MASTER THESIS

GAZE BEHAVIOR DURING REACH AND GRASP TASKS AND THE STAR CANCELLATION TEST IN STROKE PATIENTS

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1 Preface

This is the final assignment to finish my master's degree in Biomedical Engineering at the University of Twente. I am grateful that I got the opportunity to write this master thesis at Roessingh Research and Development. I had a great time and learned a lot.

First of all, I want to thank my parents, Gerrit and Gea, for giving me the opportunity to study and always supporting me. Than, of course, Anne, thank you for all your help and support. I would like to thank my exam committee, Hans Rietman, Jaap Buurke, Bart Klaassen and Gerdienke Prange-Lasonder for all their valuable comments and ideas. Johnny Lammers van Toorenburg and Bart Klaassen, thank you for lending us the Tobii eye tracker and making sure it was ready to use each time. Also, Karen Meeske and Leoni Vlutters, thank you for the help with the inclusion of the patients. And finally, I would like to thank Leendert, Jos and Wendy for all their help each time I walked into their office with a question.

2 Summary

2.1 Summary – English

After stroke, patients might suffer from upper extremity weakness or hemiparesis. [1] For example, picking up a cup of coffee might be difficult. For this reason, there is worked on an arm and hand support system in the eNHANCE project. To control this system, motion intention detection by using 3D eye tracking, which does not add cognitive load, might be used. [2] To find out if this can be used to control the system, the until now unknown gaze behavior during reach and grasp tasks in stroke patients should be mapped. This is the first part of the observational research. The other part of the observational research is about Unilateral Spatial Neglect (USN), this is a condition after stroke where the patient neglects part of the visual field. A diagnostic tool for this is the star cancellation test (SCT). This is a pen and paper test where small stars in between larger stars and letters should be canceled. However, no restriction in time or head movements are used (which might be used as compensatory strategy). Therefore, there should be looked into the effect of time and head movements on the SCT and also other potential distinguishing parameters should be investigated to make diagnosis of USN by use of the SCT more sensitive.

The goal of this master thesis was to set up the measurements and to find the valuable and obtainable parameters for the whole observational study into the gaze behavior of stroke patients during reach and grasp tasks and into the potential distinguishing parameters in the SCT. After that there should be looked into the feasibility of the measurements and the analysis.

In total, 7 healthy subjects and 3 stroke patients were measured, where 2 healthy subjects and 2 patients (1 in the reach and grasp part and 1 in the SCT part) were included in the analysis of this master thesis. Gaze was tracked by using a wearable 3D eye tracker, the Tobii Pro Glasses 2 with an integrated gyroscope. The fixations were detected by using a custom eye movement velocity threshold filter in the Tobii Pro Lab software. To map the gaze behavior during reach and grasp tasks, four different personalized simulated all day life reach and grasp tasks were programmed on a touchscreen. These tasks are a reach and touch, a reach and lift, a reach and replace and a bimanual task. Touchscreen compatible objects were built and used in the reach and grasp tasks. The data of the tasks executed three times with the dominant hand in the healthy subjects group and three times with the hand of the affected side in the patient group was analyzed. The SCT was executed once without and once with head fixation, by using a chin rest. A head movement detection script was written to find the head movements from the gyroscope data. Parameters which are valuable to the observational research and which should be obtainable from the eye tracker, the touchscreen and the SCT were listed for the reach and grasp tasks and the SCT.

Most of the parameters listed were obtainable except for the parameters which need the fixations on the areas of interest data. These parameters were replaced by others which still give information about the gaze on the areas of interest by using the raw gaze points instead of the fixations. All reach and grasp tasks were executable for the healthy subjects and the patient. The programmed tasks worked as expected and promising results were found. The same goes for the SCT with and without head fixation. In the results of the SCTs was found that the head fixation system does limit, but does not exclude head movements.

At this moment the study population is too small to draw solid conclusions in the whole observational study, but insight into the feasibility of the study was gained. In future research there should be looked into how to get the fixations on the areas of interest data. This will give information about if a subject took up information while looking at an area of interest. There could also be looked into how to find the fixations more validly with the wearable eye tracker. In conclusion, the measurement, which was set up, and the analysis are feasible. A lot of the parameters were obtainable, only those requiring the fixations on the areas of interest data could not be obtained. During this master thesis, the first steps were taken into the fundamental research into gaze behavior in stroke patients during reach and grasp tasks and into finding potential distinguishing parameters for USN during the SCT.

2.2 Samenvatting – Nederlands

Als gevolg van een beroerte kunnen patiënten lijden aan zwakheid of hemiparese in de bovenste extremiteit. [1] Het oppakken van een kopje koffie kan hierdoor bijvoorbeeld lastig worden. Hiervoor wordt binnen het eNHANCE project gewerkt aan een arm- en handondersteuning. Om dit systeem te besturen, zou bewegings intentie detectie door gebruik te maken van 3D eye tracking gebruikt kunnen worden, wat de cognitieve belasting niet verhoogt. [2] Om te onderzoeken of dit gebruikt kan worden om het systeem aan te sturen, zal het tot nu toe onbekende kijkgedrag tijdens reik- en grijptaken in beroerte patiënten in kaart gebracht moeten worden. Dit is het eerste deel van het observationele onderzoek. Het tweede deel gaat over Unilateraal Spatieel Neglect (USN), dit is een gevolg van een beroerte waarbij een deel van het visuele veld genegeerd wordt door de patiënt. Een diagnostische test hiervoor is de star cancellation test (SCT). Dit is een pen en papier test, waarbij kleine sterren, welke verstopt zijn tussen grote sterren en letters, weggestreept moeten worden. Hierbij worden geen restricties in tijd en hoofdbewegingen (welke als compensatie strategie gebruikt zouden kunnen worden) gebruikt. Daarom moet er onderzoek gedaan worden naar het effect van tijd en hoofdbewegingen op de SCT en daarnaast moet er gekeken worden naar andere potentiële onderscheidende parameters om de diagnose van USN met behulp van de SCT meer sensitief te maken.

Het doel in deze master thesis was om de meetmethode op te zetten en waardevolle en verkrijgbare parameters te vinden voor het observationele onderzoek naar het kijkgedrag van beroerte patiënten tijdens reik- en grijptaken en naar de potentiële onderscheidende parameters in de SCT. Daarnaast werd er gekeken naar de haalbaarheid van de metingen en de analyse.

In totaal zijn er 7 gezonden en 3 beroerte patiënten gemeten, waarvan er 2 gezonden en 2 patiënten (1 in het reik- en grijpdeel en 1 in het SCT deel) meegenomen zijn in de analyse in deze master thesis. Het kijkgedrag werd gemeten met behulp van een draagbare 3D eye tracker, de Tobii Pro Glasses 2, met een geïntegreerde gyroscoop. De fixaties werden gedetecteerd met behulp van een aangepast filter in de Tobii Pro Lab software, welke gebruik maakt van een snelheidsdrempel voor de oogbewegingen. Om het kijkgedrag tijdens reik- en grijptaken in kaart te brengen zijn er vier verschillende gepersonaliseerde gesimuleerde alledaagse reik- en grijptaken geprogrammeerd op een touchscreen. Deze taken bestaan uit een reik en raak aan, een reik en til op, een reik en verplaats en een bimanuele taak. Touchscreen compatibele objecten zijn gebouwd en gebruikt tijdens de reik- en grijptaken. De taken, driemaal uitgevoerd met de dominante hand in de gezonden en driemaal uitgevoerd met de hand van de aangedane zijde bij de patiënt werden geanalyseerd. De SCT werd eenmaal zonder en eenmaal met hoofd fixatie uitgevoerd, door gebruik te maken van een kin steun. Een hoofdbeweging detectie script werd geschreven om de hoofdbewegingen uit de gyroscoop data te detecteren. De parameters welke waardevol voor het gehele observationele onderzoek zijn en verkrijgbaar zijn uit de eye tracker, het touchscreen en de SCT, werden opgesomd voor de reik- en grijptaken en de SCT.

De meeste parameters waren verkrijgbaar met uitzondering van de parameters welke de data van de fixaties op de interessante gebieden gebruiken. Deze parameters werden vervangen door anderen welke nog steeds informatie geven over het kijkgedrag op de interessante gebieden door gebruik te maken van ruwe data punten in plaats van fixaties. Alle reik- en grijptaken waren uitvoerbaar voor de gezonden en de patiënt. De geprogrammeerde taken werkten naar behoren en veelbelovende resultaten werden verkregen. Hetzelfde geldt voor de SCT met en zonder hoofdfixatie. In de resultaten werd gevonden dat het hoofd fixatie systeem hoofdbewegingen limiteert, maar niet excludeert.

Op dit moment is de studie populatie te klein om conclusies te kunnen trekken in het gehele observationele onderzoek, echter is er inzicht verkregen in de haalbaarheid van de studie. In vervolg onderzoek zou er naar een manier gekeken moeten worden om de fixaties op de interessante gebieden te kunnen verkrijgen. Dit zal informatie geven over of een persoon informatie tot zich nam wanneer deze persoon naar een interessant gebied keek. Er zou ook gekeken kunnen worden naar een manier om de fixaties meer valide te verkrijgen met de draagbare eye tracker. Concluderend, de opgezette meting en de analyse zijn haalbaar. Vele parameters waren verkrijgbaar, alleen de parameters welke de fixaties op de interessante gebieden data gebruiken waren niet verkrijgbaar. Tijdens deze master thesis zijn de eerste stappen genomen in het fundamentele onderzoek naar het kijkgedrag in beroerte patiënten tijdens reik- en grijptaken en naar het vinden van potentiële onderscheidende parameters voor USN tijdens de SCT.

3 List of abbreviations

AOI	Area of interest
BM	Bimanual
CVA	Cerebrovascular accident
EmNSa	Erasmus MC modification of the Nottingham Sensory Assessment
FMA	Fugl-Meyer Assessment
RL	Reach and lift
RoM	Range of motion
RR	Reach and replace
RT	Reach and touch
SCT	Star cancellation test
TIO	Task irrelevant object
TRB	Task relevant body part
TRO	Task relevant object
USN	Unilateral Spatial Neglect

Contents

4 Introduction

4.1 Research motivation

Stroke patients might suffer from functional disabilities due to upper extremity weakness or hemiparesis. [1] These functional limitations affect all day life tasks, picking up a cup of coffee might be difficult for example. For this, assistive technology might help supporting. [2] In the eNHANCE project, there is worked on an assistive arm and hand support system for stroke patients. If the assistive technology is easy to use, there is a higher possibility the technology will be used. [2]. 3D eye tracking is a promising method to find motion intention without the addition of cognitive load. [3] Therefore, within the eNHANCE project, there is looked into the possibility to use eye tracking to control the arm and hand support system. The gaze behavior in stroke patients during reach and grasp tasks is, to our knowledge, currently unknown. Therefore, to find out if eye tracking can be used to control the arm and hand support system, the gaze behavior in stroke patients during reach and grasp tasks should be explored.

Next to the gaze behavior during reach and grasp tasks, the gaze behavior during the star cancellation test (SCT) in stroke patients suffering from Unilateral Spatial Neglect (USN) will be explored. In stroke patients, USN might be one of the symptoms where part of the visual field is neglected. [4] One of the diagnostic tools of USN is the SCT. This is a pen and paper task where the patient has to find all the little stars which are placed in between bigger stars and letters. There are no constrictions in head movements and time, which might affect the sensitivity of the test. Patients who know they are suffering from USN focus more on the neglected side. This is a compensatory strategy. [5] Therefore, there is expected that more fixations will be found in the neglected side of the field of view. Next to that, USN patients might rotate their head to put a target into the spatial side which is not neglected, therefore more head movements during the SCT might be made by USN patients. This will be done more if the patient is aware of his or her disorder. [6] If the patient is able to make as many head movements as wanted, the USN patient might not be diagnosed as a USN patient by the SCT. To find potential distinguishing parameters between USN and no USN using the SCT, the gaze behavior and the effect of head movement restriction and time during the SCT will be investigated.

In the whole observational study, the gaze behavior of stroke patients during upper extremity reach and grasp tasks will be explored and compared to those of healthy controls. Stroke patients with and without USN will be included and gaze and head movements, while executing a SCT, will be investigated using a mobile eye tracking device. During this master thesis a measurement method is set up to be able to answer the research questions of the whole observational study as described below (section 4.2). Measurements are executed and the results are discussed.

4.2 Research goal and research questions

The primary goal of the whole observational study is to find out what the gaze behavior of stroke patients is during upper extremity daily life reach and grasp tasks. Next to that, the gaze behavior in stroke patients suffering from USN and the effect of head movement restriction and time during the SCT will be studied.
The following research questions for the whole observational study were formed:

- What is the gaze behavior of stroke patients during upper extremity daily life reach and grasp tasks and how do they compare to the gaze behavior of healthy controls?
- What could be possible distinguishing parameters between patients with and without Unilateral Spatial Neglect using the star cancellation test?

The first steps of the whole observational study are taken in this master thesis. The primary goal during this master thesis is to find which parameters are to be investigated, to prepare the measurements and to assess the feasibility of the measurement set up and the analysis.
The following research questions for this master thesis were formed:

- What parameters can be obtained during the reach and grasp tasks and the star cancellation test which are valuable to answer the research questions of the whole observational study?
- Is the measurement method, which was set up during this master thesis, feasible in terms of executability and usability?

5 Background

5.1 Stroke

Stroke, a cerebrovascular accident (CVA), is the fifth leading cause of death in the United States of America. [7] Different kinds of stroke exist. In a hemorrhagic stroke, 13% of the strokes, there is a bleed in the brain. [8] In an ischemic stroke, 87% of all strokes, there is a blockage of the blood flow in the brain. [8] A Transient Ischemic Attack (TIA) is a short time blood blockage which gives short term, often not permanent stroke symptoms. It is often a warning for a future stroke. [8]

The bleeding in the brain in a hemorrhagic stroke causes the brain to swell which damages the brain cells by increasing pressure. [9] This bleeding might be caused by an aneurysm, hypertension, intracranial vascular malformations, cerebral amyloid angiopathy or a secondary bleeding caused by a previous stroke. [10] High blood pressure can cause hemorrhagic strokes as well. [9] An ischemic stroke is a brain infarction, where the blood supply to a part of the brain is cut-off and will not receive oxygen nor nutrients anymore. The impaired brain tissue due to an ischemic stroke is called the Ischemic penumbra. [10] There are two types of ischemic stroke, cerebral thrombosis, where the obstruction is built on the site of the blockage and cerebral embolism, where the obstruction is built somewhere else in the body and traveled to the blockage site. The limited blood flow can be caused by atherosclerosis, where plaque is present on the walls of the arteries which decreases the diameter of the artery for blood flow. [9] Heart and vascular diseases might cause ischemic stroke as well. Atrial fibrillation is a common cause of embolic stroke, because blood clots are formed in the heart. The clots are formed due to blood pools in the heart because of irregular and fast contraction of the chambers. [9]

5.2 Signs of stroke, prognosis and recovery

Neurological signs of stroke are an asymmetric face, arm or leg weakness, speak disturbance and a visual field defect. [11] The effect of stroke is dependent on where the damage is located and how big the damaged area is. [7] The severity of the first symptoms of stroke are an indicator of the recovery and prognosis. [12] To make sure the patient recovers as well and as fast as possible, the patient needs ongoing care and rehabilitation. In rehabilitation, the patient can receive help with language, speech and memory but also muscle and nerve problems. Next to that, the patients might need help with bladder and bowel problems, swallowing and eating and might need mental health care. [9]

5.3 Unilateral Spatial Neglect

There is estimated that about 30% of stroke patients suffer from USN after onset of stroke. [4] A stroke patient with USN can be recognized by walking against things in their environment, not eating all the food of their plate (only one half) and only dressing one side of the body. A neglect increases the risk of injury by for example falling and it has an effect on daily life activities. [4] In a study by Sunderland et al., $8-11\%$ of the stroke patients showed visual neglect three weeks after stroke onset. A neglect was found more often in right sided brain damage than in left sided brain damage. After six months, most of the neglects were not observed anymore. [13] Visual neglect often improves spontaneously. [14] There are three types of neglect, which may be present as a combination in a stroke patient. In stroke patients with a personal neglect, they have no attention for one side of the body. In near extra-personal neglect, there is no attention for one side of the reachable space. In far extra-personal neglect, there is no attention for one side of the space which is out of reach. [4] To find if a patient is suffering from a visual field defect (hemianopia) or USN (attentional defect) is not easy. [14] Patients with hemianopia suffer from blindness on one half of the visual field. This blindness is called hemiretinal, where the division, right and left, is defined by a vertical line over the retina. [15] In patients with USN, one half of the spatial field is ignored. [15] In a research into visual search in left sided USN patients was found that in a visual search experiment, less attention (fixations) was paid on the left and more attention was paid on the right side in comparison to healthy controls. [16]

Among others, a commonly used test to diagnose USN is the SCT, which is a pen and paper test where small stars have to be canceled which are placed in between big stars and letters. The test is done without time and head movement restrictions. The amount of stars canceled on each side of the test is used to diagnose USN. The eye movements during the SCT were investigated by Lievestro, there was found that the number of eye movements was higher in stroke patients, who might suffer from a neglect, in comparison to the healthy subjects. [17] However, the duration of the SCT, which was found to be longer for the patient group, was not taken into account. A patient suffering from USN can be treated in several ways. Treatments which have shown to be effective are visual scanning (executing a task on the neglected side), visual, verbal or auditory cueing (making a visual, verbal or auditory cue on the neglected side to trigger the attention), limb activation (executing tasks with a limb on the neglected side) and trunk rotation (twist the trunk to the affected USN side). Treatments with a temporary effect are using eye patches or hemiglasses (the patient has to look through the ignored side) and Fresnel prisms (shift the visual field to encourage looking at the neglected side). [4]

5.4 Upper extremity impairments after stroke

Post stroke patients might suffer from spasticity, weakness, hemiparesis or sensory loss in the upper extremity, which causes functional limitations. [1] In a study by Lawrence et al. was found that 975 out of 1259 acute stroke patients suffered from upper limb motor deficits and 381 patients suffered from upper limb sensory deficits. [18] Effects of these upper extremity impairments can be that the patient is not using the limb or is using the limb incorrectly. The resulting functional limitations from the upper extremity impairments affect all day life tasks, where assistive technology might help. [2]

5.5 Eye hand coordination

Eye hand coordination is complex. A lot of systems have to work together to be able to reach and grasp an object.[19] The visual system gives visual feedback and is used for movement planning to prepare reaching and grasping. In controlling these movements for example the weight and center of gravity of the object are taken into account. [20] Eye hand coordination also uses the vestibular system and proprioception. the vestibular system gives information about the location and movements of the head and the proprioception gives information about where the hand is located in space. [19] Control systems of the eyes, hands and head have to control the movements. Next to those, attention and memory have an influence on the eye hand coordination. [19]

In a study by Johansson et al. was found that before grasping an object, gaze is located at the points where the contact of the hand, the digits, with the object is predicted. No fixations during the reach and grasp task were found on the hand or on the moving object. [21] Brouwer et al. found that there exists a difference in gaze location on an object when a person grasps it or when it is only viewed. [22] When someone only views the object gaze is located more at the center of gravity of the object. When someone will grasp an object, the gaze is located at the locations where the digits will touch the object (edge of the object). They also found that when someone grasps an object gaze will shift to the object later than when someone just views the object. They suggest that this might be because the eyes could be waiting for the planning of the movement. In grasping, the eyes and hand start moving at about the same time, the eyes start moving only a little bit sooner. [22]

In daily life, eye hand coordination is used a lot to guide to movements of the hand. After suffering from a stroke the eye hand coordination might be affected, which affects the life of the patient. [19] In a study by Gao et al. slower movements and less accurate movements in the affected hand of stroke survivors were found. This indicates a worse eye hand coordination in the affected hand in stroke survivors. [23]

5.6 Eye movements

The eye makes several different movements to be able to see. During a fixation, the eye is kept steady pointing at the target, to take up information. [24] When the head rotates and the eyes have to stay looking at the same spot, the vestibulo-ocular reflex is used. The eyes then rotate according to the head movements made. [25] The semi-circular canals of the vestibular system detect head movement which produces rapid eye movements to correct for the head movement. [24]

Rayner investigated fixation durations during reading. [26] There was found that most fixation durations ranged from 100 to 500 ms but also a few fixations shorter than 100 ms (down to 50 ms) and longer than 500 ms were found. Saccades are rapid eye movements to change the location of fixation of the eye. Saccades are ballistic movements because once the eye is moving but the target changes position, the movement will not change and therefore make an error. Another saccade is then needed to correct this error. Saccades can be voluntary, but when the eyes are open the eyes make saccadic movements without being aware of them. It takes 200 ms before a saccadic movement starts when a target is found to be fixated on. In this 200 ms there is calculated how far and in what direction the eye should move and a motor command is generated to activate the extra-ocular muscles. [24] In a research by Rayner et al. saccade durations during reading of 20 40 ms were found. [27]

5.7 Eye tracking

To explore the gaze behavior, eye tracking is used. Several different methods for gaze direction detection (eye tracking) exist (stationary or head mounted), examples are listed below: [28]

- Electrodes placed on each side of the eye, measuring the electric potential (electro-oculogram).
- Recording the eyes by using a camera.
- Corneal reflection points of light. Using the vector between these points and the center of the pupil.
- Shape detection of the pupil and iris (use specific circular shape).
- Bright and dark pupil tracking

In dark pupil eye tracking, the eye is illuminated in a way that the pupil turns black. The black pupil can then be detected, however in a subject with a brown iris, the difference between the black pupil and the brown iris is hard to distinguish. In bright pupil eye tracking the eye is illuminated with IR light, which causes the pupil to appear white. The white pupil can then be detected. [28]

6 Research methods

6.1 Research process

For the whole observational study, the measurements were set up during this master assignment. The gaze behavior was explored by using a wearable eye tracker. In the approved Medical Ethics Committee (METC) document, the reach and grasp tasks were already described. The software to execute the tasks on a touchscreen was written and touchscreen compatible objects were made. For the USN part of the study, a head fixation system was found and a method to detect the head movements was written. A test measurement was done after which the method was adjusted. After this healthy subjects and patients were measured and the data of 2 healthy subjects and 2 patients was analyzed.

