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Published in:
In proceedings of 8th EAI International Conference: ArtsIT, Interactivity & Game Creation

DOI (link to publication from Publisher):
10.1007/978-3-030-53294-9_9

Publication date:
2020

Link to publication from Aalborg University

Citation for published version (APA):
Ilyas, C. M. A., Rodil, K., & Rehm, M. (2020). Developing a user-centred Communication Pad for Cognitive and Physical Impaired People. In A. Brooks, & E. I. Brooks (Eds.), *In proceedings of 8th EAI International Conference: ArtsIT, Interactivity & Game Creation* (Vol. 328, pp. 124-137). Springer Publishing Company. https://doi.org/10.1007/978-3-030-53294-9_9

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Developing a user-centred Communication Pad for Cognitive and Physical Impaired People

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Abstract. It is always challenging for people with disabilities, particularly having speech inhibition to communicate. In this research article, we explored the case study of the resident at the neurological centre, having a complication in conveying messages due to physical and speech paralysis. For making effective communication, we have developed a user-centred communication pad where the resident needs to swipe a finger on the pad with printed alphabets and digits (we called it communication pad). A camera placed over the communication pad detects the finger movement of the resident and extract the message to display on the computer screen or the tablet. Our tracking method is robust and can track the fingers even in varying illumination conditions. This paper also covers the main steps of design methods with various design prototypes and its user feedback. Result analysis of different design modules and user experience evaluation shows that our designed system has provided independence and convenience to the resident in conveying a message successfully.

Keywords: User experience · Design · Ambient Assistive Technology (AAT) · Finger tracking system · Augmentive and Alternative Communication (AAC)

1 Project Introduction

Since 2015 we have been working with a national neurological centre (hereafter neuro centre) with a focus on co-designing various technical systems enhancing capability for the individual residents. As these residents are unable to recover from their life-altering impairments fully, the centre provides full-time care to them and aid in organizing and supporting activities of daily living (ADL). The project collaboration aim is to investigate where technological innovation can assist residents and staff members with fulfillment of rehabilitation activities -

including enhancing individual self-control and improvement of quality of life [5, 6, 16].

One of the overall design (and research) challenges is the unique (and highly diverse) nature of the cognitive abilities of residents (for instance, apraxia and aphasia). Due to the severe and diverse conditions, the residents require assistance even for small chores. To list a couple of examples, some of the residents are fully paralyzed and bound to wheelchairs or beds, some residents have lost all speaking ability, and some have minimal short-term memory or attention spans (in some cases less than two minutes). All residents embody a combination of these impairments, but the common characteristic is that they all became impaired late in life. These conditions reflect a significant alteration of the functionality of the individual - in many cases leading to depression and general loss of life quality perceptible as a decrease of "self-control, self-worth, privacy and independence" [16].

While the primary task of the neuro centre is to provide round the clock care-giving, it also encourages technical solutions addressing the needs of these residents for specific task assistance as these residents are heavily relying on staff support even for personal and private matters. It is important to stress that it is not only a budgetary manoeuvre, but there is a grounded wish for the residents to have as much self-control as possible. Thus a major research strand orbits; how to enable designing for diversity with an inclusive design approach - such as Participatory Design.

Some companies who are working with the neuro centre furnish technical support related to rehabilitation activities but with little to no consideration of personal challenges and abilities. Most of their products are designed for rehabilitation purposes only with highly generic solutions, thus making them of little to no use for these residents. Each resident has a unique and individual challenge, for instance, one resident has a problem with remembering, he frequently forgets forcing staff to remind him time and time again about even very basic tasks. This cycle of reminding and forgetting often leads to frustration on both parts.

We have been part of a variety of different projects at the neuro centre over the years and after a series of consultation meetings (demonstration of prototypes, group talks, socialization) with staff members and residents, there was consensus to focus a project on making customized, and human-centred functional social robots to enhance independence and quality of life. The project demonstrates a well-meant objective of empowering the residents to respond to their everyday challenges and give a voice to those who are neglected or technically limited to be part of otherwise off-access traditional system development.

