Using HoloLens Mixed Reality to research correlations between language and movement: a case study

Eleonora Beccaluva
e.beccaluva@campus.unimib.it
Università degli Studi di
Milano-Bicocca
Milan, Italy

Francesco Vona
francesco.vona@polimi.it
Politecnico di Milano
Milan, Italy

Francesco Di Gioia
francescoriccardo.digioia@gmail.com
Università degli Studi di
Milano-Bicocca
Milan, Italy

Alberto Patti
alberto.patti@polimi.it
Politecnico di Milano
Milan, Italy

Alessia Guzzo
alessia1.guzzo@mail.polimi.it
Politecnico di Milano
Milan, Italy

Ilaria Cappella
ilaria.cappella@mail.polimi.it
Politecnico di Milano
Milan, Italy

Yue Ma
yue2.ma@mail.polimi.it
Politecnico di Milano
Milan, Italy

Natale Stucchi
natale.stucchi@unimib.it
Università degli Studi di
Milano-Bicocca
Milan, Italy

Franca Garzotto
franca.garzotto@polimi.it
Politecnico di Milano
Milan, Italy

ABSTRACT

Communication can be defined as the understanding and exchanging of meaningful messages. The role of communication is central to the lives of human beings as, everyday, we use language to interact with the world around us. Linguistic skills play a fundamental role in this scenario and Language Disorders (LD) are impairments that limit the processing of linguistic information. Early and accurate identification of LD is thus essential to promote lifelong learning and well-being. From an evolutionary perspective, some human language constructs evolved from an ancestral motor system and share the same neural pathways in the Broca's area of the brain. This suggests a correlation between action and language. If such a relationship is well established and reliable, it would be possible to use the former as a marker of the latter. The hypothesis of our work, in a nutshell, is that movement can be a predictor of language. To study this correlation, we developed C(H)o(L)ordination, a Mixed Reality (MR) application for HoloLens 2. The application offers several activities based on visual stimuli involving motor movements, which tap on the same skills needed to perform some language tasks. We performed an exploratory study with N=22 users to test the application usability and user experience. The results suggest that C(H)o(L)ordination is a usable and powerful tool to gather insights on the ongoing debate about language evolution and language disorders.

CCS CONCEPTS

• **Human-centered computing** → *Mixed / augmented reality*; *Usability testing*.

KEYWORDS

Mixed Reality, Microsoft HoloLens 2, Motor-linguistic correlation, Eye-tracking

1 INTRODUCTION

Research on how the human brain evolved and how it works is a relevant and growing topic of interest [25]. One of the most complex but interesting research lines is the exploration of human inborn capability to communicate and the role of linguistic skills in such phenomena [13, 44]. Through language we realise the cognitive potentialities that lead to individual socio-economic success and contribute to the common development of our society [24]. Under typical conditions, language unfolds naturally, following developmental stages common to most children [3, 7, 27]. However, for some, language development can be atypical. This is the case of subjects with Language Disorders (LD), a deficit that frequently results in educational and scholastic delays [4, 17] and adversely affects emotional development [31]. Early and accurate identification of LD is essential to promote the person's lifelong learning and the well-being [43]. In the past three decades, great attention has been devoted to exploring the mechanisms underlying language.

Evidence from literature suggests the existence of common neuro-anatomical resources that are shared by different cognitive abilities [11, 21] and used by the brain to perform different tasks [37]. The relationship between language and action is one of the most investigated ones [9, 34, 45]. There is some evidence that language and movement share important structural and neurological aspects [15, 32]. For example a hierarchical organisation of information, a representation based on syntax and a common neuro-anatomical substrate [6]. Working on this topic, researchers often employ different investigation methods that require multidisciplinary skills and expertise [10]. They usually spend years training and educating themselves to use advanced tools and techniques e.g Eye-Tracker, Bio-sensing, fMRI. Very often this challenging and time-consuming multidisciplinary expertise can be the key element that leads to new and groundbreaking discoveries [28].

