CueS: Cueing for Upper Limb Rehabilitation in Stroke

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ABSTRACT

Upper limb weakness is one of the most distressing, long-term consequences of stroke and can be difficult to rehabilitate due to an overreliance on the opposing limb in everyday life. Previous studies have shown potential for cueing to improve upper limb rehabilitation, although these have been conducted in clinical settings. In this paper we describe CueS, a wrist worn cueing device which prompts the wearer to move their upper limb more frequently in their day to day lives. We conducted two, week-long 'in the wild' deployments of CueS with seven participants to obtain reflections and experiences around using the device. All participants reported increased general activity levels from wearing CueS and objective data showed increased levels of activity following cue provision. We reflect upon the potential of wearable cueing devices for upper limb rehabilitation after stroke

Categories and Subject Descriptors

• **Human Computer Interaction (HCI)~ field studies**
• **Applied Computing~ Consumer health**
• **User Characteristics~ Seniors**

Keywords

Cueing; stroke rehabilitation adherence; wearable; lived experience; home.

1. INTRODUCTION

Stroke is the third most common cause of disability worldwide [6]. Frequent lasting issues include physical, visual, cognitive, communication and emotional problems, as well as reliance on a carer to help with everyday tasks. Strong rehabilitative focus on recovering the ability to walk is successful in 80% of cases. In contrast, arm weakness and co-ordination difficulties continue to affect up to 70% of stroke patients on one side one year post-stroke, with 40% unable to use their affected limb in the long term [13]. Loss of function in an upper limb is reported to be one of the most distressing long-term consequences of stroke and

insufficient attention is given to upper limb recovery during rehabilitation. More than half of all stroke survivors are dependent on others for everyday activities because of this. [13]. Upper limb recovery improves with intense repetitions of task-orientated movements, combined with strategies to promote more preferential use of the impaired arm [5], however, adherence to home based practice and generalization of such tasks into real life is poor due to factors including fatigue, lack of motivation and time preventing achievement of potential recovery or even sustaining current progress [8]. In this regard, technology and the employment of a cueing program, could offer the potential to improve patient motivation to conduct functional day to day movements with their impaired limb. By providing a regular cue, thus reminding the wearer to move their arm more often in multiple different daily life contexts, we can aid in the generalisation of therapeutic rehabilitative exercises into the everyday as well as orientating the wearer to the fact that they should move their arm more often generally. In this paper we describe CueS, a wrist worn digital cueing technology which provides regular (hourly) cues to remind the wearer to move their impaired arm more often. We show how the use of CueS can successfully increase an individual's use of the recovering limb through regular cueing and, through participants' experiences of living with CueS, make suggestions for future iterations of the cueing technology which would increase the usability of the device and the accessibility of the cueing rehabilitation approach

2. BACKGROUND

Exercise based gaming for stroke rehabilitation in clinical environments has received high levels of attention. [19, 20, 21, 22]. Games such as Wii Sport [21] have been successfully used to maintain and improve stroke patients' health, however the hardware and software remains unsuitable for a wider range of patients with differing complex difficulties to engage in exergaming. [22] reports positive benefits from most clinical research around exergaming, however the supervised clinical settings and short time periods fail to evaluate the user's experience of the games being played. [19] designed a motion-based video game to detect compensatory movements, using operant conditions with success to teach the user how to carry out movements properly, to avoid compensatory movements impeding progress and benefit. [20] identified the importance of 'meaningful play' and the benefit of using dynamic adjustment to alter difficulty within rehabilitative exergames to meet the needs of each individual effectively. Finally, [4] trialed the Eyetoy:Play2

with one participant who completed 20 one-hour sessions over a 4 and a half week period. Findings suggested the device was feasible and enjoyable to use in this case however the study has many limitations in terms of high participation ability and motivation levels to be conclusive.

