BEN-GURION UNIVERSITY OF THE NEGEV
FACULTY OF ENGINEERING SCIENCES
DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGMENT

Assessing transparency of a gesture-based interface for programming by demonstration

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE M.Sc DEGREE

By: Nir Sagi

JANUARY 2017

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ABSTRACT

Programming by demonstration (PbD) is concerned with the abilities of a user to teach motor skills to a robot by demonstrating a task. PbD is important for facilitating skill transfer from humans that may be unskilled in robotics. Common interfaces for PbD include motion recording sensors, kinesthetic interfaces, and telerobotic interfaces. The interface has a critical influence on system performance and transparency yet objective quantification of its role is an open research question. The current research, takes a step towards filling this gap. To this end, we have examined the transparency of a motion recording interface in PbD of a reach-to-grasp task. Participants were taught to use the interface to control a robotic manipulator with a parallel jaw gripper. After training, they were requested to demonstrate to the robot how to reach and grasp a cylinder placed on a table in front of the robot. The participant's hand motion (thumb and index finger of the dominant arm) was recorded using two Phantom premium robots with finger thimbles. Cylinders of different width were used to facilitate harnessing Weber's law for objectively examining motion transparency. During demonstrations, the task environment was viewed from two different viewpoints for examining the relative importance of task direction alignment. For conducting the experiments, we have developed a data-centric telerobotic system, a motion recording system, data processing procedures, and statistical analysis routines. Results showed that while viewpoint direct did not influence motion, participants used motion profiles that significantly differed from motion profiles used in natural reach-to-grasp tasks. The findings highlight the limitations of the examined interface and the importance of operator training.

Index Terms – Programming by demonstration, Weber's law, Human-robot interaction.

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List of Abbreviations

DDS – Data distribution service

DOF - degrees of freedom

FGA – Final grip aperture

HRI – Human robot interaction

IGA – Initial grip aperture

LfD – Learning from demonstration

MGA – Maximal grip aperture

OTR – Opening time ratio

PbD - Robot programming by demonstration

SOA – Service oriented architecture

TCP – Tool center point

TD – Task duration

TT – Aperture transport time

TTR - Aperture transport time ratio

STCPD - Scaled sagittal TCP transport distance

1 Introduction

1.1 Background

In the last decade, many robots have been introduced into the consumer world making an impact on many aspects of modern life. Modern robots are capable of exploring remote environments, manipulating objects, performing tedious, repetitive assignments, and interacting with other robots and humans (Siciliano, and Khatib, 2008). Such robots need to work alongside users that are nonprofessionals in the areas of robotics and programming. Therefore, there is a need for intuitive methods for programing robots (Argall et al., 2009; Billard et al., 2008). Robot Programming by Demonstration (PbD) or Robot Learning from Demonstration (LfD) offer such an interface, enabling users to program the robot by using gestures or by physically guiding the robot through the motion (Billard and Grollman, 2013).

Two examples of consumer robots facilitating PbD are the Baxter torso and the UR3 manipulator. Baxter (Figure 1A; Rethink Robotics) is a 90 cm tall, industrial robot. First introduced in 2012, Baxter has two 7 degrees of freedom (dof) arms for manipulation purposes, a screen that animates face expressions, and multiple sensors. Baxter can be taught to perform a task by physically moving its arms to demonstrate the required action. The UR3 (Figure 1B; Universal Robots) is mounted on a table, and can reach a radius of 500 mm. The UR3 can be programed by physically moving the robotic arm or using its touch screen tablet as a remote control. The introduction of such robots with inherent PbD capabilities into the consumer market signifies a clear shift in the robotic programming paradigm.

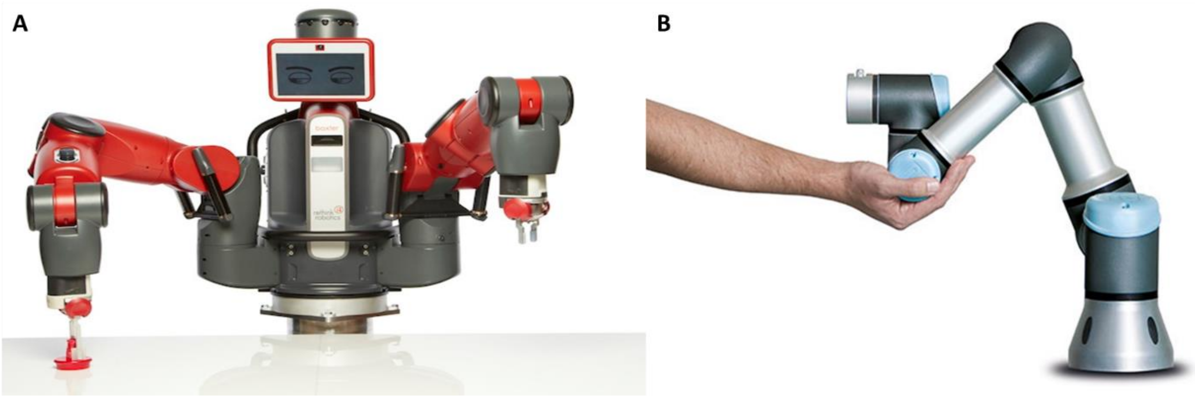

Figure 1. A: Baxter (Rethink Robotics) B: UR3 (Universal Robots)

1.2 Research objectives and contribution

The research harnesses cognitive psychology and motor control theory for objectively examining transparency of a motion-recording (gesture-based) interface for PbD. Arm and hand motion profiles as well as motion descriptors are analyzed and objective measures for transparency are defined. Weber's law is examined for uncovering underlying perception-action control mechanisms. Comparison to natural reach-to-grasp characteristics is carried out to assess the transparency of the gesture-based interface.

For conducting the experiments, a data-centric telerobotic system was constructed using Data distribution service (DDS) as communication middleware. The robotic system is based on a robotic manipulator (Motoman, Japan), and a controlled jaw gripper (Schunk, Germany). Two Phantom Premium haptic devices with finger thimbles (Geomagic, USA) comprise the systems user interface. The control software of the robotic manipulator and the jaw gripper were developed as part of the current thesis.

Publications stemming from the current work are listed in Appendix A.

1.3 Research scope and limitations

This thesis concentrated on a single user interface based on the Phantom robots. This interface introduces dynamic constraints on the motion due to the mechanical structure of the Phantom device, and the coupling between the two devices. The current work concentrated on reach-to-grasp motion. Other motion types, e.g., reaching, pointing, or surface constrained motion were not tested. Testing additional interfaces and enhancing the developed methods to include additional motion types is of great importance but beyond the scope of the current work.

The time delays of the telerobotic system were sizeable. Although subjects did not tele-operate the system during the experiment, they did practice using it prior to the experiment. Testing additional training procedures is an important future work. A robotic manipulator that facilitates smaller time delays has been recently purchased and adaptation of the telerobotic control software is currently underway. This work is beyond the scope of the current thesis.

1.4 Thesis outline

This thesis is organized as follows: Chapter 2 details the background literature review. Chapter 3 presents the developed telerobotic system. Chapter 4 presents the experiment and data analysis. Chapter 5 describes the results. Chapter 6 presents a discussion. Appendix A lists publications stemming from current work, Appendix B shortly describes additional experiments performed as part of the research, Appendix C includes instructions on how to run the telerobotic system.

2 Background

2.1 Overview

This chapter is divided into four sections. The first section describes the fundamentals of PbD along with common challenges and interfaces used for PbD. This section presents the core background of the research, which investigates a gesture-based interface for PbD. The second session reviews human reach-to-grasp motion characteristics as this type of motion was demonstrated during the experiments. The third section presents Weber's law, its occurrence in grasping scenarios and its use for assessing transparency, which was examined in the experiment. The fourth and last section discusses the main issues in telerobotics as subjects practiced tele-operating the system prior to the demonstration.

2.2 Robot Programming by Demonstration

PbD is a paradigm for teaching a robot the mapping of states and actions in the physical world using demonstrations. The demonstration of a task to a robot is an intuitive method suitable for novice users, similar to the way human-beings gesture to each other when trying to illustrate and explain a task (Argall et al, 2009). PbD incorporates ideas from many research areas such as human-robot interaction (HRI), machine learning, machine vision, and motor control (Billard et al., 2008).

PbD has evolved immensely in recent years and has become popular due to several reasons (Argall et al, 2009; Billard et al., 2008). PbD facilitates the reduction of complexity of the search space for solutions of a motion task, it does not require an accurate model of the world, it is suitable for people not experience in the fields of robotics and programming, and robots can learn new tasks on the fly.

2.2.1 Types of interfaces for PbD and their challenges

User interfaces in PbD scenarios are usually of the following types: Interfaces that record human motion, robotic interfaces, and interfaces with kinesthetic feedback. Interfaces that record human motion use various technologies including machine vision techniques, exoskeletons, and wearable motion sensors. Such technologies can precisely measure and record the motion of the human body (Ude et al, 2004; Billard and Grollman, 2013). Robotic interfaces typically employ an interface robot that resembles the controlled robot (Preusche and Hirzinger, 2007). With kinesthetic interfaces the user demonstrates the task directly by moving the robot's joint (Billard and Grollman, 2013).

Interfaces may be integrated, e.g., a multi-step learning procedure involving different types of interfaces was used for teaching object interaction and manipulation to an iCub humanoid robot (Figure 2). The user demonstrated initial hand postures using a robotic interface and then refined the robot's motion by pressing on the robot's fingertips (Sauser et al, 2012; Tsagarakis et al, 2007).

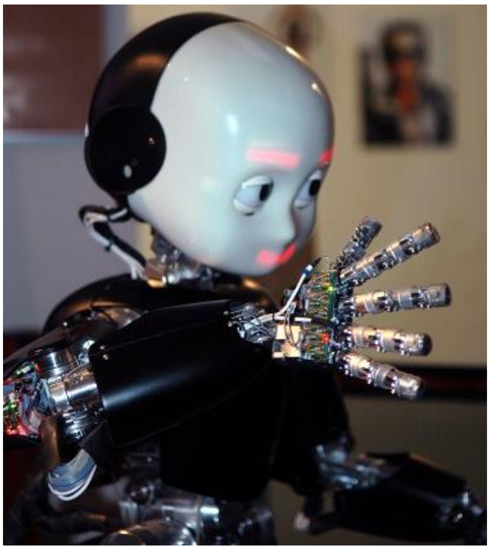

Figure 2. iCub robot (Tsagarakis et al, 2007)

Demonstrating a task to a robot is more intuitive than directly programming the task. However, demonstration methods need to address the correspondence problem, i.e., the translation of the human motion to the robotic motion taking the differences between them into account. Differences between the user and the robot are addressed in two aspects, the perception aspect, and the action aspect. The perception aspect refers to how humans perceive an environment directly through their senses in contrast to how they perceive the remote environment through feedback from the remote sensors. The action aspect refers to the kinematic and dynamic differences between the user's arms and the robotic manipulator, e.g., when the human performs a task with two arms while the robot is a single manipulator (Billard and Grollman, 2013).

