

Application of Biological Control Principle in Understanding of Human Behavior Modulations

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Abstract

Biological control principle is the mechanism inherently built in human control systems allowing human to interact with its environment.

Two experimental studies in this thesis and an additional practical work on instrumentation explore the possibilities of applying biological control principle to understand and improve human performance.

The first study is concerned about driving performance. A measure named reactive index is introduced as a ratio of proactive and reactive behaviors. Proactive behavior is considered as top-down control from intention to action, and contrary reactive control is bottom-up control generated by more direct response to environmental stimuli. In an on-track driving experiment proficient drivers are observed to express more proactive behaviors, and thus lower reactive index.

The second study targets rehabilitation of post-stroke patients. Brain damage due to stroke often leaves survivors with lateral functional motor deficits. Bimanual rehabilitation of the paretic arm is an active field of research aimed at restoring normal functionality by making use of the complex neural bindings that exist between the arms. In search of an effective rehabilitation method, a group of post-stroke rehabilitation patients is introduced to a set of bimanual motion tasks with inter-manual coupling and phasing. The surface EMG profiles of the patients were compared in order to understand the effect of the motion conditions.

The third part includes an implementation of a software platform for implementing environments for behavior control. The platform is providing a systematic approach for orchestrating various sensors and actuators tasks in laboratory and practice.

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Chapter 1

Introduction

1.1 Preface

A Rubik's cube, a mechanical combination puzzle, in all of its frivolity, has been fascinating minds for generations. The solving is based on patterns which transfer the state of puzzle to another. After learning these transformations enabling the solving of the puzzle, many find challenge in solving the puzzle as fast as possible. For those who know the puzzle, the solving time of less than one minute is impressive, while the records are in order of seconds. A specialized robot can solve the puzzle in tens of milliseconds.

Some other tasks, let's say going to a kitchen and making a sandwich, would be impossible for the previous robot, although the competitive human cube solver could probably get something done. The contemporary robots are limited with the scope of the tasks they can handle. Considering the superiority of robot in the unscrambling of Rubik's cube, and projecting the same ability to tasks which would improve the quality of life or even betterment of mankind, the robot, which was good at these tasks, would be of extreme value.

These examples high-light the difference between the control in human and machine. Robots show extreme capability in limited tasks. However, when the task demands flexibility or creativity in behaviors the robots tend to fail miserably. Human control is far away from being perfect, human has limitations in the processing capability as well as restrictions on motor performance. There are many scenarios where human performance can be improved by artificial control, e.g. exoskeleton covering mechanical weakness in human body. Another approach to use artificial control to support human behaviors is by teaching "good behaviors". Robots can be very efficient on repetitive but sensitive tasks such a rehabilitating human motor behaviors. Underlying problem in both of the approaches is the need to understand human sensory-motor behaviors in a way that the robots can be integrated for collaboration.

The collaboration with human is delicate as a collaborating robot may get rejected on many levels. In order to help humans in a way they don't feel dis-

turbed, it is necessary to understand how humans behave. Computer interface designers try to avoid unnecessary questions or actions to not to interrupt the user. Similarly, when collaborating with a robot on daily living tasks the human cannot adapt to any unnatural behaviors of the robot, but instead expects the robot to adapt to human behaviors, human expects some understanding from the robot side. In order to adapt to human behavior it is essential to anticipate what the human is intending to do. Driving is an example activity, in which driver strongly expresses intention, driver want's to move to go through certain way-points and does this by giving commands on controls of the vehicle. When the driver knows where to go and is able to handle the situation, warnings and other interventions by a vehicle are not welcomed by the driver. However, if the vehicle takes-over minor parts of control to relieve pressure from a stressed driver, the driver still feels that she is not challenged at the major driving task of pointing where she wants the car to go.

Likewise, healthy human performing essential activities of daily living, like eating, taking care of hygiene and transferring are composed of sequences of intentional movements. If a person for medical condition, is not anymore able to initiate even the simplest reaching and aiming movements, the person is not anymore able to lead normal life. In case of stroke survivors most of the parts of the human body are intact, with only some local brain-damage. The intention to move cannot get past those damaged areas. If we could somehow help the intention to reach muscles to generate movement, then the stroke survivor would be a step closer to normal life.