Significant work within HCI has focused on improving motivation for many rehabilitation purposes, including stroke upper limb rehabilitation through both], specific game interactions [15, 16] and bespoke systems [e.g. 1, 2]. [15, 16] compare specific game interactions through clinical assessments with stroke patients, showing promising results for direct and free-hand interactions in patient-computer interfaces. However, sample sizes were small and controlled and how these interactions are best realised in a game for successful upper limb rehabilitation remains unknown. [1] presents lessons learned from the customisation of 3 motion based video games for one participant, 17 years post-stroke, who played the games one hour a day for 5 days, over 5 weeks, to guide future design of therapeutic games for home use. In addition, [2] describes a seven-month bespoke deployment, highlighting that the majority of interactions with the prototype they tested occurred within the first two months of the deployment. Evaluations to date have been unable to establish the motivational potential of such systems in an individual's self-managed context, particularly with respect to functional improvement over time, or matching such systems to individual contexts of such a heterogeneous population.

Wearable technology opens up a new space for exploring opportunities to improve recovery for individuals experiencing arm weakness due to stroke, particularly with the assistance of sensors. Most relevant for our work, [3, 7 and 9] all explored the use of wrist worn devices to promote upper limb activity in stroke. The watch designed in [3] displays a visual comparison of the activity levels of individuals impaired and non-impaired arms. When trailed in a clinical setting, participants performed specified tasks however, the watch had several usability issues and required users to wear two devices, one on each wrist. Further deployments in-situ and over longer periods of time are required to explore this method of feedback as motivation further. [7] presented cues through their watch, which interacted with home based embedded sensors, to guide error correction during task performance. However, their significant technical set-up of wrist worn devices, embedded sensors and technical infrastructure was deemed too complex and unreliable for home deployment. Finally, [9] conducted a lab based evaluation of vibrating cueing wristbands which involved completing a five minute functional task under two conditions – once with cueing every 30 seconds and once without cueing. No differences in arm activity levels were found between conditions. The system also required users to wear a wristband on both arms, however users presented tolerance and acceptance of cueing, and enthusiasm for use outside of the clinic.

Current literature reveals extensive design work on stroke rehabilitation technologies [e.g. 14, 17, 18] however involvement in the design process of individuals who require the rehabilitation and also the motivation to adhere to such programmes, is varied and often insufficient, with a greater focus and reliance on information from clinical professionals and achieving clinical effect. Home based, 'in the wild' deployments of these cueing technologies are non-existent in literature to date.

We contribute to this nascent body of work through the 'in the wild' evaluation of a single lightweight wearable device – 'CueS'. The device reminds the individuals recovering from stroke to conduct purposeful, rehabilitative movements with their affected limb more often through the provision of regular vibratory cues, CueS is designed to aid the generalisation of rehabilitative exercises into daily life by being discreetly worn day to day both in the home and whilst out and about.

3. CUES – A MOVEMENT CUEING DEVICE

CueS is a re-programmable wrist worn cueing device [adapted from 10] designed for people with upper limb dexterity issues (see Figure 1).

Repurposing this device was appropriate for this study as the technical functionality was suitable for our research purpose, recording activity levels through use of a 3-axis accelerometer. In addition, the ability to cue to specified schedules through a mechanical vibration motor and ability for the wearer to log events through a front mounted accessible interaction button was desirable. The CueS device was initially designed with, and subsequently developed for, individuals with Parkinson's Disease (PD). Some of the condition's main symptoms include tremor, slow movement and inflexible muscles which also affects the manual dexterity of the hands, thus impairing upper limb functionality. A sensitive and careful two stage design process was carried out [10] which involved a set of participatory design workshops with twelve participants (8 with PD, 4 caregivers), and a follow up high fidelity iterative design phase with three people with PD, who had taken part in the workshop stage. The workshop sessions were conducted in an open manner covering a variety of issues. One particularly interesting discussion point which arises was that exploring concepts of disability, with one participant reporting feeling *"disabled"* when wearing her panic button at home – a medical device many individuals recovering from stroke are familiar with. Another interesting finding from the study was the importance of aesthetics - perceived effectiveness experienced by all participants in the iterative design phase increased in the second design iteration, even though the functionality of the device had not changed. Although Stroke and PD are by no means the same, there are many similarities between the conditions, particularly the dexterity issues and physical visibility of symptoms, reflecting the detrimental impact conditions like Stroke and PD have on social emotional elements of individual's lives within the design. CueS was not redesigned for the purpose of this study, it was instead repurposed for individuals with upper limb dexterity issues through adaptations made to how the device functions in terms of technical functionality - cueing and data recording to suit the rehabilitative needs of upper arm rehabilitation rather than that of drooling.

