**Università degli Studi di Padova**

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**TESI DI LAUREA**

# *Clinical effects of a multisensory intervention on communicative skills in patients with Severe Acquired Brain Injury: a multiple case study*

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# INDEX

# ABSTRACT

***Introduction:*** Severe Acquired Brain Injury (SBI) often results in profound impairments in consciousness and communicative engagement. Traditional rehabilitation frequently lacks tools specifically designed to bridge the gap between basic sensory stimulation and active social interaction. The Crdl, a Dutch haptic-based assistive technology, transforms skin-to-skin contact into auditory feedback, potentially facilitating non-verbal communication.

***Objective:*** This study aimed to evaluate the efficacy of sound-haptic multisensory stimulation in promoting the recovery of communicative skills, including attention span, eye contact, communicative initiative (turn-taking), and voluntary motor/verbal responses in patients with SBI.

***Materials and Methods:*** A multiple-case study design was employed within the Neurorehabilitation Unit of San Bortolo Hospital in Vicenza. The intervention consisted of daily 10–20-minute sessions with the Crdl device. Data were collected via an automated computational tool to quantify target responses (voluntary interactions and turn-taking) and clinical scales, including the Level of Cognitive Functioning (LCF) and Coma/ Near Coma scale (CNC). Absolute behavioural counts were normalized into rates per minute to ensure mathematical comparability. Linear regression models and independent samples t-tests were used to analyse longitudinal progression and differences between early and late intervention phases.

***Target Population:*** The cohort consisted of three patients with heterogeneous clinical profiles aged 14, 36, and 64 years, presenting with moderate-to-severe SBI.

***Results:*** Statistical analysis of the combined cohort revealed a significant difference in target response rates between the early and late intervention phases ($p < .001$). The results show an overall increase of responses, communicative engagement, attention time since the introduction of the Crdl in all the analysed cases.

***Conclusion:*** Multisensory stimulation represents a powerful clinical bridge for re-establishing a communicative channel in patients with SBI. This approach acts as a motivational catalyst, enhancing the velocity of communicative recovery. These results suggest that integrating multisensory protocols into traditional therapy provides a framework for emotional and relational engagement. Further research with larger samples is necessary to standardize these non-verbal communication protocols in neurorehabilitation.

# 1. INTRODUCTION

The present thesis project originates from the following research question: whether the use of multisensory and music-based stimulation may represent an effective tool for enhancing communicative abilities in SBI patients. This interest is framed within the growing trend toward integrating music and multisensory stimulation into rehabilitation interventions for patients with communicative and linguistic impairments across all ages, genders, and cultural backgrounds, with reference to individuals with severe traumatic brain injury.

Since the 1950s, researchers have begun to question the effectiveness of such stimulation in patients with severe traumatic brain injury. In recent years, numerous studies have further investigated the role of music and multisensory stimulation, as well as their effectiveness in comparison with routine clinical practice.

Certain studies indicated that sensory stimulation positively influenced arousal, awareness, neural activity, motor skills, and brain performance, while also decreasing hospital duration and lowering the rate of disability (Cheng et al., 2018; Houston et al., 2020; Padilla and Domina, 2016a, 2016b; Pape et al., 2015, Moattari et al., 2016; Lin et al., 2025). Conversely, Cheng indicated that sensory stimulation alone was insufficient to rouse patients (Cheng et al., 2014).

For the reasons outlined above, it was decided to test the effectiveness of this type of stimulation within the Neurorehabilitation Unit of San Bortolo Hospital in Vicenza on a small sample of patients, due to time constraints and clinical–organizational considerations, without excluding the interventions already implemented in the hospital. In particular, the aim was to evaluate a communicative stimulation program substantially different from those previously adopted for patients with severe acquired brain injury, who had been offered only sporadic functional activities designed to elicit automatic responses, with no specific intervention targeting communicative and relational aspects.

However, the need for a practical, compact, versatile, and easily transportable tool, suitable for use with different patient populations, soon became evident. To address this need, a device meeting all these requirements was developed in the Netherlands in 2016: the Crdl. This instrument converts touch into sound, enabling users to overcome language barriers and establish communicative interaction, yet it remains largely unknown in Italy, as well difficult to gather.

During the study, an additional need emerged for software capable of recording patients' responses in real time in order to monitor their progression and changes over time. For this purpose, an online application was developed specific for the Crdl and the patients involved in the study, allowing audio and/or video recording of patients, subject to informed consent, for subsequent analysis of their responses. In addition to this digital tool, periodic assessments were conducted through clinical observation and standardized scales, including the LCF, CNC, and GCS.

These considerations led to the primary objective of this thesis: to identify a practical, effective, functional, and non-invasive method for stimulating communicative and relational abilities from the earliest days of the post-acute phase.

This work represents a preliminary step toward the exploration and development of new communicative–relational stimulation techniques, not only for SBI patients but, more broadly, for all individuals requiring support in these domains.

The thesis project is structured as follows: the first section provides a general overview of patients with severe brain injury (SBI), multisensory stimulation, and the use of music therapy. This is followed by a description of the materials and methods employed to conduct the study, as well as an account of the training and clinical placements undertaken in the Netherlands in the spring of 2025 to acquire comprehensive knowledge of the techniques and practical applications of the instrument. Subsequently, the case studies included in the research are presented, together with an individual analysis of the data for each case. The thesis concludes with a final discussion in which the results are examined and interpreted, followed by a brief overall reflection on the study.

# 2. THEORETICAL FRAMEWORK

## 2.1 The definition of SBI

In the literature it's observed that there is a wide range of mistakenness between the definitions of: SBI (Severe Brain Injury), ABI (Acquired Brain Injury) and TBI (Traumatic Brain Injury); that are commonly switched one another without any purpose. In this paper we are going to give a proper initial definition and classification of these ones, but then we are going to use the acronym SBI.

According to the WHO and the GCS parameters a Severe Brain Injury is a brain injury resulting in prolonged unconsciousness or coma, significant disruption of normal brain function, and long-term or permanent cognitive, physical, emotional, or behavioural impairments.

A SBI can be:

- *Traumatic (TBI):* any kind of external force that can cause a trauma for the brain in a mild to severe level (e.g. car accidents, falls, assaults, sports injuries)
- *Non-traumatic (TBI or ABI):* the cause in an internal factor such as: cardiac arrest (hypoxia), stroke, brain infections, aneurysm rupture, tumour.
  The general acronym ABI is referred to all the brain injuries that occur after birth, traumatic or not and with any level of severity.

Its mainly measure evaluation scale is the GCS (Glasgow Coma Scale) developed in 1974 by Graham Teasdale and Bryan Jennett and it's now used globally to classify the severity of any kind of TBI. According to Wagner and colleagues (Wagner et al. 2021) three categorisations of TBI severity are recognised:

- mild TBI (GCS = 13–15),
- moderate TBI (GCS = 9–12),
- severe TBI (GCS = 3–8). Severe TBI typically results in a loss of consciousness, and its duration, as well as length of post traumatic amnesia (PTA) (Ponsford et al., 2016), are negatively correlated with functional recovery and poorer prognosis (Wagner et al. 2021).

### 2.1.1 Epidemiology

A Traumatic Brain Injury is characterized as organic harm to brain tissue and a disturbance in brain function resulting from external physical forces applied to the head (Pervez et al., 2018). The primary reasons include: traffic collisions, falls from elevated places, and injuries from firearms. Traumatic brain injury, often referred to as the "silent epidemic" refers to greater mortality and disabilities than any other type of trauma (Dewan et al., 2018).

The World Health Organization estimates that annually, 69 million people experience traumatic brain injuries in the world, with the highest rates occurring in the Americas and Europe (Dewan et al., 2018).

In 2021 Brazinova et al. conducted a systematic review on the epidemiology of TBI in Europe. They analysed 66 studies, and they found out that there is a range between 47.3-694 per 100,000 people each year, with a mortality index settled between 9-28.10 per 100,000 inhabitants of each European country. The most common mechanisms of injury were the same as the one presented by the WHO: road traffic accidents and falls.

Another important data is represented from the epidemiological aspect of TBI in Northeast of Italy: 212.4 per 100,000 in 2000, mainly caused by motor vehicles accidents, work-related injury and domestic accidents (Baldo V. et al., 2003). The same study showed that the percentage of male compered to female has been always higher since 1996, with a range of age settled between 13-74 years old.

### 2.1.2 Stages the consciousness' level

As Laureys and his colleagues underline during a study in 2007, the increase of the consciousness' level of an SBI patient is define by two parameters:

- *Awareness* refers to the contents of consciousness, thoughts and feelings of an individual and coincides with a person's ability to perceive and interact with the outside world. It represents the understanding that the subject has of itself and the world around.
- *Arousal* is a continuum from wakefulness to sleep and can change suddenly in the presence of significant external stimuli. It is a condition without which there can be no awareness.

Considering these parameters there can be defined three main alterations of the consciousness' level: coma, vegetative state (VS) and minimally conscious state (MCS).

There is also a particular clinic condition characterised by a total absence of motor response despite the eyes' one, but with a total or semi-total integrity of the cognitive functioning: *locked-in syndrome*. (Fig.1, 2)

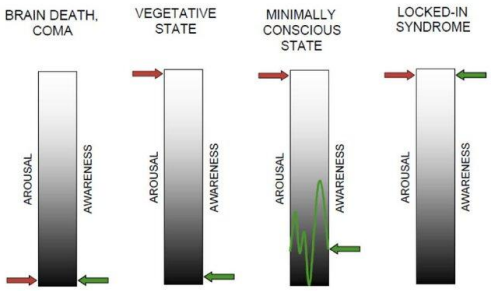


*Fig.1 Two dimensions of consciousness: arousal and awareness. According to Laureys et al. (2007), arousal and awareness fluctuate along a clinical continuum: both are absent in coma, dissociated in VS (arousal without awareness), inconsistently present in MCS, and fully preserved in LIS despite profound motor and speech deficits. (reprinted from: Giacino et al., 2009)*

*Coma state* is defined as a "deep, sustained pathologic unconsciousness that results from dysfunction of the ascending reticular activating system in either the brain stem or both cerebral hemispheres. The eyes remain closed, and the patient cannot be aroused." (Multi-Society Task Force Report on PVS, 1994).

From a neurobehavioral point of view, the patient can't open his/her eyes neither after a very intensive stimulation from the outside; he/she isn't speaking or demonstrate intentional movements. Besides this, some reflex movement can be observed. A coma patient doesn't have any consciousness parameters.

The *VS* is "a clinical condition of complete unawareness of the self and the environment, accompanied by sleep-wake cycles, with either complete or partial preservation of hypothalamic and brain-stem autonomic functions" (Multi-Society Task Force Report on PVS, 1994). In this stage the patient can't be awakened neither spontaneously nor by someone else.

From a neurobehavioral point of view there's no evidence of a behavioural voluntary responses or some other action made for purpose, maintained or replicable after an auditory, tactile, visual or pain stimulation; there's no comprehension or verbal interaction. The only thing that it can be observed is the presence of arousal, but not awareness. In 2010 Laureys et al., suggested a linguistic change to better describe the syndrome, but also to remove the idea coming from the vegetables' world, from Vegetative Status to Unresponsive Wakefulness Syndrome (UWS). From now on this second acronym will be used to describe this condition.

The last possible condition is presented by *MCS* patients, whose state is characterised by an "inconsistent but clearly discernible behavioural evidence of consciousness and can be distinguished from coma and VS by documenting the presence of specific behavioural features not found in either of these conditions" (Giacino et al., 2010). Also in this case it can be useful describing the neurobehavioral characteristics: answer and understanding or easy command, yes/no verbally or motor answers, intelligible verbalization, aimed finalized behaviour or consistent emotional response. All these performances are constant are replicable (Fig. 2).

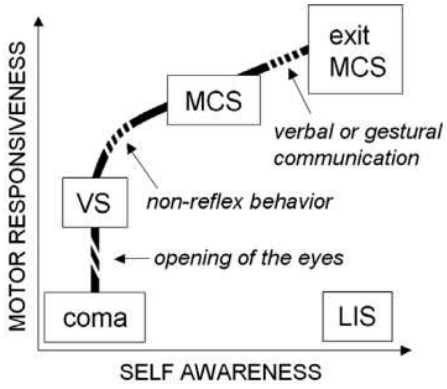


*Fig. 2 Increase in responsiveness related to the level of vigilance: The assessment of self-awareness in SBI patients is clinically constrained by their motor responsiveness. Recovery follows a continuum from Coma to Vegetative State (eye-opening), progressing to Minimally Conscious State (voluntary behaviour), and finally Emergence (functional communication). This hierarchy highlights how profound motor deficits, as seen in Locked-in Syndrome, can mask intact cognition. (reprinted from: Laureys et al., 2007)*

### 2.1.3 Evaluation of the consciousness' level

*Coma Recovery Scale Revised* (CRS-R) (Giacino, Kezmarsky, De Luca and Cicerone, 1991). First described by Giacino and collaborators in 1991 and subsequently adapted (Giacino, Kalmar and Whyte, 2004; Italian version edited by Lombardi, Gatta, Sacco, Muratori and Carolei, 2007). This scale has been developed with the intention of differentiating diagnosis between UWS and MCS and between the latter and the emergency from it (EMCS). It consists of 25 items distributed in six different scales (each organized hierarchically) that evaluate the patient's responses to auditory and visual stimuli, his motor and communicative skills and the level of vigilance:

1. Auditory functions
2. Visual functions
3. Motor functions
4. Oromotor/verbal functions
5. Communication stairs
6. Arousal scale

The mode of administration and expected scoring responses are detailed and precise. In each of the six scales, items with lower scores describe reflex activities, while those with higher scores indicate the emergence of cognitive functions.

*Coma/Near Coma Scale* (CNC) (Rappaport, M. (2000). *The Coma/Near Coma Scale*. The Center for Outcome Measurement in Brain Injury. http://www.tbims.org/combi/cnc) presents five levels that define the awakening and awareness level, as well as the grade of responsivity:

1- *NO COMA:* consistently and readily responsive to at least 3 sensory stimulations tests plus consistent responsivity to simple commands
2- *NEAR COMA:* consistently responsive to stimulation presented to 2 sensory modalities and/or partially responsive to simple commands
3- *MODERATE COMA:* inconsistently responsive to stimulation presented to 2 or 3 sensory modalities but not responsive to simple commands. May vocalize (in absence of tracheostomy) with moans, groans and grunts but no words.
4- *MARKED COMA:* inconsistently responsive to stimulation presented to one sensory modality and not responsive to simple commands. No vocalization
5- *EXTREME COMA:* no responsivity to any sensory stimulation tests; no response to simple commands. No vocalization

The difference between the CNC and CRS-R are that the first one is faster to fill out, but explores less functions than the CRS-R, so it's less accurate. From the other side the CRS-R is more accurate and precise in the functions' description, but it uses more attention and energy from the patient, so much that in the clinical practice sometimes it's impossible to conclude in just one session the scale.

The *Levels of Cognitive Functioning* (LCF) Scale (Lin et al., 2022), commonly referred to as the Rancho Los Amigos Scale, is a standardized clinical tool used to describe and track the cognitive and behavioural recovery of individuals with severe acquired brain injuries, such as traumatic brain injury (TBI) or post-coma conditions. Originally developed at the Rancho Los Amigos National Rehabilitation Centre, the scale comprises eight levels, each representing a specific stage of recovery, from Level I (No Response), where the patient shows no observable reaction to stimuli, to Level VIII (Purposeful, Appropriate Response), where the individual can function independently with minimal assistance.

The other levels of the LCF:

*Level 1:* No Response: Total Assistance

*Level 2*: Generalized Response: Total Assistance

*Level 3:* Localized Response: Total Assistance

*Level 4*: Confused/Agitated: Maximal Assistance

*Level 5:* Confused, Inappropriate Non-Agitated: Maximal Assistance

*Level 6:* Confused, Appropriate: Moderate Assistance

*Level 7*: Automatic, Appropriate: Minimal Assistance for Daily Living Skills

*Level 8:* Purposeful, Appropriate: Stand By Assistance

The LCF Scale focuses on cognitive and behavioural responses, including arousal, attention, orientation, memory, and the ability to interact with the environment. It is widely used by healthcare professionals to guide rehabilitation planning, assess progress over time, and facilitate communication among multidisciplinary teams. Though not a diagnostic tool, it provides a valuable framework for understanding the patient's current abilities and potential for further improvement.

## 2.2 SBI patient's stages and take over

The stages that an SBI patient must go through are:

1. *Acute stage* (from the moment that the trauma occurs until the stabilization of the vital parameters). This stage as a very wide range, time meaning, due to the level of the damage's gravity and the linked lesions; more less it can last from days to a certain number of weeks. The principal goals that want to be achieved are:
    - Determine the level of clinical gravity
    - Containment of primary damage
    - Stabilization of vital parameters
    - Prevention of secondary damages
    - Resumption of patient's contact with the surroundings

    In this stage the patient is in reanimation and neurosurgery departments. According to the Consensus Conference that took place in 2000 it was suggested to begin the rehabilitation intervention as soon as possible.

