How can constraint-induced movement therapy for stroke patients be incorporated into the design of a tangible interface?

The case study of the ‘Biggest Hit’

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Abstract: Stroke causes significant damage to the brain and often results in severe weakness on one side of the body. Survivors are likely to compensate for the loss of function through an increased use of the less affected arm and the nonuse of the affected arm. In some cases, this can be overcome through constraint-induced movement therapy (CIMT) by restraining the less affected arm to require the use of the affected arm when performing tasks. We report on the research and design of an interactive radio that facilitates CIMT at home. The usability of the design was assessed by stroke therapists. Feedback indicates that the radio is successful in restraining the movement while encouraging repetitive movement of the affected arm, but does not deliver CIMT fully. We highlight the opportunity to focus on the ‘part-task learning’ and ‘initiation’ components of CIMT for the design of a tangible interface for stroke rehabilitation.

Keywords: stroke rehabilitation, constraint-induced movement therapy, CIMT, medical device design, research-through-design, shaping, part-task training, iterative design, radio, design prototype, tangible interface
1. Introduction

The worldwide burden of stroke is increasing and is a topic of particular concern in New Zealand. In 2012/2013 approximately 70,000 New Zealanders were diagnosed with a stroke (Ministry of Health, 2013), and only 30% of these were subsequently able to be independent in activities of daily living (ADL) (Bonita, Broad, & Beaglehole, 1997). Rehabilitation that aims to recover lost motor function is generally limited to the 12 months immediately following the stroke and the benefits of rehabilitation during the chronic stage following rehabilitation are unclear (Aziz, Leonardi-Bee, Phillips, Gladman, Legg, & Walker, 2008). In New Zealand the trend is to promote early hospital discharge and provide rehabilitation in the community setting or home environment (Stroke Foundation of New Zealand & New Zealand Guidelines Group, 2011). In addition, because of the success of medical interventions, increasing numbers of stroke survivors are living longer, with limited access to continued rehabilitation during their chronic recovery stage. Therefore, there is a demand for effective self-directed therapeutic systems. Constraint-induced movement therapy (CIMT) has proven to deliver positive outcomes during the chronic stage of stroke recovery but it requires rehabilitation therapists to provide direct oversight (MacKenzie & Viana, 2016).

Developments in the use of digital technologies can facilitate rehabilitation following stroke (Jordan, Sampson, Hijmans, King, & Hale, 2011) and these are able to be applied to the chronic stage of stroke recovery. Using everyday objects that stroke survivors enjoy and are motivated to engage with offers the potential to deliver a meaningful form of self-directed rehabilitation. This case study presents the process and outcomes of a ‘research-through design’ method using an interactive radio with specified and controllable functionality with the therapeutic goal of requiring the stroke survivor to use their affected arm when using the device.
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2. Background

Constraint-induced movement therapy (CIMT) originated from research on primates, which demonstrated that restricting the use of the less affected arm overcame learned nonuse of the affected arm. Further studies have also demonstrated that this also applies to humans. The concept of learned nonuse is that a portion of the functional deficits is due not to damaged cells within the brain but to the development of compensatory movement (Taub et al., 2006). Initiating use of the affected arm is required to overcome this learned suppression of movement. During rehabilitation, the participant is forced to wear a mitt or cast on the less affected hand (Figure 1) while carrying out repetitive tasks designed to initiate the use of the affected arm and hand (MacKenzie & Viana, 2016; Morris, Taub, & Mark, 2006). The intervention can deliver positive outcomes but has been criticised.