Figure 1. *CueS*

CueS is unique from its previous purpose, and from other wearable cueing devices described in the literature in the nature that it operates. Firstly, it has the ability to function as a self-logging device, recording general activity of the limb; the button, when pressed, allows the user to self-log specific movements. CueS also operates as a cueing device by vibrating at pre-determined temporal intervals, providing a prompt for the wearer to complete a movement with that limb. A further function of the button is that, when pressed, it allows the wearer to 'snooze' cues, setting the cue to recur after a set time period (e.g. 5 minutes).

4. THE STUDY

This study provides an 'in the wild' pilot evaluation of CueS with individuals recovering from stroke. We were interested in exploring two elements within the study; 1) whether or not the device supported participants in increasing the number of upper rehabilitative movements they were conducting in their day-to-day lives and 2) understanding participants' experiences of living with such a device. We recruited seven participants from the Newcastle Upon Tyne Stroke Patient and Carer Panel, UK. All participants identified themselves as having longstanding arm weakness due to stroke and reduced upper limb function, affecting their ability to carry out day-to-day tasks. This was the only criteria for participation in the study. Individuals varied greatly in many other ways including general ability, amount of time since stroke and motivations for exercise, to name a few. We explicitly wanted a variety of patients to ensure the exploratory and open nature of the study was maintained.

The study was made up of two, seven-day deployments with an exit interview following each. In both phases participants were asked to wear CueS on their impaired limb as much as possible in their day-to-day lives during the deployment.

4.1 Phase 1: Logging Activity

A researcher first spent some time familiarising participants with the project and their role as a participant, ensuring full informed consent. Basic information was recorded about each participant (see table 1) including age, years since stroke, which limb they identified as impaired (Right or Left), occupation and ability in walking, using stairs, dressing, bathing and eating/drinking. Finally, to give an indication of their upper limb ability a National Institute of Health Stroke Sale (NIHSS) motor arm assessment [11] was carried out, which rates upper limb mobility on a scale of 0 (no impairment) to 4 (no movement at all). This test requires the individual to hold the arm out at 90° from the body for 10 seconds. So, whilst a score of 0 suggest no impairment, this does not reflect how upper limb weakness impacts on activities of daily living, only the ability to hold the arm extended from the body.

Once wearing CueS participants were familiarised with the device by undertaking 3 common rehabilitative movements, identified by a stroke consultant, which are commonly used in day-to-day tasks such as eating, drinking and personal care. These were reaching outwards and grasping, touching the mouth, and reaching behind the back. Each movement was repeated 5 times, pressing the button to log the movement upon completion. This activity enabled participant familiarisation with CueS as a logging device, whilst also providing gold standard accelerometer data of the individual performing these identified movements in the presence of the researcher.

In this phase, participants wore CueS as a logging device. During the deployment participants were asked to log, by pressing the button, when they practiced any of the 3 specified movements. They were asked to undertake these rehabilitative movements as often as desired over the deployment period, logging each rehabilitative movement by pressing the button on CueS as practiced in the familiarisation stage. The purpose of participant self-logging was two-fold; 1) to gain an indication of individuals' current activity levels in terms of general movement without cueing and 2) to develop understanding of what individuals deemed as rehabilitative activity and how often they were doing this on a day-to-day basis. O course, recording current activity levels does have its limitations as a means of obtaining a true representation of individuals 'normal' activity levels, due to the increased awareness created by wearing CueS and the task of logging movements. However, given that compensatory movement is often carried out using the non-impaired limb in daily tasks, specified use of the impaired limb is often a conscious task. As such, the logging activity enabled us to develop understanding of when conscious and purposeful movement was occurring.