Thus the inclusion into design is cardinal and a priority that the residents provide input during design sessions and contribute to the aesthetic and functional properties of the systems. This deliberate inclusion has so far provided the residents with a visible sense of ownership. As an example, in some situations, the residents suggested making the design to closely reflect the portrayal of their favourite movie character or other more personal traits. What was initially the project, became an umbrella for several individual projects. Albeit being very different in function and aesthetic, they all followed the same development model rooted in problem-oriented development. The first phase was best characterized as an ethnographic approach into the life world of the resident and the particularities of their situations requesting a technical solution. Following this phase resembled a typical collaborative sketching/illustration on paper phase whereby ideas were externalized (for instance by using cardboard). The last phases involved prototyping with 3D printers, assembly using electronics and always with several sessions together with the resident. These social robots were from the beginning customized for and with a specific user - one system for one resident.

1.1 Case Study

People with motor, speech and hearing inhibitions face severe difficulties in conveying their messages traditionally (for instance using sign language). In many cases, they are dependent on Augmentative and Alternative Communication (AAC) technologies so there is always a need of a specific communication system, for instance, one that can track hand or finger gestures. Thus, such a camera vision system able to transcribe finger or hand movement or sign language into text or speech would, conceptually, be useful for productive interaction (reliable and fast).

In this case study, the resident is suffering from speech inhibition and paralysis and is used to communicate with staff through an analog communication tool, a big-sized letter-board, with digits and numbers printed as illustrated in the Fig 2. First of all, the board with printed numbers is quite big, making it unfit to use it in all situations. For instance, if a resident require assistance while travelling or even social communication outside the resident's apartment, he is not able to use this tool as it is often only available in his apartment. The actual one-to-one communication requires staff members to point on various letters to overtime construct words and sentences and vice versa. Pointing out the letters on the board is very tedious for the resident as well as for the staff member, and most of the time, it leads to confusion. Therefore, residents and staff members have to repeat the process many times over to exchange even basic information.

In addition, this process is exposing the privacy of the resident to the staff members. The resident is like the other residents staying at the neuro centre permanently and can not communicate freely with visiting friends or family members without the presence of staff. Most visible is the problem when the resident exchanges text messages with family and friends. The staff member will have to (besides decoding the intended message on the board) type the message on the resident's mobile phone and afterwards return to read it out loud. In some cases and because of this troublesome process, the resident is hesitant to communicate with ex-situ family members.

We decided to address the challenges both at the vector of the physical system design side and at the vector relating to the convenience and privacy issues for the resident. Having these factors in mind, we devised a proof of concept vision-based system called "visual communication pad" (Vis-Com pad). The Vis-Com pad concept was scoped around making a vision-based real-time text recognition system that automatically detects the finger movement over the pillow-board (letter-board) to infer the text message that can be displayed to a screen or sent to the receiver through a communication device; such as a mobile phone. At the end the Vis-Com pad has enabled the resident to convey a message without the intervention of staff. Section 3 provides the details of system designing and implementation. Before addressing the design and implementation of the system, we will address the technical landscape on which the system rests.

2 System related literature

Most of the camera-based systems, which use a hand as the basis for non-verbal communication, conform to a sequence of steps: detection and segmentation; tracking and feature extraction; and finally classification. The first step is detection and segmentation of hand or fingers in the field of view (FoV) of the camera. In the next step, the detected hand is tracked, and visual features are extracted. In the last step, spatiotemporal data that is extracted in the previous step are grouped and assigned specific labels.

The primary aim of vision-based hand gesture recognition systems is the clarification of the semantics of hand movement, posture attribution or bodily expression cues [15]. These signals play an integral part in the understanding of the message. It is also necessary to process this information in real-time and to enable the system to respond accordingly. We can distinguish the gesture recognition systems based upon the input data type such as RGB, thermal or depth; methods used to process the input information (employment of various segmentation, feature representation and classification approaches) like geometric, graphical or machine learning or deep learning approaches; and application of system with static or kinetic background [15, 17, 18].