Stroke is a form of brain injury caused by lack of blood flow or oxygen delivery to parts of the brain, causing irreversible injury. It affects 15 million people annually. A third of those people die, while a further third is left with a persistent disability (McKay & Mensah, 2004). The impact on an individual depends on the location within the brain and the severity of the stroke (Mallory, 2006) and can manifest in both physical and psychological symptoms. Due to discrete brain cell damage, stroke survivors can experience unilateral motor impairment in the form of hemiparesis, which is weakened muscles, or hemiplegia, which involves paralysis of muscles (DePiero, 2011a, 2011b). Stroke survivors are likely to compensate for the lost motor function with enhanced movement of their less affected side. This self-taught behaviour drives neuroplasticity changes in the brain opposite to where the stroke occurred (Adkins, Bury, & Jones, 2002). This learned suppression of movement limits possible recovery that could be gained through rehabilitation of the affected arm (Allred, Maldonado, Hsu And, & Jones, 2005; Taub, Uswatte, Mark, & Morris, 2006).
by therapists for being expensive and resource intensive in clinical practice (Viana & Teasell, 2012). The original protocol requires 6 hours of training for 10 consecutive working days, during which the restraint needs to be worn for 90% of waking hours. Stroke survivors criticise the need to wear the physical constraint and the long therapy hours and see those factors as a main reason for not participating in CIMT (Page, Levine, Sisto, Bond, & Johnston, 2002).

3. Aim

The aim of this research is to design a tangible interface using a radio and digital technology to facilitate self-directed CIMT for chronic stroke patients with an affected arm.

In the next section, we describe the development of an interactive radio that incorporates the principles of CIMT to restrain the less affected arm to force the use of the affected arm. The two core elements of intensive practise and restraint of the less affected arm are focused on to overcome the learned nonuse (Taub et al., 1994).

Based on the principles of CIMT the following criteria were used for the development of the tangible interface (Ullmer & Ishii, 2000).

- The object encourages the use of the affected body side.
- The object induces a repetitive movement.

Task specific training that is used in the rehabilitation process often employs everyday tasks and real objects; for example, using conventional cutlery to practise eating (Hubbard, Parsons, Neilson, & Carey, 2009). The interaction with the radio described in this paper focuses on re-educating the user to carry out one particular movement: reaching and grasping. This movement is essential in ADL and relearned during the rehabilitation process with therapists. Carrying out this movement requires a combination of gross and fine motor skills involving shoulder rotation, forearm flexion and extension, wrist tangential velocity, global hand rotation, as well as hand pronation, supination, adduction and abduction (Fan, He, & Tillery, 2006).

The functionality of a radio was chosen based on the motor activity log (MAL) (Morris et al., 2006), which is a structured interview used within CIMT to determine tasks of everyday living that the participant can focus on. The radio can play an essential part in peoples’ lives but if the user experienced difficulties interacting with it, a malfunction would not cause any harmful effect.

Incorporating enhanced repetition of the movement that leads to neuroplasticity in the brain is achieved by limiting the time that the radio plays music. The radio turns on when the affected arm interacts with it and turns off after a pre-set time interval. The user is required to interact repeatedly with the radio in order to keep it working.

4. Methodology

4.1 Research through design

An iterative research through design process was used to develop the tangible interface ‘The Biggest Hit’. The term ‘research through design’ was introduced in Frayling’s pamphlet (Frayling & Royal College of Art, 1993). The author differentiates between research into design, research by design and research through design, but does not clearly define the latter. Dorst and Dijkhuis (1995) distinguish between two design research streams: design as rational problem solving and design as a
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reflective process. This correlates with Burdick’s (2003) description of design research. Designers create new information through the process of making and the cycle of prototyping, testing, analysing, and refining the work in progress (Burdick, 2003). Burdick emphasises the fact that critical reflection is an essential part of design research practice. Designers must be able to articulate their questions and conclusions (Burdick, 2003). Kroes (2002) argues that despite its process-oriented nature design methodology needs to address the nature of products that are designed. In the context of this paper Burdick’s description of design research will be used, where the cycle of prototyping is connected to the reflective process about those design outcomes (Figure 2).