6.2 Study population

For the whole observational study, 10 stroke patients with USN, 10 stroke patients without USN and 10 healthy controls will be included. There will be attempted to get 3 age and gender matched groups. The following inclusion and exclusion criteria were drawn. The data of two healthy subjects and two patients was analyzed in this master thesis, where the data of one patient was used in the reach and grasp tasks and the data of the other patient in the SCT. In total, 7 healthy subjects and 3 patients were measured during this master assignment. The subject characteristics can be found in table 1. Approval from the local METC was received and all subjects signed informed consent prior to the measurement.

Table 1: Subject characteristics.

				If applicable:	**If applicable:**	**If applicable:**	**If applicable:**
	Age	**Gender**	**Dominant hand**	**Time since stroke**	**Right or left hemisphere**	**Affected body side**	**Diagnosed USN**
H1	52	Female	Right				
H2	65	Male	Right				
P1	50	Female	Right	5 months	Right	Left	No
P2	56	Female	Left	9 years, 2 months	Right	Left	No

6.2.1 Inclusion criteria

The following inclusion criteria should be met by the post-stroke patients:

- Patients should be clinically diagnosed with unilateral, either right or left sided, middle cerebral artery stroke (ischemic or hemorrhagic)
- between 18-80 years of age
- Time since onset of disease is at least one week
- Sufficient cognitive status to understand two-step instructions
- Patients should be able to lift their affected arm on the table and to grasp a cylindrical object while seated in a chair
- Provide written informed consent

All healthy controls should meet the following criteria:

- Between 18-80 years of age
- Sufficient cognitive status to understand two-step instructions
- Provide written informed consent

6.2.2 Exclusion criteria

A subject who meets any of the following exclusion criteria will be excluded from the study:

- People with severe acute pain of the (affected) arm and hand
- People having insufficient knowledge of the Dutch language to understand the purpose or methods of the study
- People with visual deficits; either ophthalmic (e.g. wearing glasses or lenses stronger than -5 or +3) or cerebral
- Severe contractures limiting passive range of motion in the upper extremity
- Co-morbidities limiting functional use of the arm and hand

6.2.3 Recruitment

All stroke patients were and will be recruited from Roessingh Rehabilitation center in Enschede. During the elderly fair on the 20th of April in Enschede, Roessingh Research and Development (RRD) occupied a stand. A list where elderly people could sign up to be contacted to participate in scientific research at RRD was present. The healthy controls were and will be recruited from this list and from personal acquaintances.

6.3 Clinical measurements

The following clinical measurements were executed during the measurements. The results will be used in the whole observational study but were not discussed in this master thesis.

6.3.1 Fugl-Meyer Assessment of Motor Recovery after Stroke - Upper extremity part

The Fugl-Meyer Assessment (FMA) was executed to find the amount of motor impairment in the stroke patient groups. This test was not done in the healthy control group. Several tasks in five categories (motor function, sensory function, balance, joint range of motion and joint pain) were performed. Each task was scored with 0 (cannot perform), 1 (performs partially) or 2 (performs fully). The scores were summed. [29] An excellent test retest reliability was found for the total motor score (ICC > 0.95) by Platz et al. [30]

6.3.2 Erasmus MC modification of the Nottingham Sensory Assessment

The Erasmus MC modification of the Nottingham Sensory Assessment (EmNSA) measures the somatosensory impairment in intracranial disorder patients. [31] This test was done for all subject groups to find possible impairments in tactile sense, sharp/dull discrimination and propriocepsis. Only the upper extremity part of this test was used. The intra-rater reliability is good to excellent ($\kappa = 0.58 - 1.00$) and the inter-rater reliability is good to excellent ($\kappa = 0.46 - 1.00$). [31]

6.4 Eye tracking glasses

For the observational study a wearable eye tracker is needed which is able to track gaze in 3D, to find the location of gaze in space. Two wearable eye trackers, available for testing, were considered: The SMI eye tracking glasses 2 (figure 2a) and the Tobii Pro glasses 2 (figure 2b). Both systems are described below and the choice is elaborated.

(a) SMI eye tracking glasses 2 Wireless with head and motion tracking modules. [32]

(b) Tobii Pro Glasses 2 with recording unit. [33]

Figure 2: Considered eye trackers.

6.4.1 SMI eye tracking glasses 2

With the SMI Eye tracking glasses 2 Wireless (SMI ETG 2w) the gaze behavior can be tracked in real time. The glasses are lightweight, 47 grams, and come with an Android smart recording unit weighing 176 grams. It uses binocular eye tracking with a sampling rate of either 60 or 120 Hz. A frontal camera is built into the glasses with a resolution of 1280 x 960 pixels, a microphone is present as well. The eye tracker makes use of a one or three point calibration and an offline calibration correction is possible. The glasses have an accuracy of 0.5 degrees. Contact lenses can be worn but also prescription glasses are available which can be snapped onto the eye tracker from -4 until 4 diopter. The data can be analyzed with available SMI software. An optical head and motion add on module can be bought with the glasses (SMI 3D Stereoscopic Vision Module), to make tracking of the head movements possible. [34] [35]

6.4.2 Tobii Pro Glasses 2

The Tobii Pro Glasses 2 is a wearable eye tracker (3D) consisting of a lightweight head unit (45 grams) and a recording unit (312 grams). It uses a sampling rate of either 50 or 100 Hz. It is a binocular eye tracker using dark pupil, corneal reflection eye tracking. The Tobii Pro Glasses 2 are equipped with two cameras per eye which record the location of the illuminated pupil. One point calibration is used to calibrate the eye tracker. The Tobii Pro Glasses 2 contains a scene camera with a resolution of 1920 x 1080 pixels and also contains a microphone. The accuracy in degrees is not given by Tobii. A gyroscope and an accelerometer are integrated in the eye tracker. Prescription glasses for the Tobii Pro Glasses 2 are available from -5 until +3 diopter. The data can be analyzed using Tobii Pro Glasses Analyzer software, where among other things areas of interests (AOIs) can be indicated and the gaze data on an AOI can be obtained. [33]

6.4.3 Choice for Tobii Pro glasses 2

First, there was looked at the SMI eye tracker because this eye tracker was already purchased by the eNHANCE project. It was found that only the video could be obtained from the eye tracker. No eye position data or gaze location data was received from the eye tracker. The reason for this is that the software for this eye tracker was not purchased with the eye tracker. Therefore, no data from the eye tracker could be received.

Next, there was looked into another solution, the Tobii Pro Glasses 2. This eye tracking system was purchased by the BMS lab of the University of Twente. It looks like the system is accurate and the data can be obtained easily. An accelerometer and gyroscope are integrated in the system which can be used for the head movement detection. All the gaze points in the video data should be mapped onto a snapshot in the Tobii Pro Lab software. A snapshot is a picture in which all components in a certain task are visible. AOIs (e.g. the right hand) can be indicated in this snapshot where the software will count for example the number of fixations and the time spent on each AOI. For this reasons there was chosen to use the Tobii Pro Glasses 2 for the study.

6.4.4 Fixation detection

To obtain the fixation data, a custom I-VT filter (Velocity-Threshold Identification) was used in the Tobii Pro Lab software. When the angular velocity threshold of the eye movement is exceeded, an eye movement is indicated as a saccade. When the angular velocity is lower than the threshold, the eye movement is indicated as a fixation. The settings of this filter were set to an angular velocity threshold of 90 degrees/second for the reach and grasp tasks and an angular velocity threshold of 35 degrees/second for the SCT. When fixations were found closer to each other than 20 ms, they were merged. A minimal fixation duration of 60 ms was set. The choice for this custom filter is explained in appendix A (Fixation detection).

6.5 Simulated personalized daily life reach and grasp tasks

For this study several simulated personalized daily life reach and grasp tasks were used to find the gaze behavior during reaching and grasping. These tasks consist of a reach and touch task, a reach and lift task, a reach and replace task and a bimanual task. The tasks were executed using a touchscreen (IIYAMA TF4237MSC, 42 inch), which was placed on a chassis which makes it movable and adjustable in height. The touchscreen was placed in horizontal, landscape, table position, to enable the placement of objects on the touchscreen. By using the touchscreen the tasks are similar for every subject and the press and release times and locations can be saved. During the tasks, the subject sits on a chair in front of the touchscreen.

The tasks were personalized by measuring the range of motion (RoM) of every subject making sure the whole task is executed within 85% of this RoM. The RoM measurement task was written using Matlab 2016a. The simulated personalized daily life tasks were programmed by using Java, with the RoM results used as input. Which conditions the tasks should meet and how all tasks were programmed can be read in appendix B. For three out of four tasks, objects on the touchscreen were needed. These objects should be compatible with the touchscreen. How the objects were devised can be read in appendix C. Each task was executed three times with the dominant hand and three times with the non-dominant hand in the healthy control group and three times with the affected hand in the stroke group and if possible also the non affected side was measured three times. In this study only the data of the dominant hand in the healthy subjects group and the data of the hand of the affected side in the patient was analyzed.

First the **maximal range of motion** of the dominant hand in the healthy subjects and the hand of the affected side in the patients was measured. To do so, the subject was seated in front of the touchscreen and touched the touchscreen with the hand in a continuous movement from the left lower corner to the right lower corner as far as he or she could reach. The touch points were saved to be used in the tasks programmed in Java.

The first task is the **reach and touch (RT) task**. In this task the aim is to reach with the hand to a target which is located inside the 85% of range of motion and touch this target. The subject was seated in front of the touchscreen where after pressing the start button a red target appeared which needed to be touched. After touching the target, the start button needed to be touched again so the next target appeared and so on. The total amount of targets was 15. The touching of the start button in between every target touch was implemented to decrease the amount of searching gaze behavior after touching the target.

The second task is the **reach and lift (RL) task**. In the reach and lift task, the subject was seated in front of the touchscreen, where four objects were placed within the subject specific 85% range of motion at specific locations (orange circles on the touchscreen). When the starting signal was given by the researcher the subject should touch the gray base rectangle and after that reach with the hand for the object which was indicated to be lifted (a red circle). When the subject lifted the object and put it down again, the hand of the subject should go to the base position again. The next object was then indicated to be lifted and so on. After eight reach and lift tasks the trial was finished.

The third task is the **reach and replace (RR) task**. In the reach and replace task, two objects were placed on the touch screen on two of the four predefined locations (orange circles). The subject was seated in front of the touchscreen. When the task was started by the researcher, two of the four orange circles turned red, where on one red circle an object was present and where the other one was empty. The subject had to reach to the object and place it from the red circle to the other red circle which was empty. When this was done, there was indicated which object had to be reached and replaced next. After six replacements the trial of this task was finished.

The last task is the **bimanual (BM) task**. The bimanual task is a task where the gaze behavior will be investigated in an explorative way. Therefore, not a lot of restrictions to the task were given to the subject because the natural manner of the bimanual task was studied. In the bimanual task, rice had to be poured from one cylindrical object (the bottle), where a cap had to be removed from first, into the other cylindrical object (the glass). The only assignment for the subject was to pour the rice into the glass which needed to be placed in the middle of the touchscreen. When this was done, the cap should be placed back on the bottle and the bottle and glass should be placed back in their original position. After this the task was ended.

6.6 Star cancellation test

The star cancellation test (SCT) is a pen and paper test which can be used to see if a stroke patient suffers from USN. It is a test for neglect in the near extra-personal space. [36] It consists of an A4 sized paper on which 52 large stars, 13 letters, 10 short words and 56 small stars are pictured. The assignment of this test is to cancel all the small stars. There are no time and head movement limitations set in this test. If less than 44 small stars were canceled the patient is said to suffer from USN. Next to that a laterality index can be found which is the number of stars crossed on the left side divided by the total number of stars crossed. If this laterality index has a value between 0 and 0.46, the USN is present in the left hemispace. If the laterality index has a value between 0.54 and 1 the patient suffers from a USN present in the right hemispace. [36]

The paper was placed in landscape position in front of the subject, with the mid-line of the paper according to the mid-line of the subject. First, two little stars in the middle of the paper were crossed by the reseracher as a demonstration. After which the subject received the assignment to first look at the blue dot placed above the SCT for a few seconds, after which the starting signal by the researcher was given to cross all the little stars present on the paper. When the subject was convinced to have canceled all the little stars, the subject should look at the blue dot again for a few seconds. The blue dot was used in this test to receive a certain amount of time in the gyroscope data where the head was approximately stationary, to remove drift. The SCT was done twice, once with and once without head fixation.

6.6.1 Head movements

The head was fixated using a chin rest (figure 3), to limit head movements during the SCT to find the effect of head movements on (the gaze behavior during) the SCT. Multiple ways to fixate the head were considered. The choice for this manner of head fixation is explained in appendix D. In this research the head movements a subject made during the SCT were investigated. The rotation of the head to the left and right is most important in this research. Therefore, the gyroscope Y data (degrees/second) from the gyroscope built in the Tobii Pro Glasses 2 were used. The head movements were found from the data by using Matlab 2016a. First, the mean value of both drift measurements (looking at the blue dot at the beginning and end of the SCT) was subtracted from the gyroscope data to limit drift after integration. The data was filtered by a 6 Hz low pass 2nd order Butterworth filter and integrated to receive the degrees of rotation over time data. The peaks in this data were found and the head movements were selected by finding peaks with a rotation of more than 0.57 degrees, a minimal duration of 167 ms and no rotation of more than 0.4 degrees in the other direction in between both peaks. Head movements closer than 100 ms to each other and in the same direction were merged. Further explanation of this head movement detection method can be found in appendix E.

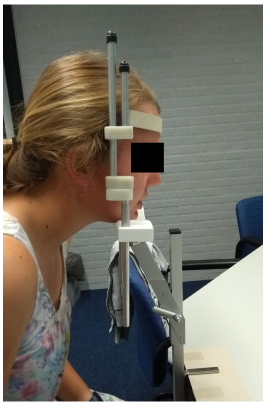


Figure 3: Head fixation system by using a chin rest.

6.7 Parameters

Valuable parameters for the whole observational study were investigated. There was looked into which parameters should be possible to obtain by using the eye tracker (according to the manual), the SCT and the programmed reach and grasp tasks. These parameters are listed below. The snapshots used to obtain the parameters can be found in appendix F.

6.7.1 Outcome measures Simulated personalized daily life reach and grasp tasks

The parameters of the reach and grasp tasks which should be obtainable from the eye tracker are:

- **Heat map** (Raw gaze data, relative duration): To visually show where gaze was located during the tasks.
- **Time to first fixation on a task relevant object**: To look into processing and reaction time.
- Percentage of time fixated on task relevant objects (%time) (**TRO gaze**): Task relevant objects are defined as the circles, start buttons, start text, and the base rectangle on the touchscreen, the touchscreen compatible objects, the SCT and the pen used during the SCT.
- Percentage of time fixated on task irrelevant objects (%time) (**TIO gaze**): To look into the amount of distraction. Task irrelevant objects are all objects except for the task relevant objects and the body parts.
- Percentage of time fixated on task relevant body parts (%time) (**TRB gaze**): To look into possible visual guidance of the arm and hand. Task relevant body parts are the left and right arm and hand.
- Percentage of raw gaze points on task relevant objects (% of total number of gaze points) (**TRO gaze**): Same as %TRO gaze by using fixations, but contains less information about uptake of information.
- Percentage of raw gaze points on task irrelevant objects (% of total number of gaze points) (**TIO gaze**): Same as %TIO gaze by using fixations, but contains less information about uptake of information.
- Percentage of raw gaze points on task relevant body parts (% of total number of gaze points) (**TRB gaze**): Same as %TRB gaze by using fixations, but contains less information about uptake of information.
- **Average fixation duration**: To look at the time needed to take up information.
- **Distribution of fixations and saccades**: This is an explorative parameter.
- **Percentage of fixations on each AOI** of the total number of fixations: To find if some AOIs draw more or less attention (fixations) than others.
- **Percentage of raw gaze points on each AOI** of the total number of gaze points: To find if some AOIs draw more or less attention than others. Less information is gained about the uptake of information than by using the fixations data for this.

- **Number of visits on each AOI** (by using fixations): To explore the search pattern, where more visits might indicate a more random search pattern. The visits are calculated by using the fixations, where one visit is a series of consecutive fixations on one AOI.
- **Number of visits on each AOI** (by using raw gaze points): For the same reason as calculated with the fixations, but now the visits are calculated by using the raw gaze points, where one visit is a series of consecutive gaze points on one AOI.

The parameters of the reach and grasp tasks which should be obtainable from the touchscreen are:

- **Total duration tasks**. If for any reason the total duration can not be obtained by using the touch screen, the video of the eye tracker will be used.
- **Average lift duration** in the Reach and Lift task: To receive extra information about the total duration (a longer lift duration increases the total duration of the task).
- **Time from start to first release** in the Reach and Replace task: To look into the search skills and reaction time (how fast did the hand reach the target).

6.7.2 Parameters Star Cancellation Test

The parameters of the SCT which should be obtainable from the eye tracker are:

- **Heat map** (Raw gaze data, relative duration). To visually show where gaze is located during the SCT.
- **Number of fixations until last star crossed**. To find the number of fixations needed (information input) to cancel the stars.
- **Number of fixations at 30, 45, 60 and 90 seconds and in total**. To find the number of fixations (information input) until specific time points to exclude the influence of time.
- **Average fixation duration**. To look into the time needed to take up information.
- **Distribution fixations and saccades**. This is an explorative parameter.
- **Percentage of fixations on each AOI** of the total number of fixations. To find if some AOIs draw more or less attention (fixations) than others.
- **Percentage of raw gaze points on each AOI** of the total number of gaze points: To find if some AOIs draw more or less attention than others. This contains less information about the uptake of information than by using the fixations data for this.
- **Number of visits on each AOI** (the four vertical regions of the SCT). To explore the search pattern, where more visits might indicate a more random search pattern. The visits are calculated by using the fixations, where one visit is a series of consecutive fixations on one AOI.
- **Number of visits on each AOI** (by using raw gaze points): For the same reason as calculated with the fixations, but now the visits are calculated by using the raw gaze points, where one visit is a series of consecutive gaze points on one AOI.

The parameters of the SCT which should be obtainable from the video data of the eye tracker are:

- **Time first star crossed**: To find how fast the first star was found and canceled, which gives information about search skills and reaction time.
- **Time last star crossed**: To look into the time it takes to cancel the stars, excluding the time checking at the end of the SCT.
- **Start location** (location of the first star canceled): This is an explorative parameter.
- **Laterality index** (if 44 or less stars were canceled): To find if neglect is present in the right or left hemispace.
- **SCT score at 30, 45, 60 and 90 seconds and endscore**: To find the influence of time on SCT outcome.