2. *Post-acute stage* (from the stabilization of the vital parameters until impairments' stabilization). This stage can be divided into other two sub-stages:
    a. *Early stage:* the multidisciplinary rehabilitation programmes are focus on the Activity Daily Living (ADL). The patient is usually staying in a specialized rehabilitative structure, that in Italy are called UOC (Unità Operativa Complessa)
    b. *Late stage:* at this stage the patient achieves a quite stable condition. For this reason, the multidisciplinary rehabilitation goals move to a higher level of difficulty to achieve the highest and the best functional autonomy possible, as well as the highest QoL (Barr O., 1997). This stage is usually achieved at about 6 months after the trauma happened.

3. *Outcome*, this final part of the clinical treatment aims to find again a social integration by reducing as much as it's possible all the impairments, also through the introduction of new assistive technologies. If this last condition is needed, the most important thing to underline is the necessity of a specific training for the patient and his/her care givers, that teach how to use and take care of the device.
   This final stage can be predicted by some prognostic factors. Murray et al. (2007) argued that the most significant prognosis factors are: age, GCS score, pupillary response, TAC evaluation, prothrombin level spread in time, hypotension, hypoxia, verbal and visual score at the GCS, glucose level and the number of platelets (Murray et al. 2007). According to other studies another relevant factor that can help to predict the outcome level is PTA's duration (Post-Traumatic Amnesia), during the post-acute stage (Brown et al., 2005; Willesme-van Son, Ribbers, Verhagen e Stam, 2007). This factor is usually registered through the GOAT scale (Galveston Orientation and Amnesia Test) (Levin et al. 1979).

Often the framework of compromise in SBI patients is so complex as to require a path that involves health and social interventions and therefore presupposes multidisciplinary management.

The term "multidisciplinary" emphasizes the impossibility of a therapeutic intervention carried out by a single professional of rehabilitation who can, alone, meet the different clinical and care needs of this type of patients (Basaglia, 2002).

"Taking charge" means the implementation of an "integrated and continuous process and the management of an articulated and coordinated set of interventions which affect conditions that hinder social, educational and occupational integration" (Conferenza Nazionale sulle Politiche dell'Handicap, 1999). In 2005, within the framework of the II National Consensus Conference on GCA (2005), the need for a multidimensional and interdisciplinary approach to the patient is stressed, which guarantees not only the medical-health care adapted to the clinical conditions, but also to satisfy the right to autonomy, to integration in the family and community, the right to work and study. Rehabilitation therefore aims to act on the multidimensional sphere identified by the ICF (International Classification of Functioning and Disability, WHO 2001) and must involve both health professionals and professionals outside the hospital who can ensure the patient's take care aimed at social reintegration (Fig. 3). For these reasons, the rehabilitation path of people with serious brain injuries should be made up of coordinated and integrated interventions by different operators, according to a group work approach (Basaglia, 2002). Carried out with the active involvement of the patient and family. The Cochrane review published on this topic (Turner-Stokes, Nair, Sedki. Disler and Wade, 2005) highlights how the integrated approach of multiple professionals promotes a better outcome in SBI aged 15 to 65 (sample to which the studies are analysed).

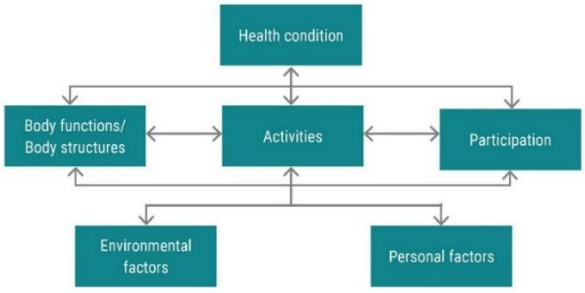


*Fig. 3 Bio-phyco-social model of the International Classification of Functioning Disability and Health (ICF)*

In a professional rehabilitation project, the team comprises the patient, their family, and a large range of specialists working toward shared therapeutic goals (Basaglia, 2002). Literature distinguishes between a multidisciplinary approach, focused on impairment and single-function recovery, and an interdisciplinary (or interprofessional) approach, which prioritizes social participation and activity levels (Koerner, 2008). For patients with high impairment or SBI, the interdisciplinary model is considered superior (Basaglia, 2002; Heruti and Ohry, 1995), requiring structured communication between all stakeholders to ensure effective awareness and goal alignment.

### 2.2.1 Communication and language impairments in SBI patients

After a brain injury due to vascular or trauma causes, anoxia or other conditions, a person can develop communication and language impairments, resulted from brain distress and strictly connected to the level of consciousness and cognitive functioning. Moreover, the specific impairment is also the result of the area that was involved during the previous said injury. Some specific deficits that can be observed in a SBI patient are: dysarthria, aphasia, pragmatic impairment, articulation impairments and general communication problems due to a lack of the communication prerequisites (arousal, awareness, attention, eye contact, space/temporal/personal orientation, motivation, collaboration).

Communication and language impairments not only affect the functional level of a person, instead they have also a big impact on the QoL, autonomy and his/her participation in the social life after the recovery. In fact, SBI patient that are already in an outcome stage can still present noticeable impairments that affect the person's social surroundings. One that note the rehabilitation goal for the speech and language is in the first acute stage, to try to get in contact with the patient by building a strong and solid connection with him/her; only from that it can be build a basis yes/no answer and perhaps also a verbal binary response.

Finally, the rehabilitation aim of speech and language impairments in a SBI patient is not only focused on the treatment of that specific impairment, but also and, perhaps, mainly with the training to handle his/her difficulties in a daily routine in the best possible way (WHO, 2002).

### 2.2.2 The multisensorial stimulation

Starting in the early 1950s, researchers at the Institutes for the Achievement of Human Potential (IAHP) in Pennsylvania have presented and backed the notion that "programs of environmental stimuli via all five sensory channels, at levels of frequency, intensity, and duration well beyond what is typical in hospitals, may improve the speed and extent of recovery from coma and potentially facilitate synaptic reinnervation." They indicated that "in comatose patients, while the issue is mainly cerebral, there exists a state of 'environmental deprivation' which may result in extensive impairment of cognitive and perceptual functions along with alterations in cerebral electrical activity." (Le Winn EB et al., 1978).

Sensory stimulation involving hearing, touch, sight, taste, and smell, which is non-invasive, cost-effective, and straightforward (Park, 2016), has been applied in practice. Nonetheless, the findings of research regarding the efficacy of sensory stimulation are questioned. Certain studies indicated that sensory stimulation positively influenced arousal, awareness, neural activity, motor skills, and brain performance, while also decreasing hospital duration and lowering the rate of disability (Cheng et al., 2018; Houston et al., 2020; Padilla and Domina, 2016a, 2016b; Pape et al., 2015, Moattari et al., 2016; Lin et al., 2025). Conversely, Cheng indicated that sensory stimulation alone was insufficient to rouse patients (Cheng et al., 2014).

For all the reasons presented above and a strong amount of studies that underline the need of multidisciplinary approach through different types of stimulation, our study will just add another strong stimulation without cutting of all the other ones.

## 2.3 Music Therapy in SBI

In the last decade, a new rehabilitative approach has started to emerge with strong efficacy evidence: auditory stimulation through music and meaningful sounds.

Listening to music enhances cognitive abilities like memory, attention, and behavioural improvement. In rehabilitation, therapies involving music demonstrate a high success rate for treating depression and anxiety, as well as in neurological conditions like restoring bodily integrity following a stroke (Toader et al., 2023). At the heart of our emotional connection to music lies the limbic system, a complex network of neural circuits and pathways. Essential elements of this system, like the amygdala, linked to emotional processing and the hippocampus, crucial for memory consolidation, get activated during exposure to music. These neural actions explain the compelling ability of music to elicit strong emotional and memory-related experiences (Toader et al., 2023). The resultant effects can be noticed when a person is emotionally carried to a different time or place upon listening to a specific musical composition or when a range of emotions is felt in reaction to sound stimuli (Brown, Martinez and Parsons, 2004). The therapeutic effects of music have also been demonstrated to aid in post-operative recovery, easing pain and anxiety while decreasing reliance on painkillers (Särkämö, 2018).

Robust evidence suggests that music listening is vital for neurological rehabilitation (Bilge et al., 2008); it is believed that music affects neural networks, boosts synaptic

plasticity, and enhances perception systems (Riganello et al., 2015; Schnakers et al., 2016). Additionally, engaging with music successfully stimulates the limbic system and reward pathways in the brain, resulting in feelings of comfort and tranquillity for individuals (Luaute et al., 2018; Rollnik and Altenmuller, 2014). To support this thesis, more neuroimaging studies have been conducted and found that music stimulation can activate a large brain network in both temporal lobes, but also the frontal one and the parietals, cerebellum and limbic structures (Sarkamo et al., 2008). As we already know these structures are closely related to attention, executive abilities, language comprehension and production and a lot of other prerequisites that are fundamental to build a connection and then a communication system with the patient.

For all the pre-mentioned studies it has been thought about Crdl as the perfect instrument that can help a patient to build the first connection and then a proper communication system, useful for the client's family, too.

### 2.3.1 Efficacy of Crdl as an instrument of reconnection and communication

The Crdl represents a multisensory stimulation just by itself, thanks to its touch, needed to evoke music; the sounds produced and the suggested eye contact in order to gain a faster connection with the patient.
During the last few years some therapists got interested in what Crdl could do and what could its application be. Most of the studies that were conducted, used Crdl with dementia clients to build a non-verbal connection with them and perhaps help the family to restore a connection with their beloved ones; a connection that without the Crdl would have been lost. In fact, one of the main purposes of this study was also linked with this discovery; thus, try to rebuild a lost connection between the patient and his/her family.

In the dementia field the Crdl has been known to have the power to bring memories back to life, promote and support a conversation, create a connection and at final relax and calm some people's stressful and agitated behaviours (Teunissen, Luyten and de Witte, 2017; Luyten et al., 2018; Janssen-Bouwmeester et al., 2020).

Other studies have been conducted about the use of Crdl in a population of people with PIMD (Profound Intellectual and Multiple Disabilities) with a wide age-range, whose results showed that the Crdl was effective in improving mood and reducing behavioural problems in some children and young adults. Moreover, the effect of the Crdl on alertness

and initiative varied within and between participants and each group's characteristics (Peters-Scheffer, Tuenter, Frankena, 2018).

Moreover, one of the latest field of research in which the Crdl has been starting to be studied is about the hypothesis that touch and sound can affect heart rate and so, prevent from heart diseases. About this topic more studies have to be conducted, as well as in all the applied fields and with different kind of patients, too. This will improve the lack of evidence that is now observed and give more value and relevance to all the thing that this instrument can do.

The latest study conducted by Dr. Anthony M. McCrovitz in May 2024, explored the potential benefits of using the Crdl, focusing on its impact on ten specific indicators of emotional and cognitive well-being (interest, excitement, frustration, engagement, relaxation, boredom, attention, cognitive stress, cognitive pressure, cognitive load), measured trough a wearable EEG (Fig. 4). The study revealed that regular use of the Crdl significantly enhanced the QoL for all twelve seniors involved, evidenced by increased emotional and cognitive engagement and reduced mental strain over time. The positive trends across the ten indicators suggest that the Crdl in an effective tool for fostering meaningful interactions and improving overall well-being, as well as a reduction of anxiety. These finding highlight the potential of the Crdl to support cognitive and emotional health, offering a promising approach to enhancing the quality of life in aging populations.


*Fig. 4 Pre and post-Crdl scores across 10 indicators: the graph illustrates the results of the study conducted in the U.S. and shows the ten indicators' level before and after Crdl's stimulation*

# 3. MATERIAL AND METHOD

## 3.1 Aim of the study

This thesis aims to identify an effective strategy for enhancing communicative abilities in severe brain injury (SBI) with very low levels of consciousness, in whom functional activation is particularly difficult (LCF levels 1–3). Additionally, it seeks to implement a mode of stimulation that is more motivating from a communicative and relational perspective, using a single multisensory instrument: the Crdl. The strategy that has been applied it's different from the one that is currently use at Vicenza's ICU (Intensive Care Unit), where the internship took place. Currently, the rehabilitation protocol involves functional stimulation of the patient through exposure of individuals in a UWS or minimally conscious state to functional contexts aimed to elicit an automatic response. For example, physiotherapeutic interventions include postural management, such as transferring the patient from the bed to a wheelchair, as well as mobilization procedures intended to prevent pressure ulcers and tissue atrophy. Internal hospital protocols also would include the involvement of occupational therapists in the performance of activities of daily living (ADLs), including hygiene at the sink, the use of utensils during meals, personal care, and other daily tasks tailored to each patient's needs. However, due to organizational and clinical constraints within the hospital timing and needs, these activities are often reduced or discontinued. Furthermore, this type of stimulation is merely request-based on the part of the speech therapist and relies on a single sensory channel; that is, it primarily engages either vision or hearing to elicit responses from the patient, without providing meaningful motivation or feedback that could actively encourage participation or facilitate the production of a response.

In contrast, the Crdl approach and multisensory stimulation strategies involve the simultaneous use of multiple sensory channels, thereby offering stronger and more meaningful motivational support, as the intervention is specifically tailored to the individual patient's needs.

Consequently, patient management frequently relies predominantly on pharmacological treatment, particularly the administration of dopaminergic agents (e.g., amantadine) aimed to enhance cerebral dopaminergic activity. Nevertheless, this medication presents a significant contraindication, namely an increased risk of epileptic seizures; should such

events occur, the drug must be immediately discontinued, along with the associated dopaminergic stimulation.
From a communicative and relational perspective, no targeted intervention is typically provided by speech and language therapists, aside from periodic assessments and monitoring activities.

For the reasons outlined above, it was therefore considered necessary, appropriate, and clinically relevant to test the use of multisensory stimulation delivered through a practical, portable, and easily adaptable device. The goal was to implement stimulation from the earliest days of the acute phase in order to elicit foundational communication skills (extension of attention span, stimulation of communicative interaction, increased motivation, promotion of communicative initiative, eye contacts and voluntary responses to requests), such as eye contact, turn-taking, imitation, increased attention span, and the emergence of voluntary responses, in order to improve a faster and more effective recovery. Moreover as the literature suggests, an auditory stimulation can significantly affect the level of consciousness (Çevik et al, 2018), moreover if it is done through familiar sounds that were significant for the patient before the accident occurred (Vanoni et al. 2021).

## 3.2 The instrument: Crdl

The Crdl is an interactive care instrument made of high-quality wooden material that can translate touch into sounds.
Crdl is meant for making a significant impact on relationships among individuals. It offers a sensory journey that delves into the sensory realm of the beauty of tactile sensation and auditory stimulation (Fig. 5).

*"Touch is care, and care is an innate need of all of us"*

*Fig. 5 The Crdl*

*From* https://centriahealthlab.fi/sv/utrustning/crdl-2/

### 3.2.1 The history of the instrument and the company's founders

The Crdl was assembled by Dennis Schuivens and Jack Chen, friends who were studying Architecture and Design in the Netherlands at the Sandberg Institute for their Master's degree. They dedicated three months to their graduation project, collaborating with a care institution to investigate how design could enhance the lives of individuals with dementia. Following four years of experimentation and development, the inaugural Crdl was ultimately prepared for manufacturing by 2016. The founders view all humans as being inherently interconnected and believe that care goes beyond just a service.

### 3.2.2 Structure of the instrument: product specifications

Dimensions: 405 * 250 * 155 (l * w * h in mm)
Weight: 3,2 kg.
Operating temperature Range: 10 - 40 °C
Operating Humidity Range: 40 - 60% relative
Battery type: Lithium-Ion
Average operating time on 1 battery charge: 24+ hours
Battery charging time (empty to full): 5 hours

Crdl Safety & Maintenance Summary

- *Contraindications:* do not use with pacemakers or during pregnancy.
- *Environment:* avoid liquids, direct sunlight, extreme heat, and high humidity.
- *Handling:* prevent impacts/drops, do not disassemble, and keep away from electromagnetic sources (TV/radio).
- *Cleaning:* use only a soft, dry cloth; avoid organic solvents.
- *Emergency:* stop use immediately if smoke, heat, or unusual smells occur.

The Crdl is crafted from premium solid wood, a natural material characterized by inherent variations in grain, density, and colour. Although pre-treated with protective wood oil (Rubio Monocoat Pure) to mitigate environmental susceptibility, the instrument remains sensitive to fluctuations in temperature, light, and humidity. Consequently, prolonged exposure to direct sunlight or extreme environmental conditions should be avoided to preserve its structural and aesthetic integrity. To ensure optimal preservation, it is recommended to store the device in its dedicated high-quality suede and felt-lined case when not in use. For maintenance, a soft, slightly damp cloth is sufficient for routine

cleaning, while antimicrobial wipes may be employed for disinfection; however, the use of organic solvents or aggressive chemical agents is strictly prohibited.