We consider the ways to modulate biological regulation mechanisms in human for desired outcome as *intelligent behavior control*. In this thesis we investigate ways to augment human behaviors with technology and ways to make use of brain capability to reorganize for desired behaviors. We demonstrate the use intelligent behavior control principles in contexts of driving and neuro-rehabilitation.

1.2 Structure of thesis

We start by an introduction to cybernetics, a study of control and communication in the animal and machine, in Chapter 2. We survey the human neural mechanisms behind of sensing and acting on the environment. Along with the survey we investigate, how to monitor and alter the states of human nervous system at different levels. We introduce models of *neural synergy system* and *hierarchy of controllers* as a model to explain how human brain is able to deal with the overwhelming complexity of the environment. Using these models we describe a proficient driving behavior and recovery in post-stroke rehabilitation.

In Chapter 3 we investigate the roles of top-down, intention driven, and bottom-up, environment driven, controls in the driving. Based on data on a demanding driving task, we model the driving behaviors and consider ways to support unskilled driver with the model.

Rehabilitation is concerned about restoring damaged functionality. Chap-

ter 4 deals with bimanual rehabilitation for patients, who have impaired functionality caused by strokes. We develop a set of electromyography indices to characterize bimanual muscle activity. Using the indexes, we evaluate performance of post-stroke patients against performance of healthy subjects on a specific bimanual exercise device. We investigate the selection of rehabilitation task suitable for promote improvement in the patients.

We introduce a software framework to generate rehabilitation environments in Chapter 5. The environments are a set of orchestrated sensors and actuators that work on a neural rehabilitation task. We discuss possibilities and issues related to use of body area networks, internet of things and cyber-physical systems.

In Chapter 6 we give a critical and reflective assessment of the work related to thesis. Here, we discuss the outcome of the work and also the further work. The thesis is concluded in Chapter 7.

1.3 Contributions

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Chapter 2

Background

2.1 Cybernetics

In his book “General System Theory” [230] Bertalanffy explains how the view of organisms has been related by the scientific and technical advances of the society. During the time of renaissance Descartes depicted animals as machinery, such as a complex clockwork, where physiological phenomena was explained in by mechanical principle of levers, pumps etc. In the wake of steam engine and thermodynamics, an organism was perceived as a heat engine. The introduction of servomechanisms, regulators with thermostats, self-guiding missiles and likes, brought into focus *cybernetics*, “control and communication, in the animal and the machine” as Wiener defined it [238]. Although Bertalanffy found already 1968 other new paradigms in science describing organisms in terms of molecular machines and chromosomes, cybernetics remain viable as it assimilates information processing in human and human made systems.

Self regulation and communication can be observed in on many levels of organisms as well as artifacts. Our interest is in human and human made machines, we call these together as *agents* in a reference to an agency, the capacity to act in a given environment. In the following we discuss the core terms of cybernetics as laid by Ashby in his book “An introduction to cybernetics” [8]. Next, we introduce an abstraction of intelligent agent and consider large scale systems of consisting of interacting agents.

2.1.1 State of a system

A dynamic system changes on the course of time. Ashby defines state of a system as “well-defined condition or property that can be recognized if it occurs again”.

Gait of a bipedal robot or a human can be effectively described in two states: stance and swing. In stance both feet are on the ground and in swing one foot is supported on the ground and other leg is gaining distance while swinging in the air. The walking is thus repetition of these alternating states. However,

when looking at a leg in more detail, we can see that it is articulated to several segments connected with joints. In order to explain the state of walking system would be interesting to describe the mechanical states, e.g. position, velocity etc., of each of these segments and also the interactions with other part of the body, torso and other limbs, and environment, most importantly contact surfaces on the ground. Furthermore, depending on the point of view the most interesting thing might be the motivation why the agent is moving and the description of these states. This to say that depending on the purpose we can have various resolutions and points of view for describing the states of a system.