Motion recording interfaces must solve the correspondence discrepancy between the physical attributes of the user and the robot (Ude et al, 2004) while, kinesthetic interfaces circumvent this problem by requiring the human demonstrator to fully adhere to the robot's motion capabilities (Billard and Grollman, 2013).

The difficulty of translating a motion performed by a human to a robot has inspired harnessing methods from the field of Human robot interaction (HRI), a field in robotics that inquires on interactions between humans and robots. Looking for insights regarding user abilities and characteristics to assist correct and effective feature extraction. Integrating implicit and explicit cues of important features during user demonstrations into PbD can help speed up the learning process. Understanding motion goal is essential for solving situations in which the robot is unable to perform the task as demonstrated by the human (Billard et al., 2008).

2.2.2 Assessing transparency of PbD interfaces

A main concept underlining the naturalness of PbD interfaces is interface transparency. Full transparency is achieved when the human operator cannot distinguish between performing the task naturally (without the robot) or by using the interface. Computing transparency for human-robot interfaces is problematic and it requires an understanding of the perceptual and motor capabilities of the user (Nisky et al., 2013). Perceptuo-motor transparency can be evaluated by harnessing human perception-action laws such as Weber's law and Fitt's law (Ganel et al., 2008; Goodale, Jakobson and Keillor, 1994).

A human-centered three-layer transparency measure was suggested (Nisky et al., 2013). The layers of the model include perceptual transparency, local motor transparency, and remote transparency. Perceptual transparency is assessed by quantifying perceptual bias and discrimination. Local motor transparency is assessed through comparison of motion profiles of the human operator when operating the telerobotic system and his ideal movements when performing the task naturally. Remote transparency is assessed through comparison of the difference between the movements of the robot to the ideal movements needed to perform the task.

2.3 Human reach-to-grasp motion

Human skill in effortlessly grasping and manipulating objects, stands in contrast to the high complexity required for robotic planning and execution of such tasks. There are many contradicting goals to achieve, and there are many possible solutions (Bernstein, 1967). The complexity of a grasping task is increased when considering the uncertainty inherent in a real-world environment (Argall et al, 2009).

Reach to grasp motion comprises two, synchronized components, movement of the arm towards the object and the composition of the grip by the hand (Lacquaniti, and Soechiting, 1982). Arm movement obeys the two-thirds power law. It also adherence to Fitt's law for objects of different sizes and shapes (Crossman, and Goodeve, 1983). Formulating a grip includes two phases, first opening the fingers, and then closing the fingers while approaching the object in order to grasp it (Jeannerod, 1984).

Reach to grasp motion profiles in teleoperation differ from reach to grasp motion profiles in natural grasping scenarios. Parallel research found that in our telerobotic system, which has substantial transmission delays, operator motion was considerably prolonged. In addition, subjects opened their grip very early in the motion and moved their arm with an open grip towards the target. Such a transport phase is not found in natural grasping.

2.4 Weber's law

According to Weber's law, the sensitivity of human perception, at virtually all sensory modalities, to a change along a physical dimension is linearly related to the intensity of the stimulus (Equation 1), i.e., the just noticeable difference (JND) is larger for stronger stimuli (Baird and Noma, 1978).

$$1. \quad \frac{JND}{Magnitude\ of\ the\ stimuli} = Constant\ value$$

In a weight perception example, if we assume that for a certain subject the JND for a 1kg weight is 0.1kg, then the JND for the same subject for a 2kg weight is 0.2kg (Figure 3).

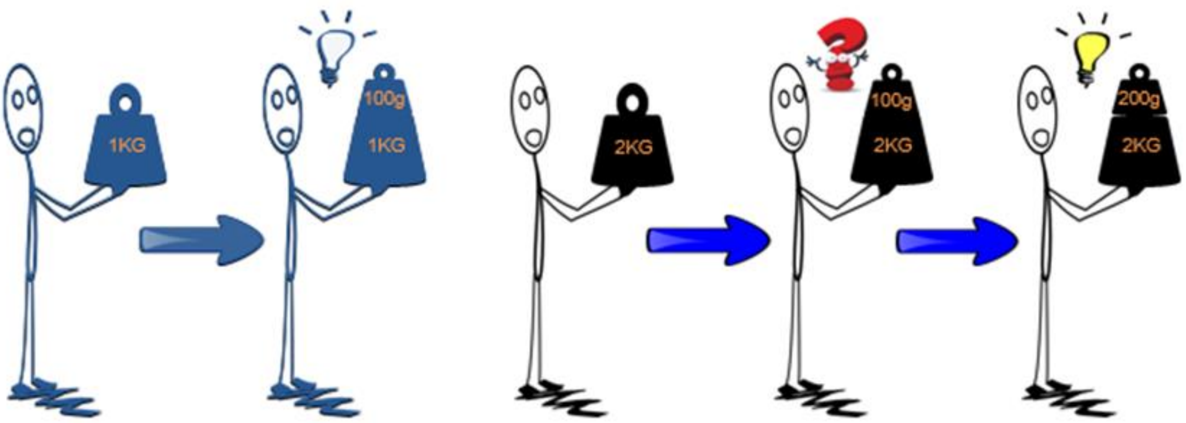

Figure 3. Weber's law in a weight perception example

In grasping scenarios, the grip aperture during the reach-to-grasp motion is used to determine the subject's JND. Grip aperture is often determined as the maximal grip aperture (MGA) during the reach-to-grasp motion. MGA is closely correlated with object size (Jeannerod, 1981;

Jakobson and Goodale, 1991; Ganel et al, 2012). The variance of grip aperture in different reach-to-grasp trials towards a constant object measures the JND as it reflects an "area of uncertainty" between the subject's estimation of object size and its actual size (Ganel, Chajut and Algom, 2008; Ganel, Freud and Meiran, 2014).

2.4.1 Violation of Weber's law in visuomotor control scenarios

Studies show that Weber's law in grasping scenarios is violated, i.e., the standard deviation of the MGA does not linearly increase with object size. This is in contrast to situations where subjects were asked to demonstrate the object's size with their fingers. In the later cases, the standard deviation of the final finger aperture did comply with Weber's law (Figure 4) (Goodale and Milner, 1992; Ganel, Chajut, and Algom, 2008).

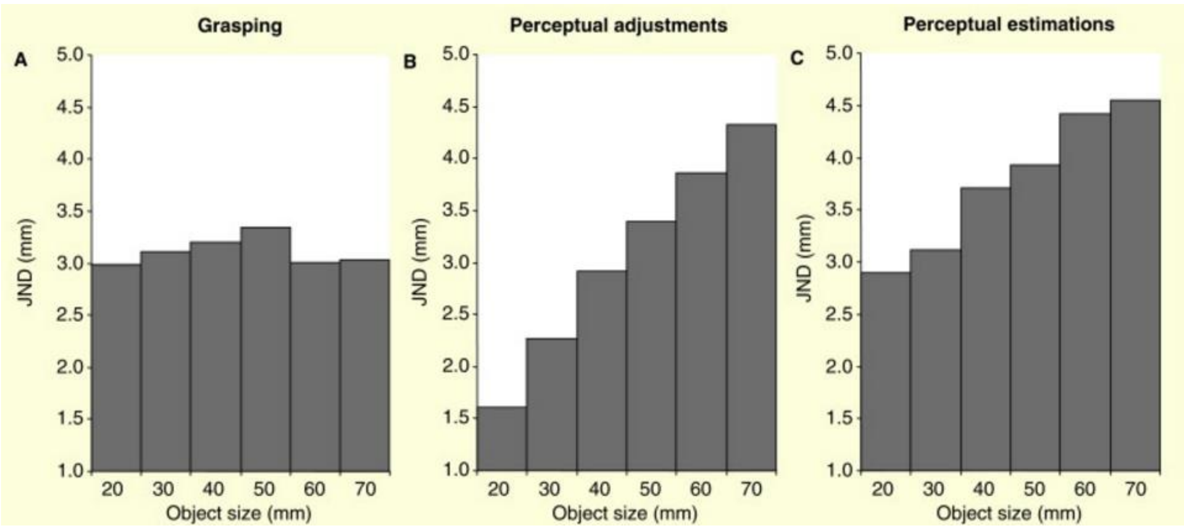

Figure 4. Compliance with Weber's law (Ganel, Chajut, Algom, 2008)

The separation of the visual pathways for perceptual estimations and visually guided action scenarios has been suggested as an explanation of the violation of Weber's law in reach-to-grasp movements (Ganel, Chajut, Algom, 2008, Goodale and Milner, 1992). The disassociation between visual perception and visuomotor control is explained by neuropsychological, electrophysiological, and behavioral evidence that show a separation in the process of visual information between the inferior temporal cortex and the posterior parietal cortex. While the projections of object identification are done via a 'ventral stream' that reaches the inferior temporal cortex, projections of visual control of actions are done via a 'dorsal stream' that leads to a posterior parietal cortex (Ungerleider and Mishkin, 1982).

Smeets and Brenner (1999) suggest that grasping is based on position information, and therefore Weber's law should hold for size, weight, and distance, and not for orientation or position (Smeets and Brenner, 2008). In Ganel, Chajut and Algom (2008) perceptual estimations and perceptual adjustments experiments, the measure of interest was object size, and therefore results complied with Weber's law. While in their grasping experiment, the visual measure of interest was the position of each finger on the object to be grasped, which as described above, is not a metric that complies with Weber's law as shown in the results.

Lowenkamp et al. (2015) conducted experiments of perceptual estimations and reach-to-grasp movements with and without visual information about the objects. In the no visual information conditions, subjects were given auditory semantic information regarding object size. Weber’s law was found in both perceptual conditions and was violated in both grasping conditions. Lowenkamp et al. (2015) suggest that the violation of Weber’s law may be due to ceiling affects caused by the natural limitation of the human finger span, and a human tendency to avoid large and uncomfortable apertures.

Utz et al., (2015) conducted a grasping experiment where an optical illusion created a discrepancy between the object's actual position and its presumed position. Weber’s law was violated during grasping even in these conditions. These results contradict Ganel's claim of a functional separation of visual systems, because when the object appears in a different position then it really is, the visual information is expected to be processed via a ventral stream, and therefore Weber's law should hold. The results also conflict Smeets and Brenner's proposal that subjects evaluate position rather than size during reach-to-grasp movements. Because the object isn't where it seems to be during the experiment, the subjects can not relay on position for path planning and thus should evaluate object size. Therefore, Weber's law should hold (Utz et al., 2015).

2.4.2 Effects of velocity on the SD of grip aperture

As detailed in the previous section, Weber's law does not affect the MGA prior to grasp. Heath (2011) shows that aperture during reach-to-grasp movements complies with Weber's law for the early stages of the movement (until 50% of movement time), but not for later stages of the movement, which include the maximal grip aperture that is normally achieved at 60%-70% of movement time (Ganel et al, 2012).

