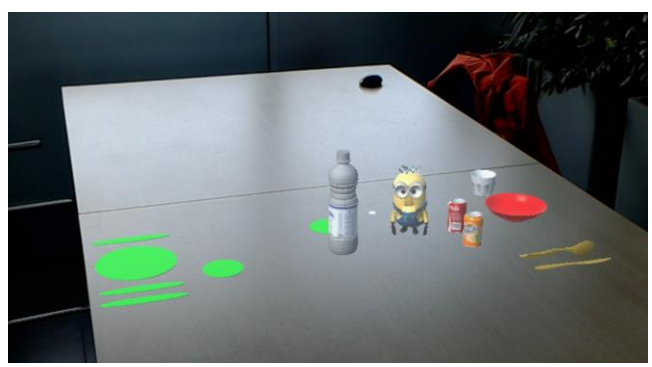

Figure 3: "Laying the table" activity

The MR environment consists of the space surrounding the user (which must include a table) and some holographic objects, which appear at one edge of the table (of course holograms should not "float" in the air), while some areas are highlighted on the other edges (Figure 3). To complete the task, the user must move all the holograms to the correct positions, which correspond to the highlighted areas, by gazing each holographic object to move the cursor on it, and then dragging and dropping the grasped element using "sustained" air-tap.

Using a simple menu (Figure 4), the therapist can configure the level of complexity of the activity, setting the number of people for whom the table must be prepared (up to three people, to avoid having too many elements on the table, which could be confusing) and choosing the types of objects to be placed. For instance, in the "easy" configuration, the participant should set the table using basic objects such as glasses, cutlery, plates and one bottle of water. In a more complex configuration, there are additional objects such as cans of beverages, or more glasses of different shapes. In the most advanced configuration, the number of objects is larger, and their shape and color are more complex.

We exploited the spatial mapping function of HoloLens to create the MR space at the beginning of each session. The first operation performed by the application before the user can start the activity is to scan the surrounding environment, until a sufficiently large table is detected (with an area of at least one square meter), to place the holograms on it, and to highlight the destination areas on the table surface.

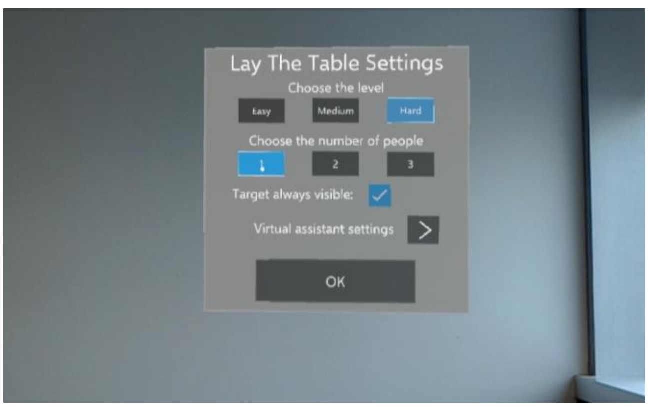

Figure 4: "Laying the table" settings menu

"Garbage collection" activity

The purpose of this activity is to help the user learn how to perform garbage collection properly.

The MR environment consists of the room where the user is located, different holographic bins placed on the floor - a paper bin, a glass bin and a plastic bin (Figure 5), and some pieces of trash located nearby. The goal of the activity is to move each holographic trash object inside the correct bin.

As in the "Laying the table" activity, the application uses the spatial mapping feature of HoloLens to scan the surrounding environment, to identify the floor and to place the objects in a meaningful way.

To ensure also in this activity a high level of customization, the therapist can choose the number of bins and the number of trash items that the user must throw into them.

Figure 5: "Garbage collection" activity

Virtual assistant

The virtual assistant is animated (to attract attention and promote engagement) and has various behaviors, depending on the difficulty the therapist wants to set in the activity.

We have currently implemented three configurations for the virtual assistant.

In the *static* one, the character stays idle, giving feedbacks only after the user places an object in a target position: if the position is correct it looks happy, otherwise it expresses disappointment.

In the *dynamic* configuration, the virtual assistant waits for a while, then it walks to the nearest object and moves its arms to point at it, in order to encourage the user to grasp and drag it (Figure 6). If the user is dragging an object but doesn't know where to put it (e.g. because he/she is moving it in the wrong direction, the assistant walks towards the position in which the item should be placed, and points at it.

In the *reactive* mode, the virtual assistant remains idle until the user says something like "help me", and then walks either to the nearest object or to the nearest target position.