### 3.2.3 Functioning

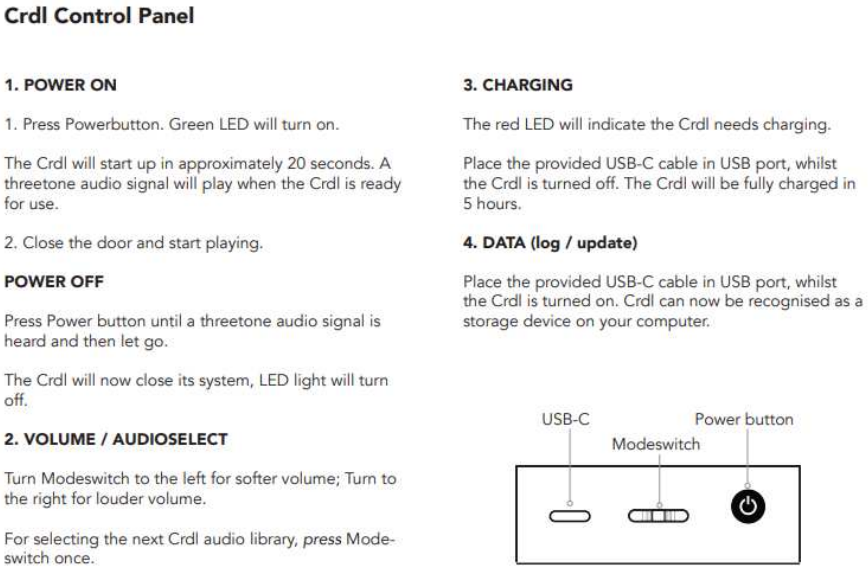


*Fig.6 Crdl control panel: the image illustrates Crdl's functioning (from the Crdl brochure)*

To operate the Crdl, press and hold the Power button until the led turns green; the device is ready after a 20-second startup and a three-tone signal. To power off, hold the button until the same signal sounds and the light extinguishes. A red led indicates a low battery, requiring approximately five hours for a full charge (Fig. 6).

The Crdl features 15 pre-programmed soundscapes. Users can access the configuration menu by double-tapping the device. Once the menu signal is heard, tilting the instrument toward either hand-rest allows for sound selection, while clockwise or counterclockwise rotation adjusts the volume. A final audio signal confirms that the settings are saved and the menu has been exited.

Crdl can be touched in different ways; each one of them produce different kind of sounds based on the theme (principal trace) that has been chosen. During the creation of a sound there is no obligation to link all the gesture to a sound; this means that if a sound remains empty, when you will make that gesture no sound will be played, unless the ambience one.

- *Ambience:* it's the background layer that can be used to steer the overall feel. This sound will be heard every time that the Crdl is touched and it will turn off once there's no more interaction.

- *Holding:* this layer will be heard as long as you hold each other while touching the Crdl.
- *Stroking:* the sound connected to this gesture will appear when stroking or rubbing slowly back and forth during a Crdl interaction.
- *Tipping:* this layer is the shortest touch that can be recognised during a Crdl session, and it is triggered by a single brief touch, usually performed with one single finger. This gesture can be linked to one or more sounds.
- *Tickling:* this gesture is performed by multiple single taps that are quickly repeated within 0,5s from each other. This gesture can be linked to one or more sounds.
- *Kneading:* this gesture is likely to be played less frequent than others, because it's the least comfortable one from a patient's perspective. It can be triggered when exerting point-pressure on a body part, for example squeezing a phalange of a hand. This gesture can be linked to one or more sounds.

The sounds that are pre-programmed on the Crdl are:

01. Nature: Atmospheric soundscape of a beach scene with an ambient background.
02. City: Soundscape around the theme of a early 20th century city.
03. Farm: Soundscape describing a scene of animals at a cottage-farm.
04. Sitar: Instrumental composition highlighting sitar as the main instrument.
05. Atlantis: Atmospheric soundscape describing a scene of an underwater grotto.
06. Chopinish: Musical composition with piano as lead instrument.
07. Drummer: Rhythmic composition with a drum set.
08. Hang drum: Atmospheric soundscape with hang drum as lead instrument.
09. Impressionist: Musical composition with piano.
10. Fm Synth: Generative soundscape with synthesizer as main instrument.
11. Rainforest: Atmospheric soundscape describing a jungle scene.
12. Birds: Soundscape carrousel of bird sounds. Every touch triggers a new bird.
13. Spring Orchestra: Musical composition with piano, clarinet and violin.
14. Twinkle Twinkle Little Star: Lullaby with playground ambience.
15. Solstice: Atmospheric soundscape describing a sunrise scene with an ambient layer.

The Crdl system offers five distinct auditory responses per soundscape, dynamically triggered by varied tactile gestures between the operator and the patient. Beyond the 15 pre-installed themes, researchers can develop customized auditory protocols via the Crdl

Soundscaper web interface. This platform facilitates the upload of external audio files, original recordings, and the mapping of specific sounds to designated gestures. Modified soundscapes are subsequently transferred to the device via a USB-C interface for local installation.

### 3.2.4 Crdl concept and use

The Crdl is a touch-based device that transforms user interactions into an auditory feedback. It is created to facilitate different types of communication among individuals facing challenges with social interaction or communication, like individuals with dementia, autism, or mental disabilities and their caregivers, loved ones, or friends. The Crdl encourages users to interact with one another through playful and adventurous physical contact. In order to convert touch into sound, it is crucial for users to create a closed circuit with the Crdl.

The simplest way to make the instrument work would be:

1) Two individuals place one hand each on the opposite touchpad of the Crdl.
2) While their hand is placed on the touchpad, users make contact with each other's bare skin, effectively completing a circuit.
3) The Crdl detects and acknowledges various types of contact between individuals and converts them into audio/music snippets.

Additional users can easily be included in the circuit by adding them in, similar to adding links in a chain (Fig. 7).

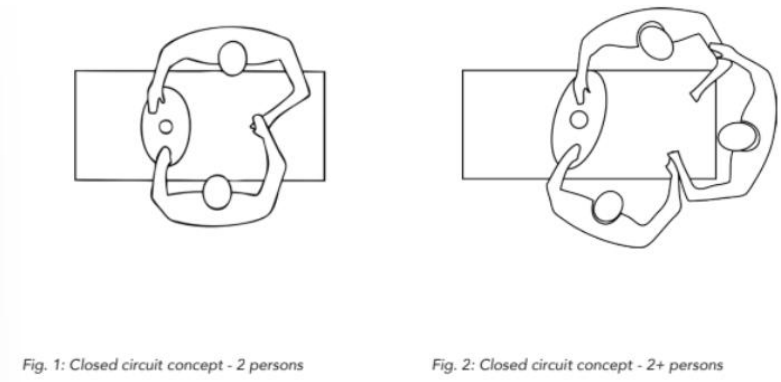


*Fig. 7 Crdl's options in the function: single use or in a chain of as much people as you want (from the Crdl brochure)*

The functioning of the Crdl may be impacted by the temperature, humidity of the environment, and the hydration level of the body. For users with extremely dry skin it's suggested to apply moisturizing cream before using the Crdl device.

### 3.2.5 Availability and distribution

The device is currently being used at over 1,500 healthcare facilities across Europe, Asia, and North America and received a respected CES Innovation Award 2023 and the 2022-editions of: the Dutch National Care Innovation Award, Social Enterprise Held Care, Purpose Award, NRC Live Moonshot Startup of the Year, and NRC Live Care Technology Startup of the Year (from: https://time.com/collection/best-inventions-2023/6327166/crdl/). In Italy there are just two of them: one at the University Federico II in Naples and one in an elderly care house near Bologna.

### 3.2.6 Target population nowadays

Nowadays experts from many healthcare areas say that the Crdl has been used with many different kind of pathologies as: Alzheimer disease, Dementia, Autism, Cognitive disabilities (e.g. ADHD, cerebral palsy, different types of syndromes, etc.), patients with motor limitations, blindness, behavioural difficulties (mainly children), PIMD (Profound Intellectual and Multiple Disabilities) and in the palliative care field. Nowadays there aren't many studies as it should, about the use of Crdl in all these fields. Most of the researches are about dementia probably, because the instrument was born initially for this target of patients and then it has expanded to a larger group.

This instrument has no age target; indeed, it has been used with a large target of patients, age meaning (Dr. Nienke Peters-Scheffer et al., 2018).

## 3.3 Fieldwork experience

In order to have a proper understanding of the Crdl in winter 2024 I apply to SEND internship project and I won a scholarship that gave me the opportunity to go to the Netherlands where the Crdl born and where all the main experts are. My internship lasted from the 29$^{th}$ of March 2025 until the 30$^{th}$ of May 2025, during which I was given many opportunities that enriched my knowledge about Crdl but also about SBI. During that time I stayed at the University of Zuyd where the teachers Pauline Lahoye and Jessica Frembgen helped me in my research. But I didn't just settle for a theoretical study, I also got in contact and went to visit Crdl's industry with the manager and founders of Crdl: Ger Schuivens, Denis Schuivens and Jack Chen. To conclude my professional education, I also arrange a meeting at two Sevagram residences with two music therapists that use Crdl with people with dementia in different stages.

### 3.3.1 Internship at Zuyd University

During my stay in the Netherlands the majority of my time was spent at Zuyd University in Heerlen, a small city near Maastricht. During the first month I was able to deepen the knowledge of SBI, thanks to the rich library both physical and digital that the University offered to me. Moreover, I had the opportunity to speak with some teachers that during their career have used Crdl in different fields such as: nursing, speech and language therapy, palliative care, music therapy and creative therapy. I discovered that in the Netherlands exists a lot of bachelor's degrees that in Italy doesn't really exist or perhaps they are just master's degrees or even available courses that you can do after your main degree.

The first specialist with whom I spoke with, was a nurse that in his past worked in a residence where people with different kind of cognitive disabilities lived, most of them with dementia syndrome. He gave me very precious advices about how to structure a Crdl session; firstable you have to discover a bit about the patient (past history, family, job, personal interests, hobbies, favourite songs, etc.), then you have to engage him and try to gain his/her trust. Only at that point you can start to use Crdl with the highest frequency that you can have according to the busy schedule that every clinician has. On that note he highlighted something true that I've never thought about: Crdl hasn't got any side effects despite of other types of medication, its only cons is that the effects that Crdl brings are mainly in that moment and perhaps a few moments after, but not long-lasting.
He used Crdl whenever he had time, with the aim of relaxing patients and change their behaviour from aggressive to calm. He also used it as an instrument of communication between care givers and the people that lived in the residences, so when their beloved came, he brought the Crdl out and used it to make them feel in contact in that moment. During the several sessions he noticed that the most frequent reaction after a Crdl's therapy was the reawakening of past memories and an increase of the sense of engagement and relaxation towards the patient. Moreover, every patient had his/her own sound chosen according to: what goal he wanted to pursue, what emotions he wanted to arise and what was the patient's story-life. A very nice story the nurse told me, was about a patient with dementia at a very severe stage that wasn't talking anymore, but during a Crdl's session he started to talk again by reawakening a past memory. From that moment also their beloved could achieve a connection with the man, a connection that they have lost before.

The Crdl is used in many fields and also in the palliative care area as an instrument of distraction from the pain and a way to calm and relax the patient.

Another very important use is made by the creativity therapists; a very interesting figure that uses art forms (dance, painting, music, drawing, clay modelling, etc.) to help treat certain conditions, mainly mental, emotional and physical issues. This type of therapy is very interesting because doesn't require a person to have any sort of artistic ability, but it uses the artistic channel to give a person the possibility to express his/her feelings and thoughts in a non-verbal way. So, the Crdl was also used in this field at Zuyd University by putting one hand on top of the Crdl and with the other play with the clay. Because the clay is a conductive material as well as wood, the connection was established and the Crdl made sounds.

The last expert I met at the University was an SLP (Speech and Language Pathologist) who worked is a "special school" before becoming a teacher at Zuyd University.
In the Netherlands there are three types of primary school:

- *Regular school*, where all typical kids go
- *Special school*, attended by all those atypical kids with any kind of diseases: Autism, severe ADHD, behavioural problems, blindness, deftness, language problems, brain injuries, cerebral palsy, genetic syndromes, etc. In these schools all children receive both school education, as well as rehabilitation sections in combination with periodically medical checks
- *Special-regular schools*, which is a mixture of the two above, but in whom there's no rehabilitation given to special children

In this school SLPs used Crdl to reach different goals such as: make contact, get a reaction from the surrounding environment, language prerequisites as imitation, relax, stimulate a communication and adjust a phoneme pronunciation or an articulation problem by putting the sound of the phoneme as one of Crdl's sounds. She said that sometimes it takes a lot of time to see a reaction from a child due to his /her attention level, but the strongest reaction was registered when the music stopped, so when the contact between the children and the therapist was cut off, because the kids wanted to hear the music more. This shows us that even though it seems that children aren't pay too much attention on that, in the reality they are.
She also told me that the most frequent sounds that she used, were children's songs, in order to engage the patient with a music he/she new and also liked.

### 3.3.2 Visiting at Crdl's factory

On April 16th, a site visit was conducted at the Crdl manufacturing facility in Haarlem, Netherlands, for a technical consultation with the device's creators, Denis Schuivens and Jack Chen. During this session, practical training was provided regarding the latest hardware iterations, including sound-gesture optimization and the programming of customized auditory protocols via the web portal.

The conceptual origin of the Crdl, as detailed by Mr. Chen, is rooted in clinical observation within geriatric care settings. The impetus for the device arose during a volunteer engagement at a residential facility for patients with neurodegenerative disorders. Specifically, Chen observed a disconnect between a patient at Stage 4 of the Global Deterioration Scale (Reisberg et al., 1982) and his family member; despite a perceived emotional presence, verbal communication had become ineffective.

This clinical gap inspired the development of a medium capable of facilitating non-verbal, tactile-based connection. Following an iterative design process spanning several years, the Crdl was developed to restore a sense of 'interpersonal linkage' through a sensory-mediated interface, allowing for emotional engagement when traditional communication channels are compromised.

### 3.3.3 Sevagram's experience

On the 29th of April I had the opportunity to experience the real power that Crdl can give to people at one of the many residences of Sevagram's healthcare organisation: Molenpark (Henri Dunantstraat 3, 6419 PB Heerlen).

Sevagram is a leading Dutch geriatric care organization operating 19 centres across the Limburg region (Heerlen, Maastricht). It specializes in intensive neurorehabilitative care for patients categorized under the CIZ (Care Needs Assessment Centre) profiles VV5 and VV7. Specifically, the VV7 profile designates individuals requiring sheltered housing and highly intensive intervention due to severe psychogeriatric, neuropsychiatric, or behavioural challenges associated with dementia, Korsakoff syndrome, Huntington's disease, or Acquired Brain Injury (ABI).

This research was centred at Molenpark, a 125-resident facility in Heerlen specializing in moderate-to-severe dementia care. The centre utilizes a multidisciplinary rehabilitative framework encompassing physiotherapy, speech-language pathology, and creative therapies (music, dance, and theatre) to maximize Quality of Life (QoL). Given the

degenerative nature of these pathologies, the clinical objective shifts toward optimizing the "here and now," focusing on environmental enrichment and the immediate well-being of the patient.

When a patient and his/her beloved ones arrive at Sevagram they receive a psychological session where the expert figures out what are the patient's main issues and what kind of goals they can pursue. Then there is a multidisciplinary discussion with a couple of experts where it's decided what kind of activities of therapies can be offered to the patient. From that moment the therapists start to observe the patients and perhaps evaluate him/her to figure out what would it be the best thing to do. Moreover the very best thing that most of the clinicians do at Sevagram's residences is that they do not work with a proper pre-schedule plan; instead, they go around the residence talking to patients and make them feel welcomed and cared, trying to engage them. When they see a patient that they are following, be ready and in a good moment to receive therapy they go to him/her and give a therapy session as if it was part of his/her daily "normal" life.

Thanks to a couple of teachers from Zuyd University I found a MT (Music Therapist) that gave me the possibility to participate during some sessions where the Crdl was used. Before going to the patients we talked a bit about Crdl: how she uses it and for what kind of goals. She explained to me that the instrument has been used with any typologies of dementia syndromes for a session of about 15 minutes, after that the patient usually loose his/her attention. Of course, not every person enjoys the Crdl, which means that it doesn't work with everyone, but certainly with the majority of them. The main goals that she can pursue by using the Crdl are:

- Build a contact with a person that is starting to lose it, by closing her/himself to the surroundings
- Increase a better mood in those patients who are depressed and relax those people who are both physically and verbally agitated
- Increase the attention and concentration level
- As a "distraction" from the surrounding if it makes the patient nervous

During my daily stay I had the big opportunity to meet three patients, two of which I had also the privilege to speak with, through the German language, which both parties knew. They told me a bit about some memories coming from their past and I was truly honoured by that. All the patients I saw where female aged in their nineties with a diagnosis of dementia in medium-severe stage. Every session lasted between 10 to 15 minutes each,

after that the level of attention and concentration of the person was gone. Crdl's sounds that have been used during all therapy sessions were: citar and piano music.
At the end of the session with the first lady, she said that she could focus on the music by closing her eyes and she seemed to us really enjoying the instrument. Moreover, after these considerations, she started to talk about her past and some other memories of her. She also decided to play the Crdl through the MT's hand and not only undergo the movement. The session finished because she said to us that, even though she felt more relaxed and focused, the activity cost her a lot of energy and now she was tired.
The second lady with whom we used Crdl was quite disoriented time and space meaning, but when we started to play the instrument she seemed much more in that moment, as well as relaxed and concentrate. She lost her attention three times but, without saying nothing, she immediately refocused and enjoyed that moment. An interesting gesture that showed us she appreciated the therapy session, was when we were tapping and tickling her hand and she stretched her finger in order to give us the possibility to "play her finger", too. We tried also to explain her how to play the Crdl through our hands, but unfortunately, she didn't understand what she had to do. At final we can still say that this patient was a success, too.
The last patient we saw just for a couple of minutes was a woman in a wheelchair sited at a table with other three people, with whom she wasn't talking to. We came closer to her and started to talk with her both in Dutch and German. After engaging her the MT decided to try the Crdl, but even though she said that she was enjoying the music and she seemed also a bit more talkative, she took her hand off the Crdl just a couple of minutes after the start of the sound. Two tries where done with her but the same response was received, so the therapist decided to finish the session and say goodbye to her.