The parameters of the SCT which should be obtainable from the gyroscope inside the eye tracker are:

- **Number of head movements after 30 seconds**: To look into a possible compensatory strategy for USN. The first 30 seconds were used because there is expected that all subjects would not be finished within 30 seconds.
- **Mean head movement duration** (to the left, right and in total): To receive information about the way the head moves, to look into a possible compensation strategy for USN.
- **Percentage of time the head is moved** in percentage of total duration SCT (to the left, right and in total): To gain insight into the way the head moves, to look into a possible compensation strategy for USN.
- **Mean rotation angle**: To find the rotational angle of the head movements to gain insight into the way the head moves, to look into a possible compensation strategy for USN.

7 Results

7.1 Parameters

Some of the parameters were found to be not possible to obtain. These are the parameters which use the fixations on the AOI data. In figure 4 can be seen that at the first time instance of one fixation (T1), the gaze point was located on the circle. On the second time instance of the same fixation (T2), gaze shifted a bit and is now located on the finger of the right hand. The gaze points of this fixation are therefore first mapped on the circle (T1 snapshot) and later on the finger of the right hand (T2 snapshot). The Tobii Pro Lab software calculated this fixation to be located on the left hand, which was not present in the video and where no gaze points were mapped on.

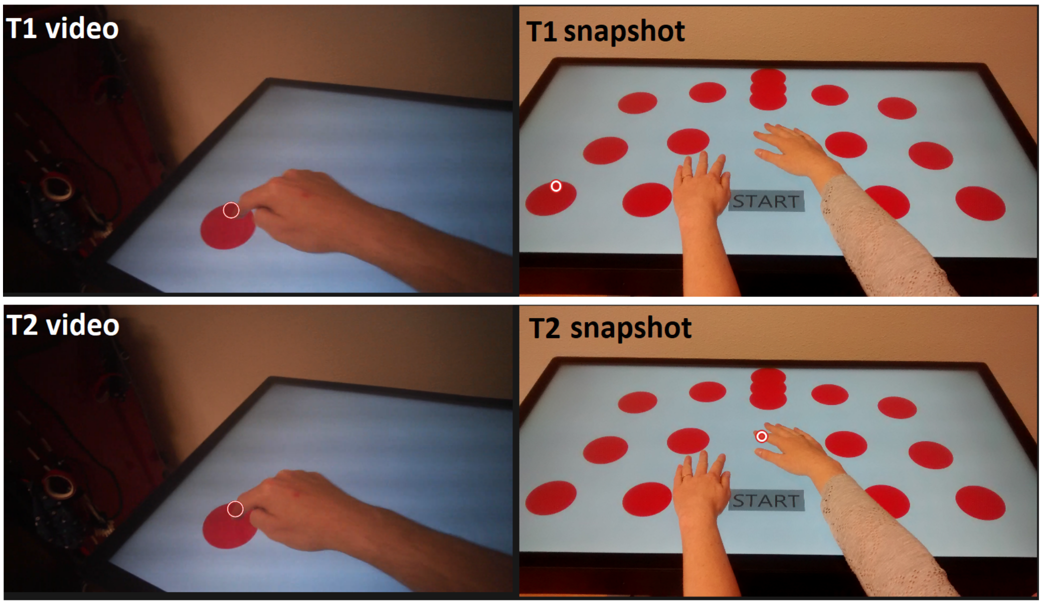


Figure 4: Gaze points in the video and the corresponding mapped points in the snapshots for two time points (T1 and T2) during one fixation. A small location shift in the gaze point data in the video can be seen, where a large shift in the mapped points in the snapshot is present.

For this reason, the fixation data on the AOIs are invalid. Therefore, the following parameters were not obtainable:

- Time to first fixation on a TRO
- Percentage of fixations on each AOI
- Number of visits on each AOI (by using the fixations)
- %TRO, %TRB and %TIO gaze (by using the fixations)

However, the following parameters were still obtainable:

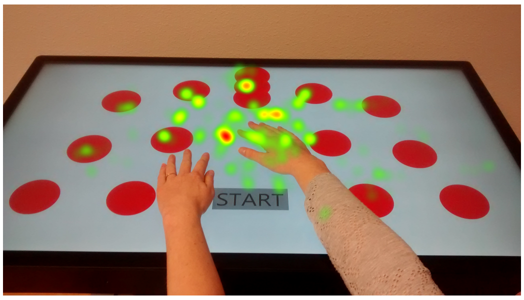
- Percentage of raw gaze points on the AOIs
- Number of visits on the AOIs (by using the raw gaze points)
- %TRO, %TRB and %TIO gaze (by using the raw gaze points)

7.2 Reach and grasp tasks

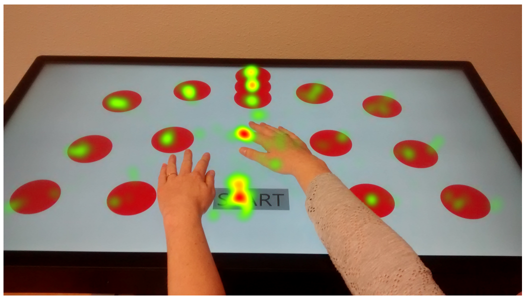
The results of the reach and grasp tasks of 2 healthy subjects and 1 patient are shown.

7.2.1 Reach Touch task

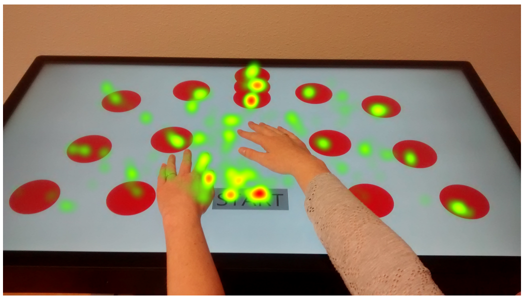
H1 showed different gaze point waiting locations while waiting for the next target to turn red (in the middle) than H2 and P2 (on or close to the start button). The waiting location can be recognized in the heat maps (figure 5). In the heat map of P2 in comparison to the healthy subjects can be seen that the gaze points were more spread. Both healthy subjects showed more fixed locations. Noticed during the RT task was that in the beginning, the subjects looked more at the start button to be touched than at the end of the task.



(a) H1.



(b) H2.



(c) P2.

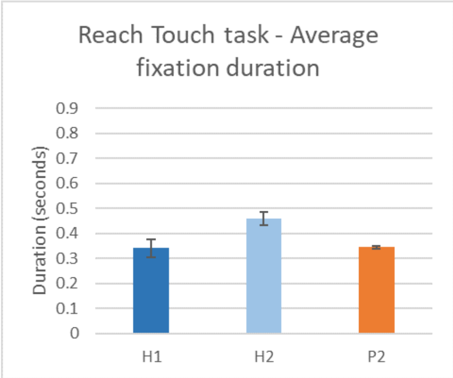
Figure 5: Heat maps (raw gaze data, relative duration) of the first trial of the RT task, where red indicates a location with a lot of gaze points.

In table 2 the total duration and the %TRO, %TRB, %TIO gaze (based on the raw gaze points) are shown. H1 executed the complete task the fastest and H2 the slowest. Clear differences between the subjects were found in %TIO and %TRO gaze. Where H1 showed the lowest %TRO gaze and the highest %TIO gaze. H2 showed the lowest %TIO in comparison to H1 and P2.

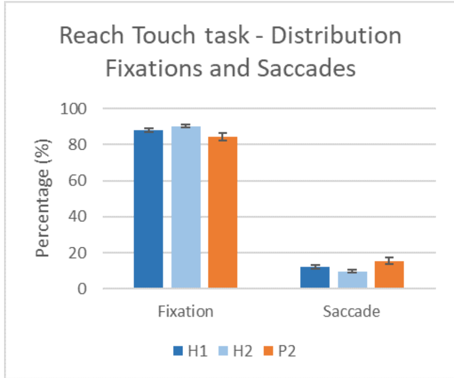
Table 2: RT task: total duration and the %TRO, %TRB, %TIO gaze (based on raw gaze points).

		H1	H2	P2
Duration (ms)	Mean	15783	19805	18971
	SD	796	361	506
%TRO		20.68	58.85	40.56
%TRB		20.57	19.38	14.82
%TIO		58.75	21.77	44.61

The average fixation duration during the RT tasks can be found in figure 6a. H2 showed the longest fixation duration, but no clear differences between P2 and H1 were found. The distribution of fixations and saccades in time during the RT tasks are shown in figure 6b. The percentage of saccades was slightly higher and the percentage of fixations slightly lower in P2 in comparison to H1 and H2.



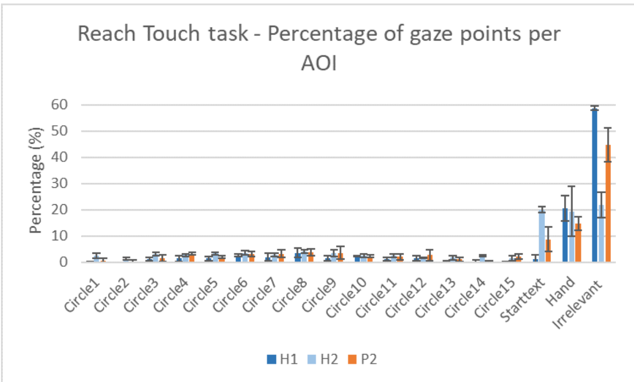
(a)



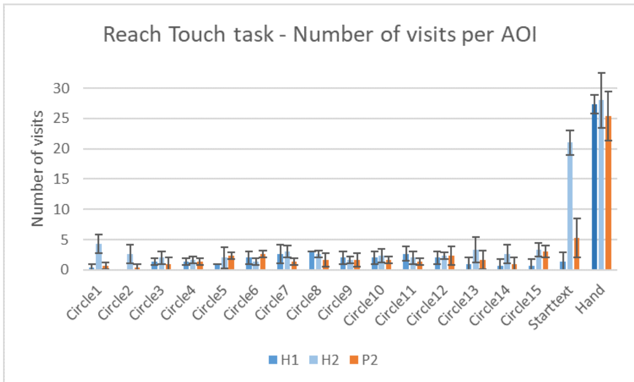
(b)

Figure 6: Average fixation duration (6a) and the distribution of fixations and saccades (6b) during the three RT tasks.

The percentage of gaze points per AOI and the number of visits (based on the raw gaze points) per AOI are shown in figure 7. In comparing the percentage of gaze points on the circles, it can be seen that gaze was located most at the circles in the middle and less on the circles on the most left and most right. However, H2 visited the circles on the most left and most right more than H1 and P2 did. P2 showed the highest percentage of gaze points and the most visits on the start-text in comparison to H1 and P2. The lowest percentage of gaze points on the hand was found in P2, also slightly less visits in P2 were found on the hand in comparison to H1 and H2.



(a)

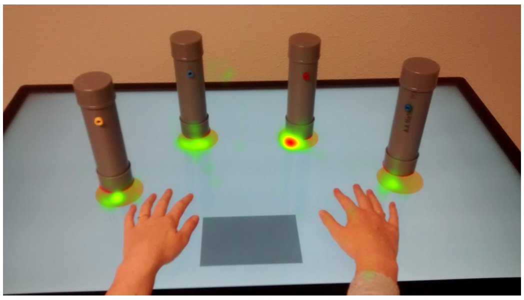


(b)

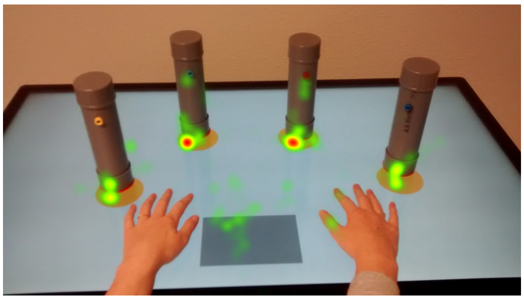
Figure 7: Percentage of gaze points per AOI (7a) and the number of visits per AOI (7b) during the three RT tasks.

7.2.2 Reach Lift task

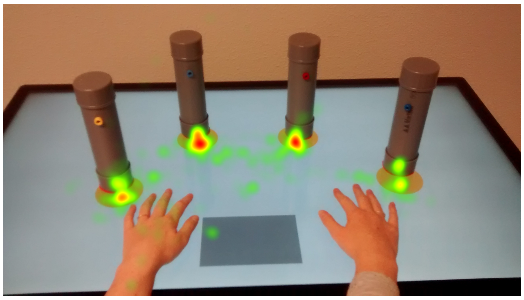
The heat maps of the RL task can be found in figure 8. For all subjects gaze was located most at the base of the objects. In the heat map of H1 almost no gaze points can be seen on the hands and on the base. Next to that, almost all colored spots are located on a TRO. In the heat map of H2 a few gaze points can be found on the base. The gaze points on the hand were located on the thumb and index finger. In H2, gaze points on the object were, before grasping the object, located at the location where the thumb would touch the object. In the heat map of P2 multiple spots on the white area in between base and objects can be found. The gaze points of P2 on the hand were distributed over a large area of the hand. During the task, the next target to lift was often (incorrect) predicted by looking at a circle.



(a) H1.



(b) H2.



(c) P2.

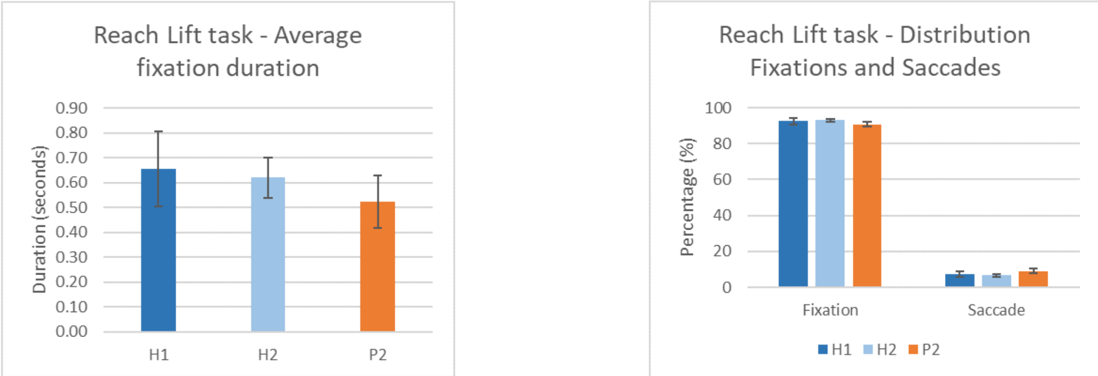
Figure 8: Heat maps of the first trial of the RL task (raw gaze data, relative duration), where red indicates a location with a lot of gaze points.

In table 3 the mean total duration of the RL tasks, the mean lift duration and the percentages TRO, TRB and TIO gaze (based on the raw gaze points) are shown. P2 executed the task the fastest and also showed the shortest lift duration. P2 showed the lowest %TRO gaze and the highest %TIO gaze. The %TRB gaze was similar for all subjects. Both healthy subjects showed similar %TRO, %TRB and %TIO gaze.

Table 3: RL task: Total duration, mean lift duration and the %TRO, %TRB, %TIO gaze.

		H1	H2	P2
Duration (ms)	Mean	24700	25890	22661
	SD	1386	2222	1766
Mean lift duration (ms)	Mean	2802	2836	2522
	SD	187	279	198
%TRO		80.84	81.47	72.16
%TRB		3.65	4.32	4.54
%TIO		15.51	14.21	23.30

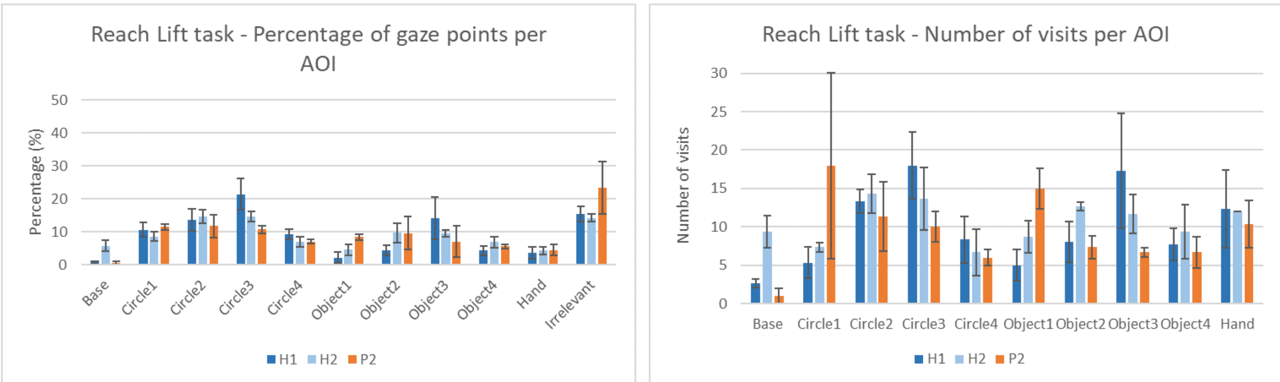
The average fixation duration during the RL tasks can be found in figure 9a. P2 showed a lower average fixation duration than the healthy subjects. The distribution of fixations and saccades in time during the RL tasks are shown in figure 9b. A slightly higher percentage of saccades was found in P2 in comparison to the healthy subjects.



(a) (b)

Figure 9: Average fixation duration (9a) and the distribution of fixations and saccades (9b) during the three RL tasks.

The percentage of gaze points per AOI and the number of visits (based on the raw gaze points) per AOI in the RL tasks are shown in figure 10. H2 showed a higher percentage of gaze points and more visits on the base in comparison to H1 and P2. In general, all three subjects showed more gaze points on the middle two circles and objects than on the right and left circle (1 and 4). In the number of visits can be seen that for P2 the number of visits decreased from the most left (1) to the most right (4) circle and object. Where for H1 and H2 the number of visits on both middle circles and objects (2 and 3) were higher than the outer ones (1 and 4). The percentage of gaze points on the hand was similar for all three subjects.

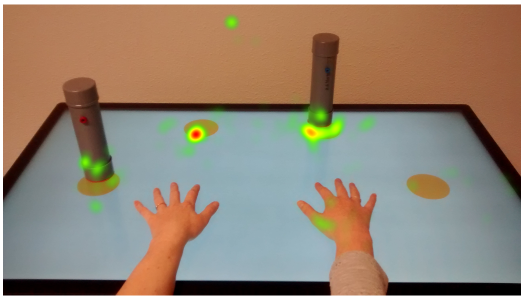


(a) (b)

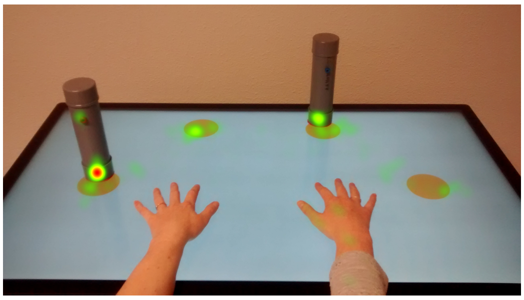
Figure 10: Percentage of gaze points per AOI (10a) and the number of visits per AOI (10b) during the three RL tasks.

7.2.3 Reach Replace task

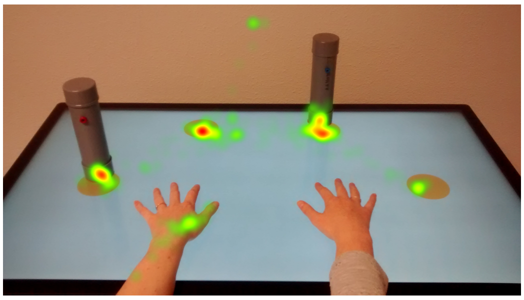
In figure 11 the heat maps of the RR task for all three subjects can be found. On the object, gaze was located most on the bottom of the object. Before grasping the object, sometimes gaze was located at the location where the thumb would touch the object. This was especially seen in subject H2. The next target was predicted a lot (often incorrect), gaze was often not waiting for the new target in the middle for example, but on a circle. In the heat maps of H1 and P2 it can be seen that gaze was located most on the middle circles (circle 2 and 3). In the heat map of H2, the gaze point locations were more fixed in comparison to H1 and P2. In the heat map of P2, a big spot can be found on the left hand.



(a) H1.



(b) H2.



(c) P2.