2.1.2 Homeostasis

Homeostasis is by origin a biological concept referring to regulation of the internal environment of an organism. The term was coined by Cannon in his discussion how human is able to survive in a relative weak body by maintaining the internal status despite environmental changes and requirements [28], for example human is able to self-regulate body temperature despite potentially fatal changes on the environment, and on the other hand dissipate heat generated by working of muscles that would render body defunct.

Homeostasis in Ashby's presentation is a state of a system, where there is no change. A homeostat is a system that runs into state of equilibrium despite disturbance, something that moves the state of system out from equilibrium. Considering a standing human on the ground, perturbing by pushing slightly at the back might cause that human to wobble for a while until the balance is regained.

2.1.3 Controller

The task of a controller is to regulate the state of a system, which can be biological or man made. Figure 2.1 shows three different kinds of controllers. A thermostat is a typical controller made to adjust temperature of something, let's say a room. Thermostat receives set point, desired temperature, and set's control signal of the heater, the plant in the figure. This control signal would adjust how much the heater would radiate heat for the room in order for the room to reach the desired temperature.

Considering the heating system for a room, thermodynamics of which were well-known, then open loop controller, Figure 2.1 (a), with precise model of the room dynamics could be able to regulate the room temperature. In a simplified case this could be a rule to set the heater on for two hours every the night as room would get cold otherwise.

Feedforward controller, see Figure 2.1 (b) uses a measurement of the environmental change to model suitable response to meet the desired temperature. This measurement might be the measurement of the change in the temperature of the night that affects the room temperature, not the room temperature itself. As the name suggests, the characteristics of feedforward controller is that it adjusts the control in anticipation to a change in the system: in some another

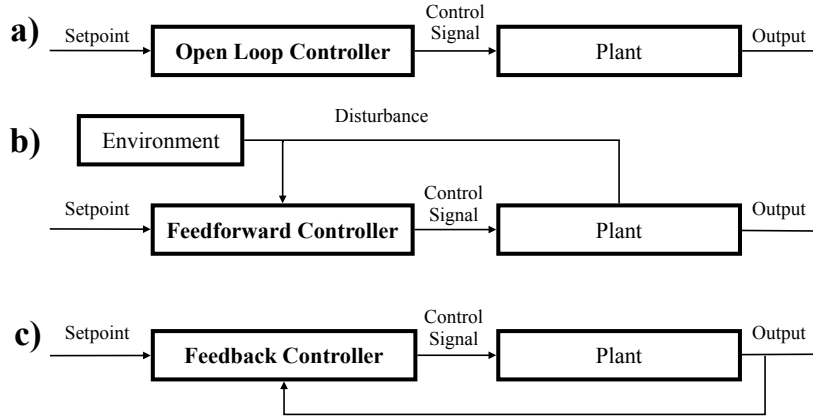


Figure 2.1: (a) Open loop controller, (b) Feedforward controller, and (c) Feedback controller

domain this could mean predicting a trajectory of an object in order to intercept it.

Another approach to implement a thermostat would be to use a sensor to measure the room temperature and adjust the heater according to error between the measured temperature and the desired temperature. This type of controller, feedback controller in Figure 2.1 (c) contains a feedback loop: the state of controller is reflected back to the controller itself after being modulated in the rest of the system. In practical implementation different control methods may be adjusted to the control signal or different controllers may be applied depending on the system state.

2.1.4 Intelligent agent and behavior

An intelligent agent is an abstract concept grown in artificial intelligence and robotic societies to describe system interactions with its environment [186]. Intelligent agent uses sensors to perceive the environment and actuators to change the environment, Figure 2.2. If we consider an artifact, such as contemporary robot, the sensors such cameras, microphones, ultrasonic transducers provide information about the environment. Actuators are used to change the environment. A robot can use speakers to make sound and servomechanisms to manipulate physical objects.