To foster the research on action-language correlation and to provide experts with a simple but effective tool, we developed a Mixed Reality (MR) application for HoloLens 2, named C(H)o(L)ordination. The application offers several activities based on visual anticipatory stimuli involving motor movements, which should tap on the same skills needed to perform some language tasks [8, 16, 20, 23]. HoloLens 2 allows, simultaneously, the administration of stimuli, the collection of behavioural information about the subjects' responses and the tracking of eye movements. We performed an exploratory study with N=22 users to test the application usability and user experience. The results suggest that C(H)o(L)ordination is a usable and powerful tool to gather insights on the ongoing debate about language evolution and language disorders.

2 THEORETICAL BACKGROUND

2.1 Action, Language and Anticipation Skills

According to longstanding theories, some human language constructs evolved from an ancestral motor system and share the same neural pathways in the Broca's area of the brain [14, 18]. More specifically, the evolution of language syntax has capitalised and built on parts of a "pre-existing syntax" used by the motor system. Numerous brain-imaging study corroborates this theory [32], confirming the narrow relationship between these functions. Furthermore, it has been established that subjects with language disorders also have limitations in other nonlinguistic skills, such as anticipatory skills [16]. This is because both movement and language share the same predictive mechanisms [30]. Anticipatory skills are the ability to predict an upcoming or next event. They can also be described as the ability of individuals to put in place motor sequences to build and anticipate the performance of a subsequent occurrence [1]. These skills have been extensively investigated using different research techniques as eye-tracker [19, 22] and reaction and response time [12, 46]. We believe that anticipation skills in motor tasks can be a predictor of language competences. Moreover, we believe that subjects with LD have poor or any anticipatory abilities compared to neurotypical peers and this difference can be detected by tailor-made motor-anticipation tasks.

2.2 The role of perception

C(H)o(L)ordination is an application that uses visual stimuli perceived by the subject to trigger a motor response. In this section

we will provide basic notions on human perception functioning. Studies on perception have uncovered that biological movements look uniform to the human eye. A Uniform Motion is a type of motion in which the velocity of the body remains constant as it covers equal distances in equal intervals of time [33]. According to Viviani and Stucchi, see for the full paper[40], in 2D drawing movements, tangential velocity and radius of curvature co-vary in a constrained manner. If this biological constrain is satisfied, the velocity of point stimuli is perceived as uniform even if the variation of velocity exceeds 200%. Surprisingly, 2D stimuli moving at a constant velocity are perceived as nonuniform, generating a strong illusion for the observer. The theory that explains such phenomena is based on the assumption that the process of perceptual selection is influenced by the motor schemes and that the central nervous system has an implicit knowledge of the movement that is capable of producing [39, 41], see [35] for a review. In a few words, movements that comply with physical gravity laws are perceived as continuous and uniform by the observer. Those that do not, alter the observer's perception and are discerned as non-uniform. These discoveries were central for the development of C(H)o(L)ordination's activities. Appropriately and correctly perceived stimuli are processed as unbiased by the brain [29]. Therefore, using the physical principles described above, we ensured that subjects could not encounter disruption or cognitive illusions.

2.3 Benefits of Mixed Reality

Mixed Reality delivers experiences in which virtual and real environments are consistently integrated, giving users the illusion that the holograms generated by the technology are actually part of the real world around them. The ability to immerse the user in such well-integrated environments not only increases the immersiveness of the experience but also provides a setting in which different stimuli can be submitted in a controlled and safe manner. This is the reason why, in recent years, mixed reality has been investigated as a potential tool also in therapies for persons with physical and/or cognitive disabilities, such as language disorders [26, 38, 42]. Most of these studies, though, focus on teaching. For example, [38] aims at the learning of morphosyntactic constructs in English in children with already diagnosed language disorders, whereas [42] addresses more the learning of daily tasks in individuals with neurodevelopmental disorders. As far as we know, our system is the first that exploit a mixed reality application to investigate correlations between language and movement.