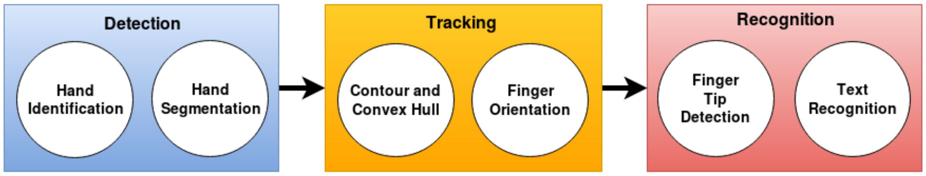

Fig. 1. System Flow Process for Visual Communication Pad

In order to identify hand gestures and finger movement, various sensors can be employed like Microsoft Kinect camera, IR sensor or RGB sensor. Modern technologies for hand gestures are incorporated with information of depth and distances captured by a 3D camera. The Microsoft Kinect camera can provide depth information at low cost and is a central part of hand gesture recognition systems. Raheja et al.[14] used Kinect camera for gesture recognition in a contact-less manner and tracked fingertips and demonstrated 99% accuracy with extended fingers. Depth based systems have achieved the accuracy of 99.07% whereas RGB-based systems are accurate up to 99.54% and combined modalities have demonstrated the 99.54% of accuracy [9]. This suggests that RGB based systems are good enough for hand gesture recognition systems as there is not a significant difference in accuracy between RGB and depth systems.

Vision based systems make use of various body features for hand and finger recognition. Some researchers have applied graphical models for visual object recognition and tracking, graphical models with depth information and exploiting the bag of 3D points method [18][11][8]. Some researchers have exploited skin texture and color information to detect hand or fingers [13], hand shape [2][7], pixel values [3], 3D hand models [3] [2][4], and utilization of hand motion knowledge through boosted histograms [12]. Muhammad et al. proposed a hand gesture system which detects the hand and identifies its center and thus the hand movement is tracked with the position of the hand [1].

Each technique has its embedded advantages and disadvantages and selecting the most appropriate one can not be done without contextual understanding. As we will demonstrate, not all decisions are guided by technical performance but is instead a combination of various factors. After all, the system is not intended as a pure technical construction for a lab experiment, but intended to function in a 'wild' setting intertwined with both social relationships, contextual factors (such as lighting conditions) and individual technical abilities.

3 Implementation of the Vis-Com pad system

The formulation of the Vis-Com pad system was informed as a combination of technical possibilities, and from the field informed contextual factors and human factors (such as lighting and the complex set of abilities of the resident).

Modern vision systems are incorporated with RGB and depth sensors, but we chose only RGB sensors due to the following reasons. First, there is not too much difference in the accuracy of two sensors for hand gesture and finger identification, as mentioned by [9]. Secondly, the use of the Microsoft Kinect camera was imposing bulkiness to the system. In short, we chose the RGB sensor by keeping the device employment precision, reliability, weight and size, and suitability for the resident use. In terms of software development, We have employed geometrical descriptors to segment out hand features as the hand is the closest object to the camera. Threshold and region-growing techniques are used to identify hand features as in [13][7]. In the next phase, we applied the contour, and convex hull techniques to detect the shape and boundary of hand and fingers as illustrated in the Fig 3. We also applied the thinning algorithm to detect the fingertips. We did not apply hand silhouettes as shape descriptors as it is erroneous when fingers are folded [7][2]. Our method is relatively close to [1] with fixed coordinate values of the letter board, where finger movement is tracked. For construction of

Alphabets on White board

Pillow Board

Fig. 2. Design progress from white board to Pillow board

sentences, the finger position over the communication pad is identified, tracked, and labels are assigned based on the spatiotemporal data.

The first step towards the development of Vis-Com Pad is the reduction of the big-sized board to 42-by-30 cm board fixed on top of a pillow as seen in the figure 2. This "pillow-board" is used to train the resident to move fingers over different letters/numbers, and staff members infer the message and write on a whiteboard or speak verbally to confirm intended meaning. This process helped in two ways; firstly, it involved some physical movement of the hand, considered as physiotherapy for the disabled resident at a basic level. Secondly, it provided the resident with added freedom and motoric ease.