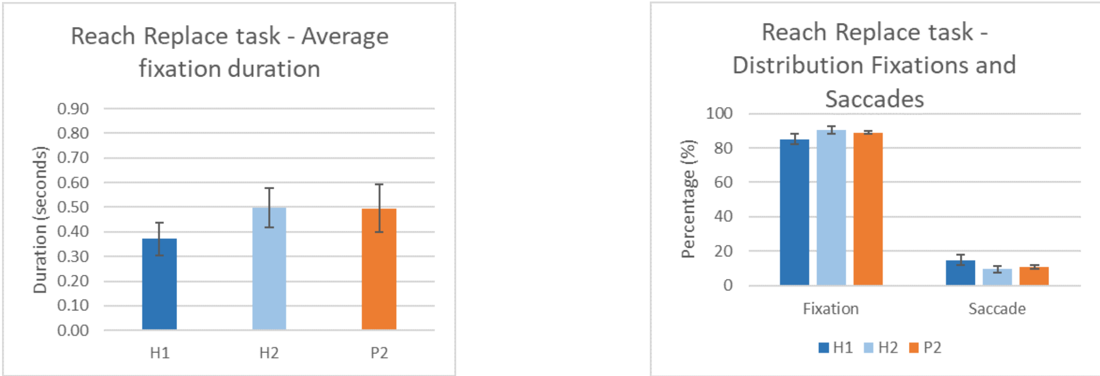
Figure 11: Heat maps of the first trial of the RR task (raw gaze data, relative duration), where red indicates a location with a lot of gaze points.

The mean total duration of the RR task, the time from start to first release and the percentages TRO, TRB and TIO gaze can be found in table 4. On average, H1 executed the task the fastest and P2 needed most time to complete the task. It took H1 less time to release the first target from the touchscreen in comparison to H2 and P2, where H2 needed the most time. %TRO and %TIO were similar for H2 and P2, where %TRO was higher for H2 and P2 than for H1 and %TIO was higher for H1 in comparison to H2 and P2. %TRB gaze was the lowest for H2.

Table 4: RR task: Total duration, time from start to first release and the %TRO, %TRB, %TIO gaze.

		H1	H2	P2
Duration (ms)	Mean	10997	13443	14290
	SD	1012	1296	1836
Time to first release (ms)	Mean	1089	2107	1722
	SD	57	901	129
%TRO		59.13	69.16	68.04
%TRB		8.21	5.73	9.18
%TIO		32.67	25.12	22.78

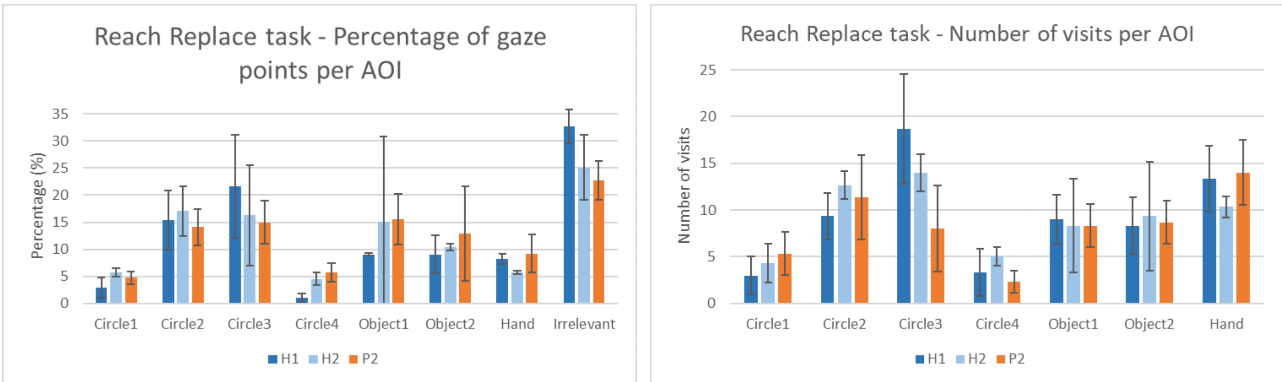
The average fixation duration during the RR tasks can be found in figure 12a. H1 showed the shortest average fixation duration, where H2 and P2 showed similar results. The distribution of fixations and saccades in time during the RR tasks are shown in figure 12b. H1 showed a higher percentage of saccades in comparison to H2 and P2.



(a) (b)

Figure 12: Average fixation duration (12a) and the distribution of fixations and saccades (12b) during the three RR tasks.

The percentage of gaze points per AOI and the number of visits (based on the raw gaze points) per AOI in the RR tasks are shown in figure 13. The gaze of all subjects was located most on the two middle circles (2 and 3) and less on circle 1 and 4. H1 showed the lowest percentage of gaze points on the objects in comparison to the H2 and P2, but the number of visits on the objects were similar for all subjects. H2 showed a lower percentage of gaze points and less visits on the hand than H1 and P2.



(a) (b)

Figure 13: Percentage of gaze points per AOI (13a) and the number of visits per AOI (13b) during the three RR tasks.

7.2.4 Bimanual task

In figure 14 the heat maps of all subjects can be found. In the heat maps can be seen that the gaze of the subjects was located most on the top of the glass and bottle objects.

(a) H1.

(b) H2.

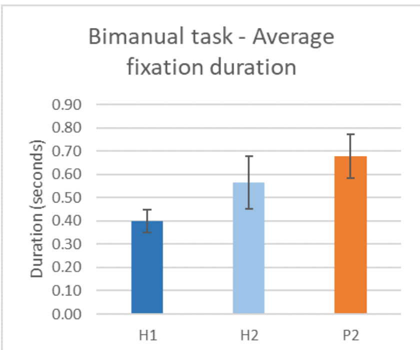
(c) P2.

Figure 14: Heat maps of the first trial of the BM task (raw gaze data, relative duration), where red indicates a location with a lot of gaze points.

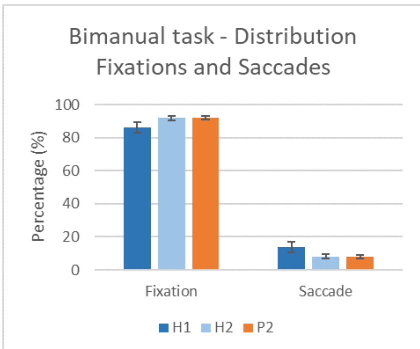
In table 5 the mean duration of the task and the percentages TRO, TRB and TIO gaze (based on the raw gaze points) can be found. The patient needed the most time to complete the task. The %TRO gaze was similar for H2 and P2, where H1 showed a lower percentage. The healthy subjects showed a higher percentage %TRB gaze in comparison to P2. H1 showed a higher %TIO gaze than the other two subjects.

Table 5: BM task: Total duration and the %TRO, %TRB, %TIO gaze.

		H1	H2	P2
Duration (ms)	Mean	9364	11500	16383
	SD	3028	732	1414
%TRO		61.25	82.11	79.28
%TRB		10.15	8.41	4.96
%TIO		28.60	9.47	15.76



(a)

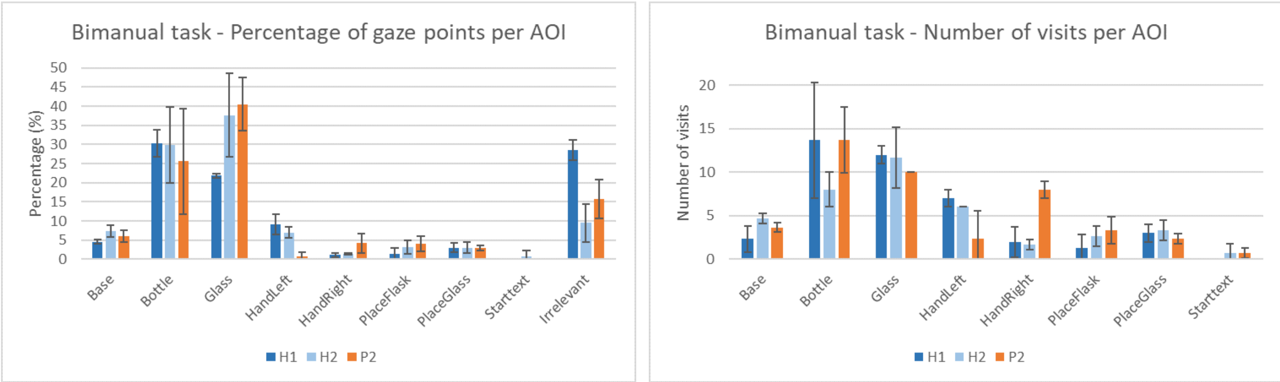


(b)

Figure 15: Average fixation duration (15a) and the distribution of fixations and saccades (15b) during the three BM tasks.

The average fixation duration during the BM tasks can be found in figure 15a. The healthy subjects showed a shorter average fixation duration than the patient. The distribution of fixations and saccades in time during the BM tasks are shown in figure 15b. H1 showed a higher percentage of saccades in comparison to H2 and P2.

The percentage of gaze points per AOI and the number of visits (based on the raw gaze points) per AOI in the BM tasks are shown in figure 16. In the percentage of gaze points on the hands can be seen that gaze was located most on the non-dominant hand. Also, most visits were found on the non-dominant hand.



(a)

(b)

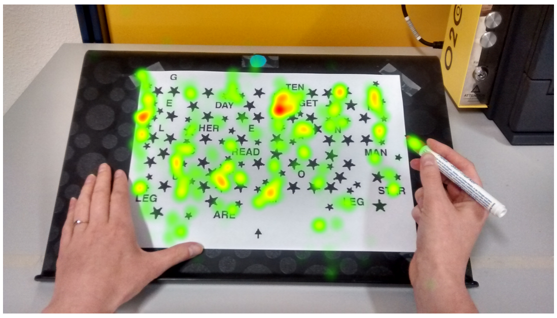
Figure 16: Percentage of gaze points per AOI (16a) and the number of visits per AOI (16b) during the three BM tasks.

7.3 Star cancellation test

The SCT results are shown for two healthy subjects and one patient. All subjects canceled all the stars, except for H2 in the SCT with head fixation where one star was not canceled. In the patient measurement without head fixation, the instruction to look at the blue dot after finishing the test was not clear or not understood. The patient canceled all the stars after about 2 minutes, however the patient kept searching until the SCT took 8 minutes. There is expected that the patient was already finished and therefore the endpoint of the last star crossed was taken for the analyzed parameters.

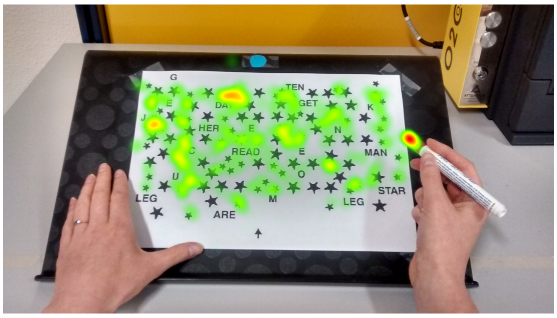
Different search strategies were found. In the SCT without head fixation, the patient (P1) started searching on the top, left of the middle and then shifted to the top right side of the SCT. The patient used an up-down search strategy, first canceling the stars on the right side of the paper, checking the right side of the paper if all stars were canceled and after that canceling the stars on the left side of the paper using a more random search pattern. After the whole SCT was checked, the last stars on the left side of the SCT were canceled. H1 canceled the stars in the SCT without head fixation starting on the top, at the right of the middle. First the stars on the left side and after that the stars on the right side were canceled. The search pattern was random. H2 canceled the first star in the SCT without head fixation on the top left side of the SCT. H2 used an up-down search strategy, first canceling the stars on the left side and after that canceling the stars on the right side of the SCT.

In the SCT with head fixation, H1 and P1 showed a slightly different search strategy in comparison to the SCT without head fixation. P1 started canceling stars in the top right corner. Notable is that the patient did not cancel the stars directly which were very close to a star which was canceled, the patient came back to this location later to cancel these stars. The patient used an up-down search pattern again from the right to the left side of the paper, with sometimes a slight deviation from the pattern. The stars on the left side of the SCT were canceled by using a more random search pattern in comparison to the right side of the paper. After the whole SCT was checked, the last two stars in the lower left corner were canceled. H1 canceled the first stars in the top right corner of the SCT. A random search pattern was used, however all stars on the right side of the SCT were canceled first, before canceling the stars on the left side of the paper. After checking the whole SCT, the last star in the middle was canceled.



(a) H1.

(b) H2.



(c) P1.

Figure 17: Heat maps (raw gaze data, relative duration) of the SCT without head fixation for both the healthy subjects and the patient, where red indicates a location with a lot of gaze points.

The heat maps (Raw gaze data, relative duration) of the SCT without head fixations for each subject can be found in figure 17. There can be seen that the borders of the spots in the heat map of the patient are less precise than those of the healthy subjects. The location of the gaze points of the healthy subject were more stable in comparison to the patient, where more shifts in gaze location were found in the patient. By looking at the heat map of the patient, there can be seen that bright colored spots are located on the left side of the paper slightly more than on the right side. In the heat map of H2 (figure 17b), not much color difference can be seen on the SCT.

In table 6 the time until the first star was crossed and the time it took to cross all the stars are given. Next to that, the number of fixations used from the start until the last star was canceled and the location of the first canceled star (start location) are given. It can be seen that it took more time for the patient to cancel all the stars and more fixations were used. Also, the healthy subjects found and canceled the first star earlier than the patient did. It took more time for the patient to complete the SCT with head fixation than without head fixation, which was not the case in the healthy subjects. In the healthy subjects, the duration of the SCT decreased the second time it was executed. For H1, H2 and P1, the SCT was executed without head fixation first.

Table 6: SCT: Times first and last star crossed, the number of fixations used until last star crossed and start locations. For the SCT with (Fixated) and without (Not fixated) head fixation.

		First star crossed (ms)	Last star crossed (ms)	Number of fixations until last star crossed	Start location
Fixated	H1	1360	30670	64	Top Right
	H2	3028	41370	58	Top Left
	P1	4598	116210	241	Top Right
Not fixated	H1	2039	33130	61	Top, right of the middle
	H2	4149	45310	72	Top left
	P1	6718	103780	212	Top, left of the middle

In figure 18 the number of stars canceled at 30, 45, 60, 90 seconds and at the end of the task are shown. From this graph can be seen that the healthy subjects finished the SCT faster than the patient. One star was not canceled by one healthy subject. In the results of the patient can be seen that the number of stars canceled at 45 seconds was lower in the SCT with head fixation than in the SCT without head fixation.

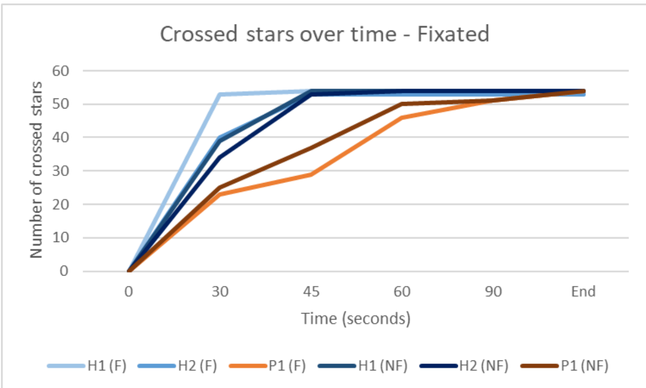
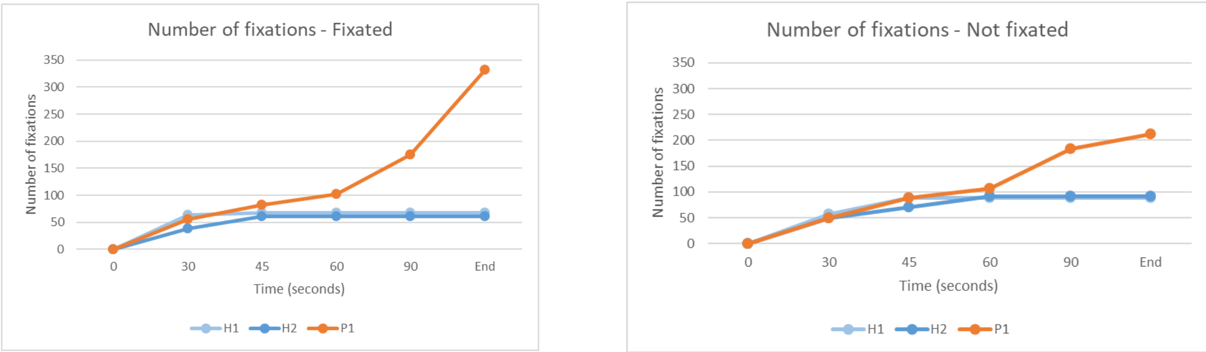


Figure 18: Number of stars canceled at different moments in time (with (F) and without (NF) head fixation).

In figure 19 the number of fixations at 30, 45, 60, 90 seconds and at the end of the SCT with and without head fixation are shown. The healthy subjects completed the SCT faster than the patient, therefore their number of fixations stays the same from 45 seconds. From 0 to 45 seconds it looks like the number of fixations over time was not very different between the healthy subjects and the patient.

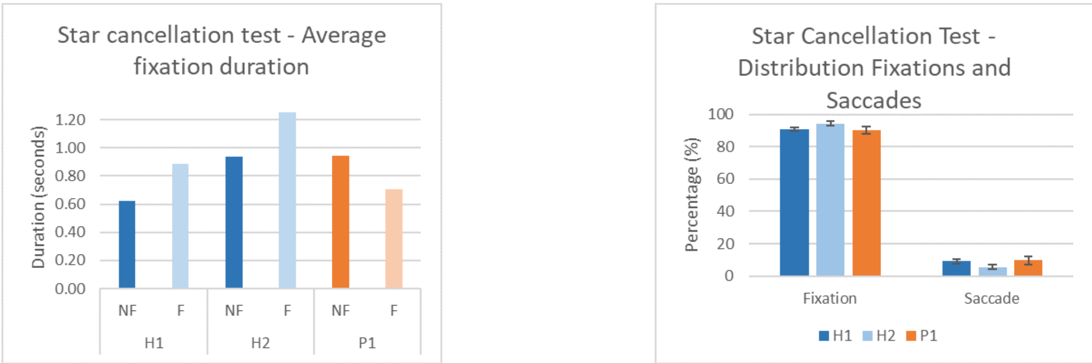
The average fixation durations in the SCT with and without head fixation can be found in figure 20a. The average fixation durations of H1 and H2 are lower in the SCT without head fixation than in the SCT with head fixation. The average fixation duration of the patient is higher in the SCT without head fixation in comparison to the SCT with head fixation. The distribution of fixations and saccades in time are shown in figure 20b. It looks like the results of the patient do not differ from the healthy subjects. However, H2 showed a slightly lower percentage of saccades in comparison to H1 and P1.



(a) With head fixation.

(b) Without head fixation.

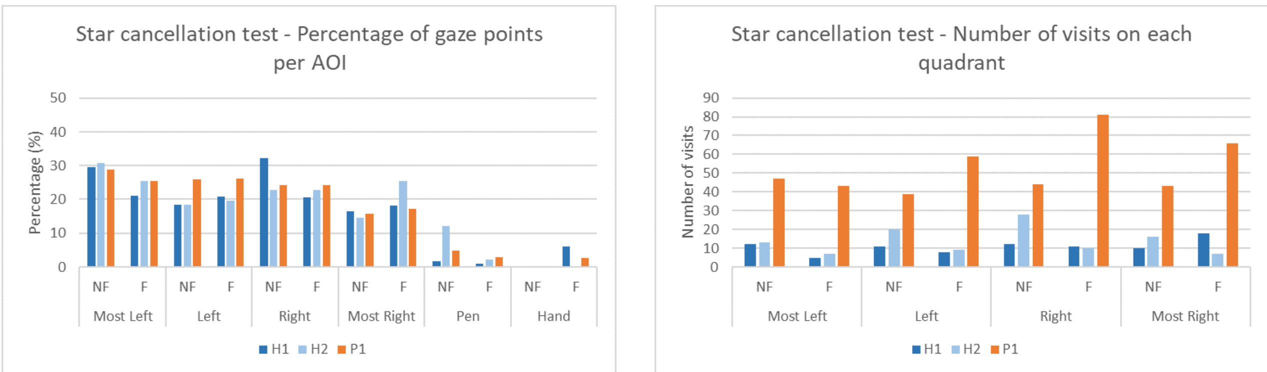
Figure 19: Number of fixations over time with (19a) and without (19b) head fixation.



