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Towards the development of interfaces for students with speech disorder and motor impairments

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Abstract

In a complex case of speech disorder, the communication is entrusted to systems equipped with a speech synthesizer. When the user has a motor disability, in addition, hardware and software interfaces are personalized to make technology more accessible. Interaction design methods can be applied to develop improved assistive systems and, particularly, for Augmentative and Alternative Communication (AAC). Interaction design methods and usability evaluation could have a positive impact in reducing product barriers and improving performances as the effort state associated to its use can be reduced. Minimizing cognitive and physical efforts through the development of new solutions and interface optimization can be challenging. A usability test and an interface optimization of a personalized AAC system developed for a student of the University of Naples Federico II with complex communication needs due to a traumatic injury and motor impairment are discussed to fix usability issues, highlight critical areas and design new prototypes.

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1. Introduction

Design of assistive technologies should consider an inclusive approach, as the user plays a role in the product development and, thus, the product becomes personalized in relation to the needs. These needs are assessed by means of standard methodologies and observational studies and differ from one individual to another depending on the specific condition and the tasks the user intends to perform as "there are multiple models of disability in operations and, often, in opposition". [1]

The main priority is the inclusion of people with disabilities in community participation, and the role of the design of personalized interfaces is to promote devices that increase the individual capabilities instead of merely compensate some reduced functions. In fact, "once the person is stabilized medically, they may receive medical rehabilitation designed to strengthen the remaining capabilities and compensate for those that have been lost." [2].

Currently, the technological offer doesn't fully match user requirements in cases of disability that involves multiple impairments. Systems should be customized to reduce the mismatch between technology and user needs and a multi-disciplinary team is required for the identification of these needs with a good level of accuracy. [3]

The translation of the user needs into functional requirements (FR's) requires the user involvement in the project phases. The user is asked to verify that the solution, proposed in the early stage even as a virtual prototype, is close to the fulfillment of the needs. This phase occurs cyclically until the elimination of barriers and the improvement of performances [4]. Even if the availability of commercial systems has increased in the last years, promoting deliverable technologies and many stand-alone devices, in cases of custom systems are necessary when commercial systems doesn't fully satisfy the user requirements. [5] The user requirements were determined by means of observational studies, using a participatory approach in which the user was involved into the decision-making process.

In the current research, a usability evaluation assesses the interaction between an Augmentative and Alternative Communication (AAC) System and a user with spastic quadriplegia and speech impairment. In this context, usability test finds out critical issues, determines user performances and guides the team towards the prediction of results and the achievements of objectives. Instead, the task analysis provides software and hardware optimization. The case study is supported by an Analytical Hierarchy Process (AHP) and a Multiple Criteria Decision Analysis (MCDA) approach. [6]

Several improvements and corrective actions are proposed from the data analysis. As the issues are general, design solutions and guidelines can be defined, e.g. aggregating symbols by type, avoiding critical actions, improving intuitiveness and learnability of the system, sizing functions to user needs, reducing cognitive load and defining operations by rules [7].

These systems also require cognitive demand as discussed in a previous work. In particular, the paper analyzes the role of learnability in product development providing some examples of actions that could reduce the cognitive load and improve automatism, for instance, implementing tutorials when new features are introduced, as the time spent in learning could represent the main waste of time [8].

Moreover, the manufacturability of this kind of devices could be strongly supported by additive manufacturing technologies, from the adaptation of commercial tools to the printing of the whole device.

An integrated combination of technologies, interaction design and usability evaluation could improve user performance such as speed in communication, low error rate and time and could permit the user to achieve a better expressive depth and to minimize the physical and cognitive barrier when interacting with a new technology.

2. Augmentative and Alternative Communication

An Augmentative and Alternative Communication (AAC) System is a communication aid aimed at individuals with disabilities to replace oral communication when it is impaired. AAC devices must be efficient to reduce time waste and effective to reduce errors in those cases in which the user repeats a great number of operations to achieve a goal. In addition, the interaction must be effortless when spasticity occurs in people with neuromotor disease and reduced motor functions.

An AAC System can be unaided, low-tech or high-tech depending on its technological content. A high-tech AAC System needs battery to work.