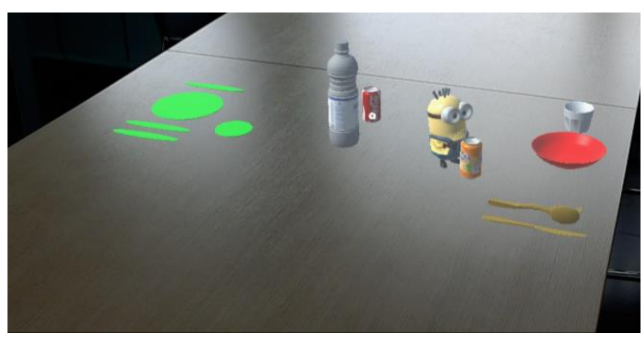

Figure 6: Virtual assistant in action

IMPLEMENTATION OF HOLOLEARN

The main software tools we used in the implementation of HoloLearn are Unity [40] and Visual Studio [35]. HoloLearn scripts were coded in C#, which is more supported than other programming languages by both Microsoft and Unity technical documentation.

The application source consists of Unity assets and C# scripts. Unity assets are managed by the Unity engine and include the 3D models used for the holograms, the UI elements, and the Mixed Reality Toolkit [33]. The Mixed Reality Toolkit is a collection of components provided by Microsoft which accelerate the development of applications for Microsoft HoloLens and other Windows Mixed Reality headsets. The Toolkit is organized in different modules, each of them containing scripts and Unity prefabs that facilitate the implementation of the interaction paradigm of HoloLens and provide other useful features. For instance, the input module contains scripts that interpret inputs such as gaze, gesture, and voice. The spatial mapping component is used by HoloLearn to map the real world into the MR environment (Figure 7). We also exploited some of the UX controls provided by the Toolkit (for instance sliders, buttons, checkboxes, etc.) to implement the HoloLearn menu.

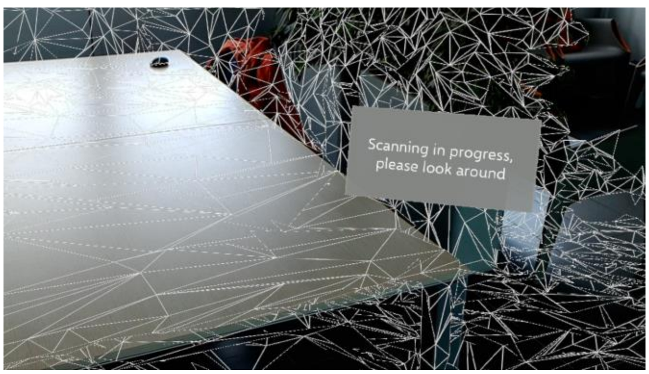

Figure 7: Spatial mapping

To develop the virtual assistant, we found some useful animations on Mixamo.com service by Adobe [1] and applied them to the 3D model of the virtual character. We managed model animations by means of the Unity animation management tool [41]. The behavioral rules of the assistant are defined by a state machine implemented in C#. To provide the proper hints, assistant animation changes according to what the user is doing. For example, if the user drags an object, the assistant state becomes “walk”, and the character walks towards the nearest target position.

Visual Studio is used to load and compile the code from the PC where the application is developed into the HoloLens device.

HoloLearn is currently executed as a client-side application, and all the data are managed by the application itself. For instance, it is possible to save the configuration parameters set for each activity performed as persistent data and re-use them in following application executions.

HoloLens supports UWP (Universal Windows Platform) applications, so our final product can be deployed on the Microsoft Store.

EXPLORATORY STUDY

We performed an exploratory study on HoloLearn at the “*Fraternità e Amicizia*” center involving *20* subjects with different disorders in the NDD spectrum, and their 3 caregivers.

Goal of the study and research questions

To our knowledge, no published research explores the use of HoloLens technology among people with NDD; little is known on how these people behave when they are exposed to HoloLens devices and applications.

The first goal of our study was therefore to investigate *device acceptability*, i.e. if subjects with NDD (hereinafter referred to as “*users*”) would accept to wear the HoloLens headset, and *usability*, i.e. if they would have difficulty in understanding and using the main interaction mechanism (air-tap gesture coordinated with gaze).

In addition, we wanted to explore some HoloLearn-specific aspects, e.g. the degree of *complexity of the user tasks and the role of the virtual assistant*. Finally, we investigated how users would perceive the overall experience with HoloLearn (*likeability* and *satisfaction*).

We organized our main *research questions* along the above lines:

Device Acceptability:

- Q1: Do users accept to wear and use the HoloLens device?

Usability of the interaction mode:

- Q2: Do users understand the air-tap gesture, and can they perform it?
- Q3: Do users understand how to stare at holograms with their gaze?
- Q4: Are users able to coordinate gaze and air-tapping?

Task complexity:

- Q5: Do users understand the goal of the tasks?
- Q6: Were users able to contextualize the tasks in the MR space, i.e. to understand that they are performing the tasks in a virtual environment and not in a real space?

Virtual assistant role:

- Q7: Do users try to interact with the virtual assistant?
- Q8: Do users understand the role of this character?

Likeability and satisfaction.