We decided to automate this finger tracking and text recognition process by the installation of the camera at the top of pillow-pad despite the proximity of the camera and letter board. This camera installation caused additional computer vision challenges such as illumination issues, false detection, and occlusion problems that are discussed in detail in section4. Additionally, subjects with paralysis may have issues with placing or pointing fingers at one alphabet/digit at a time. On the other hand, installation of the camera with pillow-pad-arm created issues of inconvenient use due to size and weight of pillow-pad and pillow-arm. While designing the pillow-pad, we considered the size of alphabets or digits should be big enough so that the staff member can see it from a far distance. It was designed for the resident training through a staff member. However, in the final prototype, it was not required when text recognition is carried out by the camera. After careful observation and user's input, we decided to make an A4-size letter board with only 29 letters and 0-9 digits printed on one side of it and the other side with an additional few emojis.

We also decided to install a ring of light around the camera to counter the lightening issues. This light-ring can change its intensity if required, or the resident wants to communicate at any time relying less on the room light. Furthermore, in the final phase, this letter board is printed over plastic due to lightweight and preventing it from potential damages due to exposed use. To make this portable, we used a Raspberry Pi connected with a camera for tracking finger movements. The tracked information is sent wirelessly to screen or monitor to display the text. This system provides the facility to edit word or sentence before finalizing it or sending it to the intended user to ensure preciseness of the text. Technical details of finger tracking and text recognition system are presented below.

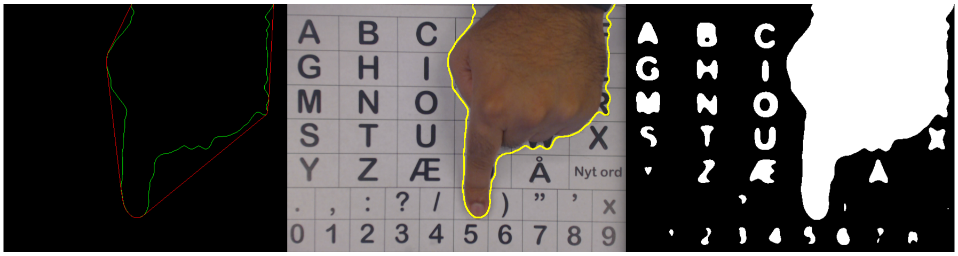
Background substraction Hand detection on Letter board Hand segmentation

Fig. 3. Hand Detection and Segmentation process: Central figure illustrates the identification of hand over the letter board; left figure illustrates the background substraction along with contour (green line) and covexhull (red line) application; Left figure is demonstrates the application of thresholding on detected hand

1. **Hand Detection and Segmentation** The first step is the detection of hand and its separation from the background, in our case, it is a letter board. As our background is static, background subtraction is applied to segment out a hand. We applied thresholding to segment the hand from the background, assigning a particular threshold value to the hand region, as illustrated in Fig 3.
   For the segmentation, we assume that the subject uses only one hand at a time, and it occupies a significant portion in the Field of View (FoV) of the camera. Furthermore, the hand is closer to the camera, and there is no occlusion between camera and letter board besides the hand. There is a small distance between the communication pad and its camera-arm that is approximately 36cm.

2. **Hand Tracking** At this stage, hand motion is tracked over the letter board. Contour and convex hull techniques are applied to draw contour lines around the hand blob and then convex hull around the contour of the hand like an envelope. When a subject moves his hand over the letter board, corresponding segmented hand regions are identified in previous and current frames.