The access to AAC devices can be either direct or indirect. The former requires the user to point directly to the item they wish to select. The major benefit of direct access method is the flexibility, but it requires a greater level of motor control and coordination. An AAC system also requires a method of output for the user to transmit messages. The output could be either a synthesized speech or a text.

An AAC system may support receptive and expressive communication. The former refers to systems and strategies which support an individual able to understand the information [9].

Technical skills are required when operating a system. Such operational competencies should involve sensory abilities, e.g., vision, and cognitive abilities, e.g., sequencing, planning, memory etc. [10]

2.1 Test system

In a high-tech AAC System with direct selection, the ideal user's task model consists of 4 actions: (1) locate target symbol; (2) positioning in the row; (3) positioning in the column; (4) selection of the symbol.

The first action involves cognitive skills as symbol recognition and position recall in the grid and doesn't involve any physical effort. The actions 2 and 3 involve motion of the body segment into the hardware interface and push of the corresponding switch. These actions can be performed in reverse order. The action 4 is performed, as in 2 and 3, using a sensor. In an errorless case at least three sensors are required: two sensors for positioning and the other one for selection. When errors occur at least 1 sensor must be added for corrective actions.

The task requires both cognitive and physical skills, thus, the hardware and software interface should be analyzed at the same time, since the dependence of these two aspects is explicit. [11]

Using the Test System described below and the obtained data, the communication rate of the user was at the average 4-5 characters/min, representing a low value. The introduction of new features provided a decay rate.

The test system was properly reviewed many times to improve user interaction. The number of sensors was five and the sensors were divided into mechanical switches activated by pressure or bending. The curve on which the sensors are arranged and their expansion in space were also considered as a design requirement.

The test system, consisted of four switches for up, down, right, left keys and one blending sensor for confirmation, when the final revision was carried out. The function of a sensor may be identified by its cap color which is memorized by the user (fig. 1). The sensors are used to navigate into a grid with symbols. Symbols are: alphabetical, functions, numbers and special characters distributed into two grids (fig.2). The sensors are activated with fingers or hand.

2.2 Grid layout

The software interface app consists of character, function, numeric and special character symbols. These symbols are split into two grids and the passage from one to another is guaranteed by home and return functions.

The lexical content of the user written and 'spoken' communication, mostly made of fundamental and high use lexicon, was analyzed with a code that took texts as entry points and gave the frequencies of characters as output. Different sample sizes were investigated, obtaining an array of alphabetical symbols ordered by frequency. The user's native language the vocals have a high impact on communication and should be distributed in the grid at a minimum operation path.

In the grid, the home cell can be fixed or floating. In the prototype the home cell was set in the first position of the grid ('Read' cell in fig.2). A 5x4 alphabetical grid and cells in the secondary grid were chosen to improve the user's cognitive abilities, simultaneously satisfying two conditions: frequent symbols (a, e, i, o) are on the shortest path and the alphabetical order is respected. Vice versa, a grid of different sizes in which characters are generally weighted by frequency allows a better save operation, however increasing the cognitive load and learning time.

3. Usability assessment

Usability is defined by the International Organization for Standardization, as the extent to which a product can be used by specific users to achieve specific goals with effectiveness, efficiency and satisfaction in a given context of use [12].

In this model, an Evidence Based Practice approach is employed promoting the use of statistical data analysis and measurement based on information retrieval, while Analytic Hierarchy Process and decision tools are used to validate the data analysis outcome.

The experimentation, lasting two months, permits to evaluate the system learnability, the point of transition from novice to expert mode, and the correlation between performance and physical condition also through the increase of task difficulty. The experimental campaign is divided into 10 sessions on a weekly basis where each daily session consists of 4 tests with a pause every 2 tests. The main task of each test is writing a pangram†. Each main task consists of sub-tasks in which the user is forced to use character symbols, function symbols and special character symbols with different frequencies that determines the overall difficulty.

Fig. 1 – (a) AAC System Test Prototype (b) Jelly Bean Switch Ablenet Inc. (c) Ribbon Switch Ablenet Inc.