4.2 Phase 2: Prompting Activity

All participants of phase 2 had previously taken part in phase 1, they were therefore familiar with the research and CueS. In this phase, participants wore CueS as a cueing device, where it actively cued upper limb movement in day- to-day life. CueS remained the same in design, however altered in purpose, to that of a logging device. It was therefore important that we took some time to familiarise participants with the new functionality.

As a cueing device CueS was initially set to prompt the wearer to complete a 'target rehabilitative movement' once an hour. This timing was advised by an NHS[1] Stroke Consultant, to ensure participants did not feel compelled to over work themselves, reducing the risk of any strain or injury. Further measures were taken to enable self-management of cueing through re-purposing of the button on CueS as a 'snooze' feature. This could be pressed after a cue was received, causing the cue to repeat again in 5 minutes—alternatively they could simply ignore the cue. Participants were asked to identify their 'target rehabilitative movement' (reaching up, out or behind) which they would like to practice when cued. Participants were asked to specify operational hours of CueS, i.e. when CueS would start cueing (e.g. 9am) and when it should stop cueing (e.g. 8pm).

Table 1: Participants

ID	Age	Years Since Stroke	Impaired Limb	NIHSS
M1	66	2	Left	0
M2	70	<1	Right	3
F3	60	4	Left	0
F4	77	9	Left	2
M5	68	5	Right	0
M6	56	9	Right	4
M7	64	1	Right	0

[1] National Health Service

After 24 hours of deployment, each participant was visited to ensure CueS was operating correctly and also to provide the option to adapt the chosen operational hours, or the frequency of cueing as required for each individual's needs based on their experience with CueS so far.

4.3 Living with CueS

Participants were asked to keep a daily diary throughout phases 1 and 2, to reflect on their experiences with CueS, including ease of use, impact on their movement and any barriers they incurred along the way. Adherence and use of the dairies varied amongst participants with a trend for the amount of feedback to decrease as the week progressed.

At the end of both phases, participants also took part in semi-structured exit interviews. Although the responses in the daily diaries varied, and was limited amongst participants, the material was beneficial for giving a focal point for the interviews. Phase 1 interviews explored past rehabilitation, user experience of CueS—including ease of use, barriers/benefits, design, and perception of others—and any desired changes for the device itself., Although redesigning the device was not in scope for this study we were very interested in how successful the repurposing of CueS had been to a different user group and how it could be best designed for such individuals in future studies. Phase 2 interviews explored perceived effectiveness and experiences of cueing, the snooze function, design of CueS and long-term potential benefits or drawbacks. Semi-structured interviews lasted from 10-48 minutes, with an average of 20 minutes in relevant discussion for phase 1 and 11-27 minutes, with an average of 20 minutes in relevant discussion for phase 2. Each was audio recorded and transcribed for inductive thematic analysis at a later stage.

The target length of time for participants to wear CueS was 7 days for two key reasons. 1) Firstly, this was the first time CueS had been used with individuals recovering from stroke, in the wild, for the purpose of monitoring activity levels (phase 1). Also, as a cueing device (phase 2), it was important to keep the deployment phases long enough to provide quantitative data, to explore and analyse the impact of CueS as a device, whilst also maintaining participant expectations and values should no benefit be found from Cues. 2) Secondly, 7 days provided participants time to become familiar with CueS and experience it in a 'typical' week of their lives, whilst also ensuring that, when the researcher came to collect the device and carry out an exit interview, the experience was still fresh in their minds—enabling us to gather qualitative data which was a detailed and reflective account of their experience of living with CueS.

5. RESULTS

In total, five of the seven participants completed the full study. M2 and M7 were eliminated from the data due to reasons explained below.