3. **Hand Feature Extraction and Finger Identification** The position and orientation of the hand are determined after the identification of hand regions. As the letter board has printed letters and numbers with a specific orientation, thus hand orientation should be parallel to letter board orientation. However, dealing with paralyzed persons, it is difficult for them to keep their hands in an upright position. The hand position was determined by three directions; up, left and right. The finger is then identified and tracked, and we used fingertip of the subject as the input pointer just like a mouse pointer. For the precise allocation of the finger over letter board, counter tracing algorithm is utilized that detects all the fingertips. The pointing finger and fingertip are determined in two steps. In the first step, the centre of the palm is identified with finger directions. In the next step, the maximum

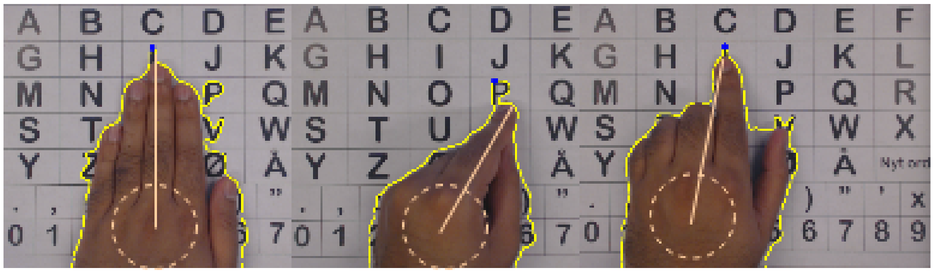

Fig. 4. Identification of a pointing finger by measuring the maximum distance from center of the palm to the fingers

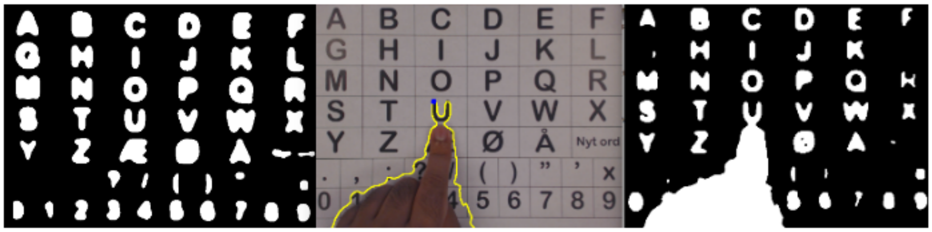

Fig. 5. Letter recognition process with letter board thresholding and fingertip allocation over letter board to identify the letter.

distance from the palm-centre to the fingertip is calculated to identify the pointing finger, as illustrated in figure 4.

4. **Text Recognition** Text recognition is done in two parts. In the first phase, the letter board is processed with thresholding to identify individual letters and numbers. As their positions are fixed, so their coordinates are stored. In the second step, the fingertip of the pointing finger is located over the letter board coordinates to identify the text.

In the neuro centre, we tried to implement this Vis-Com pad system by utilization of the mentioned computer vision techniques and modified the design parameters. As this project is implemented in a real setting, many challenges have been faced, and various prototypes were tested and designed iteratively.

4 Loops of evaluating the Vis-Com pad

In order to evaluate the system, the basis consisted of three questions all typical resonating conversation. In each prototype evaluation, these three questions were asked in Danish ”Hvad hedder du (What is your name)?” ”Hvor gammel er du (How old are you)?” ”Hvad kan du lide at spille (What do you like to play)?” Previously, staff members used to point out letters on the board to construct a sentence and then sought confirmation by the resident, who would nod in agreement or disagreement. The staff members knew the resident name, age and sports-liking so they can quickly infer and write it down for the resident. However, in other real-life scenarios, this approach, as already mentioned, is time-consuming and prone to errors. Therefore, in Vis-com system, instead of a staff member, the camera tracked the hand and finger positions of the resident and registered the alphabets or letter to formulate the sentence for the intended message. We recorded the video of the whole process accounting for the accuracy of letter registration, time of completion, and the number of repetitions to execute the task. Details of each prototype development and evaluation outcomes are presented in the following section.

4.1 Prototype-I: Short description and findings

In the prototype, Vis-Com pad has a wooden arm with 36cm in height and an adjustable camera holder. This camera holder allows the camera to stay at the center of the letter board that is made up of cardboard with a printed sheet of letters and numbers on it. Vis-Com Pad can be placed on the top of the pillow and can be used by the resident in sitting and lying positions. The whole setup was small and portable. The camera is connected to a Raspberry Pi that is fixed at the base. Text can be displayed to the monitor or tablet screen through wireless communication. When we conducted the evaluation, we encounter the following challenges that lead to the development and implementation of the second prototype.