3 C(H)O(L)ORDINATION

C(H)o(L)ordination is a novel MR application for HoloLens 2 that offers several activities based on visual anticipatory stimuli involving motor movements. The tasks require the user to tap on a moving holographic planet that shifts along predefined trajectories. Our hypothesis is that neurotypical subjects, exploiting their anticipatory skills, will be able to progressively reduce the temporal distance (delta) between the presentation of the stimulus and the touch. On the contrary, we expect that subjects with LD, having poor or any anticipatory skills, will have random and unpredictable performances. All activities are based on the work by Viviani et al.[40] as described in section 2.2. We applied specific continuous planar

trajectories to the stimuli in order to test the anticipatory capacities of the subjects. For the iteration we selected the asymmetric lemniscate movement following the parametric function:

$$a \cdot (\cos{(t)} + b) \cdot \frac{\cos(t)}{1+\sin^2(t)} , \, a \cdot (\cos{(t)} + b) \cdot \frac{\cos(t)\sin(t)}{1+\sin^2(t)}$$
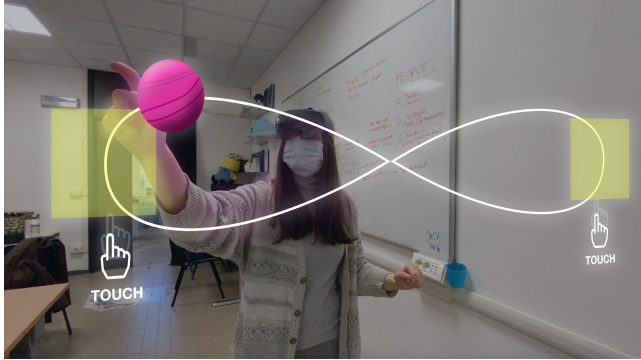

Figure 1: Artist's rendering of a user executing the Figure-Eight Trajectory task.

3.1 User Experience

Before starting the session, a tutorial is provided to the subjects, which allows them to become familiar with the tool and the different interaction techniques that will be performed during the activities. The tutorial is divided into two parts: at first, the user has to touch a motionless planet in front of him/her, secondly (s)he has to touch a moving planet with linear simple harmonic motion. Further instructions are provided about the basic mechanic of all activities, namely that the moving planet can only be interacted with when it is in a certain section of the environment, i.e. a yellow box, placed in specific points of the planet trajectory. Multiple cues were inserted to provide feedback to the user's action. First of all, when the user interacts with the planet correctly (i.e. when the planet, following its trajectory, passes within the marked areas and the user touches it) the planet itself will change colour. Additionally, to emphasise the correct action, if the planet is located in the yellow box, the system will also give auditory feedback upon touching. On the contrary, if the user tries to interact outside the box, or when the planet is not located in it, no feedback will be given, prompting the user to try again.

3.2 Design Choices

We chose a Mixed Reality Head-Mounted Device, specifically the Microsoft HoloLens 2, as the most suitable tool for our system. This headset provides benefits for both data collection and user experience. As the holograms are correctly integrated in the real-world environment, the subject has the possibility of using natural movements to interact with them. Additionally, we exploited different features of the device to collect other relevant data such as the user eye gaze during the tasks through the Eye Tracker. Although the system provides output to the user only when it's relevant to their action, it keeps collecting data for the researcher. In particular, the activities are structured to take into account not only whether the user was able to interact with the planet correctly, but also several

additional equally relevant data. Among these, the system collects the number of interactions with the moving object in the areas just before or just after the zone of interest. The former interactions are due to the user's attempts to anticipate the movement of the object itself and thus to anticipate its entry into the boxes, while the latter ones are due to a delayed touch which, if repeated several times, underlines a difficulty in the execution of the task. Information about the number of touches made by the user is not collected along the entire trajectory of the planet. This choice was taken to prevent the data from being affected by the various null attempts the user might make by interacting with the objects incorrectly. Additionally, the system also collects the user's reaction time, measured from the moment the planet becomes interactive, to the moment the user touches the object within the area of interest. Specifically, the planet becomes interactive when it comes into contact with the edge of the yellow area, even when it is not completely inside it. From this moment on, a timer is triggered and stops in the case of a successful touch, saving the reaction time. Lastly, among the data collected, we also track in which interaction area the user touched the planet, so that we can subsequently analyse the number of interactions per area.