At the end of the study four of the five participants reported that they perceived a positive impact on their upper limb range of movements from wearing CueS as a cueing device (Table 2, Perceived). Mean Activity Level (Table 2, MAL) of each individual was calculated using the accelerometer data, to gauge an objective indicator of individuals' activity levels before and after the cueing intervention. MAL was calculated using the (gravity normalized) energy of the signal over the period that CueS was worn, to produce an average quantification of activity levels for each participant's deployment period, similar to [12] and according to the equation:

Table 2: *Cueing Impact on Mean Activity Level*

ID	Impact of cueing		Mean Activity Level (MAL)	
	Perceived	*Quantifiable*	*Phase 1*	*Phase 2*
M1	Y	N	1.09	1.01
F3	Y	Y	1.71	13.4
F4	Y	Y	0.95	5.92
M5	Y	Y	0.94	6.12
M6	N	N	1.21	1.25

$$\mathrm{MAL} = \frac{1}{N} \sum_{i=1}^{N} \| \left(\sqrt{x_i^2 + y_i^2 + z_i^2} \right) - 1 \|$$

where x_i, y_i, and z_i represent samples of the time-series (length: N) corresponding to the three axis of the sensor. More vigorous motions exhibit higher signal energy, consequently this can be used to estimate the level of activity displayed by the participant. The numerical value of signal energy represents the proportional amount of an individual's movement per second, where 0=no movement. The higher the numerical value of signal energy the higher the level of activity.

Comparison of individual MAL from Phase 1 and Phase 2 was calculated to see if the impact of CueS was 'Quantifiable' through the data (Table 2, Quantifiable). T*hree* participants substantially increased their upper limb activity (substantial MAL increase from Phase 1 to Phase 2), *one* participant achieved a slight increase (minor MAL increase from Phase 1 to Phase 2), and *one* participants recorded a slight decrease in upper limb activity using CueS as a cueing device (MAL decrease from Phase 1 to Phase 2), when compared to their levels of activity during phase 1 (Table 2).

By testing differing values, we discovered that an increase in the activity measurement of 25% was sufficient to distinguish between the majority of ignored and successful prompts. The total number of cues delivered during the duration of deployment differed between participants, based on how often they chose to receive the cues when revisited 24 hours after the initial deployment in phase 2. Participants successfully responded to an average of 58% of cues delivered - where activity levels increased by more than 25% after the cue. Participants ignored an average of 30% of delivered cues - where activity levels increased by less than 25% after the cue. 'Unclassified' cues were calculated based on periods where the device was switched on and cueing but not being worn by the participant—based on a flat line in all activity. There were on average 13% 'Unclassified' cues per participant (Table 3).

5.1 Phase 1

At the end of Phase 1 six participants reported wearing the device for seven days, one participant wore the device for five days due to ill health. The exit interview explored past rehabilitation, user experience, logging movements, benefits/barriers/perceptions of CueS. During deployment of CueS as a logging device one participant M7 pressed the button 861 times in total. It became clear that he was affected by comprehension difficulties due to stroke related aphasia (language difficulty) and he expressed confusion around when was appropriate to press the button—reporting pressing the button to view the digital display on the

	Cues Delivered	Response to Cues		
ID	Total	Successful (%)	Ignored (%)	Unclassified (%)
M1	128	58	30	12
F3	127	59	41	0
F4	64	77	22	2
M5	65	57	43	0
M6	55	25	20	55

watch, or if the light came on. This data was therefore deemed an outlier and not included in the data. During deployment the button was pressed to log a rehabilitative movement on average 152 times, ranging from 51 to 404 presses between six of the participants, with a clear trend for decline in the number of button presses throughout the day during the deployment period.

The high range in number of button presses amongst participants is clear. Discussions in exit interviews uncovered a strong link between personality and use of the device. The individuals with high levels of motivation towards the research, and positive behaviors towards the device, had increased use of the logging function. For example, F3 (NIHSS=0) was highly motivated, and expressed positive behaviors towards CueS, reflecting the high number of button presses achieved, whilst M5 (NIHSS=0) experienced other medical issues affecting his mobility and vision, negatively impacting his motivation and positive behaviors towards CueS. Ability of individuals in terms of NIHSS assessment did not correlate with increased logging activity.