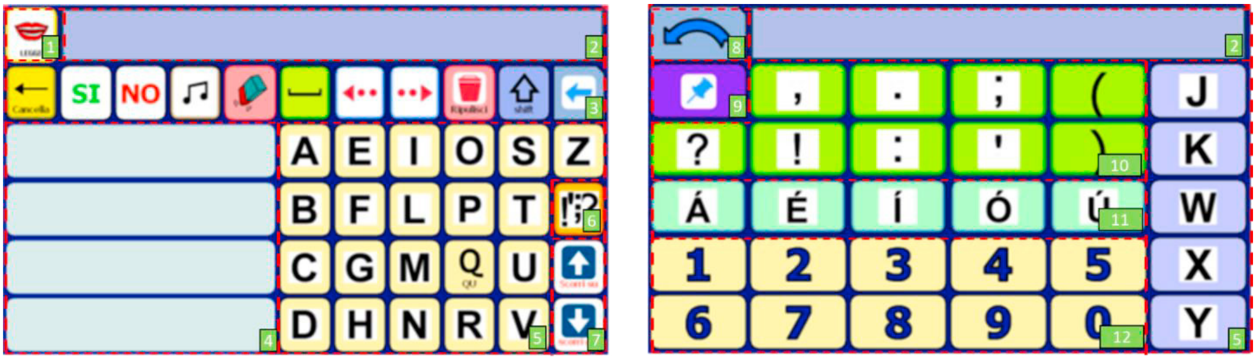

Fig. 2 – (a) main grid (b) secondary grid, (1) Read/'Home cell' (2) Text output (3) functions (4) --- (5) alphabet (6) secondary grid (7) scroll (8) back (9) pin (10) special (11) accent (12) number

3.1 Analytical Hierarchy Process approach

The Figure 3 shows the decomposition of the usability according to the AHP approach. At a first level we set the AAC system usability index (UI) that is decomposed according to [13, 14] in Usability Dimensions (UDs) within the second level (tab.1).

Table 1. Usability dimension and definition.

Usability Dimension	**Definition**
Effectiveness	the level of accuracy and completeness with which the student achieves a specified goal
Efficiency	the level of effectiveness achieved to the expenditure of resources
Satisfaction	the condition of freedom from discomfort and positive attitude towards the use of the device

† A pangram is a sentence is a sentence using every letter of a given alphabet at least once.

At the third level, the UDs are broken down in Usability Functions (UFs) that are related to the experimental task.
A linear additive evaluation model could be applied because we assume that the hierarchy of the factors are independent of each other. The measures could be combined into one overall value using MCDA [15, 16]. The measure of each factor is multiplied by a weight, and then the weighted scores are summed up.
Data are different in terms of nature and magnitude. Therefore, a normalization is required to make a comparison. The normalization techniques adopted for the UFs are reported in Table 1.

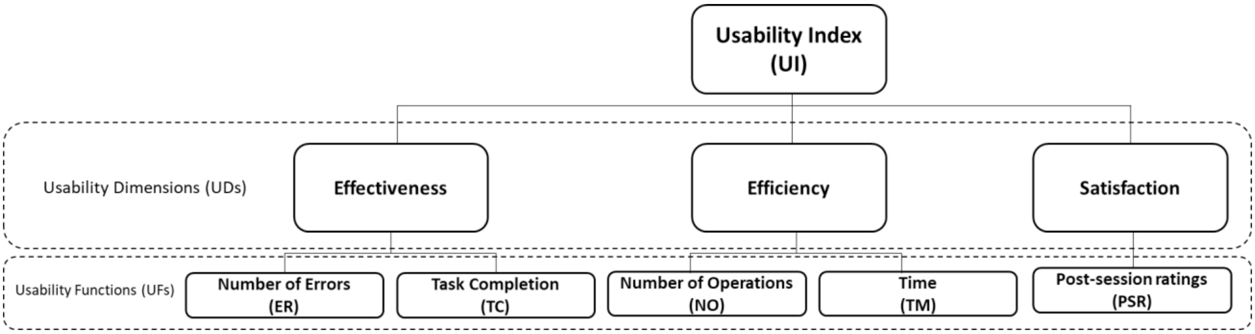

Fig. 3 – Usability Index 'Analytical Hierarchy Process'