4 USER STUDY

C(H)o(L)ordination was developed as a tool for researchers but also as an engaging activity for individuals involved in experimental sessions. Therefore we considered it imperative to evaluate the UX experience from both ends. In this section we report the result of a pilot study conducted on N=22 neurotypical subjects.

4.1 Study goals

The aim of the study was to investigate: *usability*, including the interaction paradigm, the launch and management of the application and the data collection download; *engagement*, as the ability to keep the subject hired in the activity for a prolonged period of time; *likability*, as the degree of appreciation and the easiness to use. The main goal was thus to verify whether the features of the application, the design and the implementation were optimal for our target users: researchers without a background in Computer Science and little or any experience in the field of Extended Reality (XR). We focused particularly on usability since the application's easiness of adoption is a substantial requirement for an effective research tool.

4.2 Target group

The study involved N=22 neurotypical subjects, age 22 to 26, mean 25.09, SD 5.4, 10 female, 12 male. Each subject had never used HoloLens before and had little or no experience with XR. All participants were previously notified and recruited on a voluntary basis. Informed consents, including details about the study procedures, goals and data treatment, were collected prior to the beginning of the study. The Ethical Committees of Politecnico di Milano approved the study protocol and authorised its execution.

4.3 Variables and metrics

Data gathering methods include:

- *Quantitative measure* administered to the subjects at the end of the session:
  - SUS: System Usability Scale questionnaire[2], the most used questionnaire for measuring perceptions of usability (see [5] for a retrospective);
  - UEQ; User Experience Questionnaire [36], a standard questionnaire which cover a comprehensive impression of user experience;
- *Qualitative measures* as direct observations of users behaviours and comments during the performances.

Observations were manually reported on a structured form to facilitate the collection of all relevant information (e.g. task success, task completion time, user's errors) as well as relevant behaviours and feedback.

4.4 Procedure

Each participant performed a single 30 minutes-session. All subjects were required to use C(H)o(L)ordination mimicking an experimental session, both as they were a researcher and an experimental individual. Subjects were randomly assigned to role-play order. 11 participants acted first as researchers and then as subjects and the other 11 vice versa. When participants were acting as researchers they were required to start the application, explain Hololens gesture, and have their colleagues wear the headset. When they were playing the subject role they had to follow the given instructions and execute the activity. The test consisted of a single scenario of three main tasks, each logically connected one to another as a continuous narrative. One of the investigators provided some introduction of the general scenario, then each task was introduced by a small overview. The study was held in a laboratory of Politecnico di Milano. The tests were conducted in an empty and quiet room as the application needs a safe and controlled space to allow the subject to move around. To administer the questionnaire we decided to use Google form. All subjects filled in the questionnaires after both role-playing and were requested to evaluate the overall experience.

4.5 Data Analysis

4.5.1 Quantitative measures. SUS results suggest that 75% of the users did not find the tool unnecessarily complex but rather easy to use. 45% of the participants considered necessary the support of a technical person to be able to use the system. This is probably due to the use of HoloLens, a cutting-edge technology that exploits different methods of interaction from the traditional ones. 75% of the users stated that the tool is able to integrate the various functionalities without many inconsistencies. UEQ output confirmed such results and pointed out that 70% of the users found the application easy, clear, efficient and supportive. More than 90% of participants found the various tasks exciting and interesting, despite the use of straightforward graphics. Finally, for about 85% of the participants the application seemed inventive and leading edge.

4.5.2 Qualitative measures. 70% of the interviewees felt very confident in using the tool and have stated that they believe that most people would learn to use the application very quickly. All feedback, behavioural observations, number of errors or requests for

support collected during the sessions indicate that the study participants were able to complete the entire experience without any difficulties or problems. When playing the role of the experimental subjects, they often repeated that they were enjoying themselves with exclamations such as "that's cute", "very funny", "nice graphics". They were also involved and very engaged in the activity. No one complained of motion sickness, headaches or eye strain.