(a)

(b)

Figure 20: Average fixation duration during the SCT (total duration of the test) with (F) and without (NF) head fixation (20a) and the distribution of fixations and saccades (20b).



(a)

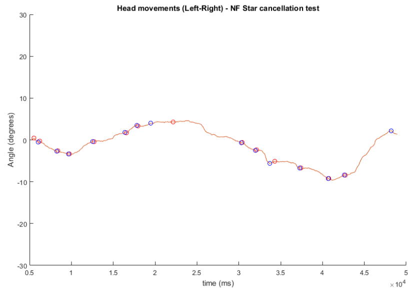
(b)

Figure 21: Percentage of gaze points per AOI (21a) and the number of visits (based on raw gaze points) per AOI (21b) for the SCT (total test duration) with (F) and without (NF) head fixation.

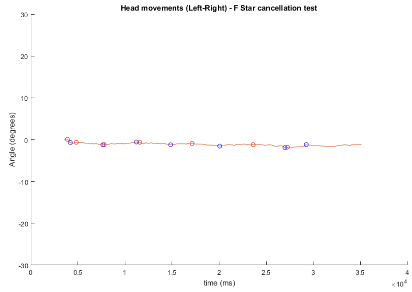
In figure 21a the percentages of gaze points per AOI of the total number of gaze points are plotted. The patient showed a higher percentage of gaze points on the left AOI of the SCT in comparison to the healthy subjects. In the patient the percentage of gaze points is higher on the left side than on the right side of the test. No gaze points were found on the hand in the SCT without head fixation. In figure 21b the number of visits on each vertical quadrant, based on the raw gaze point data, is shown. The patient showed way more visits than the healthy subjects showed. In the SCT with head fixation, the patient showed more visits on the right and most right AOI than on the left and most left AOI, however this difference was not found in the SCT without head fixation. In the SCT with head fixation, H1 and H2 showed similar results except for the most right AOI. In the SCT without head fixation, H2 showed more visits than H1 did.

7.3.1 Head movements

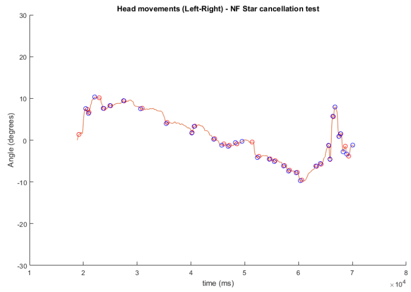
In figure 22 the head movements from left to right and right to left during the SCT with and without head fixation are plotted for all subjects (an increase in angle (degrees) is a movement to the left and a decrease in angle (degrees) is a movement to the right). It can be found that the patient made more head movements with and without head fixation than the healthy subjects did. The start and end angle deviated slightly in all subjects, where most deviation was seen in the patient.



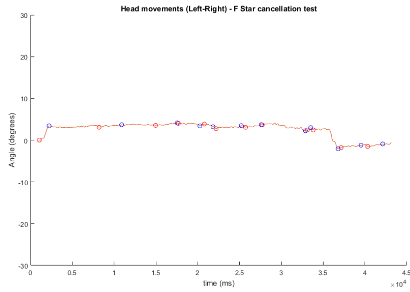
(a) H1 without head fixation (14 head movements).



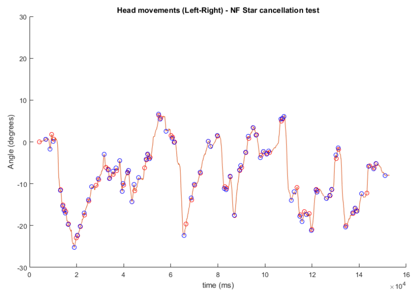
(b) H1 with head fixation (7 head movements).



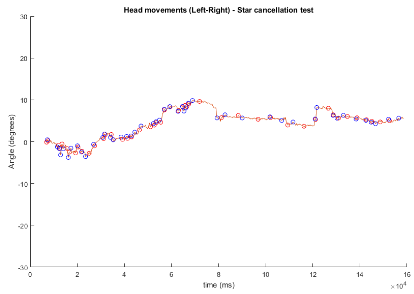
(c) H2 without head fixation (33 head movements).



(d) H2 with head fixation (12 head movements).

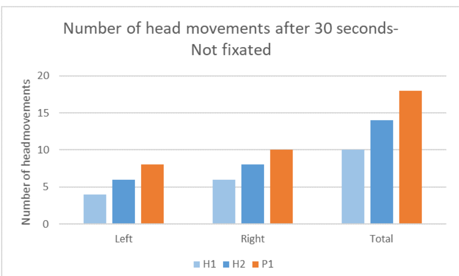


(e) P1 without head fixation (82 head movements).

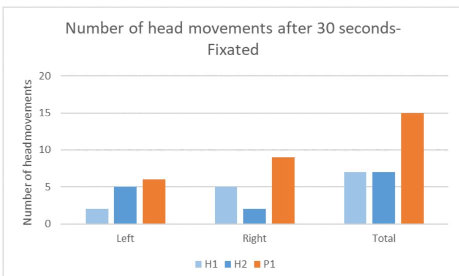


(f) P1 with head fixation (48 head movements).

Figure 22: Integrated gyroscope Y data (head rotation from left to right and right to left), angle (degrees) over time. Head movement detection for all subjects without (21a,c,e) and with (21b,d,f) head fixation. A red circle indicates the start of a head movement where a blue circle indicates the end of a head movement.



(a) Without head fixation.



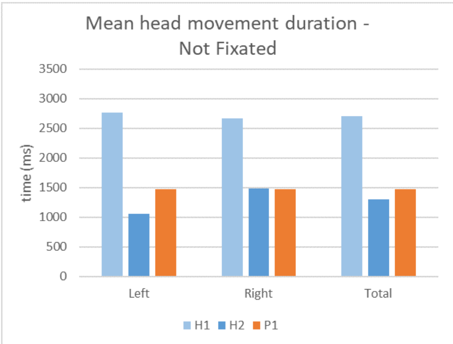
(b) With head fixation.

Figure 23: Number of head movements to the left, to the right and in total, during the first 30 seconds of the SCT without (22a) and with (22b) head fixation.

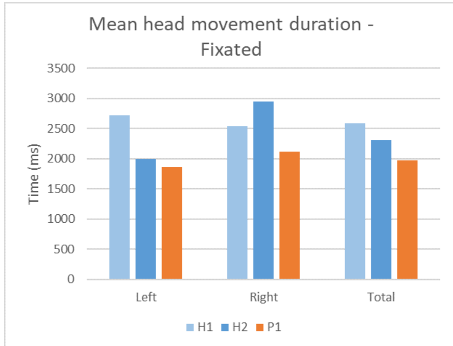
The number of head movements to the left, to the right and in total during the first 30 seconds of the SCT can be found in figure 23. In the SCT without head fixation, all subjects used more head movements to the right. In both the SCT with and without head fixation, the patient made the most head movements.

The mean head movement duration for both the SCT with and without head fixation can be found in figure 24(a,b). In the SCT without head fixation, the head movement durations of H1 were longer than those of H2 and P1, which were more similar. In the SCT with head fixation, the durations of the head movements of H2 and P1 lay closer to those of H1. For H1 the head movement durations of the SCT with and without head fixation were similar. In the SCT with head fixation, the patient showed the shortest head movements in comparison to the healthy subjects.

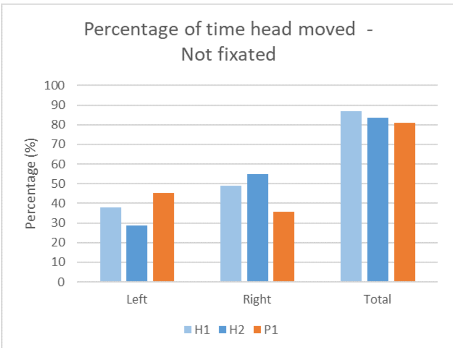
The percentage of time the head was moved during the SCT with and without head fixation can be found in figure 24(c,d). The total percentage of head movement decreased when the head was fixated in comparison to the SCT without head fixation. In the SCT without head fixation, the patient showed a higher percentage of head movement to the left and a lower percentage of head movement to the right in comparison to the healthy subjects. In the SCT with head fixation it can be seen that H1 showed a higher percentage of head movement to the right and a lower percentage of head movement to the left in comparison to H2 and P2.



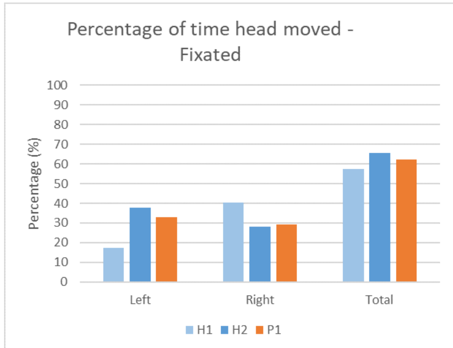
(a)



(b)



(c)



(d)

Figure 24: Mean duration of head movements to the left, to the right and in total (23a,b) and percentage of total time the head was moved to the left, to the right and in total (23c,d).

The mean rotation angle (degrees) per head movement can be found in figure 25. In the SCT without head fixation the rotations of the head were larger than in the SCT with head fixation. In the SCT without head fixation the patient showed the largest angle of rotation per head movement, where in the SCT with head fixation the angles of rotation were more similar for all subjects (slightly smaller for H1).

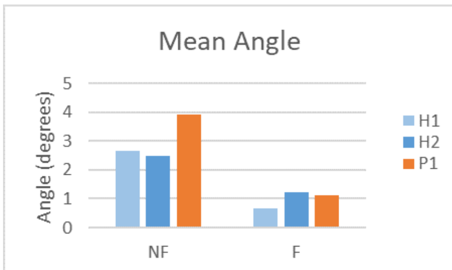


Figure 25: Mean rotation angle per head movement in the SCT with (F) and without (NF) head fixation.

8 Discussion

During this master thesis, the first steps were taken in the fundamental research into gaze behavior in stroke patients during reach and grasp tasks. Next to that, the first steps were taken in the research into the distinguishing parameters of USN in the SCT, to distinguish USN more sensitively using the SCT. The goals of this master thesis were to find the valuable and obtainable parameters, to prepare the measurements and to assess the feasibility of the measurements and the analysis. For this purpose, the personalized simulated reach and grasp tasks were programmed, touchscreen compatible objects were built, a way to reduce head movements was found and an eye movement (fixation) and head movement detection method was obtained. After the measurements were successfully prepared, 7 healthy subjects and 3 patients were measured, where the data of 2 healthy subjects and 2 patients were analyzed during this master thesis.

8.1 Parameters

First, a list of parameters which should be possible to obtain and would be valuable to the observational research was made. After the measurements, it was found that a lot of these parameters were possible to obtain except for the parameters involving fixations on the AOIs. To obtain the fixation data on each AOI, the raw gaze points should be mapped from the video into an image where all components during the measurement are present (a snapshot). It is assumed that, when the gaze points of a fixation shifted in location over time, and crossed a border of an AOI, the software selects a fixation location in between the AOIs (in the snapshot) visited in the fixation. When the AOIs are not close to each other in the snapshot, the location in between these AOIs might be a completely other AOI than visited in the fixation. For example, a fixation on the left hand was found where the left hand was not present in the video at all. For this reason, the fixations on the AOI data is invalid.

Instead of the percentages TRO, TIO and TRB gaze by using the fixations and the percentages of fixations on the AOIs, the percentages TRO, TIO and TRB gaze by using the raw gaze points and the percentages of raw gaze points on the AOIs were found. In this way, it is still possible to find what percentage of the time gaze was located on the AOI, only the information about if the subject was fixated (taking up information) on the AOI is missing. However, these parameters will still give insight into the gaze behavior by indicating where a subject was looking at during the task.

In previous research in healthy subjects, wearable eye trackers were used in 3D situations as well. In a research by Pelz and Canosa into the gaze behavior during hand washing and filling a cup with water, a wearable eye tracker was used. [37] The parameters found were the fixation duration, the fixation locations and the amplitude (degrees) of the saccades. [37] These parameters were found manually, by analyzing the video data frame by frame, which must have cost a lot of manual labor. The fixations were defined as a stationary period of the pupil of 33.4 ms, which is subjective because this data was manually obtained. In another research, by Land et al., gaze was investigated while making tea. [38] A wearable eye tracker was used from which the number of fixations, their locations and the fixation duration were obtained. Also the saccade amplitude (degrees) and duration were found. Their definition of a fixation was not described. By using the AOIs in the snapshot in the Tobii Pro Lab software a lot of parameters can be found by mapping the gaze points onto the snapshot. Once this is done, most of the parameters (except for the fixations on the AOI data), can be obtained directly from the software which decreases the amount of manual labor in comparison to the the research by Pelz and Canosa and the research by Land et al. The heat maps and the %TRO, %TRB, %TIO gaze and the number of visits on each AOI parameters were obtained in this master thesis, but not in both previous researches.

8.2 Reach and grasp tasks

Reach and touch task

The reach and touch task was executable by the healthy subjects and the patient. In the reach and touch task, the subject had to touch the start button, after which a red target appeared which had to be reached and touched. After this the start button had to be touched again and a new target appeared.

In a research by Gao et al. a longer movement duration in a pointing task by using the affected hand in comparison to the unaffected hand was found in stroke patients. [23] In the results of the reach and touch task in this master thesis, the duration of the patient was found to not be the longest. However, the impairment level of the included patient was not high. When more healthy subjects and patients will be added, a longer duration in the patient group might be found. A higher %TIO gaze was found in H1 in comparison to H2 and the patient and might be explained by the waiting location of gaze for the next target to become red. The waiting location of H1 was located in the middle (a TIO) where the waiting location of H2 and the patient was located on or around the start button (a TRO). H1 executed the task the fastest, which might be related to this waiting location. Gaze was located closer to the targets when the waiting location was in the middle in comparison to the waiting location on the start button. This decreases the distance gaze needs to be shifted from the waiting location to the red target. By looking at the percentages of raw gaze points on the AOIs, it can be seen that, in all subjects, gaze was located on the circles on the right and left side less than on the circles in the middle. A possible explanation for this might be that the hand was often in front of the circle targets on the left and right, where the gaze points were mapped on the hand instead of on the circle in the snapshot. H2 showed more visits on the circles on the left and right side, however no clear difference in percentage of gaze points was found between the subjects. This might be because in H2, gaze shifted between the hand and the circle which caused multiple visits, without a higher percentage of gaze points. The lowest percentage of gaze points on the hand was found in the patient, which might indicate that the patient did not visually guide the hand during the task.

Reach and lift task

Both healthy subjects and the patient were able to execute the reach and lift task. In this task, four objects were placed on four circles on the touchscreen. The subjects were asked to first touch the base, after which a circle underneath an object turned red. This object had to be lifted and placed back again, after which the base should be touched and the next target would turn red and so on.

In H2, before grasping, gaze was located often where the thumb would touch the object, which was also found by Johansson et al. [21] In the results of the patient can be seen that the colored spots in the heat map of the patient are distributed over a larger area on the white in between the objects in comparison to the heat maps of the healthy subjects, which can also be recognized in the higher %TIO gaze in the patient. The patient showed a lower average fixation duration and a higher percentage of saccades in comparison to the healthy subjects, this might indicate that the patient used more but shorter fixations than the healthy subjects did. In general, higher percentages of gaze points were found on the middle two circles and objects in comparison to the left and right circles and objects, this might be because the hand shifted in front of the circles and objects on the left and right side, causing the raw gaze points to be mapped on the hand instead of on the circles. In the patient, the number of visits on the circles decreased from the left to the right circle. This might be due to shifts in location of gaze points just over the edge of the AOIs of the circles, which happened most on the left side. This might have been caused by a bad calibration or a skewed positioning of the eye tracker on the head.

Reach and replace task

The reach and replace task was executable by the healthy subjects and the patient. In this task, four circles were present and two objects were placed on two circles on the touchscreen. After starting the task, 2 circles turned red. The object with the red circle underneath it should be reached, grasped and replaced to the empty red circle. After this the next two circles turned red. Some subjects, especially the patients, mentioned to have some difficulty with the indication of which objects should be replaced and where an object should be replaced to. There might be looked into another way to indicate which object should be replaced to which location. One patient grasped the objects alternately most of the time. This caused that sometimes the wrong object was grasped and replaced because a couple of times the same object had to be replaced twice in a row.

Before grasping, gaze was sometimes located at the location where the thumb would touch the object, as was found by Johansson et al. [21]. Gaze was located most on the middle two circles as can be seen in the heat maps and in the percentage of gaze points. It was observed that on these circles the subjects waited most for the next targets to show. In a study by Johansson et al. was found that in object manipulation, no fixations were located on the hand in healthy subjects. [21] In the results of this master thesis, there were gaze points found on the hand in all subjects, however there cannot be said if the subjects fixated on the hand. The gaze of the patient was located on the hand more in comparison to the gaze of the healthy subjects. A higher percentage of raw gaze points on the hand and a higher percentage TRB gaze was found in the patient than in the healthy subjects, however the difference between the patient and H1 is not large. Next to that, a bright green colored spot can be found on the left hand (affected side) in the heat map of the patient. The patient executed the task the slowest. The patient mentioned that the task had a large cognitive load, which might explain the longer duration in the patient because in a task with a large cognitive load, more working memory needs to be used. [39] The working memory of the patient might be impaired because memory dysfunction is often seen in stroke patients. [40]

Bimanual task
The bimanual task was executable for all subjects. In this task, rice was poured from a bottle into an empty glass. After the task was started, the cap should be taken off the bottle, the rice should be poured into the glass, and everything should be placed back into their original position where the cap was placed back on the bottle.

In a research by Kantak et al. was found that the bimanual coordination of stroke patients was impaired and that stroke patients needed more time to execute bimanual tasks in comparison to healthy controls. [41] This might be recognized in the results in this master thesis, where the patient needed more time to execute the bimanual task in comparison to the healthy subjects. Among others, the impairment in the bimanual coordination might have made the task more complicated to execute for the patient. In a previous research by McCormick et al. was found that in a more complicated task, the fixation duration in action execution and action observation was longer. [42] In the results in this master thesis this might be recognized in the longer average fixation duration during the bimanual task in the patient in comparison to that of the healthy subjects. The found percentages of gaze points on task relevant and task irrelevant objects can be recognized in the heat maps. Often the gaze of H1 was located just next to the object, where the gaze point was mapped on the wall, which might explain the higher %TIO in comparison to the other subjects. The %TRB gaze is the lowest in the patient in comparison to the healthy subjects, which might indicate that the patient did not visually guide the hands. For all subjects, gaze was located more on the non-dominant than on the dominant hand. This might indicate that the non-dominant hand might needed more (visual) guidance to execute the task.