Ganel (2014) argues that the aperture during reach-to-grasp movements does not comply with the effects of Weber's law throughout the entire grasping trajectory, and that adherence to Weber's law in early stages of a reach-to-grasp movement is confounded by task demands, meaning that the experimental procedure might influence the adherence to Weber's law. In Heath (2011), subjects were instructed to keep their fingers closed before performing reach-to-grasp movements. In this case, in order to grasp larger objects, subjects needed to open their fingers faster than when grasping smaller objects. Velocity profiles of finger aperture support this claim as they show higher velocity of finger aperture when grasping larger objects, but it is evident only for the early stages of the reach-to-grasp movement, which is exactly where the movement complies with Weber's law.

A grasping experiment was conducted where subjects were told to keep an open initial aperture prior to the reach-to-grasp movement (Figure 5), as this setup should eliminate the effects of velocity on the grip aperture (Ganel, Freud and Meiran, 2014). Results show a linear decrease in JND for larger objects in early stages of the reach-to-grasp movement, which implies a relationship between aperture velocity and JND. The relationship between aperture velocity and

JND suggest that when assessing effects of Weber's law in grasping, it's important to observe it at stages in the reach-to-grasp movement where velocity doesn't affect object size, e.g., the MGA which is typically achieved in later stages of the reach-to-grasp movement.

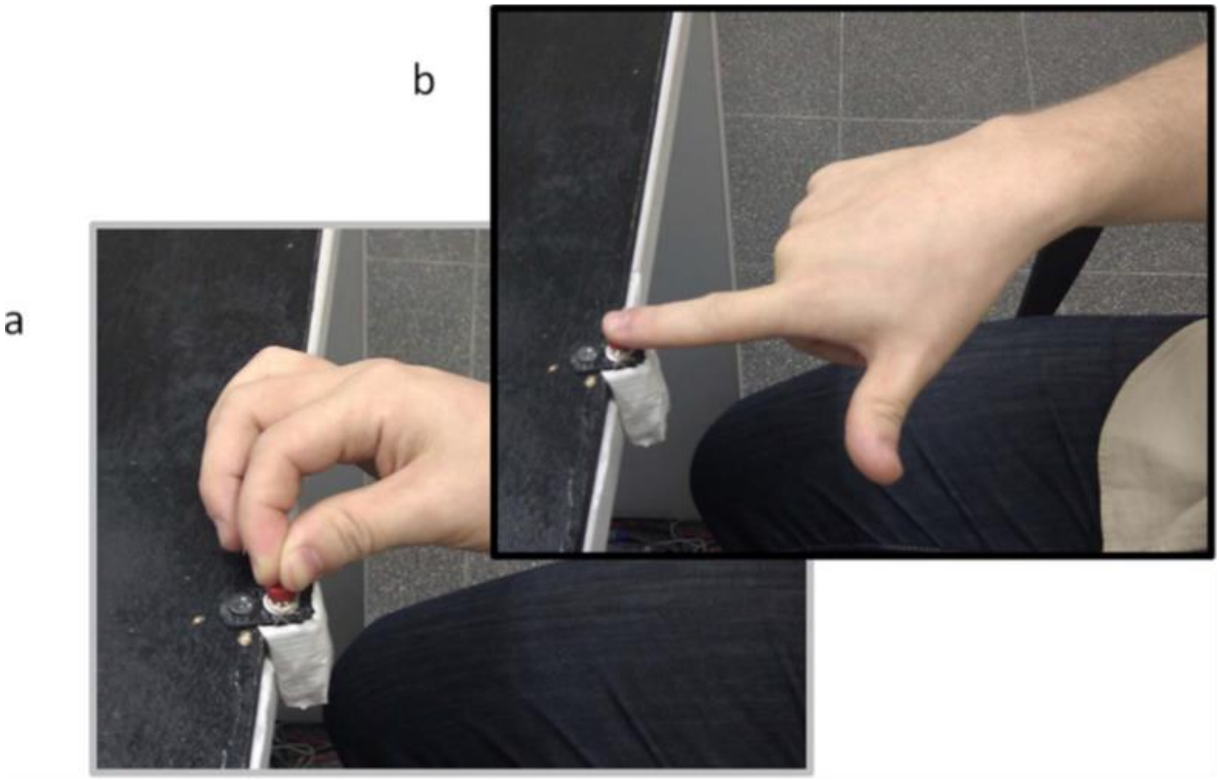

Figure 5. Initial starting point prior to reach-to-grasp movements (Ganel, Freud and Meiran, 2014)

In an additional experiment it was determined that the subject initial aperture will be neither closed nor opened, but in accordance to the object to be grasped (10 mm smaller than the object's actual size). In these conditions, it was expected that any influence that the aperture velocity had on object size would be revoked, and any linear increase in JND throughout the entire reach-to-grasp movement will be attributed solely to the effects of Weber's law. Results indeed show no increase in JND throughout the entire reach-to-grasp movement (Ganel, Freud and Meiran, 2014).

2.5 Telerobotics

Telerobotics refers to control of a robot from a distance using wired, wireless, or internet communication systems. Telerobotics combines two concepts – teleoperation, performing an operation from a distance, and telepresence, i.e., that the human operator located in the control side of the system feels like he is in the remote environment. The term "tele" is taken from the Greek language, meaning distance. It comes to emphasis the barrier between the operator and the remote environment (Hokayem and Spong, 2006). Remote control of a robot is suitable for situations that might put the operator in danger or when precision is required (Niemeyer et al, 2008). Robotic systems must maintain stability. This may contradict the requirement for transparency (Hokayem and Spong, 2006).

Telerobotic systems are conceptually divided into three sub-systems (Figure 6; Niemeyer et al, 2008): The operator's environment, where the human operator has the required elements to sense and operate the system (joystick, keyboard, mouse, computer, and visual display), the remote environment with the robot and various sensors, and the communication middleware.

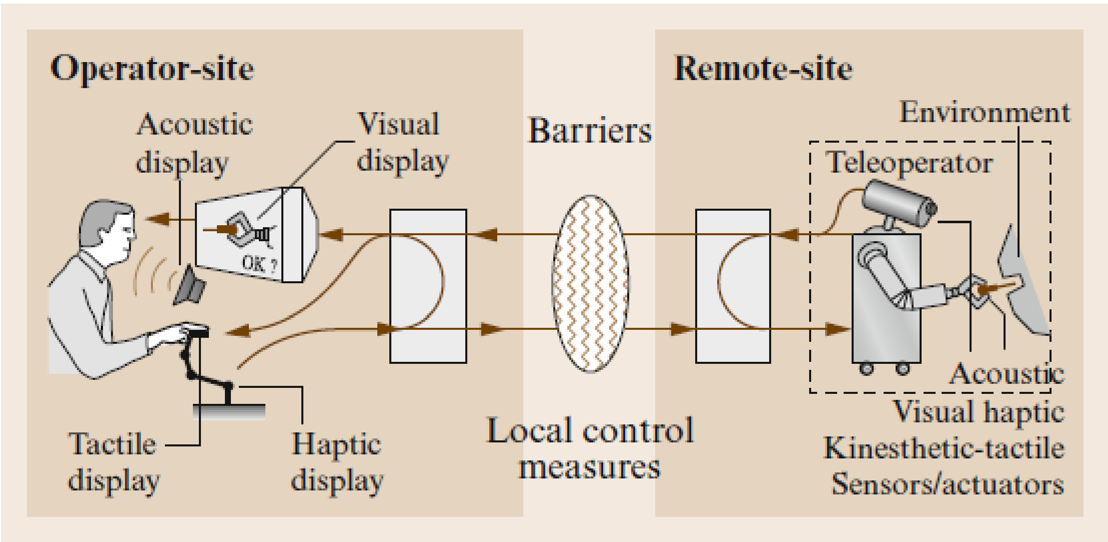

Figure 6. Conceptual separation scheme of a telerobotic system (Niemeyer et al, 2008)

The different telerobotic control architectures can be divided into three main categories based on the level of operator (Sheridan, 2002). Direct control, where the robot is fully controlled by the human operator (Niemeyer et al, 2008). Shared control is a combination of human control with automatic control based on local sensors (Hirzinger et al, 1992). Supervisory control delegates to the robot a high degree of autonomy, e.g., the robot receives a target from the human operator yet, plans and executed the motion to the target autonomously (Sheridan, 2012). Various combinations of these basic architectures can be found in practice.

2.5.1 Applications

Raymond C. Goertz was the first to use teleoperation in his nuclear research during the forties and fifties of the last century (Goertz and Thompson, 1954). His system introduced the first master-slave telerobotic system and gave a human operator control of radioactive substance behind a defensive barrier. Later on Goertz replaced the system's direct mechanical mechanism that included cable connections in a servo-electric mechanism (Figure 7).

Figure 7. Raymond C. Goertz using electrical and mechanical teleoperators to handle radioactive substance (Goertz and Thompson, 1954)

The use of medical telerobotic systems allow conducting invasive procedures through small incisions for minimizing the trauma inflicted to the patient. In 2000, the "Da Vinci" telerobotic system (Figure 8; Intuitive Surgical) was the first commercialized system approved by the American health administration for performing telerobotic surgeries on human beings (Sung and Gill, 2001).

Figure 8. The Da-Vinci telerobotic surgical system (Sung and Gill, 2001)

Telerobotic applications in space started in the sixties with the US space race, when NASA designed telerobotic vehicles for landing and performing missions on the moon (Sheridan, 2002). In 2003, two telerobotic vehicles developed by NASA, Spirit and Opportunity, were sent to mars on a research mission (Figure 9). Due to extreme time delays in communication between the vehicles and their operators back on earth (average of 8 minutes delay), a supervisory control architecture was implemented (Preusche and Hirzinger, 2007).

Figure 9. Spirit, a NASA's space vehicle

2.5.2 Transparency and telepresence

Current research in telerobotics strives to achieve full transparency and telepresence. In remote exploration tasks, the human relies mostly on visual feedback in order to investigate and analyze the environment. Haptic feedback is required for assisting manipulation and interaction with objects (Preusche and Hirzinger, 2007). Several challenges prevent achieving full transparency in telerobotic systems: time delays between operator and remote sites (Mackenzie and Ware, 1993; Niemeyer and Slotine, 2004); Data loss due to limitations of the communication channel, e.g., losses in packet-switched networks (Hokayem and Spong, 2006); Discrepancies between operator and robot due to differences in attributes such as shape, degrees of freedom, and size.

Human performance of motor tasks in interactive systems decreases when transparency is reduced. The decline in performance with delay of visual feedback can be explain by including delay magnitude in Fitts index of difficulty. Fitts law is a model of the human movement that predicts that the time to get to a certain point is a function of the distance to the point and its size (Fitts and Paul, 1954). Delay in haptic feedback also decreases human performance but in contrast to the model for delayed visual feedback, it is essentially impossible to perform remote manipulation with delayed haptic feedback since forces in unexpected times act as significant disturbances (Sheridan, 2012).

2.5.3 Communication middleware

The use of the internet to transmit information between locations is an important tool in the development of telerobotic systems due to the low cost and high accessibility of this infrastructure (Niemeyer and Slotine, 2004; Hokayem and Spong, 2006).