The results of the normalization procedure are the usability measures (*umi*) that range from 0 to 1.
The Usability Dimension Index (UDI) is defined as:

$$\boldsymbol{UDI_i = \sum_{i=1}^{n} w_i m_i \;(1)}$$

where w_i is the weight of each usability measure. There are three usability dimension indexes: effectiveness, efficiency and satisfaction.
The weighted sum of three indexes provides the overall results for the UI (2):

$$\boldsymbol{UI = \sum_{i=1}^{n} w_i UDI_i (2)}$$

The AHP is applied to evaluate the relevance of the factors in the hierarchy, considering the analysis of AAC system interaction. According to [16] and starting from the hierarchy structure of the model, the matrix of weights is defined. Once the pair comparison matrix is defined, the weight of each element is assumed as (3):

$$\boldsymbol{w_i = \frac{(\prod_{j=1}^{n} a_{ij})^{1/n}}{\sum_{i=1}^{n}(\prod_{j=1}^{n} a_{ij})^{1/n}}\,;\, i, j = [1, n](3)}$$

In (3) n is the metric dimension related to the element and *a*ij is the generic matrix element. The allocation of weights follows a bottom-up logic.

3.2 Experimentation

The experimental campaign was divided into 10 sessions on a weekly basis where each daily session consisted of 4 tests with a break of an hour every two tests. The first pangram was set as the control task as it doesn't introduce any new feature previously unknown by the user. In tab. 2 four on ten pangrams are showed.

Table 2 – Examples of pangrams used in the experimentation.

#	Pangram	NC	*NW*	*NS*	*NSC*	P	C	NO
1	*Quel Fez sgembo copre davanti*	*29*	*5*	*4*	*0*	*223*	*33*	*256*
2	*ivi dorme il buffo ghiro paziente subacqueo*	*37*	*7*	*6*	*0*	*263*	*34*	*297*
3	*Tv? Quiz, Br, Flm, Dc… Oh, spenga!*	*21*	*7*	*6*	*9*	*337*	*46*	*383*
4	*yellow quick crazy fish is jumping over the dark box*	*39*	*10*	*9*	*0*	*343*	*52*	*395*

NC: number of characters NW: number of words NS: number of spaces NSC: number of special characters
P: pushes C: confirms NO: number of operations

3.2.1 Number of operations (NO)

The NO to compose a pangram range from about 250 to 400 operations. The number of operations can be reduced using strategies, for instance modifying the position of the home cell and arranging symbols using weights. The weight can be obtained from observational study and task analysis. The NO of pangrams (tab.2) represents the lower value of operations, if errors occur the NO increase dependently by the magnitude and type of the error.

3.2.2 Number of errors (NE)

The errors were divided into different types. We identified five types of error: blink, slip, uncertainty, lifting and false push. A blink error occurs when the user activates a switch positioned in the corner of the grid in the border direction. The effect of blinking is cell flashing without moving, as it adds a physical effort without any response on the system except for a visual feedback. A slip error occurs when the user, reaching a target cell of the interface goes beyond it. To recover the target, he performs additional operations, oscillating horizontally and vertically. Regarding the lifting error, the user goes over the blending sensor in the trial to activate it. To prevent such error, an ergonomic analysis is required as it should reveal an incorrect posture. False pressure occurs when the user activates a switch along the path to reach the target. Uncertainty is about a misunderstanding of the action planning.

3.2.3 Time (T)

The reference target value for time is the pangram with the minimum number of operations compared with those being affected by less errors. It can be used for a qualitative analysis and quantifies the time required in the expert mode. In the case of novice user this value has been multiplied by 1.5. Thus, from the experimental data, it can be assumed that the time of pressure is about one second for operation when user masters the system.

3.2.4 Task completion (TC)

Considering the previous considerations, the completion of the task can also be used as an index of the cognitive abilities of the user when he uses the device. For the assessment, the task completion was found to be 1 for most tests.