As participants were self-logging rehabilitative movements, it is by no means assumed that button presses are a quantification of the amount of rehabilitative movements achieved, however, it does make suggestions towards individuals' perceptions of what rehabilitation is and what it means to them.

5.2 Phase 2

Six of the seven participants wore CueS for 4-7 days. One participant, M2, reported wearing the device—unfortunately the accelerometer data suggests he chose not to—this data was eliminated from analysis. All participants were visited 24 hours after the initial deployment of CueS, two of the six participants chose to increase the cueing schedule from hourly to every 30 minutes (F3 and M1). As seen from phase 1, there is low correlation in terms of NIHSS score and device usage—once again it was the participants who were more highly motivated towards their rehabilitation and CueS who chose to increase the cueing occurrence. The exit interview explored perceived effectiveness, experiences with cueing and snoozing and long term potential for CueS.

The results of this study teach interesting lessons regarding the quantification of the impact of CueS as a cueing device. Although the deployment phases were short and limitations were present, four participants in total presented a quantifiable increase in levels of activity when using CueS as a prompting device. This result is based on comparison with phase 1 where CueS was used as a logging device, potentially raising individuals' awareness of their impaired limb and therefore activity levels—therefore, to present an increase in activity from an already potentially increased level

provides strong grounds for further exploration of CueS as a cueing technology. One participant, M1, presented a decrease in their activity levels from phase 1 to phase 2, however, based on discussion during exit interviews it become clear that the participant remained highly motivated throughout both phases of the study, tending to focus on finer grain movements in his hand. This participant felt that his hand and arm had become much looser as a result of phase 2, suggesting that the current technical capabilities of CueS may have been insufficient enough to measure this increase in fine movement activity. Although quantifiable measurements are crucial to proving the success of the device, it is a positive outcome that this participant felt he had benefited from using CueS as a prompting device, even if the data did not suggest this was the case.

5.3 Participant Response

Overall, participants experienced varying levels of perceived impact of CueS as a rehabilitative cueing device, with some participants experiencing usability issues—inconvenient timings of prompts, confusion around use of the 'snooze' button and the design of CueS, which was deemed bulky and clinical, which in turn impacted on its effectiveness.

In terms of actual response, all of the participants filled in their daily diaries to some extent, however, the level of detail and adherence varied amongst individuals, with a clear trend for decline in information and detail as the week progressed. One participant, F3, filled in the diary with great detail on a daily basis, adding extra notes and detail around the structured questions. The rest of the participants followed the structure of the diary and wrote very little in terms of extra comments of information. Although the diary data alone was of little value, the combined use of the exit interviews and daily diary enabled us to develop an understanding of each individuals' perceived impact and experience of CueS. This is described below.

5.3.1 Perceived Impact of CueS

All participants reported that their general activity levels had increased as a result of wearing CueS. Four participants perceived a positive effect on their target movement from CueS, however accelerometer data analysis shows one of these participants, M1, did not increase his overall activity levels during phase 2. Our two final participants reported no perceived effect – M6 & M7.

Individual perception of how reduced function in the impaired limb impacts on daily life strongly influenced their perceptions on the impact of CueS. M7 scored 0 on the NIHSS arm test, was highly independently mobile and experienced only slight weakness in his impaired arm. An analysis of his data shows he achieved the highest percentage of 'successful' cues—comparison of mean activity levels support this. In contrast, M6 suffered from a stroke nine years ago, scoring 4 on the NIHSS arm test with no movement in his arm, he expressed feelings of independence and received sufficient support in achieving anything he could not do himself. Seemingly at peace with his impairment, he recognized that CueS might have been beneficial had it been available sooner in his recovery: (M6) *"had it been 7 years ago you know then spot on but as it is 9 year – so no."* M6 noted also that: "*with other people it [*CueS*] could be good really, you know"*. Comparison of M6's activity levels show an increase in activity during phase 2, suggesting his activity levels did indeed improve as a result of cueing. These cases suggest the stage and severity of stroke can heavily influence individual's perceptions of effect and movement recovery.