- Q9: Do users have fun using HoloLearn?
- Q10: Are users satisfied with this experience?

Participants

The study involved two groups of people who attend the care center on a regular basis, are aged 16-43 and have different disorders in the NDD spectrum. The *severity* level was homogeneous within each group: *severe* for Group 1 and *moderate* for Group 2.

"Severity" is a clinical measure designed to be used at initial evaluation to inform treatment planning, to establish a baseline for comparison, and to monitor changes. Severity takes into account various aspects, such as the intensity, frequency and the duration of symptoms associated with a specific disorder in the NDD spectrum.

Criteria and guidance to rate severity are provided in the DMS-5 [2]. In intellectual disability, the "severe" level for people in the age range of the participants in our study is characterized by little understanding of written language and concepts involving numbers, quantity, time and money, limited spoken language, and the need for supervision at all time for all daily-living activities including meals, dressing, personal hygiene.

The "moderate" level is associated with limited academic skills (reading, writing, maths), assistance required to complete conceptual day-by-day living tasks, difficulty in perceiving and interpreting social cues accurately, and the need of reminders and instruction in practical tasks involving eating, dressing and hygiene.

Group 1 (n=11, average age = 27,27, SD=5,04) is described in Table 1. Group 2 (n=9; average = *31,33*, SD=5,67) is described in Table 2.

ID	Gender	Age	Disorder	Sessions attended
S1	M	25	Intellectual disability	1
S2	M	34	Intellectual disability	1
S3	F	24	Intellectual disability	1
S4	M	27	Asperger syndrome	1
S5	M	28	Intellectual disability and psychosis	1
S6	F	28	Intellectual disability	2
S7	M	16	Prader-Willi syndrome	2
S8	F	33	Intellectual disability	2
S9	F	24	Pervasive developmental disorder	2
S10	F	31	Intellectual disability	2
S11	M	30	Down syndrome	2

Table 1: Study Participants - Group 1 (severity level = severe)

ID	Gender	Age	Disorder	Sessions attended
M1	F	35	Intellectual disability	1
M2	M	25	Intellectual disability	1
M3	M	31	Intellectual disability	1
M4	F	36	Intellectual disability	1
M5	M	29	Intellectual disability	1
M6	F	28	Intellectual disability	1
M7	M	28	Intellectual disability	1
M8	F	43	Intellectual disability	1
M9	F	27	Intellectual disability	1

Table 2: Study Participants - Group 2 (severity level = moderate

Procedure

Each session took place at the therapeutic center in a room that was familiar to all participants (Figure 8). The activity selected for the study was *Garbage collection*, which the therapists considered easier than *Laying the table* since it involves simpler movements. During a session, the person with NDD used HoloLearn for approximately 10 minutes with the assistance of his/her caregiver; an additional therapist while two members of the university team participated as observers and took notes.

Figure 8. Using HoloLearn during the exploratory study

We connected HoloLens to a PC and a large display screen, so that all the people in the room could see what the current user was seeing inside the device, and the caregiver could provide more contextualized help when needed.

Before starting the activity, the therapist explained its goal and told the user what he/she had to do and how to interact with the application. He/she gave instructions during the session when explicitly asked by the user, or when he/she needed help.

In some cases, it was enough to give suggestions by voice. In other cases, the caregiver had to interact physically with the user, in two ways: i) The caregiver manipulated the user's head to help him/her focus the gaze on the cursor, to move the cursor toward the hologram, and to drag the hologram to the proper position; ii) The caregiver moved the user's fingers to explain how to perform air-tap.

The caregivers and the users answered a set of questions at the end of each session. Caregivers filled in a questionnaire based on research questions Q1-Q8 on a 3-value response scale: *1 = yes, with no or only initial support; 2 = with evident difficulty and frequent support; 3 = not at all.*

Users provided voice answers to two questions - based on research questions Q9 and Q10 (about fun and satisfaction respectively) which were asked by the caregiver.

RESULTS AND DISCUSSION

We initially planned to perform one session per user in both groups. Six users in Group 1 (S6, S7, S8 S9, S10, and S11) who have the strongest disability were also involved in a second session (after one week) since they had enormous difficulties in the first session and we wanted to find out if, after some familiarization, they could achieve some improvement.

In the rest of this section, we report the main numerical results for each group, and then also discuss the findings in light of the notes taken by the observers.

Main Results - Group 1 (severity level = severe)

The first set of the following tables (Table 3, Table 4, and Table 5) reports the results of the caregivers' survey about device acceptability and usability, which was filled-out for the entire Group 1 (n=11) after the *first* session of use of HoloLearn.

Table 6A and Table 6B presents the results of the caregivers' questions on usability for the 6 participants in Group 1 who attended two sessions with HoloLearn and allow us to compare the results for these subjects in the first and second session.