8.3 Star cancellation test

The SCT is a diagnostic tool for USN. Possible distinguishing parameters for USN were investigated which might provide a way to diagnose USN more sensitively by using the SCT. The SCT was executed twice for each subject, once with and once without head fixation. A notable observation is that different start locations and search strategies were found between the subjects. In a research by Behrmann et al., the mean start location of a visual search experiment in left USN patients was found to be located on the right of the middle, where healthy subjects started on the upper left corner. [16]

Notable is that the borders of the colored spots in the heat map of the patient are less precise in comparison to those of the healthy subjects. During the analysis was found that gaze shifted more in location over time in the patient in comparison to the gaze of the healthy subjects. Also, in the patient was seen that stars which were located close to a star which was canceled, were not directly canceled, where in the healthy subjects was seen that gaze stayed at a certain location and the surrounding stars were canceled. This might all indicate that the patient used the periphery sight less than the healthy subjects did. This might be due to an impaired peripheral vision as found in a research by Fisk et al., where an impaired peripheral vision was found in stroke survivors in comparison to the healthy controls. [43] In total, the patient showed a lot more visits than the healthy subjects did, this is related to the longer duration of the SCT in the patient. However, the more shifts in gaze location in the patient might have increased the number of visits in the patient as well. More visits but not a higher percentage of gaze points was found on the right and most right AOIs in comparison to the left and most left AOIs in the SCT with head fixation results of the patient. The patient checked the SCT on the right side, where gaze location shifted a lot over the border of the right and most right AOI, which might explain the higher number of visits. The patient used more time and more fixations to finish the SCT, where the higher number of fixations is related to the longer duration. The number of fixations over time were analyzed. No clear differences were found between the two healthy subjects and the patient, which might indicate that not more fixations over time were made by the patient in comparison to the healthy subjects. In a previous research more eye movements were found during the SCT in stroke patients, who might suffer from USN, than in healthy controls. [17] However, there was not corrected for the longer duration of the SCT in the patient group in comparison to the healthy subjects. In the results of the patient, who was not diagnosed with USN, a higher percentage of gaze points was found on the left side than on the right side of the test. This can also be recognized in the heat map of the patient. In a research of Behrmann et al. into visual search in left USN patients, less fixations were found on the left side in comparison to the right side in a visual search experiment. [16]

When looking at the differences in the results between the SCT with and without head fixation there can be found that in the patient, the duration of the SCT was longer with than without head fixation, which was not the case in the healthy subjects. Also, the number of stars canceled at 45 seconds was lower with head fixation than without head fixation in the patient. This might be an indication that the patient used compensatory head movements to finish the SCT without head fixation, however the patient was not diagnosed with USN. For both healthy subjects, the second time the SCT was executed had a shorter duration. For this reason, it is important to randomize the order in which the SCTs are executed between subjects (first with or first without head fixation). The average fixation duration of both healthy subjects was lower when the head was not fixated than in the SCT with head fixation. This is not the case in the patient, where the average fixation duration was longer in the SCT without head fixation than in the SCT with head fixation. It might be that the healthy subjects used their periphery sight more when the head was fixated, where the peripheral vision might be impaired in stroke patients. [43]

Head movements
In the integrated gyroscope data was found that the patient made more head movements in comparison to the healthy subjects during the SCT, which can also be seen in the number of head movements during the first 30 seconds of the SCT. This can be an indication that head movements were used as a compensatory strategy, however the patient was not diagnosed with USN. It was observed that the patient used more head movements overall, for example during talking, which might explain the higher number of head movements. Movement disorders are a known problem after stroke, which might have caused the higher number of head movements. [44]

The percentage of head movement in time was lower in the SCT with head fixation than without head fixation for all subjects, also the mean angle of rotation is smaller in the SCT with head fixation than in the SCT without head fixation. This indicates that the freedom of head movement was limited by the head fixation system, however head movements were not excluded. A higher percentage of head movement in time to the left and a lower percentage to the right was found in the patient in comparison to the healthy subjects. If the patient was diagnosed with USN this might have been an indication of compensatory head movements, however the patient was not diagnosed with USN. In the SCT without head fixation the patient did not show the longest head movement duration, but did show the largest mean angle of rotation. This indicates that the patient must have used a higher rotational velocity in comparison to the healthy subjects. An analysis into the average rotational velocity might give extra insight into the way the head was moved during the SCT.

8.4 Limitations and future research

Study population
In the analysis in this master thesis, only two healthy subjects and two patients were included. This study population is too small to draw conclusions about the research questions of the whole observational study. However, it does give insight into the parameters which can be obtained and analyzed and it gives insight into the functioning of the measurement method and the analysis. The inclusion of patients for both parts of the study together was found to be difficult. When a stroke patient suffers from USN, the patient often suffers from severe motor and sensory impairments as well, which might make the execution of the reach and grasp tasks impossible. Next to this, the duration of the total measurement is very long, 2 to 3 hours, which costs a lot of energy. A possible solution for this is to divide the measurement into parts. In future research, more subjects should be included and the already measured data should also be included in the analysis.

Eye tracker
The advantage of the Tobii Pro Glasses 2 eye tracker is that it is wearable and a gyroscope is integrated which makes data synchronization easy. The accuracy of the eye tracker is satisfactory. Only when the eyes rotate to the corners of the glasses, it is harder for the eye tracker to find the direction of gaze. It was found that it is hard to calibrate the eye tracker well when the head is fixated, because the eyes will rotate to the corners of the glasses to be able to see the calibration dot. For this reason, the accuracy was a bit lower during the SCT with head fixation in comparison to the SCT without head fixation, which might have influenced the results. In the last measured subjects, the calibration was executed outside the head fixation system, after which the subject carefully (the glasses should not move) took place in the head fixation system. In this way, the eye tracker can be calibrated better in comparison to when the calibration takes place when the subject already took place in the head fixation system.

The eye tracker measures in 3D, which brings some difficulties in comparison to a 2D eye tracker. The head, and there with the glasses, move and next to that the objects move, where in 2D eye tracking the location of the eye tracker is constant. This makes it hard for the 3D eye tracker to detect the fixations, by using the angular velocity of the eyes relative to the glasses. If the study was split into two parts, the reach and grasp and the SCT part, there might have been looked into the usage of a 2D stationary eye tracker placed on top of a vertically placed touchscreen to execute the SCT on. In this way, the eye tracker and the SCT would be on a set distance from each other and the eye tracker would not move.

Fixation detection

At this moment there is no proper method known to find the fixations by using a wearable eye tracker. The I-VT Fixation filter in the Tobii Pro Lab software was not developed for the wearable Tobii Pro Glasses 2. [45] The fixation filter calculates the fixations by using the angular velocity of the eyes relative to the glasses. This means that when an object, where the subject is fixated on, is moving, the eyes will move relative to the glasses and the fixation will not be recognized. Another case is when the head moves while the subject is fixating. The eyes will move relative to the glasses and the fixation will not be recognized. The I-VT Fixation filter only uses the angular velocity of the eyes relative to the glasses. When the head movement data (gyroscope and accelerometer) and the video data would be added in the fixation detection method, there is a possibility that a better method to find the fixations by using the wearable eye tracker could be found. Next to that, there might be looked into the fixation detection by using frequency analysis. There should be investigated what the frequency of the eye movements is during a head movement and what the frequency of the eye movements is while being fixated and not fixated. These frequencies can then be found in the frequency analysis of the eye movements during the tasks.

A custom I-VT filter in the Tobii Pro Lab software was used in this master thesis. Most of the time, the filter found the same fixations as found by counting them from the video, a few differences were found which mostly could be explained. Most errors in the fixation detection are expected in the tasks where the objects move a lot and are followed by the eyes or when the head is moved a lot while being fixated. A different threshold was used in the custom I-VT filter for the reach and grasp tasks and for the SCT. This indicates that fixation detection is dependent on the task to be executed, which should be taken into account when finding a fixation detection method in the future. The Tobii Pro Lab software contains several steps in the I-VT filters which are not accessible and explained to the user. In the future there might be looked into writing software to detect the fixations, to be able to set the steps in the fixation detection and to make fixation detection task specific.

Mapping onto a snapshot

To get most of the parameters, the locations of all raw gaze points need to be manually mapped onto a snapshot, which brings a manual error into the results. It was not always easy to find the exact location of gaze from the video in the snapshot. For example, in the bimanual task it was hard to find if a gaze point should be mapped on the glass or on the bottle (which are located far from each other in the snapshot) when the subject was pouring the rice from the bottle into the glass. However, if the location of the gaze point is not close to a border of an AOI, a small deviation will not influence the numerical results, but it will influence the heat map.

Fixations on the AOIs

As it is now, the fixations on the AOIs found are not valid as explained before. If the fixations on the AOIs could be reliably found, more information about information uptake while looking at an AOI could be gained. Therefore, in future research, there should be looked into how the fixations on the AOIs can be found. A way to possibly find the fixations on the AOIs might be by using the start and stop times of the fixations and looking up the corresponding moments in the video data to find where the subject was fixated on. Another possibility might be to not map the raw data but the data filtered by using the custom I-VT filter. In this way only the fixations need to be mapped onto the snapshot. The difficulty with this is that the fixation might be long and shifting over multiple AOIs, where only one moment in the fixation is shown in the video in the software to be mapped. This makes it hard to indicate where the fixation was located.

It was assumed that the fixations on the AOIs are now calculated in the Tobii Pro Lab software by taking a location in between the AOIs on which raw gaze points were mapped in the snapshot during the fixation. These AOIs might be close to each other in the video, but far away from each other in the snapshot, resulting in fixation locations on AOIs on which no gaze points were located during the fixation. In future research, there might be looked into the possibility to write software where the percentage of gaze points on each AOI for every fixation will be found. In this way, the software does not draw conclusions about on which AOI the fixation was located.

Reach and grasp tasks programmed in Java

The reach and grasp tasks executed on the touchscreen were programmed in Java. All subjects were able to perform the programmed tasks without problems, however there is thought there might be some problems when patients with a higher level of impairment than the patient included in this master thesis perform the tasks. For example, USN patients might not find the targets on the neglected side or not relevant objects might be pushed over or be dropped by stroke patients with more severe motor and sensory impairments.

Star cancellation test and head fixation system
It might be interesting to find out if a star was always canceled when a fixation was located at this star. This will indicate if the star was not canceled because no fixation was located on the star or if there was fixated on the star but the information was not processed well. During the SCT in the healthy subjects, the subjects were already able to see the test during calibration, which might have given them an advantage in the test.

In the head movement results during the SCTs was found that head movement was limited but not excluded by using the chin rest. The head fixation system might be improved by putting a strap around the head and the chin rest, however this might be bothersome to the subject.

Head movement detection
There is no formal definition of a head movement known. Therefore, the head movement detection is based on assumptions. Manual input was sometimes needed because the method did not find all the head movements for some measurements, due to many peaks in the data. This causes a manual error. It looks like there are still a few degrees of drift (a different start and end angle) present in the head movement angle over time data, which might have influenced the found head movements. However, this drift might partly be due to the collaboration of the eyes and head to direct gaze. Gaze was located at the blue dot at the start and at the end of the SCT. However, the head could be positioned in a different angle at the start than at the end of the SCT, because the eyes can rotate as well to obtain a certain gaze location. The head and eye movements were plotted together to explain part of the drift found. Another possibility to explain the drift is the drift measurement (looking at the blue dot). The amount of drift removed is affected by the amount of movement of the head during the drift measurement. In future research there might be looked into the removal of the remaining drift.

9 Conclusion

During this master thesis, the first steps have been taken in the fundamental research into gaze behavior in stroke patients and finding distinguishing parameters for USN during the SCT. The measurement method was set up and promising results were found. A lot of the valuable parameters to answer the research questions of the whole observational research can be obtained, only the parameters using the fixations on the areas of interest data are not obtainable at this moment. The measurements and the corresponding analysis are feasible in terms of executability and usability. The next step will be to include more patients and healthy subjects in the analysis, to be able to draw solid conclusions in the whole observational research with the goal to map the gaze behavior in stroke patients.

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A Appendix: Fixation Detection

In the Tobii Pro Lab software, filters are available to distinguish the different eye movements. These filters are the I-VT (Velocity Threshold) Attention filter and the I-VT Fixation filter. These filters distinguish eye movements according to the rotational velocity of the eyes, this rotational velocity is calculated by using the Gaze Position 3D coordinates. A threshold is set, where a velocity lower than the threshold indicates a fixation and a velocity higher than the threshold indicates a saccade. Several steps are included in the I-VT filters: Gap fill- in by interpolation, noise reduction by a moving median filter, merging fixations which are close to each other and discarding short fixations. [45] Smooth pursuit movements and the vestibular ocular reflex are not classified by the I-VT Fixation filter (threshold of 30 degrees/second), but fixations and saccades are. By using the I-VT Attention filter (100 degrees/second), eye movements are not separated, only attention can be studied. The data which is said to be a fixation, will also contain other eye movements. [45]

After the test measurement, some unexplained results were found. A clear fixation in the video was not detected by the I-VT Fixation filter. There was looked into how the filters in the Tobii Pro Lab software work and there was found why the fixation was not detected. But, also found in the manual of the Tobii Pro Glasses 2 was that the I-VT Fixation filter in the Tobii Pro Lab software was not developed for the wearable eye tracking glasses, but for the static Tobii eye trackers. They stated that the fixations data from the wearable eye trackers using this filter is "more or less incorrect". [45]

After contacting Tobii, they recommended us to use the I-VT Attention filter. The I-VT filters in the Tobii Pro Lab software work with the angular velocity of the eyes relative to the glasses. The difference between both filters is that the I-VT Fixation filter uses a velocity threshold of 30 degrees/second where the I-VT Attention filter uses a threshold of 100 degrees/second. Both filters were not designed to find the fixations in the data from the glasses. When for example a subject is fixated on a cup and then moves the cup but stays fixated, the eyes move relative to the glasses, where the fixation will not be recognized as one. The same goes for a head movement, when a subject is fixated on for example a cup while moving the head, the eyes will move relative to the glasses, which causes the fixation to not be recognized. Therefore, there was searched for another way to find the fixations from the eye tracker data, either by setting another angular velocity threshold (using a Matlab script) or by using the snapshot data. Next to that, the fixations were counted from the video.

The following fixation detection methods were compared.

1. Counted fixations from the video with the raw gaze points
2. Tobii Pro I-VT Fixation filter (threshold 30 degrees/second)
3. Tobii Pro I-VT Attention filter (threshold 100 degrees/second)
4. Angular velocity threshold from RAW gaze data (30 degrees/second)
5. Angular velocity threshold from RAW gaze data (100 degrees/second)
6. Snapshot Gaze X and Gaze Y pixel data

A.1 Counting the fixations from the video data

The gaze points are visualized in a video from the eye tracker. There was subjectively looked at when a fixation takes place in the video data. The start and end times of the fixations were saved. The short fixations (shorter than 60 ms, as in the Tobii Pro Lab filters) were discarded and fixations which were closer than 20 ms or less to each other were merged (minimal duration saccade in reading). There is assumed that during the SCT the eye movements resemble those in reading. Therefore, 20 ms seems like a safe choice to merge fixations. If this time is set longer, fixations which are present quickly after each other might be seen as one larger fixation.

A.2 Snapshot Gaze X and Gaze Y pixel data

The data mapped on the snapshot (Gaze X and Gaze Y data in pixels) was used to try to find the fixations during the tasks. A range (a circle with a certain amount of pixels) was set in which the coordinates should stay in a certain amount of time, to be indicated as a fixation. All data points inside a circle with a radius of a certain amount of pixels around the data point of interest were put into a matrix. This was done for every data point. For this, the distance formula was used:

$$Distance = \sqrt{(X(i+1) - X(i))^2 + (Y(i+1) - Y(i))^2} \tag{A.1}$$

All data points in each matrix were discarded which did not meet the following criteria:

1. Data point in the matrix should be later in time than the data point of interest
2. The data points should be consecutive to the data point of interest

The number of fixations was found by looking at the content of the matrices. If for example data point 1 has consecutive data points from 2 to 65, 66 becomes the next data point to look from for a fixation and so on. Fixations with less than 20 ms in between were merged and short fixations were discarded (shorter than 60 ms). The fixations were calculated using thresholds ranging from 10 to 150 pixels in steps of 10 pixels and compared to the fixations found by counting the fixations from the video. The results can be found in figure 26. With an increasing pixel threshold, the amount of time in between the found fixations decreases. By using a threshold between 70 and 90 pixels, the most fixations found by counting the fixations from the video were found in the snapshot results. The results of the threshold of 80 pixels looked most like the counted fixations. Therefore, the snapshot results by using the threshold of 80 pixels were compared to the other fixation detection methods. The gaze points were manually clicked into the snapshot, therefore manual errors could have been made which affect the results.

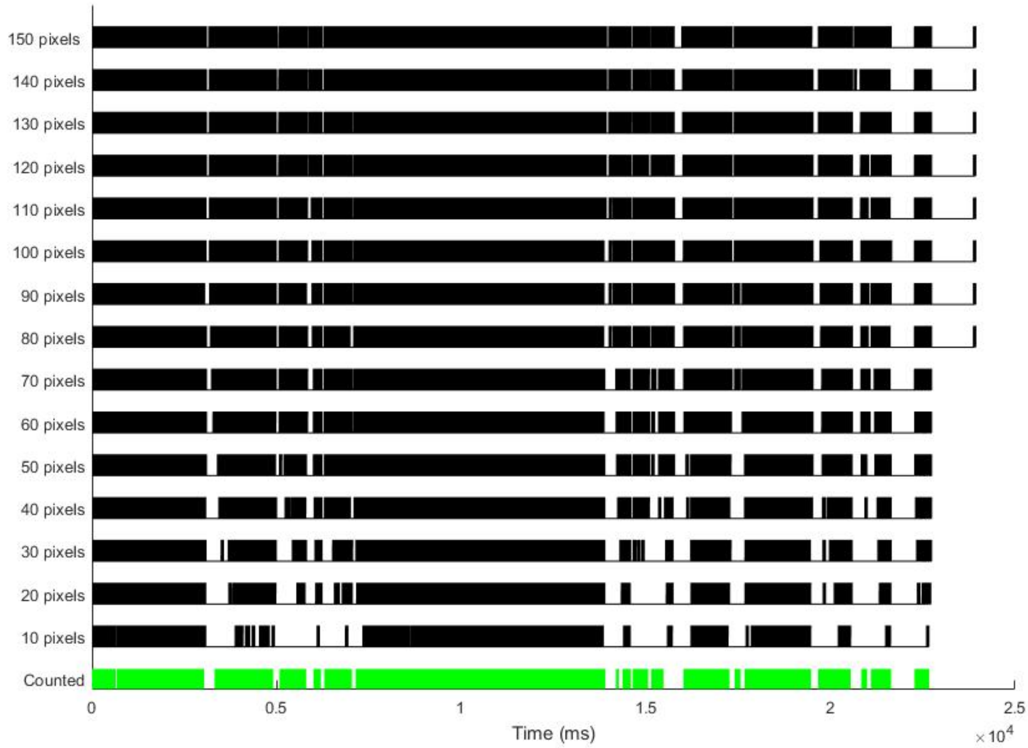


Figure 26: Fixations (black) found over time by using the snapshot data. Results were compared to the counted fixations from the video.

A.3 Angular velocity threshold from RAW gaze data

A script in Matlab R2016a was written which calculates the angular velocity over time from the combined (both eyes) 3D gaze position points. The angle between the vectors of two consecutive 3D gaze data points was calculated over a certain time, which gives the angular velocity. The same thresholds were set as in the I-VT filters, 30 degrees/second and 100 degrees/second, to find the fixations. A minimal fixation duration was set to be 60 ms (as in the I-VT filters), discarding short fixations. If fixations were closer than 20 ms or less to each other, the fixations were merged. By using this calculation, there was investigated if the fixations found with the I-VT Fixation filter and the I-VT Attention filter corresponded with the fixations found with the angular velocity threshold script with a threshold of 30 degrees/second and 100 degrees/second respectively. In this way a feeling for what the I-VT filters do exactly could be gained.

In the calculation with the 100 degrees/second threshold, 20 fixations were found by using the angular velocity threshold script. By using the Tobii Pro Lab software (I-VT Attention filter) 21 fixations were found. By changing the threshold to 30 degrees/second, the number of fixations found was 25 by using the script and 25 by using the Tobii Pro Lab software (I-VT Fixation filter). This numbers lie very close together or are the same, however the times in which the fixations start and end were sometimes deviating. Deviations might be explained by the extra steps included in the I-VT filters.

A.4 Comparison fixation detection methods

The results of all six fixation detection methods can be found in figure 27.

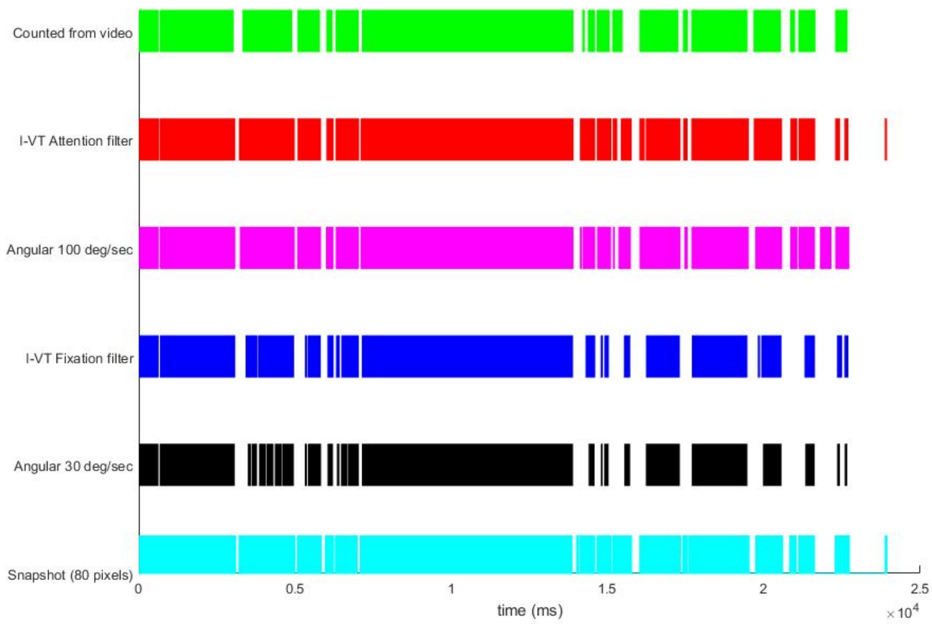


Figure 27: Fixations found over time for all fixation detection methods.