3.2.5 Post session ratings (PSR)

For each session the user and the expert panel were given a questionnaire consisting of 10 questions. The questionnaire was proposed to user, experts and family who reported an evaluation ranging from 1 to 5. Using the questionnaire, it is generally possible to measure the level of perceived satisfaction of the user. The questions were about perceived time to complete the task, perceived difficulty, state of effort, level of the user, robustness of the system, efficiency of the system, possibilities of improvement and satisfaction in use.

Table 3. Normalization techniques adopted for UFs.

Normalisation technique	**Usability Functions**	**Transformation**
e_{ij}/max_i	RT	It maintains the direction of preferences
$\min/\ e_{ij}$	ER, TC	It reverses the direction of preferences
$e_{target}/\ e_{ij}$	NO, TM	It reverses the direction of preferences and requires a target value

4. Usability evaluation, issues and corrective actions

A single task is composed by a high number of sub-tasks, both cognitive, as it involves the capability of the user to understand functions and symbols as well as to locate them into the grid, and physical moving the body segment upon the hardware interface.

Another important aspect to be considered is the design against spurious actions that can be generated, i.e. all those actions that are performed on the system because of the non-decoupling effects.

Thus, the possibility of generating action paths that improve the user's automatic mechanisms should be included.

The usability index is 0.65. To align product and user performances, a normalization through a learnability curve is recommended. As noted by data, the performances increase after a time that we should consider as a training time. Looking back at the video tests we also noted that the user started to understand shortcuts introduced into the grids, bypassing in the first stage of the sub-tasks a number of operations equal to five, which repeated and saved a very high number of operations, thus permitting the user to achieve completion of the main task faster.

The usability index is low in terms of the dimension of effectiveness. Since the task completion is very close to one, the function to be improved is NO. We have observed from the analysis of the video some critical issues that were repeated with a significant frequency and we can link them to both objective and subjective aspects.

Table 4. Weight and measure of Usability Functions

	NE	TC	NO	TM	PRS
w_i	0,7	0,2	0,7	0,2	1,0
um_i	0,4	0,9	0,7	0,7	0,6

The measures were taken from recorded video, judgements of an expert panel and questionnaires. NE was obtained counting the errors from video tests. TC was measured verifying the completeness of the task. NO was obtained counting the operations to complete the task. T was obtained by the difference between start and end time. PSR were gained from questionnaires administered to specialists and user.

We have identified and recorded these issues that are related to sensor reachability, slips and blinks; also, the user showed some problems related to uncertainty, lifting and false pressures.

To correct these issues, the chosen entry mode is a 5x4 alphabetical grid with 'Home' on A symbol as it is cognitively simpler, allows the user to move in all directions of the grid as well as a good saving on the number of operations compared to other positions.

Table 5. Weight and measure of Usability Dimensions

	Effectiveness	Efficiency	Satisfaction
w_i	0,39	0,42	0,19
UD_i	0,57	0,74	0,60

The changes made to the grid are based on four operations: cell sizing, replacement, deletion and positioning. The areas of improvement are cognitive, physical and operational and some issues are generated by a wrong programming of the action, spasticity phenomena and an incorrect understanding of the functioning.

Table 6. Usability issues and corrective action.

#	Usability Issue	Root Cause	Area of improvement	Corrective action
1	The user can't visualize correctly an entered text	Visive abilities, complexity of communication	Cognitive-Physical	Cell sizing
2	Excessive number of operations to reach the alphabetic symbols	For the novice user no shortcuts were found	Cognitive-Physical	Deletion of a row
3	Learnability	Too much elements	Cognitive	Reduction of symbols
4	High number of operations per symbol	The most used symbol is too far from the home cell	Cognitive-Physical	Home positioning
5	Accidental actions	Slips (horizontal and vertical)	Cognitive-Operational	Reordering
6	Break	The user activated accidentally the ring function	Operational	External ring
7	Unused symbol/function	Symbols have a null or low impact on communication	Operational	Deletion
8	Fatal error	Accidentally use of delete/erase functions	Cognitive-Physical Operational	Positioning in a sandbox area

9	Increasing of error when accessing new functions	Bad understanding of a new functions	Cognitive	Training and visual tutorial
10	Automatism	Self-intersecting paths	Operational	Action modelling

In addition, the hardware layout should be consequently modified. The optimal hardware configuration must verify the conditions of minumum number of generated errors and minimum range of movement; also, a characteristic of the product should be simplicity in use leading to improved automatism.