	1	2	3
Q1	90.9%	9.1%	0.0%
Q2	18.2%	27.3%	54.5%
Q3	27.2%	36.4%	36.4%
Q4	18.2%	45.5%	33.3%

Table 3: Caregivers' survey: device acceptability (Q1) and usability of the interaction paradigm. Group 1; n=11; first use

	1	2	3
Q5	36.4%	45.5%	18.1%
Q6	18.2%	63.6%	18.2%

Table 4: Caregivers' survey: task complexity. Group 1; n=11; first use

	1	2	3
Q7	90.9%	9.1%	0.0%
Q8	90.9%	9.1%	0.0%

Table 5: Caregivers' survey: virtual assistant's role. Group 1; n=11; first use

	1	2	3
Q2	0.0%	0.0%	100%
Q3	0.0%	33.3%	66.7%
Q4	0.0%	33.3%	66.7%

Table 6A: Caregivers' survey: usability of the interaction paradigm. Group 1- participants who attended 2 sessions; n=6; FIRST session

	1	2	3
Q2	0.0%	16.7%	83.3%
Q3	0.0%	66.7 %	33.3%
Q4	0.0%	50%	50%

Table 6B: Caregivers' survey: usability of the interaction paradigm. Group 1- participants who attended 2 sessions; n=6; SECOND session

Discussion of Results for Group 1

The data in Table 3-Q1 show positive results, i.e. the high level of acceptability of the HoloLens device, despite the strong disabilities of the people in Group 1. In most cases however it was difficult to capture their attention and help them understand what to do and how. According to our observations, only two people successfully completed the task while six more managed to move the objects around, placing only some of them in the proper bin.

The main problem that users encountered was to perform the interaction, and use gaze, air-tap gestures, and their combination correctly (Table 3 - Q2, Q3, Q4).

Concerning gaze, we observed that it was very difficult for the users to find the cursor. Several people also showed some difficulty in understanding the concept of moving the pointer over a hologram using sustained air-tap gesture.

These problems might be ascribed to a design weakness. We used the default cursor provided by HoloLens, which is white. On several occasions its visualization was confused because it resulted mixed up with the reflection of the light on the floor. For this reason, after the first session with Group 1 we decided to replace the default white arrowed cursor with a bigger, hand-shaped, purple-colored cursor, in order to make it more easily recognizable by the participant. We also generated a visual and sound feedback when the instantaneous air-tap gesture ("select") was performed correctly.

As for the air-tap action in itself, the users found it very difficult to learn the movement of the fingers. This is not surprising, considering the NDD is often associated with fine motor skills impairment. The users tended to open and close the whole hand, instead of using only thumb and index, or could not keep the two fingers closed while dragging the holograms around.

It is likely that these difficulties influenced task completion. Only one participant completed the task successfully, and six users managed to move the objects but without placing any of them in the corresponding bin.

Table 5 shows that the users were attracted by the virtual assistant: according to our observations, it was the first thing they noticed, and they easily recognized that it was a *Minion*. Still, no user was able to understand the instructions of the virtual character, and to use the application without the constant help of their caregivers.

The comparisons of Table 6A and Table 6B for the 6 users who attended two sessions shows an improvement in terms of usability in the second session, which means that the second time, the use of HoloLearn was simpler, even if observations show that the coordination of gaze and air-tap gesture remained very difficult to perform. The better usability might be ascribed to the improvement we introduced in the HoloLearn version for the second session: the purple cursor with feedback and its effect was probably more evident. But the usability result might also mean that in the first session the people learned something about the system that they did not forget after one week (when the second session was performed) and which they could exploit during the second experience. This would be surprising, considering the severity of the disability of these people and their memory impairments which normally affect the capability of remembering previous experiences and capitalizing on them.

Main Results - Group 2 (severity level = moderate)

Table 7 and Table 8 report the results of the caregivers' surveys for Group 2, i.e. the people with a moderate severity level of disability.

	1	2	3
Q1	100%	0%	0%
Q2	55.6%	22.2%	22.2%
Q3	66.7%	11.1%	22.2%
Q4	44.4%	22.2%	33.3%

Table 7: Caregivers' survey: device acceptability (Q1) and usability of the interaction paradigm. Group 2; n=9

	1	2	3
Q5	44.4%	55.6%	0.0%
Q6	22.2%	77.8%	0.0%

Table 8: Caregivers' survey: task complexity. Group 2; n=9

Discussion of Results for Group 2

The people in this group had less and weaker impairments than Group 1. In addition, they used the improved versions of HoloLearn in which we provided the purple cursor with feedback.

For these reasons, the caregivers were able to explain to them the interaction method and the actions to be performed to complete the activity and invite them to use the application autonomously.

According to our observations, all users in Group 2 understood what holograms meant and the purpose of the activity (Table 8).

After a few attempts and without too much difficulty, most of them were able to coordinate gaze with air-tap gesture (Table 7). Six of them completed the task successfully. The other three could not reach completion but managed to move the objects around and place some of them in the proper position.