On the 1st of May I had the opportunity to go to another residence of Sevagram organisation located in Hulsberg, called: Panhuys (address: Panhuys 1, 6336 AH, Hulsberg). Panhuys is a residence that hosts and takes care of around 60 people with a diagnosis of dementia. All the projects and activities presented at Molenpark are developed here, too, with the same aim and procedures.

Once again during my daily stay at Panhuys, I was followed by another MT, that introduce me to some patients with different kind of dementia, mainly Alzheimer, at medium-severe stage in their 80s/90s. Also in this case most of the session lasted about 10 to 15 minutes

and they took place in several places of the building according to where the patient was in that moment, when we saw him needed a moment of relax or connection.

The first patient we saw, was a 90-year-old-woman with Alzheimer disease at a medium stage. The three of us started an interaction with her through the Crdl, in German language. She enjoyed a lot Crdl, because we could see a complete change in her behaviour: the first time we saw her she wasn't talking and she was just sitting in the chair; but in the moment we started to use the Crdl her eyes lightened up and her mouth made a big smile. Moreover, we didn't have to wait long time that she took action by grabbing our hands and started to play Crdl through them. While this was happening, she started to share with us her past as a singer. When we dismiss from her, she was still smiling and talking and she seemed much more aware of the environment surrounding her. Moreover, she told us she looked forward to a new interaction with Crdl.

The next woman we saw, was older than the previous one and in a severer stage of dementia. When we approached her she was very agitated and had a lot of verbal confabulations. The MT tried to introduce the instrument to her, but she rejected it, saying that she could not put her hand on it. The only thing that we could do with her, was just let her hear some piano music through Crdl and with that she relaxed and stop confabulating.

The third 80-year-old-woman that we met had a lot of remarkable spasms due to a high level of tension and discomfort. When we approached her, she was very happy to try this new experience with the MT. The first music that was played with her was the ocean sound, that after a minute could significantly reduce the muscular tremor she had. During the session she was suggested to close her eyes and try to breathe deeply; thanks to these advices she could not only relax but also connect with us telling how she was feeling. The second sound we tried was the citar one: as soon as the sound began, she started laughing and hum the song. Only by suggestion she took initiative and started to play Crdl through our hands.

Afterall it was a very enriching experience; the suggestions that the MTs gave to me were extremely useful. It was very interesting see how the residence's system work in a foreign country, in order to try to improve ours and be a better clinician one day. Moreover, the possibility to connect with those patients that are loosing their connections with the world each day more, was amazing: they gifted me the best smiles of all and I'm very thankful for that.

## 3.4 Bibliographic research

The theme of auditory stimulation through familiar sounds and music for SBI patients, addressed in this paper, has been deepened and developed thanks to different methodological approaches.

The first section of this project, reported in the chapter concerning the theoretical frame of reference, is dedicated to the current state of the art regarding the use of Crdl and the effects of music therapy in SBI patients. First, a bibliographical search was carried out which focused on several aspects:

- Literature review concerning the different uses of Crdl in every possible healthcare field and types of pathologies. Research has been carried out in scientific databases such as: PubMed, Google Scholar, Emerald, Research.ou.nl. A lot of information were also collected from the official website of the instrument crdl.com
- Review of publications and guidelines from the leading scientific societies in the field regarding SBI rehabilitation. The sources that have been taken into consideration come from several scientific databases: PubMed, Cochrane Library, Elsevir, Lancet, WHO (World Health Organisation), NIH (National Library of Medicine), Sistema Nazionale Linee Guida dell'Istituto Superiore di Sanità, SIMFER (Società Italiana Di Medicina Fisica e Riabilitativa), FNATC (Federazione Nazionale Associazioni Trauma Cranico); and from the book *"La riabilitazione delle gravi cerebrolesioni acquisite (Metodi e pratiche in Riabilitazione)"* by Anna Mazzucchi (Giunti, ed. 2011).
- Literature review concerning the effectiveness of music therapy and auditory stimulation in SBI patients. This research has been carried out through different scientific databases concerning: PubMed, Google Scholar, Elsevier, Cochrane Library; from the journal of Iran Nursing Journal and from the books: *"IFNR Textbook of Neurorehabilitation"* by Nirmal Surya (eVANGEL, ed. 2024) and from the book *"Handbook of Neurologic Music Therapy"* by Thaut, Michael H., Hoemberg (Oxford University Press, ed. 2016)

## 3.5 Target population

The study has been conducted at the Neurorehabilitation Clinic of the hospital San Bortolo in Vicenza, a city located in the northern part of Veneto region in Italy.
The population that has been selected for the treatment was made of 3 patients that had a severe brain injury in different moments, so they started their rehabilitation programs in different stages of their recovery, even though everyone was in the sub-acute stage with different level of arousal and awareness.

All patients underwent standard physiotherapy rehabilitation treatment, according to the hospital guidelines, for one or two hours a day, 5 days a week. In addition, most of these patients were treated with specific drug therapy (such as, amantadine, citicoline, dopamine, etc.) to increase the level of consciousness and the dopaminergic brain activity.

The selection of the population was done by analysing patient's anamnestic story and their attitude, as well as interest to music. Every patient selected for the study had a story of SBI and an initial GCS 3 and LCF 1 or 2. Another criteria for the selection was the luck of some communicative skills and prerequisites or the ability to properly support a dialogue. Indeed, before the start of the stimulation every patient went through a qualitative evaluation of the communicative behaviour and attitude and everyone of them showed:

- short attention span
- no voluntary response or insufficient amount of them
- turn taking difficulties
- limited eye contact, gaze triangulation or gaze orientation
- no vocal or verbal communication
- no special, temporal and personal orientation

# 4. MULTIPLE CASE STUDY AND RESULTS

Current rehabilitation options for patients with SBI remain significantly limited, often confined to basic functional motor stimulation and ADL. However, multisensory stimulation emerges as a promising intervention during early recovery phases and for patients with higher levels of consciousness who present complex communicative-relational issues. This study explores the clinical application of the Crdl, an innovative device designed in the Netherlands. Specifically, this chapter details a multiple case study involving three patients recruited from the Neurorehabilitation Department of San Bortolo Hospital in Vicenza. The intervention consisted of daily sessions (10–20 minutes, five days a week) over a three-month period. For each case, we provide a clinical history and a detailed qualitative and quantitative description of the treatment. Finally, an individual and aggregate statistical analysis is presented to evaluate the evolution of key communicative parameters throughout the rehabilitative process.

## 4.1 Structure of the rehabilitation program and aims of the stimulation

Severe Acquired Brain Injury (SBI) often results in profound impairments in consciousness and communicative engagement. Traditional rehabilitation frequently lacks tools specifically designed to bridge the gap between basic sensory stimulation and active social interaction. The Crdl, a Dutch haptic-based assistive technology, transforms skin-to-skin contact into auditory feedback, potentially facilitating non-verbal communication, which is the easiest way to first approach a patient. Given these clinical requirements and the emerging potential of this technology, this study proposes a multisensory stimulation intervention. The objective is to evaluate whether such an approach is an efficient and motivating one. The findings of this research aim to provide a significant contribution toward optimizing treatment for patients with SBI, specifically by enhancing communicative-relational recovery in the early stages and fostering increased engagement in the later stages of rehabilitation.

The rehabilitation program was initiated with a comprehensive anamnestic analysis and caregiver interviews to establish a detailed clinical framework. Patient progress was monitored longitudinally using the GCS, LCF, and CNC scales at baseline and subsequent 30-day intervals. Central to the protocol was the customization of auditory stimuli; meaningful sounds were tailored to each patient's personal history (e.g., musical preferences) and refined through a preliminary trial phase to identify the most engaging

triggers (chapter 2.2.2; 4..1.1).During the stimulation period the sound used could be changed following the patient's evolution and clinical status.

Following stimulus selection, Crdl's stimulation started. Crdl was used by the clinicians 5 days per week once a day, in the morning or in the afternoon, according to the patients' physical, psychological and medical conditions or the hospital management requirements. The exposition time of exposition to the Crdl lasted between 10 to 20 minutes each time, once more, according to the patients' physical, psychological and medical conditions. The study lasted three months for each patient as suggested by the literature (Formisano et al., 2017; https://hdl.handle.net/11577/2267978).

According to the reasons presented in the chapter 2.1.3., it was decided to conduct an accurate clinical qualitative observation of each patient by observing the patient's reaction, recording and analysing all the sessions through the use of a webapp appositely designed for this study. Moreover a more structured evaluation was done on a monthly basis through the use of different scales, such as LCF and CNC, along the patient's needs. Each session began with a greeting to the patient, followed, when feasible, by their selection of the sound to be played from a pool of options pre-selected during the trial phase.

During the session, the clinicians observed and recorded a range of possible responses from the patient, which included establishing eye contact, demonstrating imitation, taking turns interacting with the Crdl, vocalizing, and expressing opinions about the activity. The study employed a two-step analytical approach to ensure maximum clinical precision. Initially, patient responses were recorded in real-time (online analysis) with high granular detail. Subsequently, a post-hoc review of the audio recordings was conducted to capture subtle nuances potentially missed during the live sessions, such as specific therapist gestures and the auditory feedback generated by the Crdl. This dual-verification process was essential to accurately document the multimodal interaction and patient engagement (https://giovanninicoli.github.io/CRDL4/ ) (Fig. 8).

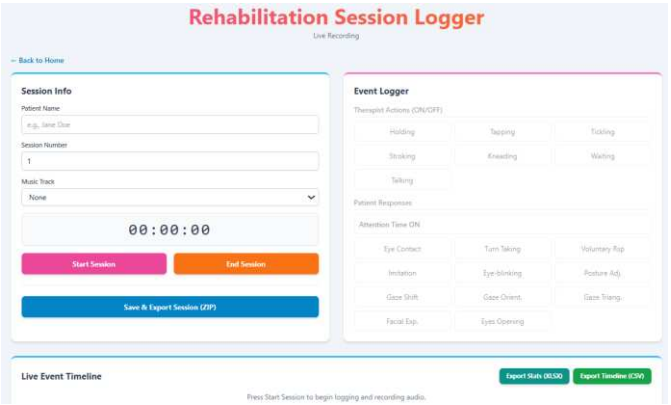


*Fig. 8 Application interface*

Moreover it would be interesting for the medical-rehabilitation area to discover more about the multisensory stimulation and what could it be used for, in order to increase medical treatments and provide better solutions for all patients in low LCF stages (1-3) and a more motivational instrument in the more advanced stages (LCF>4).

### 4.1.1 The selection of the auditory input

The rationale for the auditory stimuli selection in this study is grounded in recent neurophysiological evidence. Ling et al. (2023) demonstrated that generic musical stimuli do not elicit significantly different cortical responses compared to white noise, suggesting that non-specific auditory input may lack therapeutic salience. Conversely, Vanoni et al. (2021) observed significant differences in brain injury patients when comparing familiar versus unfamiliar stimuli, although no marked distinction was found between different types of preferred auditory inputs. Building upon these findings, this intervention utilized a three-day stimulation protocol featuring pre-selected, meaningful sounds tailored to each patient's personal history. This personalized approach aims to identify the specific auditory triggers capable of eliciting the highest level of communicative engagement.

Each patient had his/her own pre-tailored music stimuli, derived from a musical anamnesis, namely a structured interview with the patient, if possible, or her caregiver to know the patient's lifestyle history and musical taste (Spaccavento et al., 2024). After an accurate analysis and preparation of the sound, three prototypes were proposed to the patient for several sessions, to see which one worked the best. If the response to the presented stimuli was the same, the calmest sound was chosen, according to the literature results. In other cases, since the stimulation was used as auditory feedback during a conversation, the auditory stimuli used was different every session, according to the conversation's subject.

## 4.2 MULTIPLE CASE STUDY

### 4.2.1 Case 1

#### 4.2.1.1 Anamnestic story

L.R. is a female aged 14 years old. She was hospitalized in San Bortolo Hospital of Vicenza for a polytrauma with DAI (Diffuse Axonal Injury) resulting from a road accident that occurred on the 28$^{th}$ of August 2025.

L.R. is a student of the first years of high school, that actually never started. She's a national foil champion and a pianist: her two main hobbies.

The patient was found by emergency medical services unconscious, with a Glasgow Coma Scale (GCS) score of 3. A total-body TAC revealed bilateral bifrontal subarachnoid haemorrhage, haemorrhagic petechiae in the frontal cortical and subcortical regions bilaterally, in the right basal ganglia region, and in the left cerebellar peduncle; fractures of the nasal bones and of the frontal process of the right maxilla; severe thoracic trauma; abdominal trauma with the presence of free intraperitoneal fluid and a small colonic perforation; minimal deformity of the L3 vertebral body; and a fracture of the right ankle. During the stay in the Neurosurgical Intensive Care Unit (NICU) of Treviso, the patient developed acute respiratory failure secondary to bilateral pneumonia caused by *Pseudomonas aeruginosa*.

On September 12, a percutaneous tracheostomy was performed. On September 30, a tracheostomy tube change was carried out, with placement of a cuffed Primed Pro Line 6 cannula.

On October 10, a percutaneous endoscopic gastrostomy (PEG) was placed and subsequently removed in early January.

On October 29 the patient was moved to the UGC of Vicenza from Treviso hospital, at her arrival her CNC scale (Coma/Near-Coma) scored 3,42, corresponding to a level 4: Marked Coma (range point: 2,90-3,49). The corresponding level measured with LCF scale is 1. Upon admission, the patient was receiving a complex pharmacological therapy. Particular attention was paid to the use of antiepileptic drugs and muscle relaxants, as these medications may alter the level of alertness and consciousness, increase drowsiness and fatigue, and may exacerbate pre-existing psychiatric disorders.

#### 4.2.1.2 SLP evaluation and assessment T0

On the 29$^{th}$ October 2025, the patient was awake but not aware (LCF 1; CNC 4 – Marked Coma), with no response to verbal calling and no visual fixation. The patient had a Pro Line 6 tracheostomy tube with the cuff inflated ($SpO_2$ 98% on room air). She was receiving enteral nutrition via PEG, with overall good nutritional status.

On assessment, the patient could slightly open her mouth, with abundant pooled, foamy salivary secretions within the oral cavity. Tactile stimulation elicited minimal signs of a chewing reflex; the pharyngeal reflex was not elicitable, and no swallowing acts were observed during stimulation.

Spontaneous, non–goal-directed motor activity of the left lower limb was observed; the remaining body regions were plegic.

A significant modification of the pharmacological regimen was noted, with the progressive reduction of antiepileptic drugs and muscle relaxants.

#### 4.2.1.3 Treatment goals T0 and strategies

Treatment goals were:

a. Achievement independent respiratory function:
    - resensitization of the structures
    - increased tolerance to suctioning and tracheostomy tube occlusion
    - removal of the tracheostomy tube
b. Improvement of the swallowing function:
    - promotion of safe and effective swallowing act
c. Facilitation of the recovery of arousal and awareness
    - improvement of the arousal time
    - research of an efficient communication channel
    - increased voluntary response

Treatment strategies:

a. Progressive cuff deflation and capping of the cannula for increasing durations.
b. Swallowing stimulation using a cold bolus classified as IDDSI level 3 (blended apple), with the use of a small stainless-steel teaspoon to provide a more functional and realistic stimulus. The patient is also encouraged to bring the spoon to her mouth independently.
c. No specific cognitive stimulation was provided.

#### 4.2.1.4 SLP evaluation and assessment T1

On the17th of November 2025 a new evaluation was needed due to an evolution of the patient's condition.

L.R. was awake and aware for longer period of time (LCF 3).

No respiratory aids were needed because the patient achieve an independent and secure respiratory function. She was able to self-management of her oral secretions.

Upon stimulation of the swallowing act with a cold semi-liquid bolus (IDDSI 3), a high degree of motivation and cooperation is observed during the task. Labial motility on the

spoon is effective; the oral phase is slightly prolonged with effective triggering of the swallowing reflex. Reflex cough is effective. Oral and perioral clearance is good, with no indirect signs of aspiration. The use of PEG feeding is maintained for hydration and to achieve the caloric intake necessary and appropriate for the patient.

The patient is mute; sporadic attempts at articulation without phonation. Visual engagement is limited, with possible visual impairments; the head is predominantly turned to the left, with poor exploration of the right hemispace. Poor nocturnal rest is reported.

A severe bilateral decorticate posture of the limbs persists (rigidity characterized by flexion of the upper limbs toward the chest with clenched fists and extension of the lower limbs).

Regarding the pharmacological therapy, an increase in the dosage of amantadine (increases brain dopamine levels) is noted, along with a further reduction in muscle relaxants and discontinuation of antihypertensive medication.