Service oriented architecture (SOA) is a paradigm where applications are determined as services and can be remotely accessed via the internet by other applications (clients) that need the functionality that they can provide (Laskey and Laskey, 2009). Services are loosely coupled with other services. Clients are not required to have knowledge regarding service functionality works, which allows flexibility when choosing service providers, gives stability to architecture developers as service functionality is known and a-priory determined, and allows multiple access to several services that together help find solutions to business problems (Valipour, et al, 2009). While providing sound mechanisms for development of distributed applications, the components in SOA-based systems remain closely tied and must be determined a-priori.

In a data driven programing, the data required by and provided by each component within the domain is the driver of the system functionality. Each component within the domain can send out data that it is able to produce, and can select what data it wishes to receive. The main features of a data driven communication middleware include (Zhang, 2005):

- Easy implementation - there is no need to map connections between different applications.
- Efficiency - data is published only once to certain data structures, and access to these data structures are available to whomever needs it
- Resilience - the lack of connections between components within the domain allows easy extraction and addition of applications.

With the advent of data-centric programming frameworks, development of loosely tied, decentralized systems has been largely simplified. The multiple options of controlling the quality of communication service, along with ease of implementing flexible communication networks, make data-centric development suitable for real-time control systems and thus an alternative to SOA for developing telerobotic applications.

The Data Distribution Service (DDS) is a publish/subscribe communication middleware that provides a protocol and API standard for data-driven systems. DDS's data centricity ensures that all messages include the contextual information the application needs to understand the data it receives. A DDS domain participant represents the local membership of the application in the domain, which represents the communication plane. The domain participants communicate with each other through affiliated publishers and subscribers that write and read data to data-structures termed topics. DDS abstracts one-to-many communication providing asynchronous communication between a publisher and its subscribers. It supports building and integrating distributed applications, while maintaining the composing parts loosely coupled, and independently evolvable (Pardo-Castellote, 2003).

3 Development of the telerobotic system

3.1 System design

The Telerobotic system used in the experiment comprises three hardware components: Two Phantom Premium 1.5 haptic devices fitted with finger thimbles (Geomagic, USA). Each device has 3 degrees of freedom of force (input) and position (output); A UP6 robotic manipulator (Motoman, Japan), with 6 degrees of freedom; A controlled jaw gripper, AVG 55 (Schunk, Germany) with aperture from 0-100 mm.

The telerobotic system was divided into two sub-systems (Figure 10): the controller sub-system included the two Phantom devices situated together in a custom-made wooden crate. Each device is connected to a computer via two parallel port (EPP) interfaces. The controlled sub-system included the UP6 robotic manipulator and the controlled jaw gripper, which was attached to the robotic manipulator's endpoint. The robotic manipulator is controlled by a NX-100 controller, which is connected to a computer via RS232 serial communication. The gripper's controller is connected to a computer through an input\output component, via a USB port.

The thumb and index finger of the operator's right (dominant) hand were placed inside finger thimbles attached to the Phantom devices. The robotic gripper aperture was controlled by the finger aperture (between both phantoms end effectors; Equation 2) and the tool center point (TCP) along a single axis, either towards the object or along the vertical direction, was controlled by the center of the human aperture. The transmission delays of the robot and gripper were 600, and 300 msec respectively due to robotic control cycle limitations.

$$2.\quad finger\ aperture = \sqrt{(xr - xl)^2 + (yr - yl)^2 + (zr - zl)^2}$$

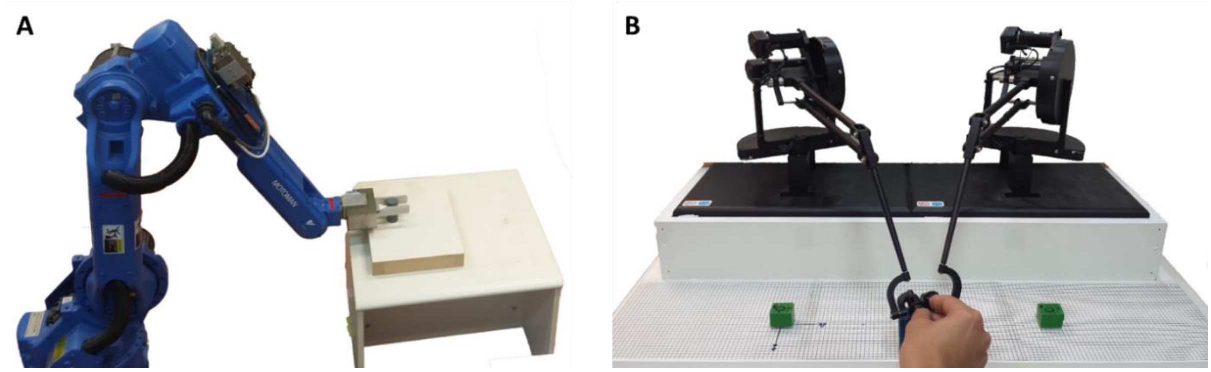

Figure 10. Telerobotic system; A: Robotic manipulator, Controlled jaw gripper; B: Phantom devices

3.2 Communication middleware

The system's communication middleware was implemented using DDS. The communication design includes a domain participant for each hardware component, and one topic. The Phantoms participant writes data to the topic and the Gripper and Robot participants read the data from the topic (Figure 11). The topic consist of eight variables: the x, y, and z position values for each phantom end-effector, the computed distance between the phantoms end-effectors, and an indication of the current experiment phase (Table 1). Data was recorded using RTI's recording service, a DDS extension that allows recording all the data published to topics within a domain, and later on converting the saved data into csv files. Quality of service was determined so that there was no history buffer for the topic, and joining applications receive only the current and updated information available within the topic.

Table 1. Data struct variables

Name	**Type**	**Description**
xr	float	Coordinate x for right phantom
yr	float	Coordinate y for right phantom
zr	float	Coordinate z for right phantom
xl	float	Coordinate x for left phantom
yl	float	Coordinate y for left phantom
zl	float	Coordinate z for left phantom
opening	float	Distance between right and left phantom endpoints
mode	short	Current experiment stage

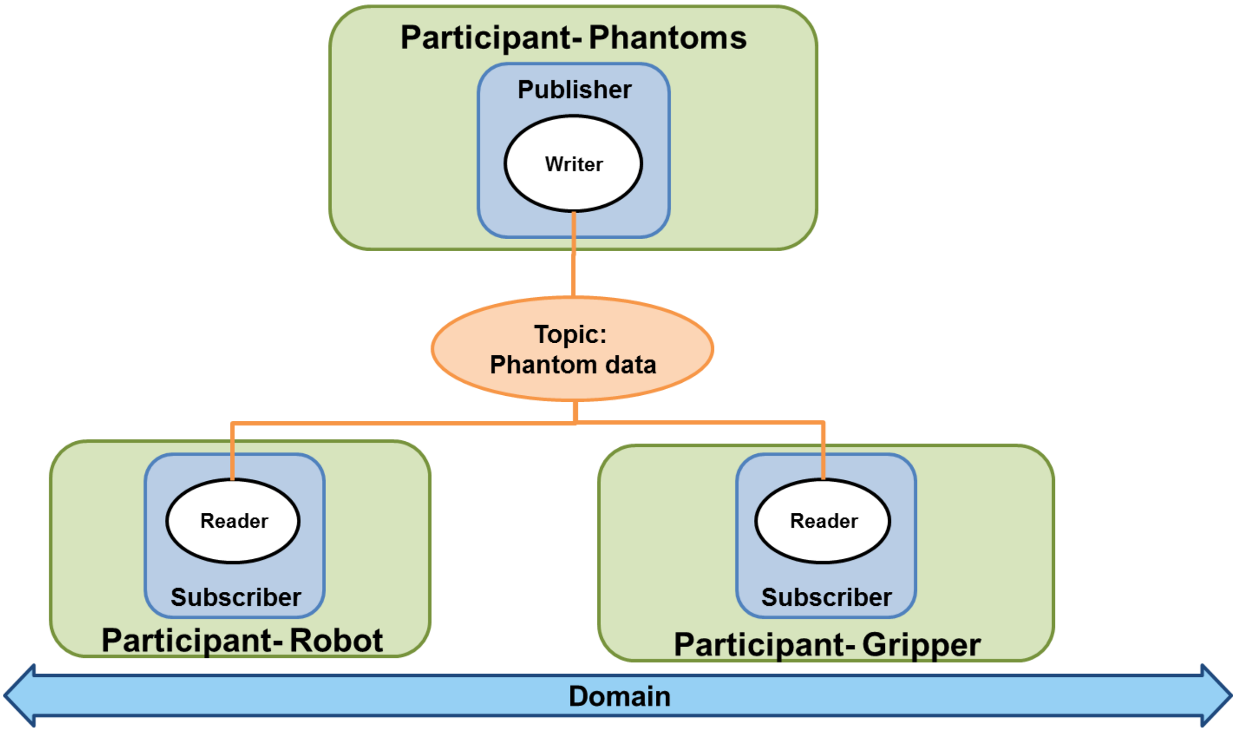

Figure 11. DDS communication scheme

3.3 Code documentation

Code was written in C++ and was integrated with generated projects from the RTI code generator that include the communication setup code. Three software components were developed (for the Phantoms interface, robot, and gripper). In the Phantoms application, communication with the devices was done via the Open Haptics API. Calibration of the devices was executed by first setting each finger thimble on its green placemat (Figure 12), which marks the position where the devices define the (0, 0, 0) coordinates. This serves as a reference position when starting the phantom application. After conducting a reference setup process, the Denavit–Hartenberg (DH) parameters were used for computing the position and orientation of both device in a single coordinate frame. Data was sent from the Phantoms\ application to the Phantom topic in a constant rate (100 HZ).

Figure 12. Phantoms interface

In the Robot application, data was received from the Phantom topic in a constant rate of 1.67 HZ. The robot's position was determined by translating the center between the phantoms end effectors to the robot's coordinate frame (Figure 13; Equation 3). Communication with the NX-100 controller was done using MotoCom robotic communication library. The robot's movement depends on a threshold of minimum distance between its current position, and the desired position.

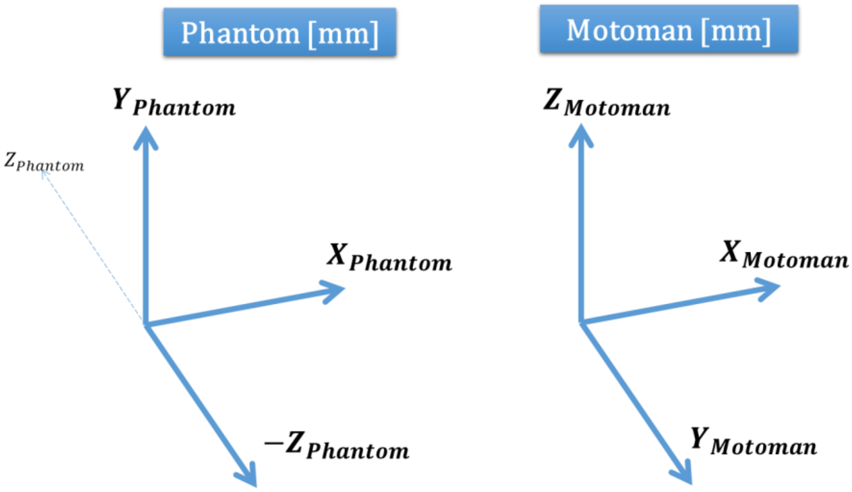

Figure 13. Transformation of position coordinates from the phantoms axis world to the robot's axis world

3. $$X_{motoman} = (X_{phantom} - 165_{mm}) * scale$$

$$Y_{motoman} = (-Z_{phantom} + 70_{mm}) * scale$$

$$Z_{motoman} = (Y_{phantom} - 50_{mm}) * scale$$

In the Gripper application, data was received at a constant rate of 3.33 HZ. The adjustment of the gripper's aperture according to the phantoms aperture was done in discrete steps. Pre-determined programs were written into the gripper's controller used to close or open the gripper in three different step sizes (step size and speed vary), and an additional program was used to close the gripper's aperture completely (Table 2). The gripper's application detected which program should be called according to a comparison between the actual gripper aperture (received via the controller's API) and the human aperture.