Like Group 1, everyone in Group 2 liked the *Minion.* In this group many people also tried to interact with it, for example by saying "hello" or talking to it. Compared to Group 1, Group 2 also made better use of the virtual assistant: all users were able to understand what the *Minion* was trying to communicate, and caregivers were able to provide them with much less assistance.

Results and discussion on users' survey

Table 9 highlights a good degree of fun and satisfaction.

	1	2	3
Q9	82.1%	17.9%	0%
Q10	85.7%	10.7%	3.6%

Table 9: Participants' survey

According to the observers' note, most people enjoyed using HoloLearn and were satisfied with their experience (only one person showed disappointment), regardless of their performance and degree of task completion.

FINAL DISCUSSION AND LESSONS LEARNED

The findings of the exploratory study are very tentative because of the heterogeneity of the participants in terms of age and impairments and the very limited exposure to HoloLearn. In addition, our study does not offer any rigorous evidence of the benefits that performing tasks in Mixed Reality could bring to people with NDD. Nevertheless, the specialists had a very positive opinion on the potential of this technology to improve autonomy and to motivate the learning of day-by-day routines.

At the end of the exploratory study, we organized a focus group involving the entire working team, including the caregivers involved in the empirical study, to discuss the outcomes of the project. Together we analyzed what worked well and what did not work, and how it should be improved, and distilled the main lessons we learned.

Lesson 1: Target Group

The results of the exploratory study indicate that the participants in Group 1 required much more support from the caregivers during the experience than the people in Group 2. This suggests that HoloLens applications might be more appropriate for people with moderate severity level of NDD, since they can better master the intrinsic complexity of the interaction mechanisms of this device (see also Lesson 2). In addition, as suggested by one therapist, these subjects might be able to perceive a stronger sense of presence in MR environments. Our findings confirm what we also experienced in other projects [16, 17, 18, 20, 21, 22], i.e. that creating innovative technologies for the strongest forms of disability could be much more challenging than for mild disabilities.

Lesson 2: Facilitating HoloLens Interaction

The built-in, most characterizing interaction paradigm of HoloLens - coordinating gaze and air-tap - might totally prevent the autonomous use of this technology for people with the most severe forms of disability in the NDD spectrum and seems to be complex - but affordable - for people with moderate severity level. The air-tap gesture is not a natural movement; coordinating it with gaze can be very hard, if not impossible, to learn. To mitigate these difficulties, several strategies could be adopted. One is to envision a possibly long period of familiarization and training focused only on learning the interaction mechanism. Other strategies can be adopted at technological level. For example, we implemented a technical improvement, replacing the white default cursor with a purple, hand-shaped one associated with feedback. This pointer was more visible and intuitive, and the participants who used it achieved better results. A complementary solution to alleviate interaction problems could be to use the HoloLens "clicker" (a physical button-shaped controller) for selection, in place of air-tap. We integrated this device in the latest version of HoloLearn and performed a short laboratory test with 8 people with NDD and moderate severity level. The use of the clicker facilitated the interaction: After an initial explanation, all participants understood how to use this device, and the coordination with gaze was immediate.

Lesson 3: Virtual Assistant

An animated virtual assistant, whose visual characteristics evoke a familiar character, seems to be effective to attract the user's attention and to promote engagement and fun - regardless of the disorder and the severity level of the disability. To increase the engagement potential of this element, and to reduce the risk of boredom during prolonged use of the system, the therapists suggested providing a variety of different characters among which the users could select their favorite one. In contrast, the role of the virtual assistant to improve autonomy in task performance seems to depend on the characteristics of the disorder. When the disability severity level is high, the virtual assistant might bring no functional benefits, because of the user's limited understanding of character behavior, the weakness of imitation skills, and the frequent habit of constantly asking therapists what to do. Caregivers suggested that in all cases, when the virtual assistant is present, they should refrain from giving task-related instructions, at least for a while, and rather try to explain what the virtual assistant is communicating through visual behavior. They also suggested extending the communication capability of the virtual assistant and enabling it to offer aural instructions to complement visual cues.

Lesson 4: Customization

Because each individual with disabilities has unique characteristics, the educational value of a technology for this target is strongly related to its ability to be personalized to each users' evolving needs. HoloLens experiences should be conceived from the very start with this requirement in mind, as occurred in HoloLearn. Tasks and holographic elements should be designed so that multiple configurations, along multiple dimensions, are possible, and should be integrated with a simple tool for therapists that enables them to personalize the application autonomously.