- The Vis-Com Pad is very sensitive to illumination conditions, so with natural light and room light results have variations and miss detection.
- Lighting positions cause the shadow on letter board, which in turn lead to the false convex hull. It is observed that this problem can be avoided if a focused light is installed over the letter pad.
- Resident hand orientation is different than healthy people hand. Therefore, the fingertip location has erroneous results.
- The letter board and the camera arm produces reflections, one contributing reason in false letter detection in the text recognition process.
- Wooden arm with camera holder was a bit bulky, creating some imbalance when placed on the pillow.

4.2 Prototype-II: Short description and findings

We overcame these identified challenges by the introduction of following changes in the physical design and computer vision techniques of the second prototype.

- We introduced a light ring made of LEDs to avoid illumination variation like [10], who introduced the external light source while collecting data for hand gestures. In our system, the camera sensor is surrounded by a light ring so that light falls equally on all parts of the letter board. This light-ring installation minimized the false detection and faulty convex hull formation.

Illumination Issue Hand orientation Issue Shadow Issue

Fig. 6. Prototype challenges at various stages of testing procedures due to illumination, hand orientation and faulty convex hull formations

- To reduce reflection from the letter pad, we painted the letter pad and camera arm with black color. The letter board remains in white with black printing. This lead to the additional problem of thresholding as letter pad and letters are now of the same color.
- We decreased the length of camera-arm from 36cm to 30cm to reduce the field of view of the camera so that it captures only coordinates of letters and numbers instead of borders. This reduction in size solved the problem of thresholding.
- Due to the unique hand orientation of the resident, we introduced the new method to locate the pointing finger by measuring the maximum distance from the centre of the palm to the direction of the fingers as illustrated in the Fig 4. In addition to that, we introduce the determination of hand orientation from three sides, namely, left, right, and bottom. This 3-sides checking ensures the right direction of pointing fingers.
- The letter pad and camera arm was bulky. Therefore, it is suggested to change the wooden arm with a light-weight aluminum rod.
- The letter board is made up of cardboard and is not durable. When the resident moves his finger over the letter board, it bends. Thus produces a change in coordinates of letters, resulting in false text recognition.

4.3 Prototype-III: Short description and findings

In the final version of the Vis-Com pad system, we made following design and technical improvements. This system addresses the challenges raised in previous testing procedures.

- Camera arm is replaced with the black-painted aluminum rod to reduce the weight issues of the system.
- Camera arm length is further reduced to 29cm with a fixed camera position, so that camera field of view (FoV) remains inside the border of letter board coordinate system as illustrated in the figure 7.
- The light intensity of the LED ring is made adjustable through an RF wireless controller. This light intensity controller provides the resident to use Vis-Cam system without depending upon room light during night time. LED

Visual-Communication Pad   Raspberry Pi   LED light ring with controller

Fig. 7. Visual-Communication Pad with Raspberry Pi, LED ring and intensity controller

ring controller works on day and night mode only to avoid any false text recognition due to illumination variation.

- The letter board of Vis-Com pad is made with dense and light-weight plastic fiber to avoid the bending problem. Plastic fiberboard is more durable and elastic resistant as compared to cardboard.

We analyzed Vis-Com system performance in terms of accuracy of writing script, time and convenience with the analog communication tool at each prototype development as illustrated in Table 1. In the first iteration or prototype-I evaluation, due to illumination, design and practical implementation issues, the camera did not extract any useful text information. In this test, the staff member inferred the information from the finger movement over the letter board. In the second prototype testing, some of the letters are printed correctly, but could not construct meaningful sentences. In this stage, staff member intervention helped in retrieving the information from the resident. In the third iteration, after addressing the illumination, speed and design issues, Vis-Com system accurately tracked the finger movement over the letter board and constructed the sentences. The resident was able to write the intended sentence precisely with a display on the screen.