#### 4.2.1.5 Treatment goals T1 and strategies

Treatment goals were:

a. Gradual resumption of oral feeding under safe conditions;
    - promotion of safe and effective swallowing
    - timing reduction of the oral phase
    - add a wider range of consistencies and tastes
    - provide an appropriate and sufficient caloric and water intake per os
b. Improvement of the level of consciousness and communication skills
    - increase attention span
    - promote a communication relationship and its prerequisites (eye contact, turn taking, imitation and voluntary response)
    - encourage verbal communication

Treatment strategies:

a. Swallowing stimulation using homogeneous IDDSI level 3 consistencies at breakfast and lunch, under SLP supervision;
   Training of the parents in the administration of all three daily meals;
   Trial of additional consistencies under safe conditions and with assistance (IDDSI levels 5, 6, and 0) through daily stimulation with different foods

b. Multisensory stimulation trough the use of the Crdl; from October 17 onward, multisensory stimulation with the device was implemented through imitation and verbal requests, eye contact, turn-taking, attention span, enhancement of motivation, promote verbal response and communication prerequisites and relationship.

#### 4.2.1.6 SLP evaluation and assessment T2

On the 9th of January 2026 the patient appears clinically stable; awake, conscious, partially cooperative, with intermittent episodes of psychomotor agitation and, at times, oppositional–provocative behaviour with episodes of motor aggression (LCF 5). Unrestricted diet and free fluid intake; start of a fluid intake diary (300–500 mL/day orally, with the remaining volume administered via PEG).
Spatial and temporal disorientation and difficulty in learning new information. The patient consistently and reliably uses affirmative/negative communication through head nods; at times, these nods are also accompanied by vocalizations of "yes" and "no" and emblematic gestures. Hypoarticulation and communicative inertia are present. During speech-language therapy sessions, the ability to correctly complete the words of familiar song lyrics is observed, with hypophonic and hypoarticulated speech.

#### 4.2.1.7 Treatment goals T2 and strategies

Treatment goals were:

a. Sufficient and safe liquid intake per os
b. Improvement of the verbal communication skills
    - promote the use of a verbal response instead of a gesture or nodding
    - increase the articulation abilities
    - increase the phonatory duration
c. Encourage spatial and temporal orientation as well as memory

Treatment strategies:

a. Train and parents and nurse how to give her water with functional instrument (plastic-rigid glass placed over her under-lip and small sips)
b. Pushing the stomach area in order to support the diaphragm muscle during phonation;
   Strengthening the articulation (tongue motricity; oral motor prompt; "speak with a very open mouth")

Vocalization of syllables CV, VC, VCCV, bysillabic words (plosive consonants: t, d, b)

c. Remember each day the daily date (day, month, year) and the place we are in (San Bortolo hospital, rehabilitation unit) and what we did the previous time we met

#### 4.2.1.8 Results

The analysed results refer to treatment sessions conducted between November 17, 2026, and December 15, 2026. After this period, the use of the Crdl with the patient was no longer considered clinically relevant due to the patient's improvement and the consequent modification of the therapeutic goals. It was not always possible to administer stimulation sessions five days per week because of hospital organizational constraints and the patient's clinical condition. Furthermore, session number 14 was excluded from the analysis due to its lack of significance, which was attributable to the patient's attentional fatigue. The patient had just completed an intensive physiotherapy session and was therefore unable to participate in any subsequent stimulation activities. During this session, the patient appeared highly agitated, inattentive, and unable to follow any of the requested commands.

Overall, the results indicate an improvement in both attentional span and the duration of stimulation sessions. The average duration during the first week of training was 7,563 min (S2–S5), while in the second week the average increased to 12,925 (S6–S10). Between the third and fourth weeks (S11–S18 average time 7,764 min), a reduction in session length can be observed, accompanied by an improvement in the patient's ability to sustain attention throughout the entire stimulation period. Indeed, in the final portion of the graph, the grey and green bars almost overlap, a trend that begins to emerge as early as the second week (Fig. 9).


*Fig. 9 Attention analysis (duration vs attention): the chart shows in the x-axis all the session that were done with the patient and in the y-axis the duration of each session (grey) and the corresponding attention span (green). The red line represents the attention trend during the entire intervention*

During each session all patient's responses were analyses, as we can see in the chart below. The total trend shows us an increase in the number of responses made by the patient, in particular an interesting trend is the one of the eye contact and the voluntary response (Fig.10, 11).


*Fig. 10 Total responses breakdown: the chart shows in the x-axis all the session that were done with the patient and in the y-axis the total amount of the patient's responses.*

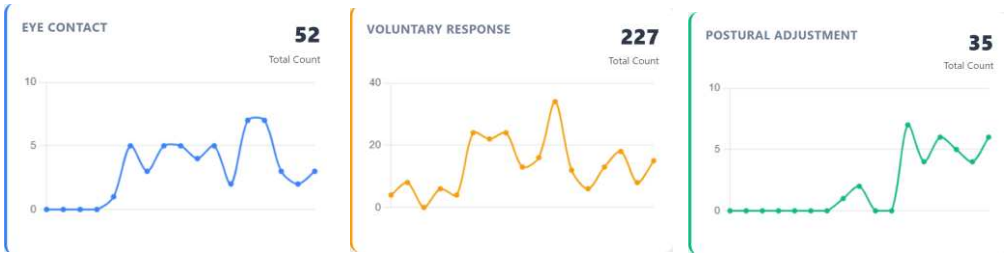


*Fig. 11 Most significant parameters analysis over time (eye contact, voluntary response, postural adjustment): the chart shows in the x-axis all the session that were and, in the y-axis, the total amount of the patient's responses for each parameter.*

On December 16, 2026, it was decided to discontinue the multisensory stimulation protocol due to an advanced level of consciousness (LCF 4) and the presence of marked psychomotor agitation. Speech and language therapy intervention was subsequently continued with a focus on vocal rehabilitation, promoting a respiratory support, pneumophonic coordination, and the improvement of articulatory skills. Given the patient's verbal inertia and a difficulty in the pneumophonic coordination, treatment also incorporated the use of singing as an automated behaviour to facilitate speech production and increase the motivation, taking advantage of the patient's musical background.

## 4.2.2 Case 2

### 4.2.2.1 Anamnestic story

J.P. is a 36-year-old female who was admitted to San Bortolo Hospital in Vicenza following a left fronto-parietal intraparenchymal cerebral haemorrhage secondary to an ASO (Acute Spontaneous Onset), with suspected arteriovenous malformation (AVM), which occurred on August 30, 2025.

She's an accountant and a mom of two children (4 and 1 years old). Her parents don't report anything relevant, neither her 29-year-old brother. She's not married but she lives with her boyfriend and her kids in a single house of two floors. J.P. got a bachelor's degree in economics; her hobbies are: horse riding and walking in the nature.

The acute event developed while the patient was riding a bicycle with her partner and children. She reported a sudden loss of sensation in the right upper and lower limbs; she was therefore assisted off the bicycle and laid on the ground. This was followed by loss of consciousness.

Upon arrival of emergency medical services, the patient was found unconscious, with a Glasgow Coma Scale (GCS) score of 3 and snoring respiration.

On August 30, 2025, the patient underwent neurosurgical intervention, consisting of a left fronto-parietal craniotomy, AVM closure, and placement of intracranial pressure monitoring (ICP/PIC) and external ventricular drainage (EVD/DVE).

On September 24 the patient was moved to the UGC of Vicenza hospital, at her arrival her LCF scale was 2.

### 4.2.2.2 SLP evaluation and assessment T0

From the speech and language therapy assessment performed on October 1, 2025, the following findings were observed: fluctuating level of awakens and alertness (LCF 2); brief eye contact with the interlocutor and short-lasting visual tracking. Inconsistent execution of simple verbal commands; mutism. The patient appears capable of learning and reliably using eye closure as a means of communication to indicate "yes."

The patient is fed via a nasogastric tube (NGT). The presence of a bite reflex, which is poorly suppressible, was noted. Swallowing assessment was done using small boluses of semi-solid food: the patient was able to occasionally open the mouth but not the teeth; nevertheless, it was possible to introduce small amounts of bolus, which were managed with slightly delayed oral phase and an adequate pharyngeal phase.

Spontaneous respiration was observed.

#### 4.2.2.3 Treatment goals T0 and strategies

Treatment goals were:

a. Gradual resumption of oral feeding under safe conditions
    - promotion of safe and effective swallowing act
    - resolution of pathological reflexes
    - timing reduction of the oral phase
    - add a wider range of consistencies and tastes
    - provide an appropriate and sufficient caloric and water intake per os
b. Improvement of the level of consciousness and communication skills
    - increase the levels of alertness, awareness and attention span
    - promote a communication relationship and its prerequisites (eye contact, turn taking, imitation and voluntary response)
    - encourage communicative relationships

Treatment strategies:

a. Swallowing stimulation using homogeneous IDDSI level 3 consistencies at breakfast and lunch, under SLP supervision;
   Training of the parents in the administration of all three daily meals;
   Trial of additional consistencies under safe conditions and with assistance (IDDSI levels 5, 6, and 0) through daily stimulation with different foods;
b. Employment of multiple communicative channels to facilitate interaction.

#### 4.2.2.4 SLP evaluation and assessment T1

The patient is alert and responsive, with stable general clinical conditions (LCF 6-19/11/2025). Mood tone is mildly depressed, particularly when discussing family-related issues. Cooperation is good and motivation is progressively improving. J.P. is space-oriented and also to personal autobiographical information, and partially oriented to time. Short-term memory deficits are present; however, the patient is able to compensate when provided with external cues or prompts. Declarative consciousness is preserved, whereas projective consciousness is absent.

The patient is generally hypoactive, with adequate attentional span. Eye contact is limited, and there is reduced communicative and motor initiative. Contribution to communication is minimal, occurring only after repeated stimulation or prompting; communicative acts are predominantly assertive. Facial expressivity is markedly reduced, with a generally apathetic presentation.

Oral intake is maintained, with an unrestricted diet and free fluids. Rehabilitative treatment is ongoing, aimed at restoring independence in transfers and reconditioning to upright posture. Spastic hypertonia is present in the right hemibody, with passive mobilization preserved. Pharmacological therapy includes antidepressant and dopaminergic agents, which are clinically relevant to report.

#### 4.2.2.5 Treatment goals T1 and strategies

Treatment goals were:

a. Stimulate spatial, temporal and personal orientation, as well as the consciousness of the acute event and the following deficits (projectable consciousness)
b. Stimulate short-term memory, attention time, projective consciousness and the ability to learn new information
c. Enhance the communication prerequisites (eye contact, turn taking, motivation) and reduction of communicative inertia

Treatment strategies:

a. Remember each day the daily date (day, month, year) and the place we are in (San Bortolo hospital, rehabilitation unit), what happened and what we did the previous time we met
b. Error less learning and stimulative activities with a multisensory instrument (Crdl)
c. Stimulative activities with a multisensory instrument (Crdl) and board games

#### 4.2.2.6 SLP evaluation and assessment T2

The patient is alert, responsive and collaborative with stable general clinical conditions (LCF 7- 19/01/2026). In the last few days there has been noticed some episodes of crying and depressed feelings due to her condition: initial presence of a projective consciousness. Spatial and personal orientation is present and appropriate, whereas the temporal one is not always very precise. Short-term memory is still fragile, with impaired retention of newly acquired information. Persistence presence of psico-motor inertia that can’t be modified even though the assumption increased of the dopaminergic treatment.

Spontaneous verbal production is limited, with speech primarily occurring following prompting. Communication prerequisites present and contextually appropriate. Increasing of the communicative motivation and positivity during structured actives,

moreover during the multisensory stimulation. Communicative inertia slightly reduced but still present.

Independence in transfers is improving. The patient requires minimal assistance for wheelchair-to-bed transfers; when the environment is properly set up, she is able to perform bed-to-wheelchair transfers independently.

In the standing position, she tends to exhibit hyperextension of the right lower limb during weight-bearing. Gait training with the Lokomat robotic system is ongoing.

#### 4.2.1.7 Treatment goals T2 and strategies

Treatment goals were:

a. Stimulate temporal orientation, as well as the consciousness of the acute event and the following deficits (projectable consciousness)
b. Stimulate short-term memory, projective consciousness, the ability to learn new information, make inferences and create her own conception
c. Reduction of communicative initiative

Treatment strategies:

a. Remember each day the daily date (day, month, year)
b. Error less learning and stimulative activities with a multisensory instrument (Crdl) View of a daily news podcast and remember of the one saw the previous day
c. Stimulative activities with a multisensory instrument (Crdl) and personally relevant and motivating conversational topics

#### 4.2.2.8 Results

The analysed results refer to treatment sessions conducted between November 21, 2026, and February 27, 2026. It was not always possible to administer stimulation sessions five days per week because of hospital organizational constraints and the patient's clinical condition, as well as other therapists' needs and interventions. From November until the end of December (S3 to S16) a basic multisensory stimulation was offer to the patient in order to enhance communicative prerequisites. After that (S16-S43) the instrument was used as a feedback to promote patient's ability to take the turn of dyadic and subsequently triadic conversation, and improve her communicative and relational skills (pragmatic level); so the therapist stopped the music, as well as the conversation, every time the patient didn't take the turn, in order to show her the time she should make an intervention and give a contribution to the conversation (Fig. 12).


*Fig. 12 Attention analysis (duration vs attention): the chart shows in the x-axis all the session that were done with the patient and in the y-axis the duration of each session (grey) and the corresponding attention span (green). The red line represents the attention trend during the entire intervention*

The graphic above shows a positive trend of the duration of the session as well as the corresponding attention time. The duration of the rehabilitation session doesn't always match patient's ability to support the stimulation, that could last longer if it wasn't for scheduling and organizational constraints within the hospital setting. Nevertheless, the general attention trend is positive (Fig. 13).

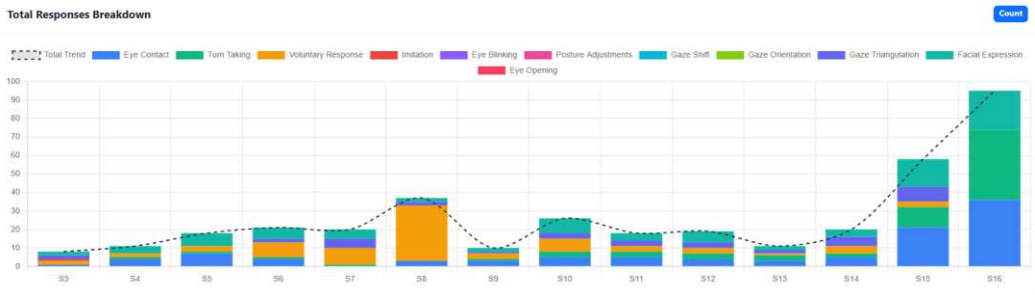


*Fig. 13 Total responses breakdown: the chart shows in the x-axis the session that were done from November 17 until December 23 and in the y-axis the total amount of the patient's responses.*

In the first part of the stimulation sessions there was a significant increase in the number of responses made by the patient, in particular: eye contact, gaze triangulation, facial expression and turn taking. The progression is clearly visible in the corresponding graphic below (Fig. 14).

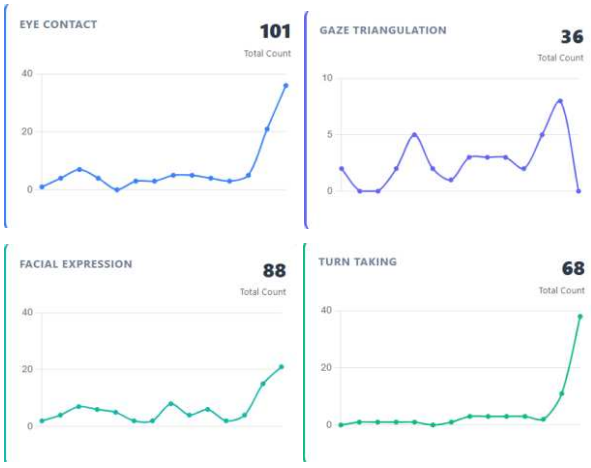


*Fig. 14 Most significant parameters analysis over time (eye contact, gaze triangulation, facial expression, turn taking): The chart shows in the x-axis the session that were done from November 17 until December 22 and in the y-axis the total amount of the patient's responses for each parameter.*

The second phase of the training program was conducted from the end of December to the end of February. Between December 29 and January 29, the primary rehabilitation objective shifted to the elicitation of turn-taking behaviours, due to the patient's marked verbal inertia. Consequently, the use of the Crdl was modified, and the device assumed the role of an important auditory feedback cue for the patient. Specifically, when the therapist interrupted the connection, the patient understood that it was her turn to take the floor and contribute to the conversation. This intervention was initially carried out in a dyadic conversational setting (S17–S28) and subsequently in a triadic one (S29–S43).


*Fig. 15 J.P. turn taking response: the chart shows in the x-axis the session that were done from December 29 until February 27 and in the y-axis the total amount of the patient's turn taking. The red line shows when the triadic conversation started*

The graph above (Fig. 15) illustrates a progressive improvement over time in turn-taking performance during dyadic conversation, with several negative peaks corresponding to shorter treatment sessions and, consequently, fewer opportunities for the patient to take conversational turns. Starting from Session 29, indicated in the graph by a red line, a general decrease in the number of initiatives can be observed, likely due to the increased difficulty of the task, followed by a subsequent recovery. This pattern suggests an initial difficulty in adapting to the change in task demands, which were clinically more challenging, followed by gradual adjustment and improvement over time (Fig. 16).