Table 2. Phrase programs of gripper's controller

Action	**Input 1**	**Input 2**	**Input 3**	**Input 4**	**Details**
Referencing	Low->high	Low	Low	Low	Open gripper completely (100 mm)
Program Phrase 0	Low->high	high	Low	Low	Close gripper completely (0 mm)

Program Phrase 1	Low->high	Low	High	Low	Open gripper incrementally by 2.5 mm in speed of 133 mm/s
Program Phrase 2	Low->high	high	High	Low	Open gripper incrementally by 15 mm in speed of 266 mm/s
Program Phrase 3	Low->high	Low	Low	High	Open gripper incrementally by 30 mm in speed of 399 mm/s
Program Phrase 4	Low->high	high	Low	High	Close gripper incrementally by 2.5 mm in speed of 133 mm/s
Program Phrase 5	Low->high	Low	High	High	Close gripper incrementally by 15 mm in speed of 266 mm/s
Program Phrase 6	Low->high	high	high	High	Close gripper incrementally by 30 mm in speed of 399 mm/s

4 Experiment

4.1 Apparatus

Subjects sat about 2000 mm from a robotic manipulator outside the robotic work-volume. A small table was placed in front of the robot inside the robot's work-volume for placing objects. The objects used in the experiment were five cylinders with 20-40mm diameter (5 mm increment) termed according to size XS, S, M, L, XL objects (Figure 14).

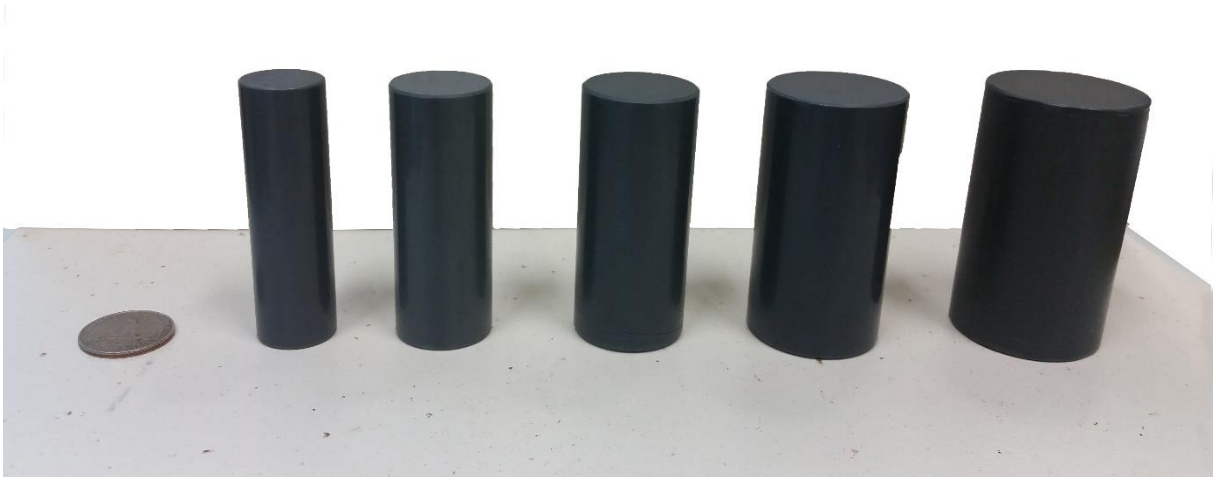

Figure 14. Objects, Cylinders used in experiments

4.2 Subjects

21 healthy right-handed subjects (age 18-28 years, average 24.1, 10 male) participated in the experiment. Subjects had normal or corrected-to-normal vision with no neurological, sensorimotor or orthopedic impairments. The subjects were divided into two groups, where each performed the experiment in one of two orientations, alongside with robot and human motion directions aligned (11 subjects) and across with robot and human motion directions mirrored (10 subjects; Figure 15). The Human Subjects Research Committee of Ben-Gurion University of the Negev approved the experimental protocol.

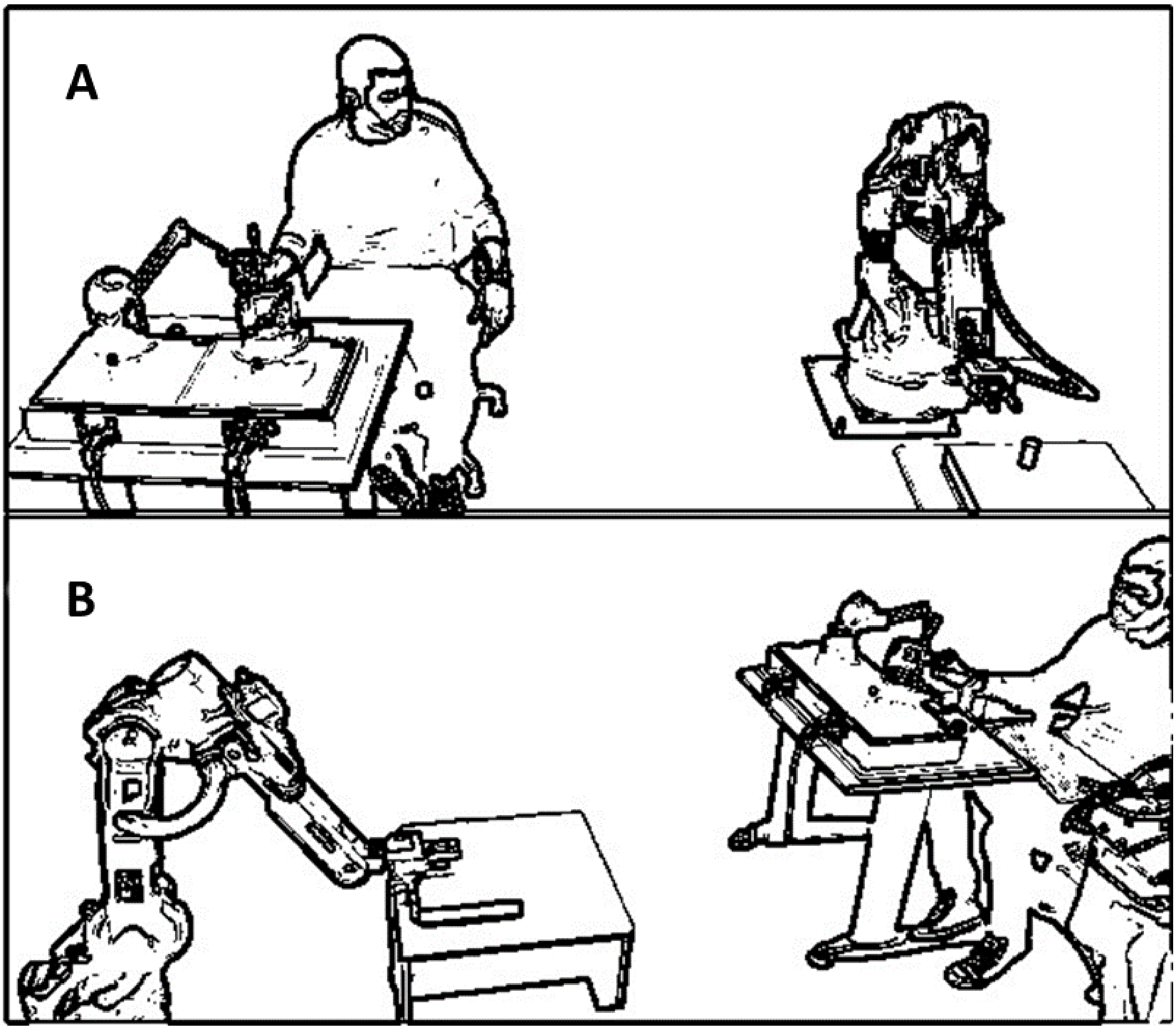

Figure 15. Spatial orientations. A: Alongside; B: Across

4.3 Experimental procedure

Before the beginning of the experiment, subjects practiced remotely grasping a cylinder placed on the table using the robotic system. This was done for several minutes until they reported feeling comfortable with the task. Subjects were then asked to demonstrate a reach-to-grasp motion to the robot, while their fingers remained in the phantom thimbles. During the demonstrations the robot or gripper did not move. Each demonstration comprised three stages: initiation, reach-to-grasp, return. During the initiation stage, the subject placed his fingers in the initial position (Figure 16) and closed his eyes while the experimenter placed one of the cylinders on the table in front of the robot. During the reach-to-grasp stage, the subject opened his eyes and demonstrated a reach to grasp movement in a 4.2 sec time window. During the return stage, the subject returned to the initial position. During the reach-to-grasp phase, subjects controlled the robot only in one axis (towards the object). During the lift phase, subjects were able to move the robot between two positions along the vertical axis, a position above the table and a position on the table. Motion towards each position started after the hand's vertical position passed a threshold (100mm above/below the low/high position). Transition between stages was marked by a computerized audio cue. The subjects performed 15 repetitions of the task for each object, i.e., 75 movements in total. Cylinder presentation order was semi-random, with two different random sets for each orientation, meaning half of the subjects in each orientation group performed the experiment with one of the sets. Subjects rested twice during the experiment after one third, and two thirds of the trials.

Figure 16. Initial position

4.4 Data analysis

Analysis was performed on the reach-to-grasp stage only. Motion profiles were filtered using a low-pass Butterworth filter (n=3) with a 5.54 Hz cutoff. Four movement phases were determined according to movement speed: movement start, end of aperture opening, start of aperture closing, and movement end (Figure 17). Movement start and end of aperture opening were determined as the time at which the aperture opening speed exceeded (decreased) and remained above (below) 10% of the peak opening speed for 0.1s. The start of aperture closing and movement end were determined as the time at which the aperture closing speed exceeded (decreased) and remained above (below) 10% of the peak opening speed for 0.1s.