Lesson 5: Shared Experience

The sessions of use of HoloLearn were performed individually, visualizing on an external display screen what the user was seeing during the experience. This setting enabled the caregiver to provide the proper guidance at the proper time. The therapists suggested that we should capitalize on the possibility of sharing the experience not only between the user and the caregiver, but also among the user's peers, i.e. other individuals with NDD. These people could enjoy what happens in the MR environment even if they do not wear the device; they could feel engaged in a shared experience, offer instructions, and ultimately learn from the current user's interactions. The physical presence of people other than the caregiver might also bring benefits to the HoloLearn user. It could reduce the risk of self-isolation which is a drawback of immersive technologies, helping the user to better feel the difference between the "real" environment and the digital one, to maintain the perception of the surrounding physical space, and to mitigate the potential stress associated with leaving the MR world and re-entering "real" reality.

CONCLUSIONS AND FUTURE WORK

To the best of our knowledge, HoloLearn is the first HoloLens application designed for people with NDD and empirically tested in a real setting. During our work, we faced several technical and methodological challenges, also because of the limited number of documented examples of HoloLens applications and their underlying design solutions, as well as the absence of publications concerning the use of HoloLens (and MR in general) among people with NDD and similar disabilities.

Our research is still in an early stage, and many issues need to be further explored. Nevertheless, some of our design solutions, the problems we encountered, and the lessons we learned, could be inspirational for the designers of wearable Mixed Reality applications devoted to people with NDD as well as other target groups with similar needs.

There are many points in our research agenda. From a design and technological perspective, we will include more options for the current activities and new types of tasks. We are currently developing new features for the "Laying the table" activity, to include new items that depend on food type. With the therapists in our team we have designed new activities (e.g. "Tidying up the room") based on a similar pattern of tasks (i.e. selecting holographic objects and placing them in different positions). We are creating new characters for the virtual assistant, inspired by stories and cartoons used during regular therapeutic activities. We will also integrate the clicker-based interaction mode in a more robust way, to complement, or replace, gaze and air-tap. The implementation of these extensions does not require an enormous programming effort due to the modularity of the system, the online availability of 3D models, and the power of Unity.

A more challenging and long-term future work is related to the need of both a stronger assessment of the features already tested in the exploratory study, and the evaluation of the benefits of HoloLearn for people with NDD to improve autonomy. The latter issue will require an articulated controlled study, for a period of at least six months, in order to compare the effects of interventions based on HoloLearn with more traditional forms of treatment. Rigorously controlled studies in the NDD arena are enormously complex because of the heterogeneity of the impairments associated with NDD, the difficulty of recruiting a sufficiently large sample of "homogeneous" subjects, and the need to control many confounding variables. We are now working with three large therapeutic centers in Milan - serving in total approximately 800 people with NDD. They will enable us to recruit sufficiently wide control and experimental groups and will help us to address the challenge of a rigorous empirical study.

ACKNOWLEDGEMENTS

We wish to thank all the people at the "Fraternità e Amicizia" center who participated in our research, and in particular their coordinator Dr. Eleonora Beccaluva, for her strong support during the entire project.

REFERENCES

1. Adobe. 2018. Mixamo. Retrieved March 20, 2018 from: https://www.mixamo.com/
2. American Psychiatric Association. 2013. *Diagnostic and statistical manual of mental disorders (DSM-5®).* American Psychiatric Pub. 33-41.
3. Beatrice Aruanno, Franca Garzotto, and Mario Covarrubias Rodriguez. 2017. HoloLens-based Mixed Reality Experiences for Subjects with Alzheimer's Disease. *In Proceedings of the 12th Biannual Conference on Italian SIGCHI Chapter (CHItaly '17)*, Article 15, 9 pages. DOI: https://doi.org/10.1145/3125571.3125589
4. Miguel Bernardes, Fernando Barros, Marco Simoes, and Miguel Castelo-Branco. 2015. A serious game with virtual reality for travel training with Autism Spectrum Disorder. In *2015 International Conference on Virtual Rehabilitation (ICVR),* 127-128. DOI: https://doi.org/10.1109/ICVR.2015.7358609
5. LouAnne E. Boyd, Alejandro Rangel, Helen Tomimbang, Andrea Conejo-Toledo, Kanika Patel, Monica Tentori, and Gillian R. Hayes. 2016. SayWAT: Augmenting Face-to-Face Conversations for Adults with Autism. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*, 4872-4883. DOI: https://doi.org/10.1145/2858036.2858215
6. Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Locomotion in Virtual Reality for Individuals with Autism Spectrum Disorder. In *Proceedings of the 2016 Symposium on Spatial User Interaction (SUI '16)*, 33-42. DOI: https://doi.org/10.1145/2983310.2985763
7. Lal Bozgeyikli, Evren Bozgeyikli, Andrew Raij, Redwan Alqasemi, Srinivas Katkoori, and Rajiv Dubey. 2017. Vocational Rehabilitation of Individuals with Autism Spectrum Disorder with Virtual Reality. *ACM Transactions on Accessible Computing (TACCESS)*. 10, 2 (April 2017), Article 5, 25 pages. DOI: https://doi.org/10.1145/3046786
8. Lal Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Redwan Alqasemi. 2017. A Survey on Virtual Reality for Training Individuals with Autism Spectrum Disorder: Design Considerations. *IEEE Transactions on Learning Technologies*. 11, 2 (April-June 2018),