5.3.2 Lived Experience of CueS

All participants reported that they found the device simple and easy to use, this was particularly interesting as all participants were over 65 years old, with a mean age of 66 years, defining them as 'older adults' who are often more likely to incur usability issues with technology such as wearable devices: (M1) *"well it's so simple, that's the answer 'it's simple and anything simple is easy and people accept it"*. However the level of explanation, time and experience required to develop a full understanding varied. All of our participants had some previous experiences with rehabilitation and exergaming and considered CueS, due to its simplicity, as a more desirable rehabilitative option. Mainly because it was so easy to fit into their daily lives, (F3) *"I was happy to be motivated by the buzz and the gentle vibration of the watch"*.

Cueing at home was well received by many participants, (F4) *"I'm pleased that the program came up because it's done wonders for my arm"* especially for improving awareness during long periods inactivity, such as sitting reading or watching TV. Use of the snooze button was most commonly successful for managing inconvenient cues while out and about, (M6) *"Another 5 minutes or 10 minutes or whatever it was, it would give me time to get out and then do the thing again"* For example, participants reported using the snooze button when in the middle of tasks that could not be immediately interrupted or when they needed time to prepare for exercise: (M5) *"it gave me 5 minutes or so to adjust my brain and then it would go off so I could use it better"*. Whilst some participants felt uneasy using the snooze button due to feelings of guilt and non-compliance:

(F4) *"I thought it was cheating by pressing the snooze button, I didn't want to do that because you know it implies that really I don't want to wear this watch, and that's not the impression I want to give because I really did want to do the movement when I was reminded."*

Participants wore the device in a variety of places both inside and outside of the home. Three participants reported that they felt comfortable carrying out their specific rehabilitative exercise while in public: (M5) *"It gave a few people sort of amused looks as to what I was doing but that didn't bother me"*. Three of our participants however, felt less comfortable or able to do so. These participants reported instead either ignoring the cue or modifying their rehabilitative movement to something more 'everyday' which they felt more comfortable with in the public space:

(F3) *I was on the bus... so I reached out rather than reached up"*.

All participants developed knowledge of when they expected the cues to come during the day, suggesting the device could encourage the development of rehabilitation routines, however, even in the short space of one week three participants reported experiences of *"getting used to"*, *"missing"* or *"not feeling"* cues when they expected them to arrive, based on their learnt cueing patterns: (F3) *"like on Saturday I went out shopping with my sister and had a really lovely time but I just didn't even notice it buzzing"*. This is an important barrier to consider for long term use and effectiveness of such a device once the individual becomes familiar with the device and the novelty factor is no longer present.

All participants made similar suggestions as to how the design of CueS would need to be improved for more long-term use, including the need for the device to look more like a watch and "normal" in appearance, rather than representing a medical device: (M5) *"erm well its not a watch I would buy, but, if it was a watch, like a watch, a proper watch and then just put the things (button) on the side rather than the button on the front, then yeah it would be alright."*. This reflects previous findings in [10] around the social emotional elements of conditions such as stroke or Parkinson's which very publically visible symptoms—the device should not cause unwanted attention to the individuals disability. Female participants were particularly affected by the size, 'manly' appearance and feel of CueS, likely due to the slightly bulky nature of the device which was more prominent on female wrists. (F4): *"I felt if was a bit bulky...it should maybe be a bit more unobtrusive"*.

As highlighted throughout this paper, stroke is a heterogeneous condition. Whilst we cannot suggest what the various needs and values of such a group might be from our limited study, we can add some relevant insight into the need for a these types of cueing technologies to fit in around individuals daily lives—as well as highlighting the need for supporting positive experiences with these new types of technology with the ability to track progress and results. Whilst outside the scope of this study, these are elements that should be considered further in the future.