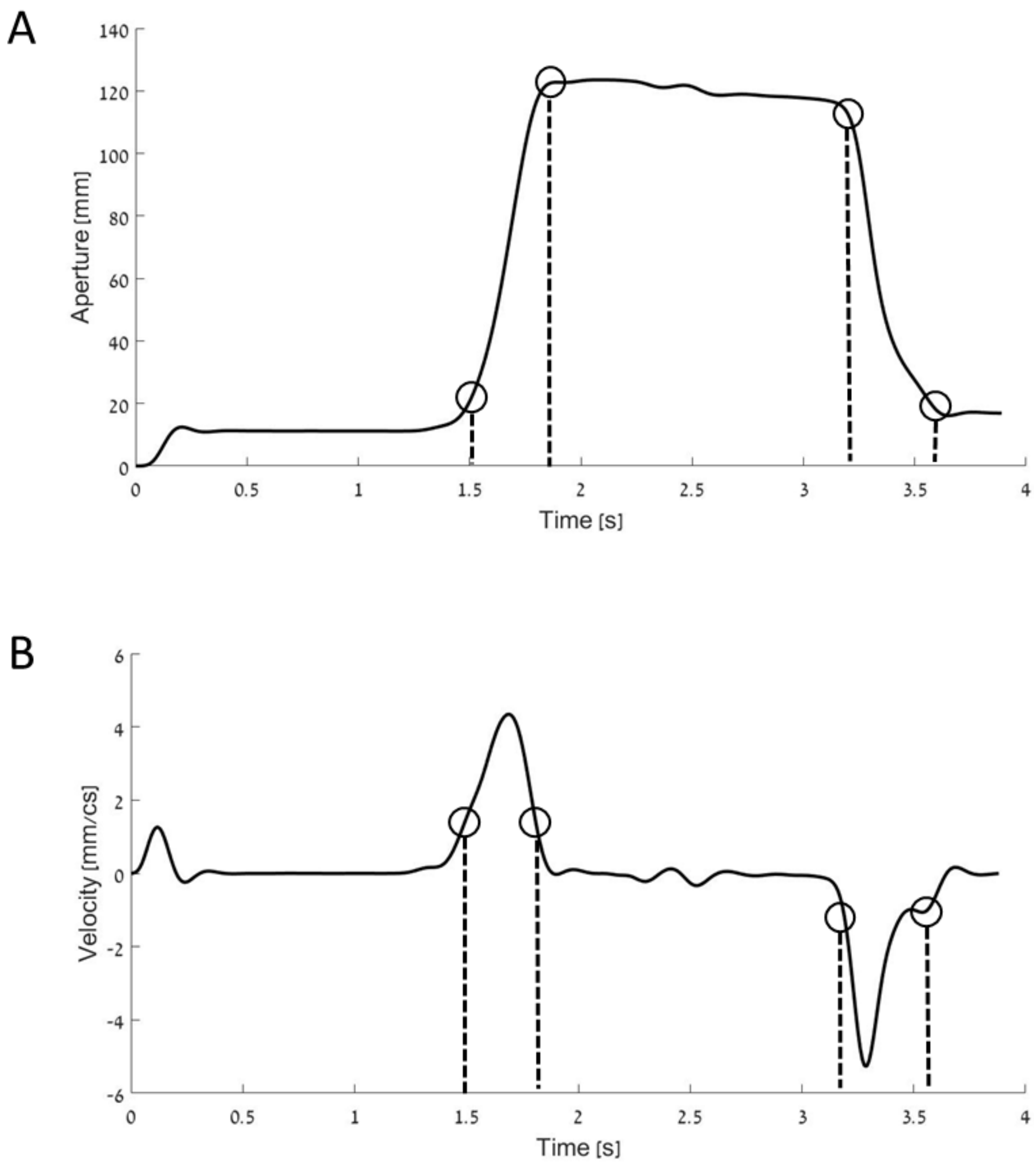

Figure 17. Segmentation of the reach-to-grasp motion: A. motion profile; B. velocity profile

MGA was computed over the aperture between movement start and end. Initial grip aperture (IGA) was determined as the aperture after the end of the opening, when aperture speed additionally decreased to 3.3% of the mean maximum aperture opening speed over all subjects. This value was chosen to ensure that aperture speed at IGA is not related to object size and that IGA was found after the end of the opening time. The constant speed at IGA was selected so aperture variability is not affected by speed, which may lead to an indirect dependence on object size (Ganel et al., 2014; Ganel, 2015).

Several movement descriptors were computed (Figure 18). Task duration (TD), the difference between movement end and movement start. Opening time ratio (OTR), the difference between the end of aperture opening and movement start divided by TD. Aperture transport time (TT) the difference between the beginning of aperture closing time and the end of the aperture closing time and aperture transport time ratio (TTR) which is TT divided by TD. The scaled sagittal TCP transport distance (STCPD) calculated as the difference between the TCP position at movement start and end normalized by the robot movement scaling-factor (2.2). The MGA slope angle calculated from the regression line fitted for every subject to the mean MGA across the different object sizes.

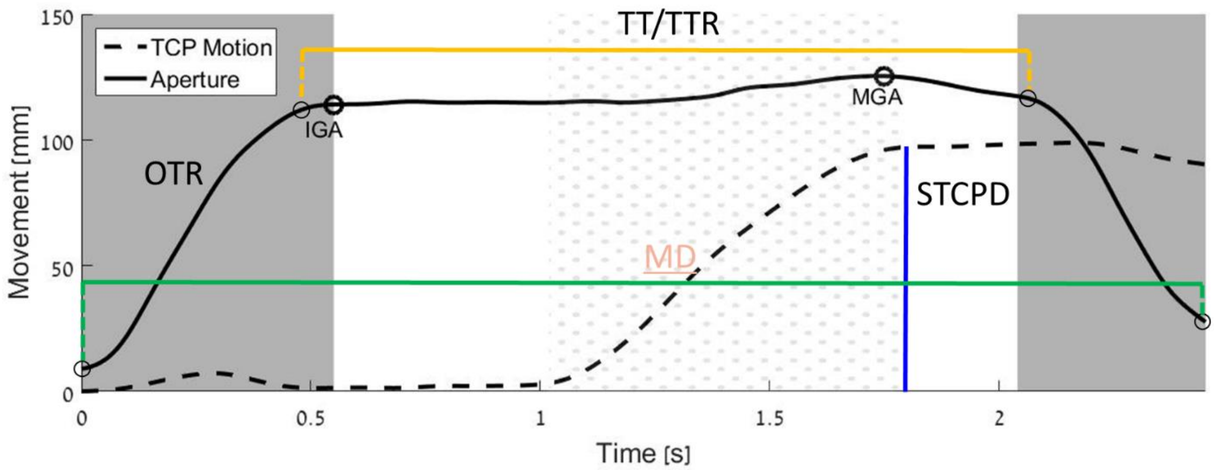

Figure 18. Movement descriptors applied on a motion profile example

4.5 Statistical analysis

Outliers for every subject were determined using the Interquartile Range (IQR) of the MGA. Subjects were excluded from the analysis if they had more than 10 failures (failure to complete the task within the designated time window) or when their mean MGA did not follow a linear trend across objects, i.e., when statistical analysis showed they were not sensitive to object size (Ganel et al., 2008). A repeated measure ANOVA analysis was conducted for MGA, IGA, TD, OTR, TT, TTR, STCPD, and Slope with orientation (Alongside, Across), and set as factors. A confidence interval was additionally determined for the mean STCPD. A linear trend analysis was used to show significant linear increase in variability in accordance to object size for MGA and IGA.

4.6 Analysis procedure

Data and statistical analysis was done using R programming language and MATLAB. The R and MATLAB scripts performed analysis in three levels: per reach-to-grasp motion, per subject and per a group of subjects.

The R-based analysis procedure was performed sequentially for each subject. Experiment data was read from the data file generated by RTI recording service, a low pass filter was applied to the motion profiles, reach-to-grasp motions were segmented according to movement speed, and outliers are marked using the IQR method. A main result analysis file was generated by the R script. In included: General features of the current subject (subject id, object order, gender, aperture size, and age); Features of each motion (object size, trial number, whether outlier or not, indices of segmentation within motion, opening time, transport time, movement duration, and start and end indices of forward arm motion); and the aperture during the reach-to-grasp motion. An additional result file was created with values of the arm motion, used later to create motion profiles of aperture and arm movement simultaneously.

A MATLAB script unified all the data into one result file, and computed IGA and MGA per reach-to-grasp motion. Information of subject id and orientation of the experimental setup were also added to differentiate between records within the database.

For the statistical analysis, a linear trend analysis test was written in R. Coefficients used for the linear components of the trend analysis were [-2, -1, 0, 1, 2] for object sizes arranged from smallest to largest respectively. IGA and MGA across object size for each subject were used as data for the linear trend analysis test, to exclude subjects that did not comply with a linear rise of object size. The standard deviation of IGA and MGA per object size for all subjects was used as data for a linear trend analysis test, this to show compliance to Weber's law. The test was conducted also for groups of subjects, determined according to motion descriptors. A repeated measure ANOVA analysis was conducted for motion features along with experimental setup orientation using R function 'anova' from the 'stats' library. A confidence interval for STCPD was computed using the 'qt' function from the 'stats' library.

All visual aids concerning the research (motion profiles, mean of mean IGA and MGA in accordance to object size, mean of standard deviation of IGA and MGA in accordance to object size) were created using MATLAB and code is documented within a MATLAB script.

5 Results

All subjects succeeded in completing the task. Three subjects (alongside orientation group: 1; across orientation group: 2) were excluded as statistical analysis showed they were not sensitive to object size (they did not show a linear increase for MGA as a function of object size). For the remaining subjects, (10 alongside, 8 across) failures and outlier's percent ranged from 0-8 (Table 3), over all .232 (percent). Additionally for these subjects both IGA and MGA increased linearly with object size.

Table 3. Exclusion percentage per subject

Across orientation		**Alongside orientation**	
Subject ID	**Exclusion [%]**	**Subject ID**	**Exclusion [%]**
1	0.00%	11	8.00%
2	2.67%	12	2.00%
3	2.67%	13	2.00%
4	2.67%	14	0.00%
5	2.67%	15	4.00%
6	4.00%	16	1.00%
7	2.67%	17	2.00%
8	2.67%	18	2.00%
9	0.00%		
10	1.33%		

The majority of movements (55.17%, 741 movements) described a grip formation that had three stages: opening, transport, and closing. During the transport stage, the aperture remained relatively constant. Remaining movements did not include the transport phase. Four subjects performed the motion consecutively, i.e., they started with opening (finger stretching), then they moved forward towards the object (arm motion) during the aperture transport stage, and then they closed their fingers (Figure 19, A and B). Eleven subjects performed parts of the task concurrently, i.e., they opened the aperture and moved forward toward the object, and then they closed the aperture typically without arm motion forward (Figure 19, C). In some of the movements, these subjects did not have an aperture transport stage, i.e., their motion more closely resembled motion in natural conditions (Figure 19, D). The remaining three subjects had movements of both types (sequential and consecutive).