Behavior is the observable dynamics in an intelligent agent that connect the sensory percept to actions. In order to justify the intelligence in the intelligent agent, the logic governing the behaviors must surpass that of simple reflex rule set connecting input to outputs of the agent. In today's standards a robot, responding to sounds with a preprogrammed dictionary of recorded messages, could not be considered representing any sort of intelligent capability. Instead,

we would require the internal states are reshaped as a result of the agents interactions with the environment, that the agent would have learnt something new or that it would be combining known things in creative ways to obtain a goal. When discussing intelligent behaviors in human, those features are often associated with cognition.

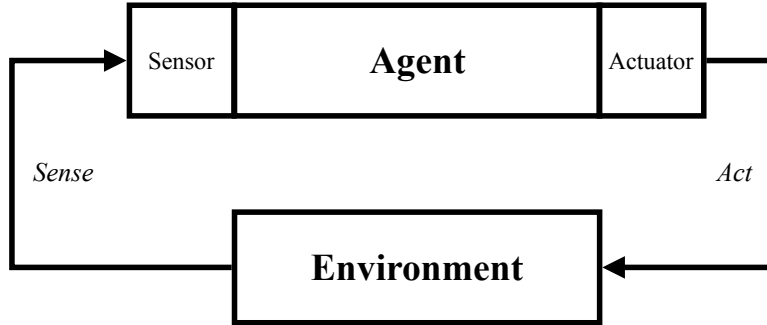


Figure 2.2: Intelligent agent

2.1.5 Cyber-physical systems

The ambitions of cybernetics were never been small: Ashby [8] expected the future cybernetics to handle systems of vast complexity: computing machines, nervous systems and societies. Now with Internet being everywhere a new breach of research as has emerged: *Cyber-physical systems*. These are networks of inter-connected machines and humans working together as systems. Examples of cyber-physical systems include intelligent transportation system with autonomous vehicles and centralized patient-monitoring with automatic drug administration.

Cyber-physical systems, a term which may have roots in science fiction literature [127], emphasis the contrast between physical world and cyber-world. Typically, things in physical world happen are time critical while the interactions in cyber-world may be seen happening in dimensions beyond time and space. Approach may not be new to cybernetics, instead the binding to new generation technologies as internet of things, sensory networks, wireless body are networks [9] bring aspects to discussion how conceive these multilayered systems with interactions to humans and distributed control. The study of cyber-physical systems brings together disciplines in computation, communication, and control engineering.

2.2 Biological behavior

In this section we have a look how behaviors rise in human individuals. Behavior is seen as much richer concept to simple stimuli-response binding in biological organisms. Based on a survey among behavioral biologists a definition for behavior has been proposed as “behavior is the internally coordinated responses (actions or inactions) of whole living organisms (individuals or groups) to internal and/or external stimuli, excluding responses more easily understood as developmental changes.” [129].

In human, two messenger systems are working together with different characteristics. *The nervous system* uses electrical signals which propagate with high-speed with targets connected with nervous tissue. The major interest in this study is at the nervous system as it provides the means for the rapid messaging need to regulate overt behaviors. Endocrine system, the secondary messenger system, uses hormones, which are distributed in blood, to regulate operations of cells. Hormones control several major processes, such as reproduction, growth and development, immunity system, body temperature, levels of electrolytes (salt, minerals) and metabolism [139].

2.2.1 Nervous system

The nervous system carries the major information transfer and processing in a human body. The nervous system is built of neuron cells, Figure 2.3 (b). The networks of interconnected neurons make complex behaviors possible.

A *neuron* has an ability to generate *action potential* on its *axon* as a result of excitement on its *dendrites*. Action potential is all-or-nothing chemical reaction, which can be observed as a change of voltage level between the interior of a cell and its surroundings. The short pulse of action potential is followed by a silent refractory period. The continuous firing of a neuron results a pulse train.

Transfer between neurons happens at a *synapse*, where an emitting axon terminal and a receiving dendrite meet. A neuron can be connected to many other neurons at both dendrites and at axon. The effect at the receiving neuron may be *excitatory* or *inhibitory*. In case of excitation the receiving neurons ability to fire is facilitated and inhibition suppresses the firing.