*Fig. 16 J.P. turn taking responses during all the stimulation period: the chart shows in the x-axis all the session that were done and, in the y-axis, the total amount of the patient's turn taking all along the treatment.*

Analysis of the session reports demonstrated a progressive increase in contextually relevant assertive speech acts. However, a persistent deficit in interrogative speech acts remained, highlighting the patients' difficulty in generating inferences and proactive conversational inquiries. Given the complexity of these linguistic nuances, this specific dimension was assessed exclusively through detailed qualitative analysis, prioritizing clinical observation over quantitative metrics.

### 4.2.3 Case 3

#### 4.2.3.1 Anamnestic story

E.F. is a 64-year-old woman who was admitted to San Bortolo Hospital in Vicenza in a Unresponsive Wakefulness Syndrome (UWS) state (LCF 1; CNC 3), with sequelae of SBI traumatic characterized by multiple cerebral contusions and subdural haemorrhage following a road traffic polytrauma that occurred on October 10, 2025.

The patient also presented with multiple rib and foot fractures, right basal hospital-acquired pneumonia, and acute anaemia requiring blood transfusions.

She is married with two children (one male and one female); cohabitation with her husband in an apartment. She is currently unemployed and works as a homemaker.

Her past medical history includes: recurrent moderate major depressive disorder treated pharmacologically; mild intellectual disability; mild bilateral sensorineural hearing loss; chronic low back pain and ovarian cysts.

On October 10, 2025, the patient was involved in a road traffic accident while cycling and was thrown approximately 5–6 meters after being struck by a car. She sustained severe traumatic brain injury with multiple haemorrhagic contusions in the context of polytrauma with multiple fractures. Upon the arrival of emergency services, she was found lying unconscious on the sidewalk with a GCS score of 3. She was therefore sedated, intubated, and admitted to the ICU.

After discontinuation of sedation, no recovery of consciousness was observed, and arousal remained fluctuating.

On November 11, the patient was transferred to the Severe Brain Injury Unit (UGC) of Vicenza Hospital. At admission, she scored LCF 1 and CNC 3 (moderate coma).

#### 4.2.3.2 SLP evaluation and assessment T0

At her arrival on the 11$^{th}$ of November 2025, the patient is alert but not conscious, with eyes open and no signs of distress (LCF 1; CNC 3, Moderate Coma). She has a nasogastric tube and a Shiley 8 tracheostomy cannula with cuff maintained inflated 24 hours/day and is breathing comfortably in room air ($SpO_2$: 99%). No swallowing attempts observed.

She is positioned in bed, with passive mobilizations performed by physiotherapists twice daily. Current pharmacological treatment includes antiepileptic and antibiotic therapy.

#### 4.2.3.3 Treatment goals T0 and strategies

Treatment goals were:

a. Achievement independent respiratory function:
    - resensitization of the structures
    - increased tolerance to suctioning and tracheostomy tube occlusion
b. Improvement of the swallowing function:
    - promotion of safe and effective swallowing act
c. Facilitation of the recovery of arousal and awareness
    - improvement of the arousal time
    - research of a efficient communication channel
    - increased voluntary response

Treatment strategies:

a. Progressive cuff deflation and capping of the cannula for increasing durations and oral hygiene with cold instruments.
b. Oral hygiene with cold instruments
c. No specific cognitive stimulation was provided.

#### 4.2.3.4 SLP evaluation and assessment T1

A second SLP evaluation was conducted after one month (18/12/2025). The patient is awake but not aware nor responsive (CNC 2, Near Coma). She seems more responsive to strong tactile and auditory stimuli, but she's unable to carry out voluntary requests, even with motor prompting. Moderate eye contact is observed; however, voluntary communicative efforts are absent. Conditioning using ocular blinking for yes/no responses was not successful.

She still has tracheostomy cannula Shiley 6 with cuff and remained deflated as tolerated following optimal bed positioning. Spontaneous swallowing attempts are observed during the oral hygiene. A PEG tube was placed for clinical reasons.

#### 4.2.3.5 Treatment goals T1 and strategies

Treatment goals were:

a. Achievement independent respiratory function:
    - increased tolerance to suctioning and tracheostomy tube occlusion
b. Improvement of the swallowing function:
    - promotion of safe and effective swallowing acts

c. Facilitation of the recovery of arousal and awareness
    - research of an efficient communication channel
    - increased voluntary response

Treatment strategies:

a. Progressive cuff deflation and capping of the cannula for increasing durations
   Oral hygiene with cold instruments
b. Swallowing stimulation using a cold bolus classified as IDDSI level 3 (blended apple), with the use of a small stainless-steel teaspoon to provide a more functional and realistic stimulus.
c. Multisensory stimulation with the Crdl

#### 4.2.3.6 SLP evaluation and assessment T2

On January 19, 2026, a reassessment of the patient was deemed necessary due to changes in the clinical condition. The patient underwent neurosurgical intervention on January 8, 2026, consisting of placement of a right frontal ventriculoperitoneal shunt (VP shunt) due to marked ventricular dilation in order to increase the awareness level.

The patient is awake, responsive, and conscious for progressively longer periods. Trials of cuff deflation have been successful for increasing durations. During capping trials, the patient tolerates the cap for approximately two hours, after which episodes of oxygen desaturation occur, necessitating removal of the cap and placement of a filter without re-inflation of the cuff. Overnight, the cuff remains inflated, and suctioning is required only infrequently.

Swallowing stimulation therapy continues, using a cold bolus (IDDSI level 3–4, trace amount). No residue is observed at T0, T1, or T2. The swallowing act is moderately effective, with delayed swallow initiation, adequate oral–lingual praxis, and an effective and functional pharyngeal phase. No indirect signs of penetration or aspiration are observed. A PEG tube remains in place to ensure adequate caloric and fluid intake.

From a communicative standpoint, the patient has begun to articulate single words or short phrases that are almost always intelligible and contextually appropriate, although verbal facilitation is required. When capped, the patient is also able to phonate. She is not consistently able to follow commands upon verbal request. Increased eye contact, turn-taking attempts, and imitative behaviours are noted during multisensory stimulation activities. Stimulation sessions are always conducted with the patient seated and properly

positioned, following physiotherapy intervention. An increase in dopaminergic therapy is also reported.

#### 4.2.3.7 Treatment goals T2 and strategies

Treatment goals were:

a. Achievement independent respiratory function:
    - increased tolerance to suctioning and tracheostomy tube occlusion
    - removal of the tracheostomy tube
b. Improvement of the swallowing function:
    - promotion of safe and effective swallowing acts
    - increase food intake
    - enhance oral intake and promote a progression across food consistencies
c. Improvement of the communication skills
    - increased voluntary motor and verbal response
    - increased communication prerequisites: eye contact, turn taking, imitation skills
    - enhance longer periods of focused attention

Treatment strategies:

a. Progressive cuff deflation and capping of the cannula for increasing durations
   Oral hygiene with cold instruments
b. Swallowing stimulation using a cold bolus classified as IDDSI level 3 (blended apple), with the use of a small stainless-steel teaspoon to provide a more functional and realistic stimulus
   Try breakfast and lunch with modified consistencies (IDDSI 3)
c. Multisensory stimulation with the Crdl

#### 4.2.3.6 Results

The analysed results refer to treatment sessions conducted between December 18, 2025, and February 26, 2026. It was not always possible to administer stimulation sessions five days per week because of hospital organizational constraints and the patient's clinical condition, as well as other therapists' needs and interventions. Moreover, this patient developed a sepsis during the last part of January. This condition promoted a general body

weakening and then on the 28th of January E. F. had a very important epileptic crisis. All these events made the doctor decide to interrupt the pharmacological treatment with the amantadine, that can cause or increase the possibility to have an epileptic crisis. After that two other multisensory stimulations with the Crdl were done.

Overall, the results indicate an improvement in attentional span, which previously could not be reliably measured due to the limited number of patient responses and the clinical difficulty in determining the presence or absence of an attentive state due to the patient's reduced level of arousal and responsiveness (Fig. 17, 18).


*Fig. 17 Attention analysis (duration vs attention): the chart shows in the x-axis all the session that were done with the patient and in the y-axis the duration of each session (grey) and the corresponding attention span (green). The red line represents the attention trend during the entire intervention*

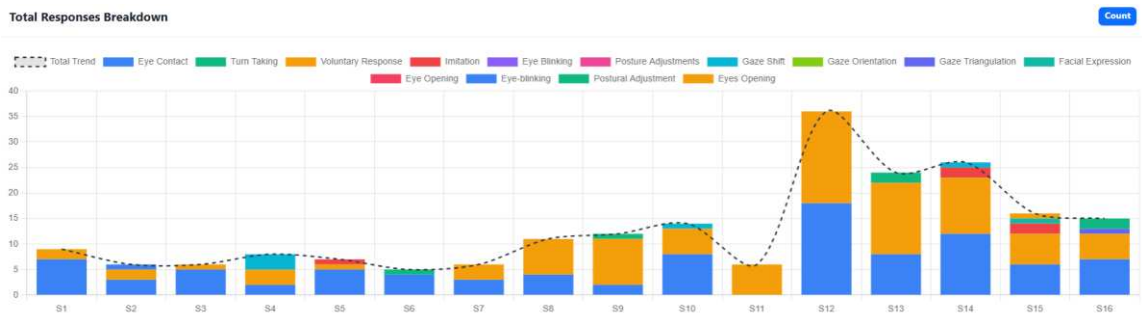


*Fig. 18 Total responses breakdown: the chart shows in the x-axis all the session that were done with the patient and in the y-axis the total amount of the patient's responses.*

Other significant parameters that show an increase during all the stimulation period are the eye contact and the voluntary response ability (Fig. 19).


*Fig. 19 Most significant parameters analysis over time (eye contact, voluntary response): The chart shows in the x-axis all the session that were done and, in the y-axis, the total amount of the patient's responses for each parameter*

# 5. GROUP ANALYSIS AND DISCUSSION

In the previous section, each case was described individually, providing a qualitative account of the patients' behavioural progression across sessions. While these descriptions illustrate the clinical evolution of each participant, they do not quantify the magnitude or reliability of the observed changes. Therefore, this section introduces statistical analyses to complement qualitative observations with quantitative evidence. By adopting both case-based and aggregate approaches, we evaluate whether clinical patterns correspond to measurable trends, while exploring the influence of temporal and clinical variables on the emergence of communicative responses during the intervention.

To identify the most informative interaction metric for each subject, an exploratory set of linear regressions was first conducted across all recorded response categories, using session number as the independent variable. This preliminary step was intended to determine which behavioural measure exhibited the most consistent and interpretable progression over the course of the intervention. For each patient, the frequency of the different interaction types (e.g., voluntary responses, turn-taking behaviours, and other recorded communicative actions) was modelled separately as a function of session order, allowing us to estimate the slope of change associated with each category (Fig. 20).

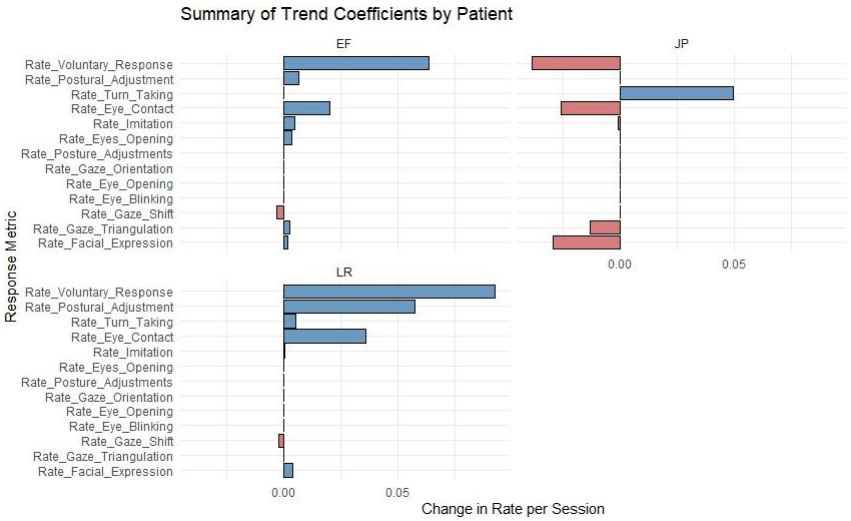


*Fig.20 Summary of Trend Coefficient by patient: linear regression models to identify the exact target response for each patient*

The resulting slope coefficients were then examined to determine which response type showed the clearest and most stable temporal trend across the treatment period. In this context (Fig. 20), the slope served as an indicator of the direction and magnitude of behavioural change: steeper positive slopes (blue bar) suggested that a given interaction type increased more consistently as sessions progressed, whereas flatter or more variable slopes (red bar) indicated weaker or less systematic trends. This comparison made it

possible to identify, for each participant, the behavioural measure that most reliably captured the evolution of interactive engagement during the intervention.

Based on this criteria, voluntary responses emerged as the most informative metric for E.F. and L.R., as they displayed the strongest and most consistent positive slopes across sessions. For J.P., however, the behaviour that showed the most pronounced temporal pattern was turn-taking, which therefore became the principal interaction metric for that participant (Fig. 20). This individualized selection procedure ensured that the subsequent analyses focused on the behavioural indicator that most accurately reflected each patient's pattern of change over time, rather than imposing a single metric across participants whose interaction profiles differed substantially.

Once the target behaviours had been identified, their raw frequencies were converted into rates per minute. This normalization step was necessary because the duration of the sessions was not perfectly uniform across the dataset. Expressing the responses as rates allowed the data to be standardized across sessions and participants, ensuring that differences in interaction frequency were not confounded by variations in session length. These normalized interaction rates were then used as the dependent variables in all subsequent statistical analyses, including comparisons between treatment phases and the regression models examining temporal and clinical correlates of behavioural change.

With the target metrics defined, frequency rates were compared between the early and late halves of the intervention in order to examine whether the treatment period was associated with measurable quantitative changes in patient behaviour. Dividing the dataset into two temporal segments (Fig. 21) allowed us to obtain a straightforward comparison between the initial phase of exposure to the intervention and the later phase, when patients had accumulated greater experience with the stimulation protocol. This approach provides a complementary perspective to the regression analyses, offering a direct test of whether interaction frequencies differed between the beginning and the end of the treatment period.

An independent-samples t-test conducted on the pooled dataset revealed a statistically significant difference between the two halves of the intervention ($p < .001$), indicating that the frequency of the selected interaction behaviours was substantially higher during the later sessions. This result suggests that, at the group level, the intervention period was associated with a progressive increase in interactive engagement (Fig.21).

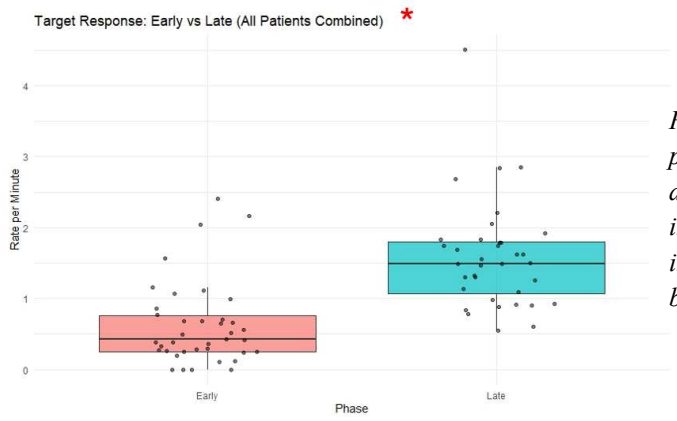


*Fig.21 Target response early vs late (all patients combined): the graphic shows the difference between the amount of responses in the first half of rehabilitation period and in the second one, with a statical difference between the two of them (p < .001)*

When examined at the individual level, the data broadly reflected the same pattern. For E.F., the rate of voluntary interactions per minute increased markedly from M = 0.25 (SD = 0.17) during the early phase to M = 0.95 (SD = 0.40) in the later phase (*p = .001*). A similar, and even more pronounced, pattern was observed for J.P., whose turn-taking rate rose from M = 0.55 (SD = 0.46) to M = 1.69 (SD = 0.36) (*p < .001*). These results indicate that both patients demonstrated a substantial growth in their respective target interaction behaviours as the treatment progressed. For L.R., voluntary responses also increased between the two phases, shifting from M = 1.13 (SD = 0.80) in the early sessions to M = 1.95 (SD = 1.32) in the later sessions. However, this difference did not reach statistical significance (*p = .156*). Nevertheless, the direction of the change remains consistent with the pattern observed in the other participants (Fig.22).