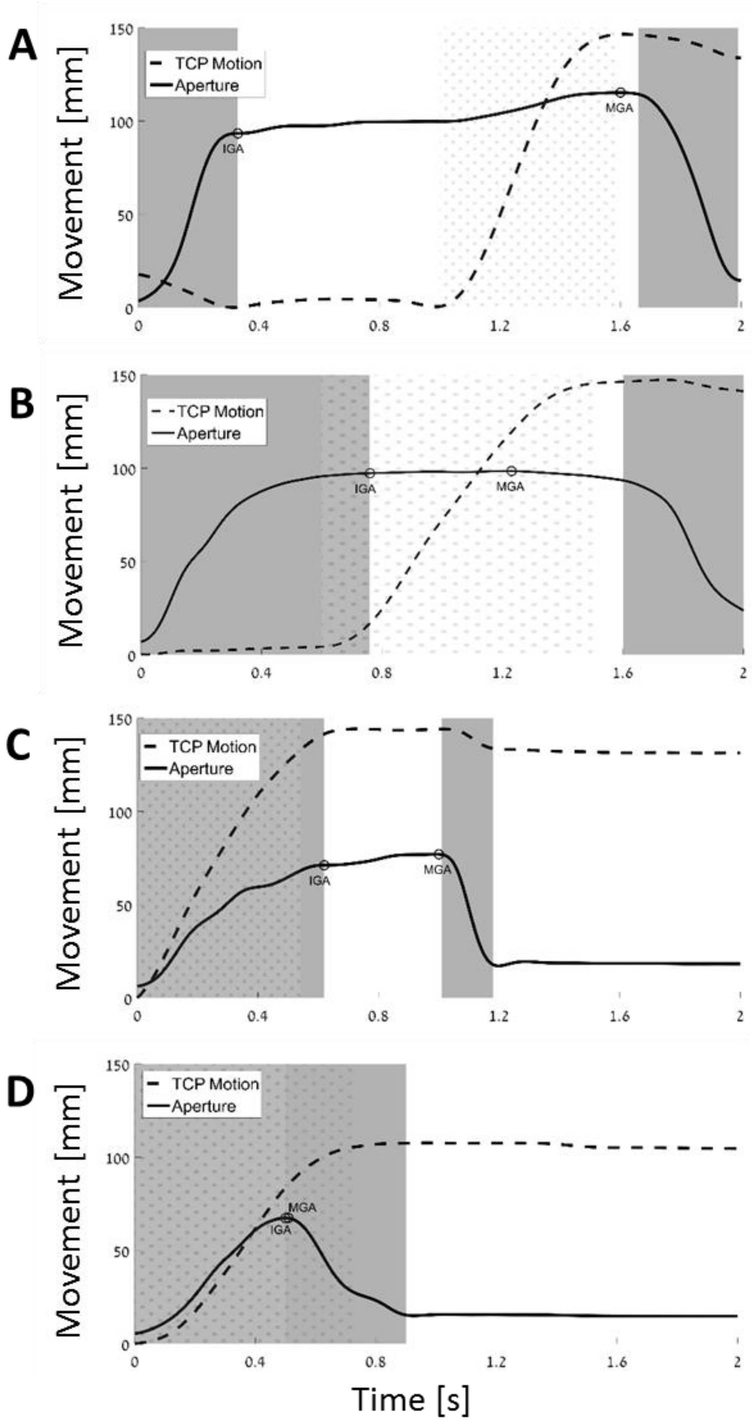

Figure 19. Representative motion profiles of reach-to-grasp movements. Sagittal tool center point (TCP) - dotted line, and aperture – full line, presented. A: Alongside, object L (Subject 13). B: Across, object XL (Subject 8). C: Across, object M (Subject 7). D: Alongside, object L (Subject 15). Grey background marks aperture opening and closing epochs. Dotted background marks TCP motion epochs

Average movement duration (MD) was 1.45 sec (0.53 SD), which is much faster then was shown for remotely controlling the robot in an equivalent task yet longer than natural reach-to-grasp motion (Jeannerod, 1984). Similarly, OTR was 32%, which is a larger percent of the motion time than found in the control task (Table 4). ANOVA tests conducted showed that subject motion measures (MGA, IGA, TD, OTR, TT, TTR, STCPD, and Slope) were not affected by the two spatial orientations and across all four sets.

Table 4. Mean values for motion descriptors, standard deviation (SD) values in parentheses

	MD [sec]	OTR [%]	TT [sec]	TTR [%]	Slope [deg]	STCPD [mm]
All Subjects	1.45(0.53)	32(17)	0.67(0.49)	40(24)	56.5(13.4)	276.1(83.3)
Mirrored orientation	1.51(0.45)	28.3(15.2)	0.74(0.4)	46.5(19.6)	59.4(12.9)	291.6(85)
Alongside orientation	1.37(0.91)	37(18.3)	0.57(0.33)	32.7(26.2)	52.9(14)	256.8(77)

A distinction between subjects was found based on descriptive measures as three subjects had a very short mean MD (subjects 14, 17, and 18 with a mean MD below 1 sec; Table 5) in comparison to the other subjects. The average MD for the remaining 15 subjects was 1.58 sec with a standard deviation of 0.39. A different distinction based on TT was found as eight subjects had a short mean TT (subjects 1, 2, 7, 10, 14, 15, 17, and 18 with a mean TT below 0.6 sec; Table 5) in comparison to the other subjects. The remaining 10 subjects had a mean TT of 0.96 sec with a standard deviation of 0.28.

Table 5. Mean MD, TT and STCPD per subject

Across orientation				**Alongside orientation**			
Subject ID	**MD [sec]**	**TT [sec]**	**STCPD [mm]**	**Subject ID**	**MD [sec]**	**TT [sec]**	**STCPD [mm]**
1	1.15	0.19	286.1	11	2.3	1.42	198.7

2	1.3	0.57	267.6	12	1.39	0.68	166.6
3	1.41	0.74	291.1	13	2.05	1.31	356.8
4	1.4	0.85	332.5	14	0.82	0.05	240.7
5	1.96	0.88	277.1	15	1.25	0.19	200.6
6	2.1	1.18	164.4	16	1.61	0.73	216.9
7	1.19	0.5	290.4	17	0.88	0.16	306.4
8	2.03	1.22	381.2	18	0.67	0.06	367.2
9	1.28	0.73	440.5				
10	1.31	0.56	184.3				

The spatial control parameters, i.e., MGA, IGA, and STCPD were larger than the values required for controlling the robot. MGA and IGA were larger than MGA and IGA values used in a previous experiment for controlling the robot (Figure 20). Mean STCPD was 271.7-280.6 mm (95% confidence interval). Taking the length of the fingers of the gripper into account the actual distance required for performing the grasp is 180-270 mm. Thus, STCPD is larger than the required forward movement distance. Only six subjects had a mean STCPD value that is within the 180-270 mm range of a successful reach-to-grasp motion (Table 5).

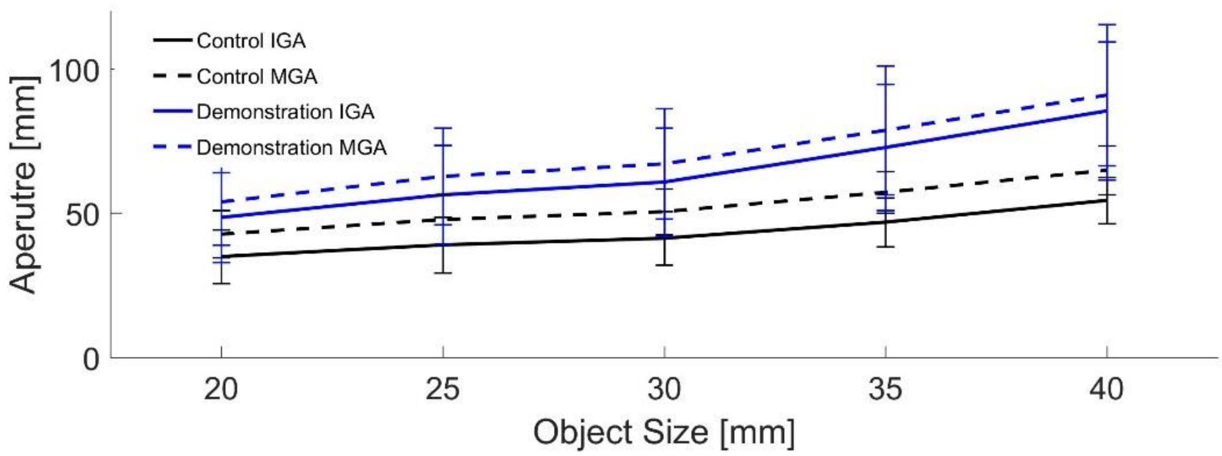

Figure 20. Mean of mean MGA across objects size (SD marked by crosshair). Grasp control aperture based on remote controlled experiment data

Across all subjects (18 subjects overall) IGA did not increase linearly with object size while MGA had a marginal linear trend ($F(1,84)=1.76$, $p<0.1$). When testing across all subjects excluding three subjects with short MD (15 subjects all with MD>1 sec), IGA had a marginal linear trend ($F(1,69)=1.79$, $p<0.1$) and MGA increased linearly with object size ($F(1,69)=2.07$, $p<0.05$) (Figure 21, top). For subjects with a prolonged transport time (10 subjects all with TT>0.6 sec) both IGA and MGA linearly increased with object size (IGA: $F(1,44)=2.32$, $p<0.05$; MGA: $F(1,44)=3.09$, $p<0.01$; Figure 21, bottom).

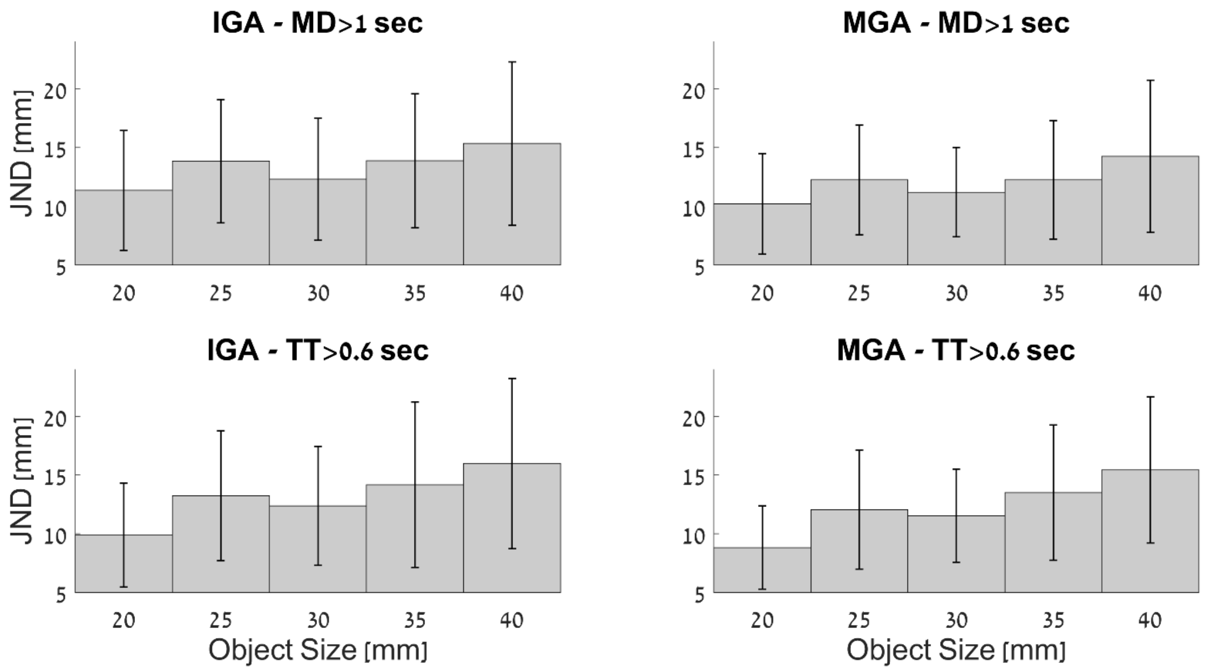

Figure 21. Mean of standard deviations (SD marked by crosshair)

6 Discussion and conclusions

Prior to the experiment, subjects practiced tele-operating the system for a few minutes, in order to give them a comprehension of the telerobotic system characteristics. The telerobotic system incorporated substantial transmission delays of the robot and gripper of 600, and 300 msec respectively due to robotic control cycle limitations. It has been shown that performing a task while encountering sensory feedback delays leads to adaptation to the delays (Foulkes and Miall, 2000; Farshchiansadegh et al., 2015; Rohde and Ernst, 2016).