The analog system complexity increases with increase in the length of sentence words or characters, due to repetition and re-writing both by the resident and the staff members. A sentence with five-words or twenty-eight characters consumed 59 seconds and 47 seconds with analog and Vis-com system respectively, as demonstrated in Table 1. The analog system is proved slow and more tedious as compared to Vis-Com system. Also, the resident valued the Vis-Com system a more convenient and efficient tool to communicate. We have analyzed the ease-of-use of the system with scale 1- to -10, with score ten at the most convenient and scored 1 with the most challenging level. Resident rated our system a more user-friendly with a rate of 8.0 as compared to the conventional approach

Table 1. Vis-Com system performance evaluation with the analog communication system in the neuro centre

Qustions		Q1 Hvad hedder du (What's your name?)	Q2 Hvor gammel er du (How old are you?)	Q3 Hvad kan du lide at spille (What do you like to play?)
Answers		**Jeg er John** **(I am Jhon)**	**Jeg er 30 år gammel** **(I am 30 years old)**	**Jeg vil gerne spille fodbold** **(I would like to play football)**
No of Words		3	5	5
No of Characters		11	19	28
Writing Time (Seconds)	**Analog System**	32	48	59
	Vis-Com System	14	31	47
Convenience Scale	**Analog System**	6	5	4
	Vis-Com System	8.5	8.5	8.0
Writing Accuracy	**Prototype-I**	Nill	Nill	Nill
	Prototype-II	60%	55%	52%
	Prototype-III	100%	99%	97%

(where the user needs to iterate multiple times before the correct extraction of the required information). Writing accuracy is measured by the number of the letters or characters falsely identified by the Vis-com system or the resident has to repeat himself for the same task. It is observed that prototype-I failed badly and prototype-II performed with an average 55% of accuracy due to illumination, design and resident physiology constraints. However, prototype-III showed the accuracy rate of 98% without any input from the staff member. Thus, the Vis-Com system has minimized the staff member role, as there is no need for a staff member to track the finger movement and identify the letters and then construct a sentence. Naturally, the premise is now only laid for more comprehensive studies on the general usability of the system over longer time.

5 Discussion and Conclusion

In this paper, we have presented our findings of developing a user-centered communication pad. In this case, the user is a cognitive impaired person facing severe challenges in communication due to physical and speech paralysis. To assist the resident and staff member, we devised a computer vision-based hand interactive system to seek enhancing the privacy of the resident in personal communicative matters.

In these types of projects, and as illustrated in the evaluation section, design challenges are easily very diverse and complex due to being rooted in contextual-, technological- and human factors. The system is now ready for more long-term studies as well as investigating how it is possible to derive design guidelines from the many findings during the work on this case study and how these can be applied in new contexts. As the evaluation section demonstrate there are many unforeseen challenges arising from the field. While this is not uncommon in many disciplines it has been visible all along. One example, is that several of the prototypes were well-considered in their technical problem solving. While the hand and finger segmentation was performing well it did not account for the resident's have a slightly different physiology than expected. Only by confronting the system in the real setting was this possible to fix. And this different phsysiology is highly individually shaped. There are many cases like this, which states two things about this type of work: a: one can not extract all valuable knowledge from the field ahead of development; and, b: a prototype is another constructed reality, which carries its own embedded agendas and must be confronted in situ. Here it stands in a philosophical contrast between Technological Determinism; of what can be constructed to function in ideal cases and that of Social Constructivism, where technology is only meaningful when the user's situation is aligned with implementation. The study thus also illustrates one of the caveats with this type of work - scalability. Custom-fitting technical solutions to individuals is of course a lengthy process. One, arguable, strength is that these types of systems and underlying methodology reflect problem-oriented development, which actually respects the individuality in design and does not assume the user from a generalized (and in some cases steretypic) viewpoint.

In conclusion, we have successfully reduced the size of the communication system and made it portable to be used in almost all scenarios thinkable for the resident (not all other thinkable scenarios). Besides this, the automation of the inferring message system provided convenience to the resident and reduced the staff members involvement, but at the expense of relying on proper light settings as well as accurate hand position for tracking the hand movement over the letter board. However, text recognized is slow due to design constraints such as the slow movement of the resident hand but still faster than analog communication tools used by staff members at the neuro centre.

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