![Iterative design process](image)

**Figure 2. Iterative design process**

To address the complex design problem of incorporating a rehabilitation intervention in the design of a tangible interface, different prototypes based on a trial and error basis were developed to validate ideas and guide further development. The prototypes helped to develop knowledge and convince other stakeholders (Toeters, ten Bhömer, Bottenberg, Tomico, & Brinks, 2012). The final prototype was evaluated by stroke therapists with clinical expertise in CIMT to validate its usability and delivery of CIMT.
4.2 Technology to deliver CIMT

Arduino, a rapid prototyping tool, was chosen. The hardware and software components offer a fast development and iteration process. To restrain movement, the Arduino Uno needs to recognise which arm is used to interact with the object. Near field communication (NFC) can offer this recognition in the form of an NFC board that is attached to the Arduino and NFC tags that the user can wear on the affected arm and hand (Figure 4). When the NFC tag is in close proximity to the radio, the Arduino and NFC shield (Figure 3) within the radio recognise the tag. The radio just plays music when the affected arm is used to interact with the radio.
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5. Results

In the following sections 5.1 – 5.7 we will present the design results and critical reflection that led to the final development of the ‘The Biggest Hit’ in chapter 5.8.

5.1 Influence of the design

CIMT requires a focus on the use of the affected arm. Different design concepts were generated based on a framework of product influence (Tromp, Hekkert, & Verbeek, 2011) (Figure 5) to direct the behaviour of the user. The different concepts incorporate CIMT components to encourage and in some cases even force the user to interact with one specific arm and hand. The framework distinguishes between the two dimensions ‘salience-force’ and ‘visibility-invisibility’, forming four different categories of influence: coercive, persuasive, seductive and decisive. Design with a coercive influence is strong and explicit in its influence and extrinsic motivation causes the behaviour change. CIMT is often described as ‘forced-use paradigm’ in the literature (Wolf, Lecraw, Barton, & Jann, 1989; Wolf, 2007); therefore, an apparent and strong design influence in the form of restriction of use was chosen for the current study. The radio can only be turned on when the affected side is used for the interaction with the object.
5.2 Prototype 01

The concept of this paper prototype is that it just plays music when the user makes it bounce. When the top component is touched (Figure 6) the radio is supposed to move and play music. The bouncing movement that the radio displays is one similar to children’s toys. It gives the user an immediate indication about the movement quality, for example whether too much force was applied. Two paper prototypes were developed in a first step to test the interaction.

Findings: The iteration indicated that paper prototypes were unsuitable for testing the interaction. The prototypes fell over easily and were too big, with a size of approximately 350mm x 250mm x 150mm.

Conclusion: The next iterations should be made out of solid materials to perform the bouncing movement and should be smaller to be easily carried around and stored in the house.
5.3 Prototype 02

The concept of this iteration (Figure 7) is based on an ellipse to increase the bouncing movement. The user has the opportunity to touch the entire top part of the radio in order to turn it on and make it move.

Findings: Because of the ellipse form is the movement of the object not as steady as the bouncing movement of the children’s toy that was referred to as a precedent. The radio started rotating around its own centre after being hit the first time. The prototype was printed using a table top UP 3D printer and ABS material, causing a lot of noise during movement. A sleeve in the form of 5mm felt was added to muffle the noise created by movement. Situating the NFC reader that restrains the functionality of the device in the top rather than the bottom component increased the connectivity of the device.

Conclusion: The form of the radio should be based on a complete circle to secure a smooth movement. The weight is required to be as low as possible to ensure a smooth movement and to prevent the object from falling over. The electronics need to be carried in the top component, which is the activation zone to start the radio.
5.4 Prototype 03

![Prototype 03 with a wooden top part and ceramic base](image)

This iteration of the radio shows a slimmer design while the materials of the object relate more to objects that are used in the home environment: wood and ceramics.

Findings: The design shows stable movement due to the heavy weight at the top. The top component did not provide sufficient space to house the NFC board, Arduino Uno and radio board (130mm x 55mm x 20mm). During bouncing, the radio can potentially fall to the ground and the ceramic material would easily break.