6. DISCUSSION AND FUTURE WORK

Our short 'in the wild' study contributes valued participant perceptions on the impact, usefulness and lived experience of a wearable cueing device such as CueS, motivating further exploration into the feasibility and effectiveness of cueing as a means of improving rehabilitation of arm weakness after stroke within the home—laying the ground for much needed long-term deployments in the home. In terms of a more general HCI audience we have contributed valuable lessons learned from an 'in the wild' deployment of a wearable technology with older adults and how this may influence the use and success of such devices within the home.

CueS has shown potential to be complimentary to programs of rehabilitation, by encouraging instigation of prescribed exercises within day-to-day life both in the home and while out and about, without the need for therapist or carer prompting and supervision. We found that the simplicity of CueS ensured it was integrated into individuals daily lives easily and therefore successfully increased everyday movement of the impaired upper limb for almost all our participants, even in cases where no perceived effect was reported—our objective accelerometer data suggested there were improvements. The repurposing of CueS as a wearable device proved successful for this group of individuals, however it is important to highlight that further work is required to improve the design of CueS for long-term use and acceptance.

Our small sample suggests that effects of cues are related to an individuals' stage of recovery, with CueS proving more effective for those who had already experienced some successful arm rehabilitation since stroke and who have the desire to improve further. As expected when working with a heterogeneous condition such as stroke, we incurred some difficulties accommodating for the wide range of symptoms which may present. This lead to one participant experiencing some confusion and misunderstanding about the study - we were fortunate to have a Speech and Language Therapist on the team who was able to informally diagnose the comprehension difficulties during the study, allowing us to accommodate for this in later stages, however other studies are unlikely to be so fortunate.

The measured effect of the study does have its limitations. Due to the nature of 'in the wild' studies not all participants were able to use the device for the full 7 days, due to factors out of our control. Because of this, exit interviews and daily diaries were a key

source of information in terms of the effect and experience with CueS. Such studies of this nature in the future would benefit from additional methods to facilitate capturing this data. Daily diary design would benefit from being more interactive and appealing to participants, including a greater variety of questions, adaptation to suit impaired upper limb individuals, considerations of the use of materials other than pen and paper, and finally, avoiding situations where participants are tracking decline or poor progress.

No clinical measurements of function were made post-study due to the exploratory nature of the study. There was a time period of 4-8 weeks between deployment periods, as such, it is possible that participants' increased movement of the impaired upper limb was due to factors external to the device. Finally, it is possible that wearing CueS as a logging tool throughout Phase 1 effected our initial MAL measurements, by drawing increased attention to the impaired limb, however, given that we carried out the study over the course of 7 days and, as expected, there was a trend in decline of button presses over the week, we expect that participants gradually forgot that they were wearing it.

The experience of inconvenient cues and habituation to cueing suggests a clear agenda for future work, explicating the need for the development of complex algorithms through machine learning, which can implement context aware cueing schedules. Allowing CueS to act and respond in context of an individual's ever changing environment and energy levels would move towards understanding and satisfying the needs and values of a heterogeneous group such as individuals recovering from stroke. Further exploration is required on the novelty effect of CueS, and how this impacts the long term use and effectiveness of such wearable devices. Future work should also focus on overcoming suspected barriers in terms of reduced cueing awareness and impact in the long term effectiveness of wearable devices, as well as the actual impact of CueS when accounting for individuals differing rehabilitation goals and needs.

Future work should also look to adopt the methods of phase 1 based on lessons learned from the study, either through analysis of the self-logging data to further explore individual's relationship with rehabilitation, or by removing the logging function and participant interaction in phase 1, working towards greater accuracy and validity of quantitative data to explore activity levels and impact of CueS. The wrist-worn device would benefit from more participatory design work with individuals with upper limb dexterity issues, to develop understanding of designing CueS for acceptance and long term use. There is also a call for greater attention to appropriate research for individuals with reduced comprehension and other language needs, a common symptom from stroke. Such issues can easily go unseen if a qualified specialist is not present to identify them, therefore it is important to ensure all research content and material is accessible enough for those with language difficulties, to avoid such issues identified in our study, and ensure such individuals need not be excluded from future research to guarantee accuracy of results.

7. ACKNOWLEDGMENTS

8. REFERENCES

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