Comparison to previous studies show that the average MD was longer than average MD found in natural reach-to-grasp motions (Jeannerod, 1984; Marteniuk et al., 1990), and much longer than MD achievable within the robot's abilities. Average STCPD was larger than the distance required to reach the object, as the lower value of the confidence interval (271.7 mm) was larger than the distance between the robotic manipulator end effector and the object, while taking into account the gripper's finger length (180-270 mm). The average IGA and MGA computed per object size were considerably larger then object width, as well as larger than average IGA and MGA found in the experiment where the robot was actually remote controlled. Despite the differences from natural and remote reach-to-grasp motions, data from this experiment was used as the basis for successful implementation of programming a robot by demonstration (Davidowitz and Berman, 2016).

Most motion profiles of the reach-to-grasp movements presented a third, transport phase between opening and closing of the aperture, in similar to motion profiles from the remote controlled experiment. Average MD, OTR and TTR were in between values found in the mentioned above experiment and in natural grasping scenarios (Jeannerod, 1984; Marteniuk et al., 1990). These results show that the motion profiles presented in this experiment are an intermediate between natural and remote controlled reach-to-grasp profiles.

Motion profiles and movement descriptors point out that most subjects acquired movement characteristics in accordance to the inherited time delay of the telerobotic system, which was noticed during the training phase of the experiment. It seems subjects have mistakenly assigned the temporal control error to system dynamics rather than to the control transmission, and tried to compensate for the sensory delay by slowing down their movement (Rohde and Ernst, 2016), even though they were only gesturing to the robot, and not actually tele operating it.

Setting up the user interface of the system in different spatial configurations, across the robot so that the visual perspective of the object is better, and an alongside orientation were the subject's movement directions are aligned with the robot's movement directions, did not have any statistically significant effect on the subject's motion descriptors. It is important to add that the lack of effect of spatial configuration might be attributed to the fact that the system incorporates a large time delay, which as suggested earlier might influence subjects behavior in the practice session and therefore mask the results. The effect of the spatial configuration on the division of subjects according to motion profile types (sequential or consecutive) is not apparent as well as subjects with motion profiles of both types were distribute equally between the different orientations.

When taking into account all subjects (18 subjects in total), findings showed a linear correlation between the standard deviation of the MGA to object size, in accordance to Weber's law. The adherence to Weber's law is clear when excluding three subjects (15 subjects in total) who moved considerably faster than average (MD $<$ 1 sec). The occurrence of a transport phase when demonstrating reach-to-grasp motions to the robot promoted assessing JND based on the aperture variability at the end of the opening phase (IGA) and not based on the MGA. Subjects that had an significantly long average TT (TT $>$ 0.6 sec; 10 subjects in total), so that most of their motion profiles were fragmented into three phases with a long transport phase, adhered to Weber's law based on the IGA variability.

The resemblance between these findings and previous findings of pantomimed reach-to-grasp movements (Goodale, Jakobson, and Keillor, 1994; Milner, Ganel, and Goodale, 2012; Whitewell et al., 2015) or grasping during teleoperation with transmission delays (Sagi et al., 2015) might suggests that subjects processed information using the cognitive ventral pathway and not the dorsal pathway. This undermines the naturalness of the gesture-based interface used.

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Appendix A: Publications

The telerobotic system was presented under the title "A data driven telerobotic system" in a lecture at the 5th Israeli conference on robotics held in Herzliya (April, 2016).

Publications based on this thesis include a poster under the title "Weber's law during remote reach-to-grasp demonstration" in the Sensing: From Minds to Machines, and the Computational Motor Control Workshop (CMCW) conferences that were held at Ben-Gurion university (May-June, 2016), and a submitted article under the title "Assessing transparency of a gesture-based interface for programming by demonstration" for journal publication.

The telerobotic system and methods developed in this thesis also contributed to work conducted by Mr. Omri Afgin on examining Weber’s law in telerobotics. This work was published in three posters titled "Weber's law during remote grasping" in the International Conference on Intelligent Robots and Systems (IROS), Hamburg, Germany (September, 2015), Sensing: From Minds to Machines, and the Computational Motor Control Workshop (CMCW), Ben-Gurion university (June, 2016), as well as an article titled "Remote grasping with communication delays adheres to Weber's law" submitted for journal publication.

Appendix B: Assessment and control experiments

Prior to conducting the experiment described in this thesis, the following experiments were held using the telerobotic system, as part of Omri Afgin's thesis. The objective of these experiments was to examine occurrence of Weber’s law in a remote control scenario. This research shares the telerobotic system, data collection and data analysis methods with the current research.

The spatial separation between the perception and execution inherent in remote environments provides an opportunity to examine the different account for the lack of Weber’s law in grasping. It can also contribute to improve design of telerobotic systems interface.

The experiment comprised of two tasks, perceptual assessment and grasp control, each conducted in two spatial configurations, alongside, and across the robot. In the assessment task, subjects were asked to indicate the cylinder’s width by opening the gripper to an equivalent aperture. In this task only the gripper opening was controlled and the robot manipulator did not move. In the grasp control task subjects were requested to grasp and lift the object in three consecutive stages, reach and grasp the object, raise the object and place it back on the table, before releasing the object and returning to the initial position.

In the control condition, subjects motion had a prolong grasp transport stage between the end of the grasp opening and the beginning of the grasp closing. Therefore, the aperture after the end of the opening stage, the initial grip aperture (IGA), was chosen as an indicator of the JND rather than the maximal grip aperture (MGA), which is susceptible to fatigue and vibration fluctuations under tele-operation control.

Results show that IGA adheres to Weber’s law, while MGA does not. Adherence to Weber’s law in remote grasping with communication delays is in-line with the hypotheses regarding the functional separation of visual information processing underling action and perception, although the contribution of haptic perception cannot be ruled out.

Appendix C: Instructions for operating the system

Phantoms: Put both phantoms end-effectors on respective calibration points (green squares), exactly on the mark. Launch the phantoms application (shortcut on desktop), perform calibration for both phantoms by pressing enter when prompt. Inform user to control the interface by putting on the phantoms thimbles, and placing his hand on the initial position (blue square). Select type of experiment (Assessment, Control or Demonstration) and press enter. The phantom interface is ready to go, pressing enter will guide through the different stages of the experiment using an audio cue. The initial stage of the program allows free manipulation of the robot and gripper, be careful because once the robot and gripper are running, the system will be working and the robot will be tele operated.

Robot: Turn on the NX100 controller (turn handle is on the controller). Make sure that the NX100 controller is in remote mode by using the attached control pad. Also make sure that the protective fence is closed as it is designed as a safety measure, and if opened it interrupts the electric currency to the controller. Launch the robot application (shortcut on desktop).

Gripper: Turn on the electric power connected to the gripper's controller. Launch the MTS program (shortcut on desktop), click on the telephone icon to search the bus and then the goggles icon to connect to the gripper's controller. Once connection established, a new window is prompt, click on manual reference and open the grip aperture to maximum using the arrow icon, press reference to confirm. Launch the gripper application (shortcut on desktop).

תקציר

למידה מתוך הדגמה (PbD) הינו תחום ברובוטיקה המתרכז ביכולתו של האדם ללמד יכולות מוטוריות לרובוט על ידי הדגמה של המשימה הנדרשת. חשיבותו של תחום זה הוא באפשור של הוראת מטלות לרובוט ע"י בני אדם שאינם מתמחים ברובוטיקה. ממשקים נפוצים ללמידה מתוך הדגמה כוללים הקלטה של התנועה בהתבסס על שיטות כגון עיבוד תמונה, שימוש בחיישני תנועה נלבשים, הזזה פיזית של הרובוט, וממשקים טלה-רובוטים. לממשק ישנה השפעה מכרעת על ביצועי המערכת ומידת השקיפות אך למרות זאת כימות אובייקטיבי של תפקידו הינה בגדר שאלת מחקר פתוחה. במחקר זה נעשה צעד קדימה ונבחנה מידת השקיפות של ממשק רובוטי להקלטת תנועה עבור לימוד מטלת אחיזה לרובוט על ידי הדגמה. נבדקים למדו להפעיל מערכת הכוללת זרוע רובוטית ותפסנית חשמלית. לאחר אימון קצר, הנבדקים נתבקשו להדגים לרובוט תנועות אחיזה אל עבר גליל הנמצא על שולחן, מול הרובוט. תנועת היד של הנבדקים הוקלטה בעזרת שני ממשקי פנטום (Phantom Premium) עם אצבעונים מותאמים לאצבע המורה והאגודל. באמצעות גלילים בגדלים שונים (רוחב משתנה, גובה קבוע) נבדק חוק וובר לבחינת שקיפות תנועה באופן אובייקטיבי. במהלך ההדגמות, סביבת המטלה נצפתה משתי נקודות מבט שונות על מנת לבחון את החשיבות היחסית של כיווני תנועה המותאמים למשימה. עבור ביצוע הניסויים פותחה מערכת טלה-רובוטית מבוססת נתונים, מערכת להקלטת תנועה, ואפליקציות לניתוח הנתונים ולניתוח הסטטיסטי. תוצאות הראו כי נקודת המבט לא השפיעה על תנועת הנבדקים וכי הם השתמשו בפרופילים של תנועה אשר שונים בצורה מובהקת מפרופילים של תנועה בו השתמשו במשימות אחיזה טבעיות. ממצאים אלו מדגישים את המגבלות של הממשק הנבדק ואת החשיבות של אימון הנבדקים לפני הניסוי.

מילות מפתח: לימוד לפי הדגמה, חוק וובר, ממשק אדם-מכונה.

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חיבור זה מהווה חלק מהדרישות לקבלת תואר מגיסטר בהנדסה

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מנחה: ד"ר סיגל ברמן

חתימת המחבר........................ תאריך.....................

אישור המנחה.......................... תאריך.....................

אישור יו"ר ועדת תואר שני מחלקתית..................... תאריך.....................

ינואר 2017

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