133-151. DOI: https://doi.org/10.1109/TLT.2017.2739747

9. Brain Power. 2018. "Empower Me" by Brain Power, Retrieved February 16, 2018 from: http://www.brain-power.com/autism/
10. Ross Brown, Laurianne Sitbon, Lauren Fell, Stewart Koplick, Chris Beaumont, and Margot Brereton. 2016. Design insights into embedding virtual reality content into life skills training for people with intellectual disability. In *Proceedings of the 28th Australian Conference on Computer-Human Interaction (OzCHI '16)*. ACM, New York, NY, USA, 581-585. DOI: https://doi.org/10.1145/3010915.3010956
11. Vanessa Camilleri, Matthew Montebello, and Alexiei Dingli. 2017. Walking in small shoes: Investigating the power of VR on empathising with children's difficulties. In *2017 23rd International Conference on Virtual System & Multimedia (VSMM)*, 1-6. DOI: https://doi.org/10.1109/VSMM.2017.8346253
12. Xavier Casas, Gerardo Herrera, Inmaculada Coma, Marcos Fernández. 2012. A Kinect-based Augmented Reality System for Individuals with Autism Spectrum Disorders. In *GRAPP/IVAPP*. 440-446.
13. Adam Dachis. 2017. What's the Difference Between AR, VR, and MR? (11 September 2017). Retrieved February 18, 2018 from: https://next.reality.news/news/whats-difference-between-ar-vr-and-mr-0171163/
14. Dan Ehninger, Weidong Li, Kevin Fox, Michael P. Stryker, & Alcino J. Silva. 2008. Reversing neurodevelopmental disorders in adults. *Neuron*, 60, 6 (December 2008), 950-960. DOI: https://doi.org/10.1016/j.neuron.2008.12.007
15. Mariano Etchart and Alessandro Caprarelli. 2018. A wearable immersive web-virtual reality approach to remote neurodevelopmental disorder therapy. In *Proceedings of the 2018 International Conference on Advanced Visual Interfaces (AVI '18)*, Article 61, 3 pages. DOI: https://doi.org/10.1145/3206505.3206595
16. Franca Garzotto and Matteo Forfori. 2006. FaTe2: storytelling edutainment experiences in 2D and 3D collaborative spaces. In *Proceedings of the 2006 conference on Interaction design and children (IDC '06)*, 113-116. DOI: https://doi.org/10.1145/1139073.1139102
17. Franca Garzotto, Mirko Gelsomini, Daniele Occhiuto, Vito Matarazzo, and Nicolò Messina. 2017. Wearable Immersive Virtual Reality for Children with Disability: a Case Study. In *Proceedings of the 2017 Conference on Interaction Design and Children (IDC '17)*, 478-483. DOI: https://doi.org/10.1145/3078072.3084312
18. Franca Garzotto, Nicolò Messina, Vito Matarazzo, Lukasz Moskwa, Gianluigi Oliva, and Riccardo Facchini. 2018. Empowering Interventions for Persons with Neurodevelopmental Disorders through Wearable Virtual Reality and Bio-sensors. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*, Paper LBW618, 6 pages. DOI: https://doi.org/10.1145/3170427.3188636
19. Franca Garzotto, Matteo Valoriani, and Laura Bartoli. (2014). Touchless motion-based interaction for therapy of autistic children. In *Virtual, Augmented Reality and Serious Games for Healthcare 1*. Intelligent Systems Reference Library, Vol 68. Springer, Berlin, Heidelberg. 471-494. DOI: https://doi.org/10.1007/978-3-642-54816-1_23
20. Franca Garzotto, Mirko Gelsomini, Francesco Clasadonte, Daniele Montesano, and Daniele Occhiuto. 2016. Wearable Immersive Storytelling for Disabled Children. In *Proceedings of the International Working Conference on Advanced Visual Interfaces (AVI '16)*, 196-203. DOI: https://doi.org/10.1145/2909132.2909256
21. Mirko Gelsomini, Franca Garzotto, Daniele Montesano, Daniele Occhiuto. 2016. Wildcard: A wearable virtual reality storytelling tool for children with intellectual developmental disability. In *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 5188-5191. DOI: https://doi.org/10.1109/EMBC.2016.7591896
22. Mirko Gelsomini, Franca Garzotto, Vito Matarazzo, Nicolò Messina, and Daniele Occhiuto. 2017. Creating Social Stories as Wearable Hyper-Immersive Virtual Reality Experiences for Children with Neurodevelopmental Disorders. In *Proceedings of the 2017 Conference on Interaction Design and Children (IDC '17)*, 431-437. DOI: https://doi.org/10.1145/3078072.3084305
23. Gerardo Herrera, Rita Jordan, and Lucia Vera. 2006. Abstract concept and imagination teaching through virtual reality in people with autism spectrum disorders. *Technology and Disability*, 18, 4 (December 2006), 173-180.
24. Gerardo Herrera, Francisco Alcantud, Rita Jordan, Amparo Blanquer, Gabriel Labajo, Cristina De Pablo. 2008. Development of symbolic play through the use of virtual reality tools in children with autistic spectrum disorders: Two case studies. *Autism*, 12, 2 (March 2008), 143-157. DOI: https://doi.org/10.1177/1362361307086657
25. Naomi Josman, Hadass Milika Ben-Chaim, Shula Friedrich, and Patrice L. Weiss. (2008). Effectiveness of virtual reality for teaching street-crossing skills to children and adolescents with autism. *International Journal on Disability and Human Development*, 7, 1