A natural design for the user also represents an optimal design. The following indications can be put in place: the highest switch stand for ‘up’; the lowest switch stand for ‘down’; primary switches are on a specific path: the error recovery switches are on a specific path; the paths don’t generate intersection of the actions.

Tab. 6 summarises the usability issues found into the interface. Root cause analysis was carried out by a multidisciplinary team and were determined by observational studied of the actions from the user identified in lacking areas suggested by the hierarchy process.

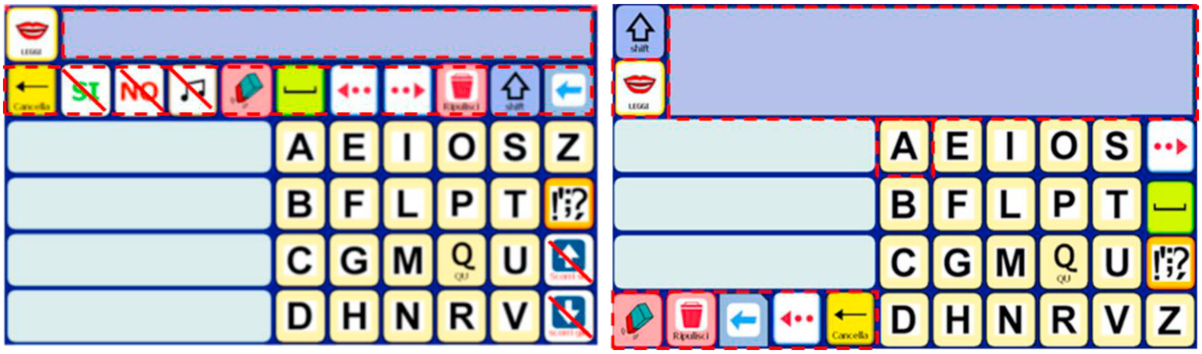

Fig.4 – (a) Usable hardware and software interface (b) and (c) customized switch adaption

Fig. 5 – (a) Render of the hardware layout; (b) Mockup of the device.

Fig. 5 reports a render of the hardware layout at rev. 6 (left) and a device mockup at rev. 5 (right) with a tablet stand implemented in the solution.

5. Conclusion

An approach towards the development of interfaces for students with speech disorder and motor impairments has been reported in the current study, focusing on usability issues, critical areas and potential design or implementation of prototypes.

To confirm the feasibility and investigate the benefits of the corrective actions a second experimentation will be carried out. An EBP approach will be used and measures will be taken using a usability assessment.

As noted, design of interfaces must be carried out simultaneously on both hardware and software, since they are dependent each other. To obtain an optimal interaction it would be needed to analyze the user's task; define the software layout that is close to user's task; choose the minimum number of sensors that allows to perform decoupled actions on the system; define the hardware layout that allows completion of the task with less effort, considering solutions for cascading errors that may be generated by a poor software interface design; find the best combination of the two layouts by imposing error reduction as objective of the experimentation, also using strategies and heuristics proposed by IxD; identify barriers; verify that the prototype meets the usability requirements; test the solution with the user.Even though the product is based on a single case, the possibility to extent the results to other users with neuromotor disease, both on the software and hardware aspect, could be possible using a parametric approach as well as the generation of general-purpose tools and methodologies

Through parametric design it is possible to obtain a class of devices which fit better the user needs. The extension to a wider number of users requires as input information the body segment employed to activate sensors (e.g. left or right arm) and the minimum activation surface for each navigation set. The navigation set could range from three to four sensors, where three represents the minimum number of sensors in direct selection and 'home cell' in a vertex of the grid.With regard to the parametric design, another important aspect is the possibility to adapt the system to different environment, e.g. to assembly it on a wheelchair, limiting the cost associated to the redesign, and to adapt it to different individuals in each stage of the growth. In an evolutionary approach, we can adapt and reprint the whole device or part of it using specific design requirements such as personal factors as age, percentile of population, range/type of movement for different body segment.

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