Conclusion: The heavy weight of the base component provides a stable and smooth movement. The top component needs to be adjusted to house the electronics, requiring increased space inside the radio.
5.5 Prototype 04

For the fourth iteration (Figure 9), the top component was changed to accommodate all the required electronics. A tactile surface that is clearly visible on the top of the radio is designed to indicate and direct the user’s interaction with the object.

Findings: The fabric in the centre is not visible and the gap is too small, which potentially traps fingers. The top part of the radio should be changeable to allow people with somaesthetic deficits in their hands to choose a pattern that they can feel.

Conclusion: The pattern indicating where to interact with the object needs to be easily changeable. Due to the increased height of the object to accommodate all the electronics, the centre of gravity situated too high.
5.6 Prototype 05

The fifth iteration (Figure 10) of the radio demonstrates a changeable interaction area at the front with a round speaker at the back. The base contains additional weight.

Findings: The movement is very stable due to the low centre of gravity. The top and bottom part are permanently glued together, limiting the ability to change the weight inside the radio. An external, additional radio board is needed because of the limited RAM of the Arduino.

Conclusion: Elements in and on the radio that can be changed by the user offer progression and challenge, which are beneficial to the rehabilitation process. There should be different textured areas available to the user and the user should be able to increase the weight.
5.7 Prototype 06

For the sixth iteration (Figure 11), the radio was divided into two main sections situated around a wooden core. The interaction area is clearly visible through a colour change and its tactile qualities.

Findings: The weight was too light and the radio always fell over after the first touch. The main concept was that the side elements could be detached from the core to offer the opportunity to adjust the internal weights. This was rather difficult to realise and the shells should be permanently attached to the core.

Conclusion: The top should contain all electronics while the base part provides the weight. The user should have the opportunity to progress in the training and so should have the opportunity to face new challenges. The ability to change the training intervals should be incorporated.
5.8 Final design iteration

For the interaction with the final design prototype a NFC bracelet carries the NFC tag that unlocks the full functionality of the radio (Figure 12). As stroke can affect the left or the right side, making a bracelet was an ideal option as it can be worn on either wrist. The appearance is similar to that of a watch to prevent stigmatising the user.

To start the radio, the user taps, touches, strokes, or hits the white interaction area at the top (Figure 13). This area addresses the somaesthetic deficits in the hands and is detachable. Once the feeling in the hand starts to get better the area can be replaced with a textured area that is less noticeable.

To restrain movement, the NFC board inside the radio recognises when the NFC tag in the bracelet is close. Once the tag is recognised, the radio turns on and plays music for a pre-set training interval that varies between 30 seconds, 60 seconds and 90 seconds before shutting down again. The user is encouraged to interact with the radio again to turn it on. This repetitive movement elicits the neuroplasticity within the brain leading to motor recovery (Kleim & Jones, 2008). In order to progress in the rehabilitation, the user is able to increase the weight in the bottom component (Figure 16).
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Figure 13. Final prototype in use

Figure 14. The back of the radio lets the user change the radio channel and volume
Figure 15: To change the training interval setting from 30 s, 60s or 90s the user pulls on the black string, which is connected to a soft potentiometer.

Figure 16: The user is able to detach the top component to add weight inside the bottom component to increase the challenge in the interaction.
6. Usability evaluation

The design prototypes were evaluated, in terms of usability and inclusion of rehabilitation effects, by one physiotherapist and two occupational therapists. A formative usability evaluation (Hartson, Andre, & Williges, 2001) during the design process helps to improve the design outcomes. This expert-based evaluation helps uncover usability problems the same way the user would (Hartson et al., 2001).

The therapists stated that interaction with the radio requires a movement that would be difficult for some stroke patients to carry out because of the wrist extension necessary to tap and make the object move. The fine motor skills for this type of movement require a high level of accuracy and small buttons at the rear of the radio would be difficult for stroke survivors to use. The therapists recommended to initially focus on gross movement and over time increase the difficulty and accuracy required for the interaction. This approach would be less frustrating for the user and be more feasible for self-directed use in the home environment. Starting with an initial easy movement and then progressing to more complex movements would decrease frustration.