4.5.3 Discussion. Taken together these findings are very encouraging for C(H)o(L)ordination usability and adoption. There are definitely some improvements that need to be done in the UX, especially with respect to gestures. We should enhance the support available directly during the execution of the tasks in the application interface and add a more specific gesture training. Ease the learning of HoloLens' use is a key factor in making the app really effective. Both qualitative and quantitative measures revealed that C(H)o(L)ordination is a usable tool for individuals with no expertise in MR or a Computer Science background. Additionally the app design is sound and allowed all subjects to set up, launch and run the application with little, if any, training.

5 CONCLUSION

C(H)o(L)ordination is an innovative MR application designed to investigate the relationship between language and action. To the best of our knowledge, our project is among the first developed by an interdisciplinary team of software engineers, psychologists and linguists. Furthermore is also the first to explore Microsoft HoloLens applications for testing anticipatory motor skills in subjects with Linguistic Impairment. The results of the empirical study, although preliminary, pointed out that the application can be easily employed and used in an autonomous and intuitive way even by subjects without specific technological competencies. C(H)o(L)ordination is a powerful tool, able to support the work of researchers by providing useful data and information regarding reaction time, gaze and subject performances. We believe that our work could be the beginning of a strand of research on the role of MR applications to gather insights on the ongoing debate about language evolution and language disorders.

6 FUTURE WORK

Our research is still at an early stage, hence there are many aspects that need to be explored further. Looking at the future, we envision many challenging directions for our work. First, in collaboration with psychologists and linguists, we will perform a broad and rigorous empirical study to investigate the relationship between motor-anticipation and linguistic-anticipation skills in young adults with LD. In parallel we will improve the actual prototype to avoid weaknesses that could be critical during a regular and intensive use. We are planning to add more features and give the possibility to choose various parameters before the execution of each activity such as: the speed of motion of the planet in its orbit/trajectory; the planet dimensions; the size of the area in which the planet is interactive. We are currently working on a data visualisation dashboard and some automated data analysis tools. Finally, we want to explore the role that rhythm plays in anticipatory skills. We will include auditory input, given by specifically composed and tailored-made rhythms.

REFERENCES

[1] Bruce Abernethy, Joanne M Wood, and Sheri Parks. 1999. Can the anticipatory skills of experts be learned by novices? *Research quarterly for exercise and sport* 70, 3 (1999), 313–318.

[2] Aaron Bangor, Philip T Kortum, and James T Miller. 2008. An empirical evaluation of the system usability scale. *Intl. Journal of Human–Computer Interaction* 24, 6 (2008), 574–594.

[3] Inge Bartning, Maisa Martin, and Ineke Vedder. 2010. *Communicative proficiency and linguistic development.* Vol. 1. Lulu. com.

[4] Dorothy V Bishop. 1992. The underlying nature of specific language impairment. *Child Psychology & Psychiatry & Allied Disciplines* (1992).

[5] John Brooke. 2013. SUS: a retrospective. *Journal of usability studies* 8, 2 (2013), 29–40.

[6] Pilar Casado, Manuel Martín-Loeches, Inmaculada León, David Hernández-Gutiérrez, Javier Espuny, Francisco Muñoz, Laura Jiménez-Ortega, Sabela Fondevila, and Manuel de Vega. 2018. When syntax meets action: brain potential evidence of overlapping between language and motor sequencing. *Cortex* 100 (2018), 40–51.

[7] Carol Chomsky. 1972. Stages in language development and reading exposure. *Harvard educational review* 42, 1 (1972), 1–33.

[8] Ruth Cumming, Angela Wilson, Victoria Leong, Lincoln J Colling, and Usha Goswami. 2015. Awareness of rhythm patterns in speech and music in children with specific language impairments. *Frontiers in human neuroscience* (2015), 672.

[9] Luciano Fadiga and Vittorio Gallese. 1997. Action representation and language in the brain. (1997).