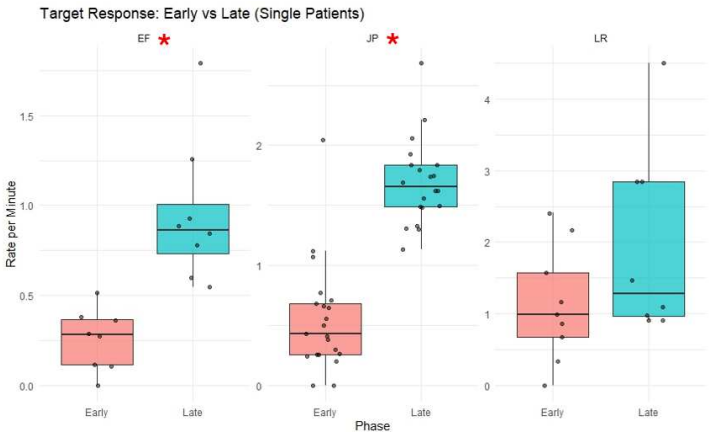


*Fig.22 Target response early vs late (single patients): the graphic shows the difference between the amount of single significant responses in the first half of rehabilitation period and in the second one, with a difference between the two of them not always statistically significant: E.F.- voluntary response (p=.001); J.P.- turn taking (p < .001); L.R.- voluntary response (p= .156)*

Overall, these comparisons suggest that the frequency of interactive behaviours tended to increase over the course of the intervention for most participants. While the magnitude and statistical strength of this change varied across individuals, the general trend supports the interpretation that the treatment period was associated with a progressive enhancement of communicative engagement. At the same time, the variability observed

across participants highlights the importance of considering individual response profiles when interpreting behavioural outcomes in small clinical samples (Fig. 22).

To further examine whether the observed increase in target responses at the group level was related to temporal progression or clinical variables, a series of linear regression models were conducted using the pooled session-level data. In each model (Fig. 23, 24, 25), the dependent variable consisted of the standardized rate of the selected target responses (voluntary responses or turn-taking, depending on the patient), expressed as interactions per minute. Separate regressions were then performed to evaluate the potential contribution of different explanatory variables.

First, a regression model was fitted to assess the relationship between response frequency and the temporal progression of the intervention (Fig. 23). Because the total number of sessions differed across participants, the session index was normalized to a standardized scale ranging from 1 to 100 (with 1 referring to the first session and 100 to the last one). This transformation allowed the temporal dimension of the intervention to be represented consistently across all patients while preserving the relative progression of sessions. The resulting regression indicated a significant positive association between normalized session time and response rate ($F(1,72) = 40.38$, $p < .001$, $R^2 = 0.359$). In practical terms, this result indicates that the likelihood and frequency of target responses tended to grow as patients advanced through the intervention (Fig.23).

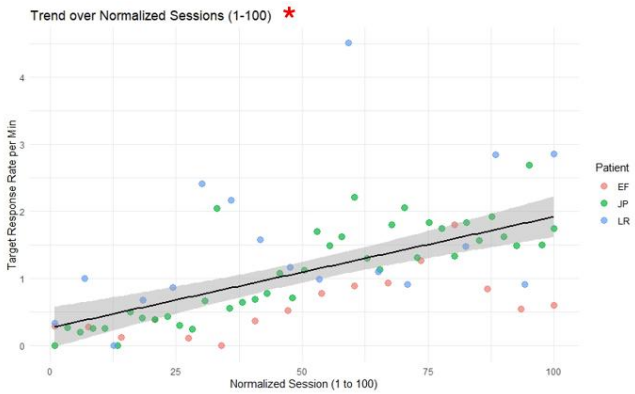


*Fig.23 Trend over Normalized Sessions (1-100): the statistically relevant linear regression evaluating the trajectory of target responses (y-axis) of all three patients over the normalized session (x-axis) (p< .001)*

A second regression model was conducted to explore the relationship between behavioural responses and the level of attention observed during the sessions. Attention scores, recorded at the session level, were entered as the independent predictor while the interaction rate remained the dependent variable. This analysis revealed a statistically significant positive association between attention and response frequency (F (1,72) =

13.62, $p < .001$, $R^2 = 0.159$). Although the proportion of explained variance was smaller than in the time-based model, this finding suggests that sessions characterized by higher attentional engagement tended to coincide with a greater number of communicative behaviours, supporting the interpretation that attentional activation may facilitate or accompany the emergence of interactive responses (Fig. 24).

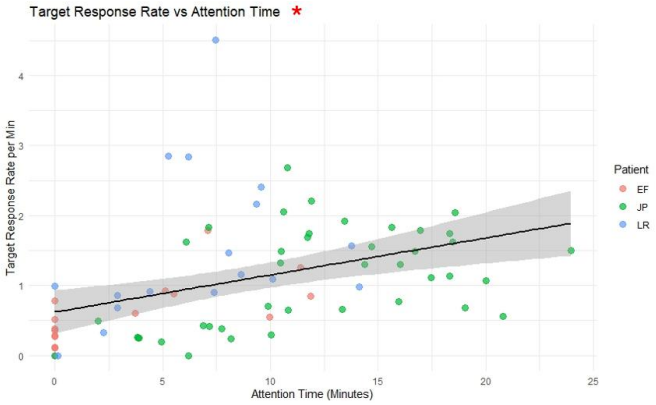


*Fig.24 Target response rate vs attention time: linear regression modelling shows the effect of attention time (x-axis) on the target response rate (y-axis) is statistically relevant (p< .001)*

A third regression model was then implemented to evaluate the relationship between interaction frequency and cognitive status as estimated through the interpolated values of the LCF scale (Levels of Cognitive Functioning). Because the LCF assessments were not available for every session, intermediate values were estimated through interpolation to obtain a continuous measure aligned with the session timeline. When these values were entered into the regression model, the analysis revealed a positive but weaker association between LCF level and interaction frequency ($F(1,72) = 3.74$, $p = .057$, $R^2 = 0.049$). Although the direction of the relationship suggested that higher cognitive functioning tended to correspond with increased interaction rates, the statistical test did not reach the conventional threshold for significance. (Fig.25).

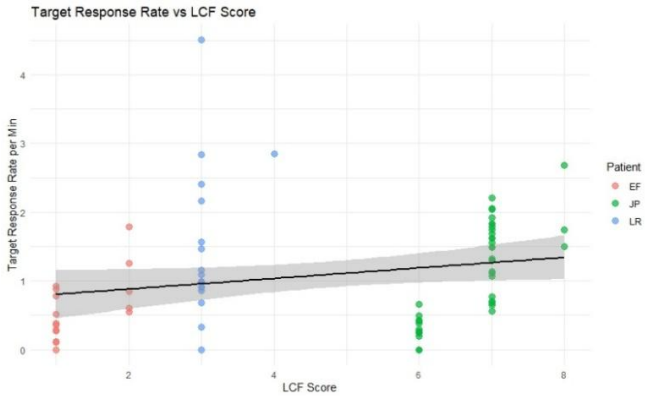


*Fig.25 Target response rate vs LCF score: linear regression modelling shows the effect of the LCF score (x-axis) on the target response (y-axis) (p = .057)*

Taken together, these regression analyses provide a complementary perspective on the factors potentially underlying the increase in communicative responses observed during the intervention. The strongest effect was associated with the temporal progression of the

sessions, while attentional engagement also demonstrated a meaningful relationship with behavioural output. The association with cognitive functioning, although positive, remained comparatively modest and fell slightly below statistical significance, suggesting that further investigation with larger samples or more frequent clinical assessments may be necessary to clarify its role.

Finally, for the two participants with complete longitudinal records, an additional analysis was conducted to examine the progression of cognitive functioning from the onset of the traumatic event. In this case, the trajectory of recovery was modelled through linear regression analyses in which time was treated as the independent variable and the LCF score as the dependent variable. This approach allowed us to quantify the rate at which cognitive functioning improved over time.

To explore whether the introduction of Crdl stimulation was associated with a modification of the recovery trajectory, the dataset was divided into two temporal segments: the pre-stimulation phase and the stimulation phase. Separate linear regressions were therefore fitted for each segment, enabling a comparison between the slope coefficients obtained before and after the introduction of the device. Within this framework, the slope represents the rate of change in LCF score over time and thus provides an estimate of the velocity of cognitive recovery. This segmented analysis makes it possible to evaluate whether the initiation of stimulation coincided with an acceleration, stabilization, or deceleration of the existing recovery trend.

For L.R. (Fig. 26), the analysis revealed a clear change in the direction of the recovery trajectory. Prior to the introduction of Crdl stimulation, the regression slope was close to zero and did not reach statistical significance, indicating that the LCF level remained essentially stable over time. Following the beginning of stimulation, however, the regression showed a significant positive slope, reflecting a consistent increase in LCF scores across the subsequent observation period. Within the linear model framework, this pattern suggests that the stimulation phase was associated with a measurable improvement in the rate at which higher levels of cognitive functioning were reached.

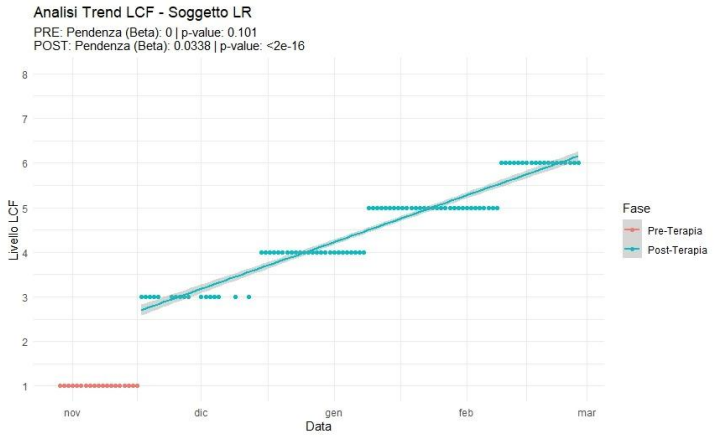


*Fig.26 LCF's trend analysis-LR: in the x-axis time is represented and the y-axis shows the increase of LCF. The red line represents the increase before Crdl, whereas the blue one the increase during the stimulation*

A different pattern was observed for J.P. (Fig. 27). In this case, the regression slope before the introduction of Crdl was steeper than the slope observed during the stimulation phase, although both trends remained statistically significant. This indicates that the patient's cognitive recovery was already progressing rapidly during the early post-traumatic phase, before the initiation of the stimulation protocol. After the beginning of Crdl therapy, the LCF scores continued to increase over time, but the rate of improvement appeared comparatively slower.

This pattern can be interpreted in light of the well-documented dynamics of recovery following severe brain injury. Several studies report that the initial stages of recovery (LCF levels 1–4) are often characterized by relatively rapid improvements, reflecting early neurobiological and metabolic recovery processes. As patients progress toward higher levels of cognitive functioning (LCF 5–8), the trajectory typically becomes slower and more variable across individuals. This deceleration is thought to reflect the increasing complexity of cognitive processes involved in higher-order functioning and the growing influence of individual factors such as age, cognitive reserve, lesion characteristics, and premorbid functioning. In this context, the reduction in slope observed in J.P. after the introduction of Crdl likely reflects the natural transition from early rapid recovery to a later phase characterized by more gradual improvements, rather than a negative effect of the stimulation.

Importantly, despite this change in slope magnitude, the regression during the stimulation phase remained significantly positive, indicating that cognitive recovery continued throughout the intervention period. This suggests that the stimulation occurred within a phase of ongoing clinical improvement rather than replacing an existing recovery trajectory.

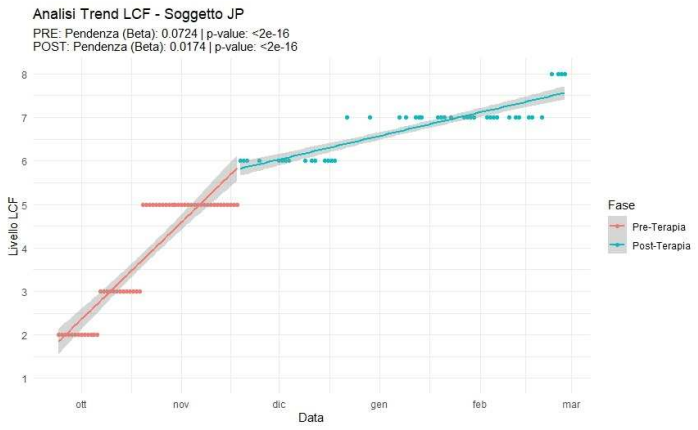


*Fig.27 LCF's trend analysis- JP: in the x-axis time is represented and the y-axis shows the increase of LCF. The red line represents the increase before Crdl, whereas the blue one the increase during the*

For logistical and clinical reasons, it was not possible to include a control group, as patients with severe brain injury (SBI) present highly heterogeneous clinical profiles. Direct comparisons between two patients are not feasible, as they invariably differ in lesion site, age, medical history, and family background.

Despite the variability in clinical conditions and levels of consciousness across participants, consistent trends were observed in all three cases:

- a general increase of attention span;
- a progressive improvement in tolerance to stimulation;
- an increase in both verbal and non-verbal voluntary responses;
- the enhancement of communicative–relational abilities related to an increase of the level of functioning (LCF).

Qualitative analysis of attentional span revealed a progressive increase across all cases, aligning with findings by Sarkamo et al. (2008). While Case 1 exhibited a late-session decline, potentially due to habituation or the transition to LCF level 4 (confused-agitated), all patients showed improved attentional efficiency. This progression resulted from the synergy of daily multisensory stimulation, neuroplasticity, and interdisciplinary collaboration (Basaglia, 2002; Heruti & Ohry, 1995). The therapeutic protocol focused on gradually increasing cognitive demands, such as imitation, verbalization, and communicative turn-taking, within a consistent procedural framework. Rather than longer sessions, improvement was marked by a reduced discrepancy between total stimulation time and sustained engagement within fixed clinical schedules.

The frequency of voluntary responses (e.g., head nods, vocalizations, and gestures) also increased. Patients favoured "tapping" and "holding" gestures, likely due to easier imitation and the direct auditory feedback provided by the Crdl. It is noteworthy that the

kneading gesture was never used and tickling was only rarely observed, whereas the two gestures most frequently employed by the patient were tapping and holding, which were by far the most commonly performed actions. This is likely attributable to the greater ease of imitation and the clearer correspondence between the gesture and its auditory outcome; for example, in the case of the piano sound, each tap corresponded to a specific key. Notably, in cases with lower initial consciousness (1, 2), a consistent hierarchical recovery was observed: imitation preceded nods, articulation, and eventually vocalization. This was accompanied by increased eye contact and postural adjustments, which in Case 1 correlated with the shift from LCF level 3 to 4.

The third case highlights the role of Crdl as a meaningful adjunct to pharmacological and surgical interventions. Despite a two-week suspension of therapy and amantadine due to epileptic seizures, Patient 3 retained significant voluntary responses and eye contact. This suggests the persistence of residual memory likely mediated by emotional activation. As noted by Toader et al. (2023), auditory and musical stimuli activate the limbic system, including the amygdala and hippocampus, bypassing traditional frontal memory circuits. Furthermore, the accelerated recovery observed following the placement of a ventriculoperitoneal shunt (DVP, a surgical procedure aimed at increasing levels of consciousness and alertness by reducing ventricular dilation, which can contribute to comatose states) and increased amantadine dosage supports Cheng et al. (2018) and Lin et al. (2025), demonstrating that integrated protocols yield a positive clinical outcome (Fig. 17, 18).

# 6. CONCLUSION

The present study enabled the introduction, within the national speech and language rehabilitation landscape, of a novel approach to the management of patients with severe traumatic brain injury during the earliest stages of recovery of consciousness and arousal. From the outset, the intervention focused on the patient's communicative and interpersonal skills through multisensory stimulation, an approach that had not previously been implemented in this context. In particular, the stimulation protocol proved effective in increasing attentional span, progressively enhancing tolerance to longer treatment sessions, and consequently promoting a greater number of voluntary responses, both verbal and nonverbal, as well as an overall improvement in the level of consciousness. Furthermore, this type of stimulation was shown to be a useful modality for increasing motivation and engagement during rehabilitation sessions, thereby facilitating the achievement of communicative-pragmatic goals even in patients with higher levels of consciousness. It is important to emphasize the central role of the Crdl within this study, which functioned as a practical, versatile, and easily portable tool, allowing the therapeutic setting to be adapted in a manner that was both appropriate and accessible for each patient. This device addresses a gap that previously existed within the Italian hospital rehabilitation context.

## 6.1 Limits of the work

The present study presents some limitations. First is the small sample size, which was constrained by logistical and time-related factors. Obtaining a larger sample would require extending the project to multiple rehabilitation centres and implementing the stimulation protocol from the first day of hospitalization through discharge, while adapting objectives and instruments to each phase of the patient's clinical course.

A further limitation concerns the frequency of speech and language therapy interventions, which was influenced by patients' clinical conditions, medical priorities, and the need to coordinate scheduling with other professionals involved in patient management, including occupational therapists, physiotherapists, and neuropsychologists.

The absence of a control group represents an additional limitation. For clinical and methodological reasons, it is not feasible to establish a control group among patients with traumatic brain injury, given the considerable heterogeneity of this population with

respect to factors such as age, sex, educational background, lesion site, premorbid brain organization, and medical history. Nevertheless, without a control group, it is not possible to determine with certainty whether the observed improvements are directly attributable to the speech and language therapy intervention or rather reflect the effects of pharmacological treatment and spontaneous neuroplastic recovery.