In comparing all six methods, it was found that the fixations found with the snapshot lay very close to each other in time and therefore the durations of the fixations found were not the same as in the fixations counted from the video. The other methods resembled the counted fixations better and therefore the snapshot method was not used for the fixation detection. Comparing the Tobii I-VT Attention filter and I-VT Fixation filter results to the counted fixations in the video, there was found that in some time intervals the I-VT Attention filter matched the counted fixations in the video better and in other time intervals the I-VT Fixation filter matched these better. Differences were found between the I-VT Fixation filter and the Angular threshold of 30 degrees/second results and the same goes for the I-VT Attention filter and the Angular threshold of 100 degrees/second results. There were some steps in the I-VT Fixation and Attention filter which were not built in the Angular threshold scripts, which might explain these differences. These steps are low pass filtering the velocity (noise reduction) and next to that, the time between fixations for merging was set to 75 ms in the Tobii Pro Lab filters, where in the calculations this value was set to 20 ms. [46]

There was chosen to calculate the fixations with angular velocity thresholds (by using Matlab) of 30, 40, 50, 60, 70, 80, 90 and 100 degrees/second and to compare these with the counted fixations from the video (figure 28). With this data a fixation filter with a custom angular threshold could be found and used in the Tobii Pro Lab software. There was investigated which angular velocity threshold gives results which are most comparable to the counted fixations from the video. The small fixation found in the video at about $1.74 * 10^4$ ms was found by the angular threshold filter with a threshold of 70 until 100 degrees/second. The threshold of 100 degrees/second showed an extra fixation at the end of the measurement ($2.18 * 10^4$ ms). The thresholds of 70 and 80 degrees/second found two more fixations than the calculation with a threshold of 90 degrees/second (at about 3800 and $1.62 * 10^4$ ms), with the threshold of 90 degrees/second these fixations were merged which resembled the counted fixations from the video. For this reasons, it looks like the angular threshold fixation detection with a threshold of 90 degrees/second works best for this data.

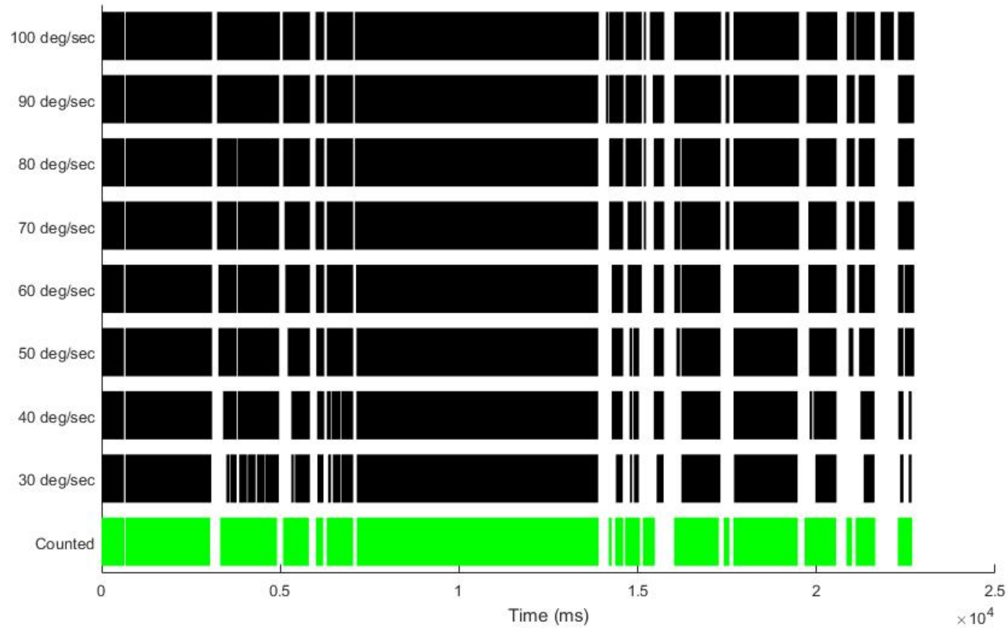


Figure 28: Different angular velocity thresholds compared to the counted fixations from the video.

Tobii recommended to use the I-VT attention filter when using the wearable eye tracker. This filter has a cut-off frequency of 100 deg/sec, which is very close to a threshold of 90 deg/sec. Next, a custom filter in Tobii Pro Lab software was made with a threshold of 90 deg/sec and a merge time of 20 ms. The other settings in the custom filter are the same as in the I-VT Fixation and Attention filter. The results of this custom filter were compared to the fixations counted in the video and to the results found with an angular velocity threshold of 90 deg/sec by using Matlab (figure 29). If the results are comparable, the custom Tobii filter could be used, which would save a lot of work.

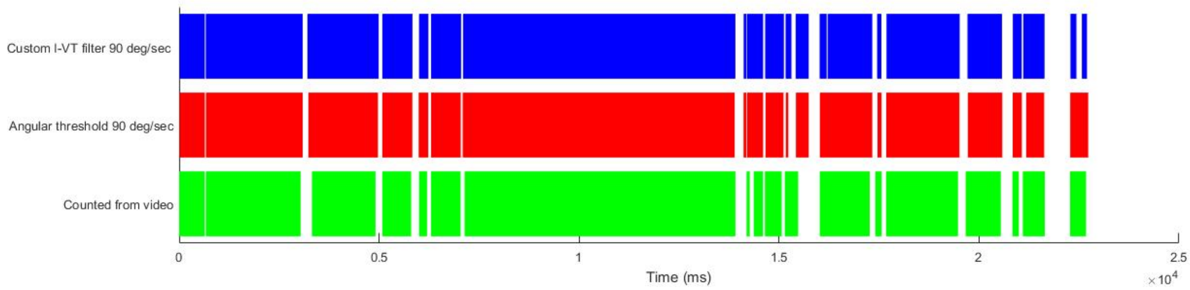


Figure 29: Comparison of the fixations found with the custom filter and with the Angular velocity threshold and counted from the video data.

The custom I-VT filter showed a difference in comparison to the other methods at about $2.22 \cdot 10^4$ ms. The custom filter detected two fixations where the other methods only detected one. When looking at the video again, there was seen that it is understandable that there were 2 fixations detected, because a gap with no gaze points was found. Another difference between the custom filter and the other two methods was found at about $1.6 \cdot 10^4$ seconds. Where there were two fixations detected by the custom filter and one by the other two methods. When looking at the video again, it is understandable why the custom filter detected two fixations. There were gaze points missing and the gaze location shifted around this gap.

In the time period from $1.4 \cdot 10^4$ ms until $1.6 \cdot 10^4$ ms differences were found between the counting and the two filters. In this time period objects and the head were moving which made it difficult to find the fixations with the wearable eye tracker. Next to that, counting the fixations was really difficult during this period because objects were moving and were for example shifting in front of a circle where was fixated on. This made it hard to distinguish what a fixation was by just looking at the video.

It looks like the custom filter can find the fixations in the data. For 70, 2% of the time where no fixation was counted, the custom filter detected no fixation as well (true negative). For 96, 2% of the time when a fixation was counted, the custom filter detected a fixation as well (true positive).

The custom filter was checked with multiple trials for two subjects. It was found that the custom filter with a threshold of 90 degrees/second corresponded for the most part with the counted fixations from the video in the reach and grasp tasks. However, in the SCT, the results of the custom filter (90 degrees/second) did not correspond well with the counted fixations from the video. Therefore multiple thresholds were tested for the custom filter for the SCT and a custom filter of 35 degrees/second was found to correspond best to the counted fixations from the video. In conclusion, the custom filter of 90 degrees/second was used for the reach and grasp tasks and the custom filter with a threshold of 35 degrees/second was used for the SCTs.

B Appendix: Reach and Grasp tasks

The reach and grasp tasks were programmed on a touchscreen using Java. All programmed tasks need to meet all the following requirements for this research:

- Detect pressed and released events and their location on the touchscreen
- Detect start and stop time, and the time of each touch event on the touchscreen
- Only respond to touch events on a target of interest
- Do not respond to irrelevant touches. Irrelevant touches are for example blinkering of a touchpoint of an object or the arm or hand of the subject leaning on the touchscreen.
- Handle multiple manners in which the object is put on the touch screen

Each individual task has individual requirements to meet. These were discussed per task together with the description of how the tasks were programmed. For three tasks, objects on the touchscreen are needed. The development of these touchscreen compatible objects is described in appendix C.

For all tasks except for the maximal range of motion measurement, the following method to check if a touch event should be accepted as a touch event was used. When a touch event is sensed, there is first checked if the target of interest was touched or not. If so, the touch event is accepted for this requirement and will proceed to the next checking step. If not, nothing will happen and the script will wait for another touch event on the target of interest. Next, there will checked if the event on the target is a pressed or released event and if this matches the event expected on the target. If so, the touch event is accepted for this requirement as well.

To make sure the programmed tasks do not respond to irrelevant touches, filtering mechanisms were built into the scripts. Before a certain touch released or pressed event is accepted, there is checked if there are touch events in a specified time (250 ms) before and after the touch event of interest. If a touch event was seen in this time frame, the touch event of interest is considered as blinkering of the touch point of the object and is therefore not accepted.

All tasks were executed three times by using the dominant and three times by using the non-dominant hand in the healthy subjects and three times by using the hand of the affected side in the stroke patients. Therefore, three different versions of each task were made to prevent prediction of which target should be reached next.

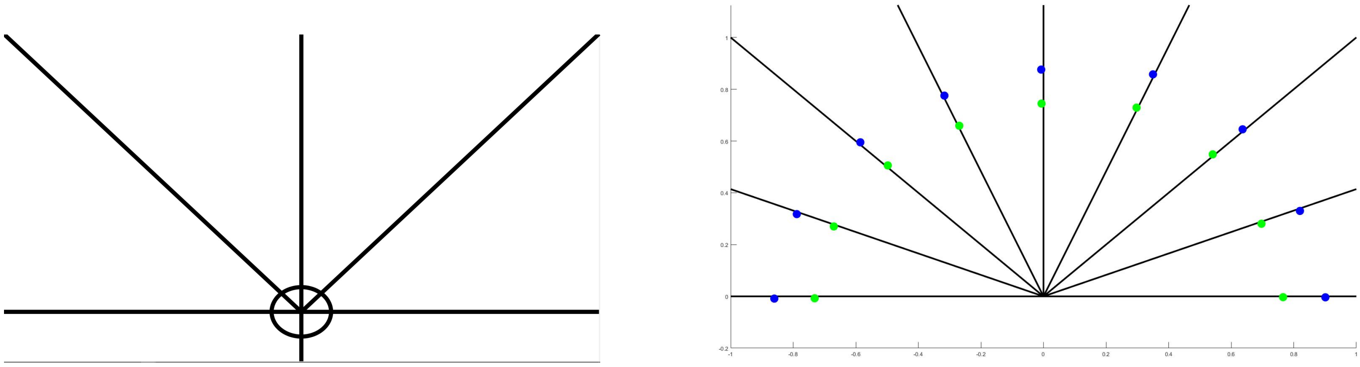
B.1 Maximal range of motion measurement

The maximal range of motion of the hand on the touchscreen while being seated has to be measured, to be able to personalize the tasks. The requirements of the range of motion measurement are:

- Measure the Range of motion over multiple lines originating from the middle
- Being able to handle unexpected movements while touching the touchscreen during the measurement
- Being able to handle an interrupted movement
- Announce when the measurement can be started

The range of motion measurement was programmed in Matlab R2016a as following. After the main script is run, a window with a ready button is shown. When this button is pressed a window with five lines and a circle in the middle will be shown (figure 30a). The origin was not set at the lowest part of the screen. In this way, the movement will start underneath the first line, to make sure the movement is going through the horizontal lines as well. The X-axis runs from -1 to 1, and the Y-axis runs from -0.2 to Y. Where Y is calculated by 2 (-1 to 1) times the pixels on the X axis of the screen divided by the number of pixels on the Y axis of the screen. Y was calculated in this way to make sure that if a screen with other dimensions is used, the scaling between the X and Y axis will stay the same.

After three seconds a beep sounds which tells the subject that the measurement can be started. The subject has 15 seconds to complete the movement from the left to the right lower corner of the screen after which the maximal range of motion points are calculated. The locations of the touch points in X and Y coordinates are obtained. These coordinates are transformed into the coordinates of the coordinate system of the task in Java.



(a) The 5 lines of the range of motion measurement.

(b) The RoM (blue dots) and 85% RoM (green dots) calculated on nine lines.

Figure 30: Range of motion measurement.

The number of lines over which the maximal range of motion is calculated can be adjusted. The endpoints of each line in the window are calculated, where π radians is divided over the number of lines. For the range of motion measurement in this research the number of lines was set to nine. For every line the script calculates which points are within 0.01 to this line. This is calculated by first finding the linear equation of each line by using $Ax + By + C = 0$. The begin (x1,y1) and endpoint(x2,y2) of the line are used where $A = y1 - y2$, $B = x2 - x1$ and $C = x1y2 - x2y1$. Then the distance to the line of a point (X,Y) is found by using the following formula: $distance = |AX + BY + C|/squareroot(A^2 + B^2)$. The distance is calculated for each point to each line and all the points which have a distance of 0.01 or less to a line are selected. From this points the point which is located furthest away from the origin is selected per line. This point is the maximal range of motion point of a line.

The maximal range of motion points for all nine lines and 85% of these points are shown to check if the measurement was executed as desired and if all points were found (figure 30b). The 85% of maximal range of motion points are used to define the area in which the tasks in Java should be executed. The values are loaded into the Java scripts for the individualized simulated daily life tasks.

B.2 Reach and touch task

The requirements for the reach and touch task are:

- Read in the saved 85% range of motion data points
- Use locations of the targets within the 85% range of motion where the amount of targets on the left and right side is the same
- Change the color of the target when it is touched
- Show the next target when the start button is touched
- Only enable to touch the start button when the previous target was touched
- Show when the task is finished

First the 85% range of motion points are loaded. The target locations and their order are predefined. This is done to make sure the task is the same for each subject. However, the task is individualized per subject by using the 85% range of motion results. The X and Y coordinate of each line of the 85% range of motion measurement is multiplied by a factor (0.5, 0.7, 0.8 or 0.9) from which the location of the target results (factor · X-coordinate and factor · Y-coordinate). The targets on the lines are shown in figure 31. Two start buttons (one which has to be touched (dark gray) and one which was already touched (light gray)) and both kind of targets (red and green circles) are created in the script. The objects created can be added to or removed from the touchscreen. By using eventhandlers in Java, touch events can be noticed by the script. In programming the tasks, the touch events pressed and released are used.

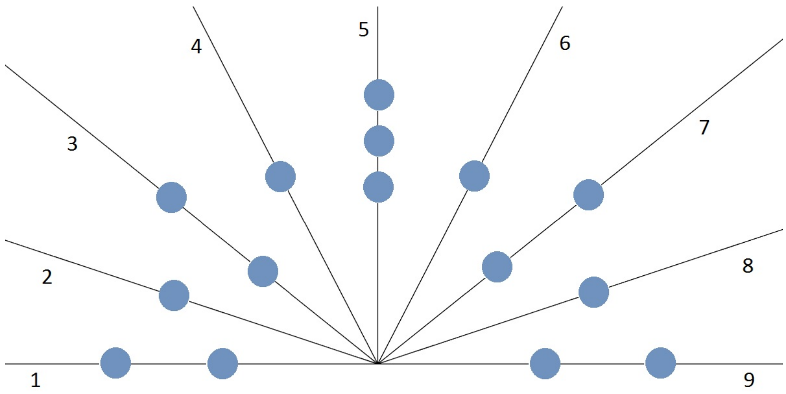
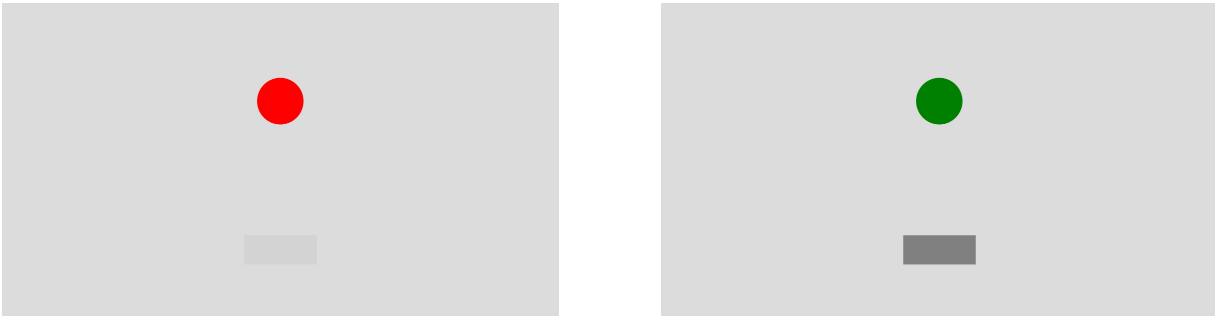


Figure 31: The targets of the reach and touch task.



(a)

(b)

Figure 32: (a) Target to be pressed (red) and (b) target pressed (green) with the grey bar to be pressed.

First, the gray start button and a start text are shown. When the start button is pressed, it turns light gray and the first target is shown in red. The moment the target is touched it turns green and the start button turns dark gray again. The start button can then be touched again and the next target will appear and so on. There is worked with multiple objects instead of changing the color of one object (green and red circle and a gray and light gray start button). This is done to make sure that when the target needs to be touched, the start button cannot be touched, because the eventhandlers are only connected to the red circle and the dark gray start button. When all 15 targets are touched, an 'end' text will appear and the data will be saved. The saved data consists of all touch points (X and Y coordinates) and touch times on the targets and on the start button.

B.3 Reach and lift task

The requirements of the reach and lift task are:

- Read in the 85% range of motion data, in which the objects should be placed
- Show which object needs to be lifted
- Indicate when the object can be put down again
- Show when the task is over
- Only react to the touch event of the target of interest

The 85% range of motion data are loaded. Four orange circles and one gray base rectangle are created. The four orange circles are created to put the objects on. The location of the four orange circles is at 0.6 times the 85% range of motion X and Y coordinates of the lines 2, 4, 6 and 8. The base is placed in the middle of the bottom of the screen (figure 33). When the task is run, the base and the four orange circles are shown in the scene. The researcher can start and stop the measurement by using the keyboard, where the spacebar is "start" and the Return key is "stop".

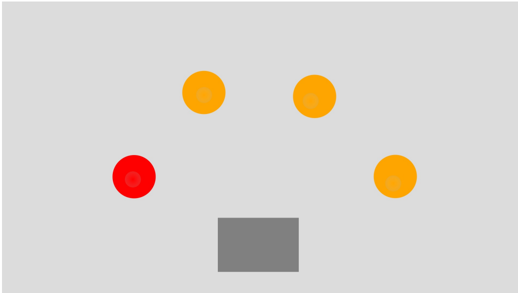


Figure 33: The object locations (orange circles), the grey base, and the indication of the object which needs to be lifted (red).

When the task is started the orange circle of the first target will turn red. The order in which the targets will turn red is predefined. The targeted object then needs to be lifted. When the release is accepted a sound will be heard, which indicates that the object can be put down again. If the press event is accepted as well, the red circle will turn orange again and the hand should be brought back to the base rectangle. The researcher will press the Enter key to stop the part of the task. When the subject is ready, the Space key can be pressed again and the next target will turn red and so on. All start, stop, press and release times are saved together with the press locations.