One of the therapists appreciated the bouncing that the radio evokes as an additional form of feedback while another therapist mentioned that the movement enhances the risk of the object dropping to the floor. Lack of balance is a common symptom post stroke, affecting up to 83% (Tyson & Kent, 2006) of all stroke survivors. This lack of balance makes it difficult for the individual to pick up objects from the ground. They recommended attaching the radio to a surface to prevent it from falling to the ground.

The therapists assessed that the interaction radio is suitable to deliver self-directed rehabilitation for the intended target group. However, they did identify that focusing on other everyday objects, for example light switches or mobile phones, could be more beneficial because people interact with these more frequently on a day-to-day basis.

The base component contains weights that the participant can increase over time to keep the interaction challenging. One therapist identified that the weights in the bottom component should be decreased over time instead of increased. The decreased weight would require a higher level of accuracy to tap the radio and not make it fall over, and challenge the user more. This needs to be confirmed with further user testing by stroke patients.

The therapists mentioned that the interaction with the object will be mastered by the user at some stage. They recommended that once this stage is reached, the object should have a purpose and be able to be used in the home environment.

7. Discussion

7.1 The design process

Stroke can produce a variety of symptoms and after getting feedback from the therapists it became clear that no one design solution fits this diverse user group. Observing a rehabilitation session was used as a starting point for the development of the radio, but despite gaining an understanding of how motor impairments of the arm and hand look it was sometimes quite challenging during the design process to decide which elements needed to be further iterated and changed.
7.2 CIMT within the design
The therapists emphasised that CIMT comprises more than a physical constraint and extensive repetitive task practise. They recommended focusing on the part-task learning within CIMT named ‘shaping’ for further development of the design prototype. Shaping breaks down the motor objective in small steps according to the participant’s motor capability and is a behavioural technique to increase the amount and extent of use of the affected arm and hand. Each functional activity is addressed in a set of ten 30-second trials and is specifically outlined and defined in its components (Morris et al., 2006).

The therapists clarified that the intervention facilitates a behavioural change. The intervention contains different behaviour change techniques that enable the transfer of the relearned motor capabilities into ADL. Techniques that are used as part of the ‘transfer package’ within CIMT are, for example, a behaviour change contract that the stroke survivor and caregiver are asked to sign, or a home diary to document the use of the affected arm and hand (Morris et al., 2006).

7.3 Use of digital technology to facilitate the initiation of use
The technology used restrained the interaction to one specific side of the body but required the NFC tag to be in close proximity for rather a long time interval. The user had to interact rather slowly so the radio could recognise the tag on the bracelet. Further iterations should focus on a closer proximity of the tag to the radio in the form of an NFC ring so the radio recognises the tag faster.

7.4 Self-directed use
The therapists pointed out that the use of digital technology offers the opportunity to collect data about the time and intensity of use. Feedback is an essential part of the rehabilitation process that influences the engagement of the participant (Morris et al., 2006). Presenting data to the participants that shows progress over time can have a positive effect on long-term engagement.

7.5 Task
The radio was assessed as being suitable for the intended target group but a focus on tasks that are currently compensated with the use of assistive technology like reading, writing or household tasks (Sørensen, Lendal, Schultz-Larsen, & Uhrskov, 2003) might offer a greater potential to motivate the user to engage in the task.

8. Conclusion
The name CIMT suggests that the intervention mainly comprises of the constraining effect that the restrictive device has. Feedback from therapists who have experience in applying CIMT in clinical practice emphasised that the intervention evokes a behaviour change and that focusing on shaping and the initiation of use is more feasible to be included in a tangible interface, rather than concentrating on delivering the full intervention.

A further iteration of the radio that is being developed will take into account this feedback. Working with stroke patients for usability testing requires Human Disability and Ethic Committee approval (HDEC) which has been granted for the second stage of this research.
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