## 6.2 Future perspectives

Future research and clinical practice should prioritize the dissemination and implementation of multisensory technologies specifically designed for individuals with Severe Brain Injury (SBI). Increasing professional awareness and knowledge of these tools is essential to facilitate their systematic integration into rehabilitation pathways and to ensure that clinicians are adequately trained in their appropriate and evidence-based use. Promoting familiarity with such technologies may contribute to more personalized, engaging, and effective therapeutic interventions for this population.

Furthermore, multisensory stimulation should not be limited to the Intensive Care Unit (ICU) or post-acute hospital settings but extended to a broader range of care environments. These include residential facilities for individuals with dementia, as well as rehabilitation centres serving children with severe neurocognitive disorders. Expanding the application of multisensory approaches across different clinical contexts may enhance patients' arousal, participation, and communicative responsiveness, thereby supporting functional recovery and quality of life across the lifespan.

From a research perspective, longitudinal studies are required to investigate the long-term effects of multisensory stimulation in larger and more heterogeneous samples of SBI patients. Prolonged observation periods would allow for a more comprehensive understanding of the stability and persistence of treatment outcomes, as well as the identification of factors that may influence responsiveness to intervention.

Finally, future investigations should aim to establish a better causal relationship between the use and non-use of multisensory stimulation. This objective can be achieved through rigorous experimental designs, including randomized controlled trials, control groups, and crossover methodologies applied to larger patient cohorts. Such methodological improvements would strengthen the empirical evidence base and clarify the specific contribution of multisensory stimulation to functional and communicative recovery.

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# APPENDIX

**Evaluation scale: GCS (Glasgow Coma Scale)**

| GLASGOW COMA SCORE | | |
|---|---|---|
| **Apertura degli occhi** | spontaneamente | **4** |
| | alla parola | **3** |
| | al dolore | **2** |
| | non apre gli occhi | **1** |
| | | |
| **Risposte verbali** | orientata, cioè il paziente relaziona con l'ambiente, capisce e risponde | **5** |
| | confusa | **4** |
| | parole non appropriate, parole a casaccio, urla, bestemmia, cose insensate, anche se pronunciate bene | **3** |
| | suoni incomprensibili, per esempio farfuglia | **2** |
| | nessuna | **1** |
| | | |
| **Risposte motorie** | obbedisce ai comandi | **6** |
| | localizza il dolore, se non vi è risposta ai comandi si applica uno stimolo doloroso che viene mantenuto finché non si abbia il massimo della risposta: inizialmente si applica la pressione al letto ungueale con il risultato di estensione o flessione del gomito; se vi è una di queste risposte allora lo stimolo viene effettuato al collo o al tronco per ricercare la "localizzazione" che si intende effettuata quando gli arti si muovono per tentare di rimuovere lo stimolo doloroso. | **5** |
| | si retrae, flette normalmente ma non localizza il dolore. | **4** |
| | Anormale flessione allo stimolo doloroso (decorticazione) | **3** |
| | Estensione allo stimolo doloroso, si ha quando la risposta è in adduzione delle braccia, rotazione interna e pronazione dell'avambraccio nel modello stereotipato della decerebrazione. (decerebrazione) | **2** |
| | nessuna | **1** |
| **RISULTATO** | | |
| Grave, con GCS ≤ 8 | Moderata, GCS 9-13 | Minore, GCS ≥ 14. |

## Evaluation scale: LCF (Level of Consciousness Functioning)

**LCF - Levels of Cognitive Functioning**

**1) NESSUNA RISPOSTA**

*Il paziente è completamente non-responsivo a qualsiasi stimolo.*

**2) RISPOSTA GENERALIZZATA**

- *Il paziente reagisce, in modo **incostante e non finalizzato**, agli stimoli, in modo non specifico.*
- *Le risposte sono di entità limitata, e spesso sono **uguali**, indipendentemente dallo stimolo presentato.*
- *Le risposte possono essere modificazioni di parametri fisiologici (frequenza del respiro ad es.), movimenti grossolani o vocalizzazioni.*
- *Spesso la risposta è **ritardata** rispetto allo stimolo*
- *La risposta più precoce a comparire è quella al **dolore.***

**3) RISPOSTA LOCALIZZATA**

- *Il paziente reagisce agli stimoli in modo **specifico ma non costante.** Le risposte sono direttamente correlate al tipo di stimolo presentato, come il girare il capo verso un suono o fissare un oggetto presentato nel campo visivo.*
- *Il paziente può ritirare una estremità e vocalizzare quando gli viene somministrato uno stimolo doloroso.*
- *Può **eseguire ordini semplici** in modo non costante, e ritardato, come chiudere gli occhi, stringere la mano, o stendere un arto. Quando non gli vengono portati stimoli, può restare fermo e tranquillo.*
- *Può mostrare una vaga consapevolezza di sé e del proprio corpo, manifestando risposte a situazioni di disagio, (come il tirare il sondino naso-gastrico o il catetere vescicale).*
- *Può mostrare **differenza nelle risposte**, rispondendo ad alcune persone (specie famigliari ed amici) ma non ad altre.*

**4) CONFUSO-AGITATO**

- *Il paziente è in stato di **iperattività**, con grave difficoltà ad analizzare le informazioni provenienti dall'ambiente.*
- *E' distaccato da quanto gli accade intorno e reagisce principalmente al suo stato di **confusione interiore**.*
- *Il comportamento in rapporto all'ambiente è spesso bizzarro e non finalizzato.*
- *Può piangere, o gridare in modo sproporzionato agli stimoli, anche quando questi vengono rimossi, può mostrarsi **aggressivo**, può cercare di togliersi i mezzi di contenimento, o le sonde e cateteri, o può cercare di scendere dal letto.*
- *Non riesce a distinguere le persone e le cose, e non è in grado di cooperare nel trattamento.*
- *La verbalizzazione è spesso incoerente e inappropriata alla situazione ambientale.*
- *Ci può essere **confabulazione**; essa può avere carattere di aggressività verbale o ostilità.*
- *La capacità di prestare attenzione all'ambiente è molto limitata, e la attenzione selettiva è spesso inesistente.*
- *Non essendo consapevole di quanto gli accade, il paziente non ha capacità di memoria a breve termine.*
- *Non è in grado di effettuare attività di cura della persona, se non con molto aiuto.*
- *Se non ha menomazioni fisiche importanti, può effettuare attività motorie automatiche anche complesse, come sedersi e camminare, ma non necessariamente in modo intenzionale o su richiesta.*

**5) CONFUSO- INAPPROPRIATO**

- *Il paziente è vigile, attento e **in grado di rispondere a comandi semplici in modo abbastanza costante.***
- *Tuttavia, se i comandi sono complessi, o non ci sono situazioni esterne facilitanti, le risposte sono non intenzionali, casuali, o al più, frammentarie rispetto allo scopo.*
- *Può presentare comportamento di agitazione, ma non dovuto a fattori interni come nel livello IV, ma piuttosto per effetto di stimoli esterni e usualmente in modo sproporzionato allo stimolo.*
- *Ha una **certa capacità di attenzione** verso l'ambiente, è altamente distraibile ed è incapace di focalizzare l'attenzione verso uno specifico compito, se non è continuamente facilitato.*
- *In una situazione facilitante e strutturata, può essere in grado di conversare in modo "automatico" (frasi di convenienza), per brevi periodi.*
- *La verbalizzazione è spesso inappropriata, può confabulare in riposta a quanto gli accade.*
- *La memoria è gravemente compromessa, e fa confusione fra passato e presente.*
- ***Manca l'iniziativa** per effettuare attività finalizzate (ad es. cura di se), e spesso è incapace di usare correttamente gli oggetti se non è aiutato da qualcuno.*
- *Può essere in grado di effettuare compiti appresi in precedenza se posto in situazione adeguata, ma **non è in grado di apprendere nuove informazioni**.*
- *Risponde meglio a stimoli che riguardano il proprio corpo, il proprio benessere e comfort fisico e, spesso, risponde meglio con i famigliari.*
- *Può effettuare **attività di cura di se' con assistenza** e può alimentarsi con supervisione.*
- *La gestione in reparto può essere difficoltosa, se il paziente è in gradi di spostarsi, perché può vagare per il reparto, oppure mostrare l'intenzione di "andare a casa", senza comprenderne i rischi o le difficoltà.*

**6) CONFUSO-APPROPRIATO**

- *Il paziente mostra un **comportamento finalizzato**, ma necessita ancora di stimoli e indicazioni esterne per indirizzarlo correttamente.*
- *La risposta al disagio è appropriata, e può essere in grado di sopportare stimoli fastidiosi (ad es. un sondino naso-gastrico, se gli si spiega il perché).*
- *Esegue ordini semplici e **segue le indicazioni**, e mostra di poter effettuare certi compiti da solo, una volta che si è esercitato (ad esempio, attività di cura di se').*
- *Necessita comunque di supervisione nelle attività che gli erano abituali; necessita di molto aiuto nelle attività nuove (che non aveva mai svolto prima), e non è poi capace di svolgerle da solo.*
- *Le risposte possono essere scorrette a causa di problemi di memoria, ma sono adeguate alla situazione.*
- *Possono essere ritardate o immediate, e mostra una diminuita capacità di analizzare la informazione, con incapacità di anticipare o prevedere gli eventi.*
- *La memoria per gli avvenimenti del passato è migliore che quelle per gli eventi recenti (accaduti dopo il trauma).*
- *Il paziente può **mostrare una iniziale consapevolezza di situazione**, e si può rendere conto che ha difficoltà a rispondere.*
- *Non tende più a vagare senza meta, ed ha un parziale orientamento nello spazio e nel tempo.*
- *La attenzione selettiva al compito può essere compromessa, specie in compiti di difficili o in situazioni non "facilitanti", ma riesce a effettuare correttamente normali attività di cura di se'.*
- *Può mostrare di riconoscere i componenti del team, e ha una miglior consapevolezza di se', dei suoi bisogni elementari ed è più adeguato nei rapporti con i famigliari.*

**7) AUTOMATICO-APPROPRIATO**

- *Il paziente è **adeguato e orientato nell'ambiente del reparto e a casa**, svolge le sue attività di vita quotidiana automaticamente, e in modo simile a quello di un robot.*
- *Non presenta confusione, e **ha una certa capacità di ricordare che cosa gli è successo**.*
- *Si mostra via via più **consapevole della sua situazione**, dei suoi problemi e necessità fisiche, dei suoi bisogni, della presenza dei famigliari delle altre persone presenti intorno a lui, così come dell'ambiente in generale.*
- *Ha una consapevolezza superficiale della sua situazione generale, ma gli manca ancora la capacità di analizzarla nella sue conseguenze, a scarsa capacità critica e di giudizio, e non è in grado di fare programmi realistici per il futuro.*
- *Mostra di poter **applicare nuove abilità**, ma ancora con difficoltà ed in modo parziale.*
- *Necessita almeno di una supervisione minima per difficoltà di apprendimento e per motivi di sicurezza.*
- *E' autonomo nelle attività di cura di se, e può necessitare di supervisione a casa o fuori, per ragioni di sicurezza.*
- *In un ambiente strutturato facilitante, può essere in grado di iniziare da solo certe attività pratiche, o attività ricreative, o sociali per cui ora può mostrare interesse.*

**8) FINALIZZATO-APPROPRIATO**

- *Il paziente è **vigile e orientato**; è in grado di **ricordare ed integrare eventi passati e recenti**, ed è **consapevole** della sua situazione.*
- *Si mostra in grado di applicare nuove conoscenze e abilità apprese, purché siano accettabili per lui e per il suo stile di vita, e no necessita di supervisione*
- *Nei limiti delle sue eventuali difficoltà fisiche, si mostra **indipendente** nelle attività domestiche e sociali.*
- *Può continuare a mostrare una **certa diminuzione di capacità**, rispetto a prima del trauma, specie riguardo alla velocità e adeguatezza nell'analizzare le informazioni, nel ragionamento astratto, nella tolleranza allo stress e ala capacità di critica e giudizio in situazione di emergenza o in circostanze non abituali.*
- *Le sue capacità intellettive, la sua capacità di adattamento emozionale e le abilità sociali possono essere ancora ad un livello inferiore rispetto a prima, ma consentono comunque il reinserimento sociale.*

## Evaluation scale: CNC (Coma Near Coma)

**COMA / NEAR COMA SCALE**

La scala è utilizzata con pazienti che alla Disability Rating Scale presentano un punteggio >= 21; viene somministrata 2 volte al giorno per 3 giorni,poi settimanalmente per 3 settimane, da allora ogni 2 settimane se DRS >= 21.

| Parametro | N° Stimoli | Stimolo | N° prove | Misura della risposta | Punteg | Criteri di punteggio |
|---|---|---|---|---|---|---|
| Uditivo | 1 | Suono di campana per 5 sec con un intervallo di 10 sec | 3 | Apertura degli occhi<br>Orientamento verso il suono | 0<br>2<br>4 | >= 3 v<br>1 o 2 v<br>nessuna risposta |
| Risposta ai comandi | 2 | Chiedere al paziente di aprire o chiudere la bocca o muovere le dita, le mani o le gambe | 3 | Risposta a comando | 0<br>2<br>4 | Risponde al comando 2-3 v<br>Tentativo o risposta inconsistente 1 v<br>Nessuna risposta |
| Visivo con preparazione (deve essere in grado di aprire gli occhi semnò punteggio 4 per gli items 3-4-5 e segnare qui _____) | 3 | Flashes di luce in faccia (1 sec x 5) leggermente a sx,dx,su e giù | 5 | Fissazione o evitamento | 0<br>2<br>4 | Fissazione o esitamento 3 v<br>Parziale fissazione 1-2 v<br>Niente |
| | 4 | Chiedere al paziente "GUARDAMI",muovere il viso 20 sec da un lato all'altro | 5 | Fissazione o inseguimento | 0<br>2<br>4 | Inseguimento sostenuto >=3v<br>Inseguimento parziale almeno 1-2 v<br>Non inseguimento |
| Risposta alla minaccia | 5 | Rapidamente muovere la mano davanti agli occhi per 1-3 sec | 3 | Blink oculare | 0<br>2<br>4 | 3 blinks<br>1 o 2 blinks<br>nessun blinks |
| Risposta olfattiva (chiudere la tracheotomia per 3-5 sec se è presente) | 6 | Tappo di bottiglia di ammoniaca sotto il naso per circa 3 sec | 3 | Allontanamento o altra risposta legata allo stimolo | 0<br>2<br>4 | Risponde 2-3 v rapidamente(>=3 sec)<br>Allontanamento lento o parziale, smorfie 1 v<br>Né allontanamento né smorfie |
| Tattile | 7 | Tocare la spalla bruscamente 3 v senza parlare al paziente,da ogni lato | 3 | Orientamento della testa o degli occhi o movimenti della spalla al tocco | 0<br>2<br>4 | Orientamento verso il tocco 2-3 v<br>Parziale orientamento 1 v<br>Nessun orientamento o risposta |
| | 8 | Tampone nasale per ogni narice (entrare senza penetrare in profondità) | 3 | Allontanamento o blink oculare o contrazione della bocca | 0<br>2<br>4 | Chiaro,rapido(in 2 sec) 2-3-v<br>Risposta parziale o ritardata per 1 v<br>Nessuna risposta |
| Dolore (lasciare 10 sec per la risposta) se c'è un danno spinale segnare qui _____ e andare allo stimolo 10 | 9 | Pizzicotto deciso sulla punta delle dita,pressione di una matita sulle unghie,da ogni lato | 3 | Vedi criteri di punteggio | 0<br>2<br>4 | Allontanamento 2-3-v<br>Movimenti generali non specifici 1 v<br>Nessuna risposta |
| | 10 | Un forte pizzicotto all'orecchio 3 v da ogni lato | 3 | Allontanamento o altre risposte correlate allo stimolo | 0<br>2<br>4 | Risponde 2-3-v<br>Movimenti generali non specifici 1 v<br>Nessuna risposta |
| Vocalizzazione (se manca tracheostomia) se presente non agire ma segnare qui | 11 | Nessuno (dare un punteggio alla risposta migliore) | - | Vedi criteri di punteggio | 0<br>2<br>4 | Parole spontanee<br>Vocalizzazione non verbale (suoni / grugniti)<br>Nessun suono |
| COMMENTI : | | Livelli CNC* 1→ 0.00-0.89 no coma (DRS 17-19)<br>2→0.90-2.00 near coma (DRS 20-23)<br>3→2.01-2089 coma moderato(DRS 24-26)<br>4→2.90-3.49 coma marcato(DRS 27-29)<br>5→3.50-4.00 coma profondo (DRS29) | | Totale CNC (sommare i punteggi) A<br>Numero di stimoli presentati B<br>Medie del punteggio CNC (A:B) C<br>Livello CNC * (0-5) D | | |

[Rappaport M.,Dougherty AM.,Kelting DL., Evaluation of coma and vegetative states, Arch Phys Med Rehabil, 73, n°7: 628-634,1992.]Nota: La sua versione italiana è stata tratta da Boldrini P.,Basaglia N.,Sarti D.,Ponti S.,Morelli M.,Filippini F., La cartella integrata o "cartella paziente" come strumento del team riabilitativo interprofessionale, MR Giornale italiano di medicina riabilitativa, 14, n°3:17-29, 2000.

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