[10] Michael D Fox, Randy L Buckner, Hesheng Liu, M Mallar Chakravarty, Andres M Lozano, and Alvaro Pascual-Leone. 2014. Resting-state networks link invasive and noninvasive brain stimulation across diverse psychiatric and neurological diseases. *Proceedings of the National Academy of Sciences* 111, 41 (2014), E4367–E4375.

[11] Angela D Friederici, Noam Chomsky, Robert C Berwick, Andrea Moro, and Johan J Bolhuis. 2017. Language, mind and brain. *Nature human behaviour* 1, 10 (2017), 713–722.

[12] Tim Gabbett, Martin Rubinoff, Lachlan Thorburn, and Damian Farrow. 2007. Testing and training anticipation skills in softball fielders. *International Journal of Sports Science & Coaching* 2, 1 (2007), 15–24.

[13] Esther Geva and Ellen B Ryan. 1993. Linguistic and cognitive correlates of academic skills in first and second languages. *Language learning* 43, 1 (1993), 5–42.

[14] Arthur M Glenberg. 2007. Language and action: creating sensible combinations of ideas. *The Oxford handbook of psycholinguistics* (2007), 361–370.

[15] Arthur M Glenberg and Michael P Kaschak. 2002. Grounding language in action. *Psychonomic bulletin & review* 9, 3 (2002), 558–565.

[16] Reyna L Gordon, Magdalene S Jacobs, C Melanie Schuele, and J Devin McAuley. 2015. Perspectives on the rhythm–grammar link and its implications for typical and atypical language development. *Annals of the New York Academy of Sciences* 1337, 1 (2015), 16–25.

[17] Yosef Grodzinsky. 1990. *Theoretical perspectives on language deficits.* MIT press.

[18] Satomi Higuchi, Thierry Chaminade, Hiroshi Imamizu, and Mitsuo Kawato. 2009. Shared neural correlates for language and tool use in Broca's area. *Neuroreport* 20, 15 (2009), 1376–1381.

[19] Falk Huettig and Susanne Brouwer. 2015. Delayed anticipatory spoken language processing in adults with dyslexia—evidence from eye-tracking. *Dyslexia* 21, 2 (2015), 97–122.

[20] Sonia Kandel and Cyril Perret. 2015. How do movements to produce letters become automatic during writing acquisition? Investigating the development of motor anticipation. *International Journal of Behavioral Development* 39, 2 (2015), 113–120.

[21] Iuliia Kotseruba and John K Tsotsos. 2020. 40 years of cognitive architectures: core cognitive abilities and practical applications. *Artificial Intelligence Review* 53, 1 (2020), 17–94.

[22] Ralf Kredel, Christian Vater, André Klostermann, and Ernst-Joachim Hossner. 2017. Eye-tracking technology and the dynamics of natural gaze behavior in sports: A systematic review of 40 years of research. *Frontiers in psychology* 8 (2017), 1845.

[23] Enikő Ladányi, Valentina Persici, Anna Fiveash, Barbara Tillmann, and Reyna L Gordon. 2020. Is atypical rhythm a risk factor for developmental speech and language disorders? *Wiley Interdisciplinary Reviews: Cognitive Science* 11, 5 (2020), e1528.

[24] Laurence B Leonard. 1981. An invited article facilitating linguistic skills in children with specific language impairment. *Applied Psycholinguistics* 2, 2 (1981), 89–118.

[25] Donald Loritz. 2002. *How the brain evolved language.* Oxford University Press.

[26] Xun Luo, Mei Han, Tao Liu, Weikang Chen, and Fan Bai. 2012. Assistive Learning for Hearing Impaired College Students using Mixed Reality: A Pilot Study. In *2012 International Conference on Virtual Reality and Visualization.* 74–81. https://doi.org/10.1109/ICVRV.2012.20

[27] Anthony F Morse and Angelo Cangelosi. 2017. Why are there developmental stages in language learning? A developmental robotics model of language development. *Cognitive Science* 41 (2017), 32–51.

[28] Raja Parasuraman and Matthew Rizzo. 2006. *Neuroergonomics: The brain at work.* Vol. 3. Oxford University Press.