B.4 Reach and replace task

The requirements of the reach and replace task are the following:

- Read in the 85% range of motion data, in which the four target locations should be placed
- Indicate which object should be reached and replaced
- Indicate to which location the object should be replaced
- Show when the trial of the task starts and finishes

The results of the 85% range of motion measurement are loaded. There are four orange circles put in the scene on 85% of the 85% range of motion on line 2, 4, 6 and 8 of the range of motion measurement. These circles are shown when the task is run. From left to right, these circles are circle 1 until circle 4. Before starting the task, one object is placed on for example circle 1 and one object is placed on for example circle 3. After the researcher starts the measurement by pressing the space bar, one circle where an object is put on will turn red and one empty circle will turn red (figure 34). The object which is placed on the red circle should be replaced to the empty red circle. When the object is put on the empty red circle and the touch event is accepted, the next two circles (one with an object and one empty) will turn red. This goes on until the objects are reached and replaced six times in total. After which the trial will be stopped by the press event on the last destination target. The start time and all touch event data (locations and times) are saved. The order in which the objects should be reached and replaced and the locations of the destination are predefined. The amount of replacements from left to right and from right to left are the same. Also, the objects to be reached are as often on the right side as on the left side. In between the reach and replacements of the different objects there is no start and stop event included. This is done because in the reach and replace task the search behavior of the subject is interesting.

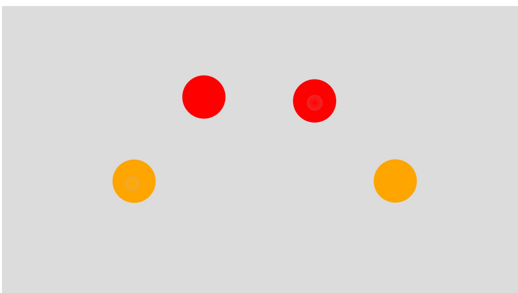


Figure 34: The orange circles where on circle 1 and circle 3 objects are placed. The object on circle 3 needs to be replaced to circle 2 (red circles).

After a meeting with psychologists from Roessingh rehabilitation centre, the colors of the circles were changed. First, the circle on which the object should be placed was pink and the circle from which the object should be lifted was red. There was a lot going on on the touchscreen with all the color changes, which might be very confusing especially for stroke patients. Therefore there was chosen that one empty and one circle with an object will turn red each time. The subject will be told to replace the object from the full red circle to the empty red circle.

B.5 Bimanual task

The requirements of this bimanual task are:

- Read in the 85% range of motion data to set the location of the objects
- Do not indicate which target should be lifted and where it should be put again
- Show when the trial of the task starts and finishes
- Save all the accepted touch event data (location and time) on the location circles.

When the task is run, three circles appear on the touchscreen, one large blue circle and two smaller orange circles. The large blue circle is located at 40% of the 85% maximal range of motion on line 5. The orange circles are located at 80% of the 85% maximal range of motion on line 2 and 8. The bottle is placed on the orange circle on the side of the dominant hand in the healthy subjects and on the affected side in the patient group.

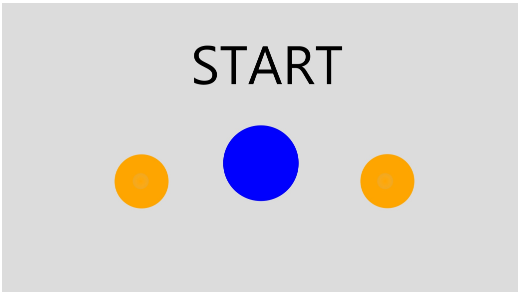


Figure 35: The orange circles for the bottle and glass and the blue circle circle where the rice should be poured into the glass. Also the start text is shown.

The trial of the task is started when the researcher presses the space bar. A start text will appear, to announce to the subject that the trial is started. The subject then executes the task in his or her own natural way. The assignment is to pour the rice from the bottle into the glass on the blue circle. The circles will not change color, they will only act as press and release targets to save the touch events which are acting on them. This is done to get the timing of lifting the objects and putting them down again during the trial. There is a lid placed on top of the bottle object to increase the difficulty of this task. The lid makes sure the subject needs both hands during this task. After the filled glass and bottle with the lid on top are placed back on their circles, the trial is ended by the researcher by pressing the Return key. The start and stop time and the timing and location of the touch events on the targets are saved.

C Appendix: Touchscreen compatible objects

A touchscreen can be resistive or capacitive. A resistive touchscreen reacts to the physical pressure of a touch, where a capacitive touchscreen works with the conductivity of the touchscreen. When the electric field in the touchscreen is interrupted by placing a conducting material close to it or on it, the touchscreen will register this as a touch event. The response to touch of a capacitive touchscreen is faster and better than in a resisitive touchscreen. [47] The sensitivity and responsiveness of the capacitive touchscreen is high. [48] The capacitive touchscreen is able to detect multiple touch points at once. [47] This is very useful in the tasks to be executed in this research. The touchscreen used in this research is a capacitive touchscreen able to detect 12 separate touch points at the same time. [49]

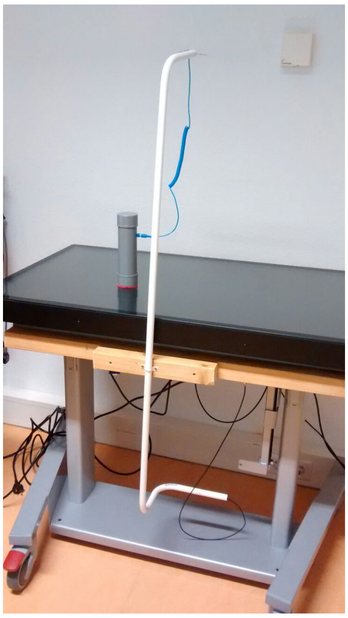
A conductive object is needed to activate a capacitive touchscreen. [47] This conductive object should be connected to a ground to complete a circuit so the electrical field will be interrupted. This can be done with a finger or with a special stylus for example. The location where the electrical field is interrupted is marked as a touch point. [48] In this research there should be known if an object is located on the touchscreen when it is not touched (no human body used as groud). Objects compatible with the touchscreen needed to be built for this research. The requirements of these objects are the following:

- The objects need to be grounded to be sensed by the touchscreen without the human body touching them
- The objects need to be stable to avoid a blinkering contact
- The objects should not cause damage to the screen
- The grasping of the objects needs to be easy
- The objects need to be conductive
- There should be a well contact between the object and the touchscreen, to avoid blinkering
- All objects need to be about the same, because the touchscreen will only detect the points with the most electrical interruption (overruling)

Several methods were tried until reaching the final object design. Some methods use the built ground system as can be seen in figure 36a. The following methods to build a touchscreen compatible object were tried, the last method was used for the measurements.

- Metal cylindrical object connected to the ground system. Due to a too large conductive area, this gave too many touch points.
- Metal cylindrical object with a small screw nut at the bottow connected to the ground system. This gave still too many touch points because the metal object was too close to the touchscreen.
- Bottle of electrode gel. Gave multiple touch points on the touchscreen without the grounding system. Interruption of the electrical field decreased over time because the ions in the gel stopped moving.
- Touch screen stylus built in a cardboard box connected to the ground system. This gave one touch point. However, many touch screen styluses would be needed.
- Stripped wire put through two non conductive coasters, stuck with a piece of metal tape (size of a fingertip) on the bottom size and connected to the ground system. One stable touch point was found.
- The previous idea added to a PVC pipe with two end caps with the wire put through the pipe. The contact between the wire and the metal tape was not reliable. Foam rubber was used instead of the coasters, which increased this effect.
- PVC pipe with two end caps (one with rubber foam) with a plastic silver coated electrode (figure 36b). The wire was clamped between the foam and the electrode. The object was connected to the ground system. This object was made with three electrodes (to always find one touch point) and with one electrode. The version with three electrodes gave unstable contact points and the object with one electrode gave a stable contact point.
- Use the previous idea not connected to the ground system, but with electrode gel inside the cap, in contact with the wires. This gives a touch point, however this touch point is less stable than the object with the electrode and connected to the ground system.

- PVC pipe with two end caps with small metal balls in the bottom cap with the electrode connected to the wire. The wire is in contact with the metal balls. A wireless solution with a stable touch point was found. This is the object used for the measurements (figure 36c).



(a) Ground system.

(b) Bottom side of the object with the electrode.

(c) Final touchscreen compatible object.

Figure 36: Ground system (a), electrode (b) and the final touchscreen compatible object (c).

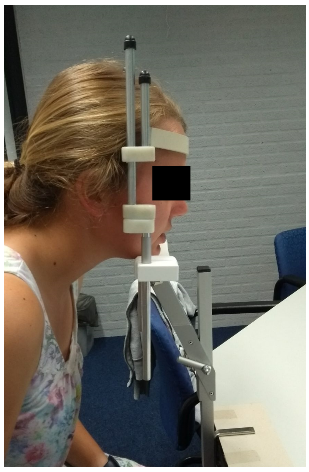
D Appendix: Head fixation

To exclude the head movements during the SCT, a head fixation/support system had to be built. The head had to be fixated, but the subject should not be bothered by the head fixation too much. Next to that, it should be easy to set up the head fixation system. Movements to the left and right are most important to be removed. To make sure the eyes do not have to look down too much so the eye tracker can still track the eyes, the head needs to be slightly tilted forward.

A headrest for a wheelchair, the Papillon, was received from Focal (figure 37a). This headrest consists of three parts, two pillows on the bottom side of the head and one on the back of the head. There are side supports available for the system, however they were not delivered with the system. When the head was placed in the Papillon as meant, the head was still able to move. Straps on the chin and forehead were added to improve fixation. A chincup, as used by an ice hockey keeper, was placed on the chin for extra support. After this addition, the head was still able to move because of the ability of the jaw to move relative to the skull. Next to that, the strap around the forehead could not be fixated well because the point of attachment of the strap was too low relative to the forehead.

(a) Head rest (Papillon) for a wheelchair delivered by Focal. [50]

(b) Head fixation setup by using Papillon.



(c) Adjusted chin rest to fit the glasses.

Figure 37: Head fixation methods

Next, there was tried to place the Papillon higher up the back of the head, using the same straps for fixation. In this way the jaw was pulled up more and the strap around the forehead could be fixated better because the point of attachment was closer to the forehead. It looked like this would work, so a system to attach the head rest to a chair was built (figure 37b). However, this head fixation method did not work. The subject was still able to move because the head support was placed on the back of the head and the head was slightly tilted forward. In this way the subject hung in the straps which allowed for freedom of movement. Also, this system might be bothersome to the subject.

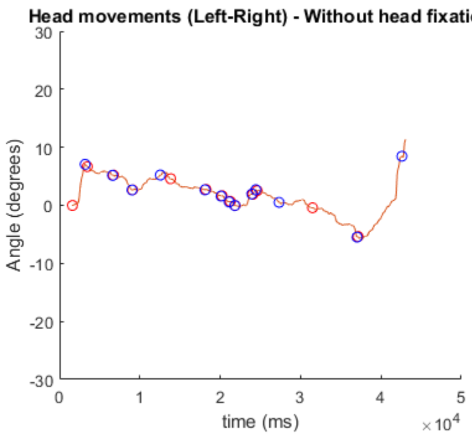
Next, head fixation at the front instead of the back of the head was considered. There was thought of a chin rest as used by opticians. A few chin rests were tried and the outcomes were positive. The chin rest manufactured by Rehacom was purchased. The chinrest was set up a bit lower than normal to make sure the subject looks down in an angle. Addition of a strap was tried but was found to be bothersome to the subject. The strap on the forehead is made of anti slip material which avoids movement. When using the chin rest in combination with the Tobii Pro glasses 2, there was found that the eye tracker did not fit in between the rods of the chin rest. Therefore the rods were adjusted. The final head fixation system used is shown in figure 37c.

E Appendix: Head movement detection

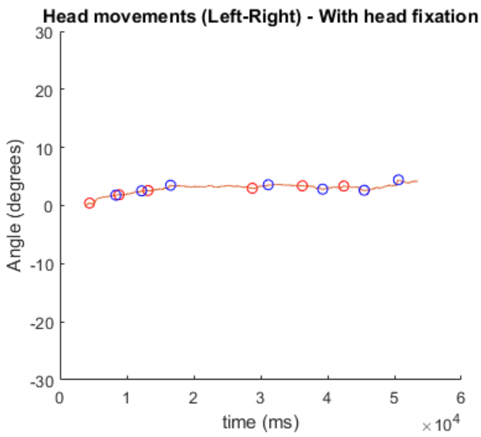
The head movements during the SCT need to be detected. The first question was, what is in this research the definition of a head movement during the star cancellation task? In previous research, no standard definition of a head movement was found so there was decided to define conditions for a head movement specifically for this research. Head movements are slow movements with a frequency of about 2-4 Hz. [51] Therefore there was decided to look at movements in the gyroscope data from 0 to 6 Hz. The minimal duration of a head movement was set to be $1second/6Hz = 167ms$. The small stars of the star cancellation task are minimally 5 mm apart from each other and there was estimated that a subjects head is located about 50 cm from the paper. By using $atan(5mm/500mm)$, the minimal angle of rotation of a head movement was set to be 0.57 degrees. Next to the duration and rotation condition, a condition that no movement in the other direction of more than 0.4 degrees should be present between the start and end of a head movement was set.

At the start and end of the star cancellation test, the subject was asked to look at the blue dot placed above the paper. In this way the head is approximately stationary. The mean value of these two periods was taken and subtracted from all the data from start to end of the task. This was done to remove the drift due to integration. If in one of both drift measurements the head was moved, the mean of one drift measurement was used. Before integration, the data was filtered by a 6 Hz low pass 2nd order Butterworth filter. After this the data (degrees/second) was integrated to find the degrees of rotation.

All peaks in the degrees of rotation over time data were found on which the head movement data points were selected. This selection was done by looking at each peak, finding which peaks later in time (maximal 20 peaks later) showed a rotation of more than 0.57 degrees and had a time difference of 167 ms. If both the degrees rotation and duration condition were met, the third condition of not having a rotation in the other direction of 0.4 degrees in between these points was examined. In this way all the start and endpoints of the head movements were detected (figure 38). The head movements which were closer to each other than 100 ms and in the same direction were merged.



(a) Without head fixation.



(b) With head fixation.

Figure 38: Head movement detection. Start (red dot) and end (blue dot) of head movements are indicated.

After setting up the head movement detection method, it looked like there was still drift present (different angle at the start and at the end of the SCT). Therefore, there was also looked at the eye movements, because the eye and head movements together specify the gaze location. The eye and head movements are plotted together, where for the eye movements the angle between the X and Z-axis (figure 39) was used. The results can be found in figure 40. There can be seen that in the end of the test, the eyes moved in the opposite direction to the head. This partially explains the rotational difference in the head movement between the start and end point of the SCT.

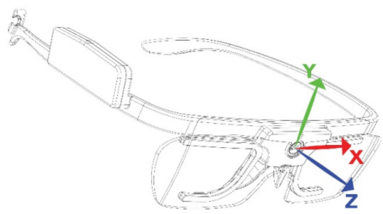


Figure 39: Defined axes of the Tobii Pro glasses 2. [45]

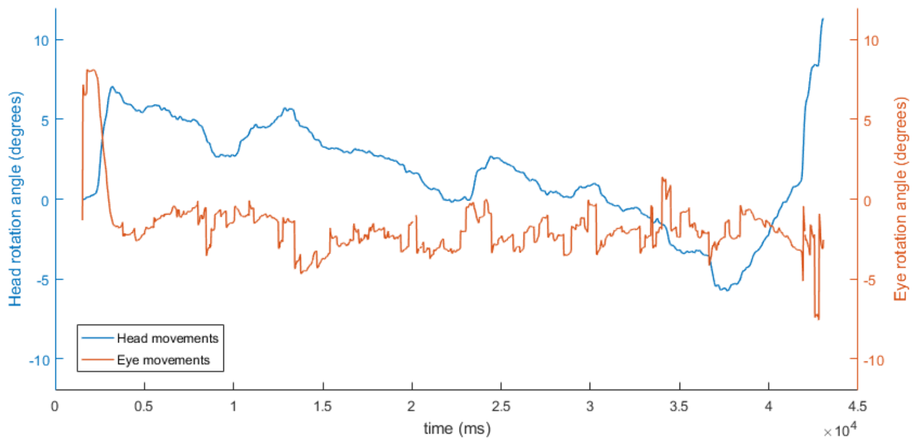
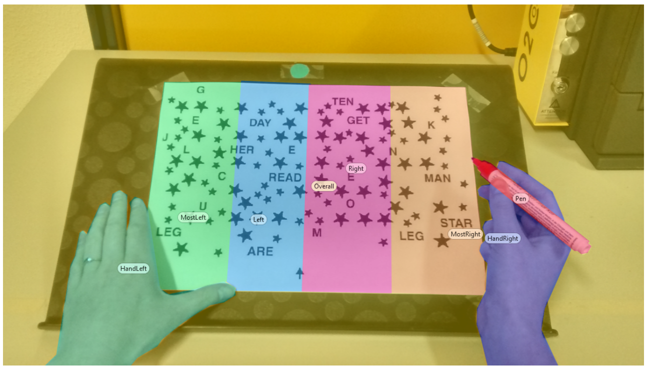


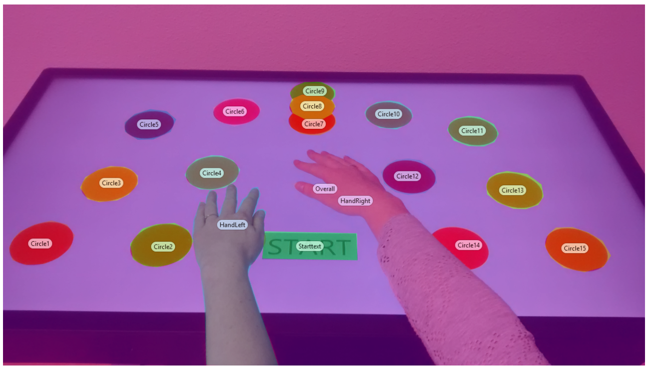
Figure 40: Head and eye movements during the SCT without head fixation.

F Appendix: Snapshots

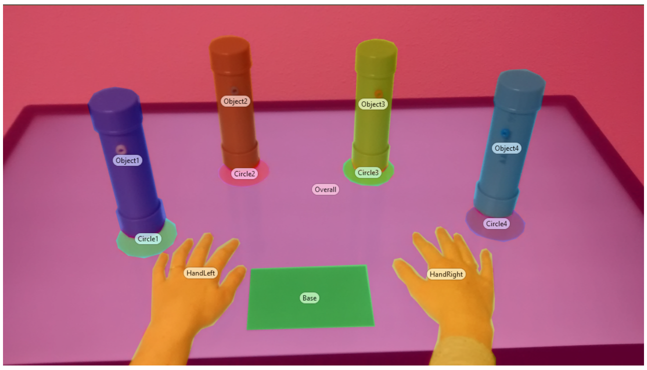
The following snapshots with AOIs (figure 41) were used for the data analysis of the SCT and the reach and grasp tasks.



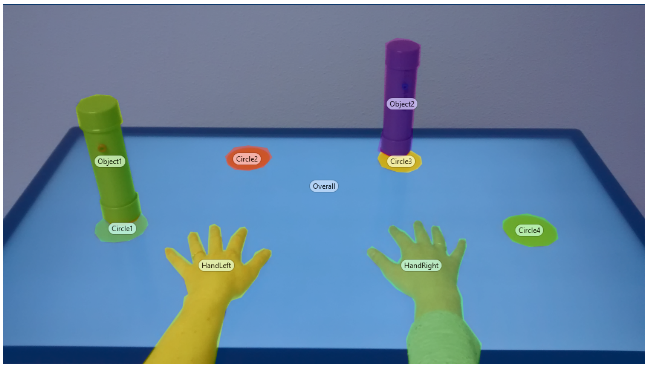
(a) Snapshot SCT.



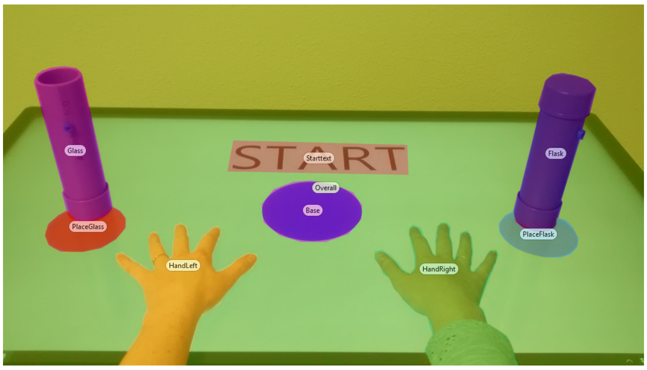
(b) Snapshot RT.



(c) Snapshot RL.



(d) Snapshot RR.



(e) Snapshot BM.

Figure 41: Snapshots (with AOIs) used for data analysis in the Tobii Pro Lab software.