(May 2011), 49-56. DOI: https://doi.org/10.1515/IJDHD.2008.7.1.49

26. Runpeng Liu, Joseph P. Salisbury, Arysha Vahabzadeh, & Ned T. Sahin. 2017. Feasibility of an autism-focused augmented reality smartglasses system for social communication and behavioral coaching. *Frontiers in pediatrics*, 5, (June 2017). DOI: https://doi.org/10.3389/fped.2017.00145
27. Microsoft. 2017. Microsoft HoloLens. Retrieved March 20, 2018 from: https://www.microsoft.com/en-us/hololens/
28. Microsoft. 2018. Microsoft Holographic Gaze. Retrieved April 11, 2018 from: https://docs.microsoft.com/en-us/windows/mixed-reality/gaze
29. Microsoft. 2018. Microsoft Holographic Gestures. Retrieved April 11, 2018 from: https://docs.microsoft.com/en-us/windows/mixed-reality/gestures
30. Microsoft. 2018. Microsoft Holographic Voice Input. Retrieved April 11, 2018 from: https://docs.microsoft.com/en-us/windows/mixed-reality/voice_input
31. Microsoft. 2018. Microsoft Holographic Spatial Mapping. Retrieved April 11, 2018 from: https://docs.microsoft.com/en-us/windows/mixed-reality/spatial-mapping
32. Microsoft. 2018. Microsoft Holographic Spatial Sound. Retrieved April 11, 2018 from: https://docs.microsoft.com/en-us/windows/mixed-reality/holograms-220
33. Microsoft. 2017. MixedRealityToolkit-Unity. Retrieved April 7, 2018 from: https://github.com/Microsoft/MixedRealityToolkit-Unity
34. Microsoft. 2017. Use the HoloLens clicker. Retrieved April 12, 2018 from: https://support.microsoft.com/it-it/help/12646/hololens-use-the-hololens-clicker
35. Microsoft. 2018. Visual Studio. Retrieved April 2, 2018 from: https://www.visualstudio.com/
36. Nigel Newbutt, Connie Sung, Hung Jen Kuo, Michael J. Leahy and Boyang Tong. 2016. Brief Report: A Pilot Study of the Use of a Virtual Reality Headset in Autism Populations. *Journal of Autism and Developmental Disorders*, 46, 6 (September 2016), 3166–3176. DOI: https://doi.org/10.1007/s10803-016-2830-5
37. Sarah Parsons & Peter Mitchell. 2002. The potential of virtual reality in social skills training for people with autistic spectrum disorders. *Journal of Intellectual Disability Research*, 46, 5 (April 2014), 430-443. DOI: https://doi.org/10.1046/j.1365-2788.2002.00425.x
38. Dorothy Strickland. 1997. Virtual reality for the treatment of autism. *Studies in health technology and informatics*. 81-86.
39. Andrea Tartaro. 2006. Storytelling with a virtual peer as an intervention for children with autism. SIGACCESS Access. Comput. 84 (January 2006), 42-44. DOI: http://dx.doi.org/10.1145/1127564.1127573
40. Unity. 2018. Retrieved April 3, 2018 from: https://unity3d.com/
41. Unity. 2018. Unity User Manual. Retrieved April 3, 2018 from: https://docs.unity3d.com/Manual/index.html
42. U.S. Environmental Protection Agency. 2013. America's Children and the Environment, Third Edition. (January 2013). 233-253. Retrieved February 25, 2018 from: https://www.epa.gov/sites/production/files/2015-06/documents/ace3_2013.pdf
43. Simon Wallace, Sarah Parsons, Alice Westbury, Katie White, Kathy White, and Anthony Bailey. 2010. Sense of presence and atypical social judgments in immersive virtual environments Responses of adolescents with Autism Spectrum Disorders. Autism, 14, 3 (May 2010), 199-213. DOI: https://doi.org/10.1177/1362361310363283