[29] Timea R Partos, Simon J Cropper, and David Rawlings. 2016. You don't see what I see: Individual differences in the perception of meaning from visual stimuli. *PloS one* 11, 3 (2016), e0150615.

[30] Valentina Persici, Natale Stucchi, and Fabrizio Arosio. 2019. Predicting the future in rhythm and language: The anticipation abilities of a group of Italian-speaking children.. In *International conference 13 Generative Approaches to Language Acquisition (GALA 13), Sep, 2017, Palma de Mallorca, Spain; The scholarly articles included in this volume are based on presentations delivered at the aforementioned conference.* Cambridge Scholars Publishing.

[31] Barry M Prizant. 1996. Brief report: communication, language, social, and emotional development. *Journal of Autism and Developmental Disorders* 26, 2 (1996), 173–78.

[32] Friedemann Pulvermüller. 2005. Brain mechanisms linking language and action. *Nature reviews neuroscience* 6, 7 (2005), 576–582.

[33] Nathan Rosen. 1962. Field of a particle in uniform motion and uniform acceleration. *Annals of Physics* 17, 2 (1962), 269–275.

[34] Teenu Sanjeevan, David A Rosenbaum, Carol Miller, Janet G van Hell, Daniel J Weiss, and Elina Mainela-Arnold. 2015. Motor issues in specific language impairment: A window into the underlying impairment. *Current Developmental Disorders Reports* 2, 3 (2015), 228–236.

[35] Eckart Scheerer. 1984. Motor theories of cognitive structure: A historical review. *Cognition and motor processes* (1984), 77–98.

[36] Martin Schrepp, Jorg Thomaschewski, and Andreas Hinderks. 2017. Construction of a benchmark for the user experience questionnaire (UEQ). (2017).

[37] Christine Marie Tipper, Giulia Signorini, and Scott T Grafton. 2015. Body language in the brain: constructing meaning from expressive movement. *Frontiers in Human Neuroscience* 9 (2015), 450.

[38] Emanuele Torelli, Ibrahim El Shemy, Silvia Silleresi, Lukasz Moskwa, Giulia Cosentino, and Franca Garzotto. 2020. Do You Speak Holo? A Mixed Reality Application for Foreign Language Learning in Children with Language Disorders. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW).* 608–609. https://doi.org/10.1109/VRW50115.2020.00155

[39] Paolo Viviani, Paola Campadelli, and Pierre Mounoud. 1987. Visuo-manual pursuit tracking of human two-dimensional movements. *Journal of Experimental Psychology: Human Perception and Performance* 13, 1 (1987), 62.

[40] Paolo Viviani and Natale Stucchi. 1992. Biological movements look uniform: evidence of motor-perceptual interactions. *Journal of experimental psychology: Human perception and performance* 18, 3 (1992), 603.

[41] Paolo Viviani and Natale Stucchi. 1992. Motor-perceptual interactions. (1992).

[42] Francesco Vona, Emanuele Torelli, Eleonora Beccaluva, and Franca Garzotto. 2020. *Exploring the Potential of Speech-Based Virtual Assistants in Mixed Reality Applications for People with Cognitive Disabilities.* Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3399715.3399845

[43] Susan Ellis Weismer and Julia L Evans. 2002. The role of processing limitations in early identification of specific language impairment. *Topics in language Disorders* 22, 3 (2002), 15–29.

[44] Roel M Willems, Miriam De Boer, Jan Peter De Ruiter, Matthijs L Noordzij, Peter Hagoort, and Ivan Toni. 2010. A dissociation between linguistic and communicative abilities in the human brain. *Psychological Science* 21, 1 (2010), 8–14.

[45] Roel M Willems, Aslı Özyürek, and Peter Hagoort. 2007. When language meets action: The neural integration of gesture and speech. *Cerebral Cortex* 17, 10 (2007), 2322–2333.

[46] A Mark Williams, Paul Ward, Nicholas J Smeeton, and David Allen. 2004. Developing anticipation skills in tennis using on-court instruction: Perception versus perception and action. *Journal of applied sport psychology* 16, 4 (2004), 350–360.