The physiological changes in the network as neurons make new connections is known as *plasticity*. *Hebbian learning* is a change in connectivity of neurons that neurons, which are repetitively active simultaneously are connected together, while connections between inactive neurons will weaken.

The nervous system in large is divided in two parts: *Central nervous system (CNS)* and *peripheral nervous system (PNS)*. CNS consists of brain and spinal cord, both having centers of highly interconnected neurons. CNS is connected to proximal parts of body with PNS. PNS connects muscles with *efferent* neural pathways from CNS. The *afferent* pathways of PNS connect sensory neurons to CNS.

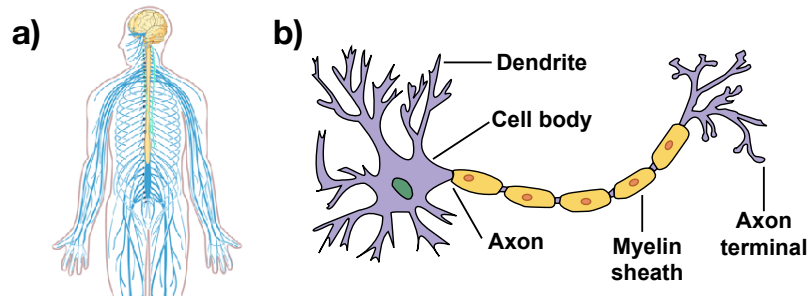


Figure 2.3: (a) Nervous system and (b) Neuron

from (a) <https://commons.wikimedia.org/w/index.php?curid=37042919>,

and (b) <https://commons.wikimedia.org/w/index.php?curid=4293768>

2.2.2 Monitoring and stimulation

Hodgkin and Huxley [98] were famously able to measure and model the propagation of action potential in neurons. The device they used was recently developed voltage clamp to measure and manipulate the membrane potential, the difference between inside and outside of cell's membrane, on a giant squid axon. As an improvement to a methodology, a patch clamp was introduced. By using filled micropipette with an electrode inside and a reference electrode in surrounding tissue, recordings on live cells were made possible [218].

The membrane potential can be measured in awake behaving animals using optogenetic manipulation [173]. Neurons, that have been genetically modified to be sensitive to light, can be visually observed and modified with light.

2.2.3 Peripheral nervous system

PNS is divided to *somatic nervous system (SNS)* and *autonomic nervous system (ANS)*. SNS regulates voluntary actions, prominently by controlling of skeletal muscles. ANS is associated with control of internal organs and glands with related functions such as heart rate, digestion, pupillary response, urination, and sexual arousal. Autonomic functions are evasive to conscious control.

2.2.4 Motor system

Human behaviors are expressed with muscles: human talks and moves with muscles. The movement is generated using musculoskeletal system, made of bones, muscles, and connectivity tissue such as tendons and ligaments. The rigid frame of human is constructed of bones. Microstructure of fibered muscles enables them reduce length on trigger from PNS. In order to obtain smooth movements muscles must be contracted and relaxed in highly coordinated fashion.

A *motor unit* is constructed of alpha motor neurons, located in spine, and connected skeletal muscle fibers [24]. Motor pool is the group of motor units that are innervating a single muscle. The strength of contraction depends on which motor units have been activated and the frequency of action potentials they are sending [63].

2.2.5 Observation of motor system

The joint torque is the outcome of skeletal muscle contraction. It is a kinematic measure, which is observable with a force transducer. The kinematics of associated body segment movements can be observed with the technology of motion capture. The registration of positions of body segments or joints can be done optically or with wearable sensors. Typical optical motion capture system comprises of a number of cameras and skin markers placed on tracked subject's body [60]. Affordable systems using single cameras with depth mapping has been introduced but with inferior accuracy [174]. The weakness of optical systems is the needed line of sight from observed objects to registering device. Alternative approach is using a fusion of miniaturized sensors, such as gyroscope, accelerometer, and compass, to obtain the orientation of body segments [229]. Because the measurements are based mostly on inertial features, these systems have difficulty to maintain absolute frame of reference for the measured positions.

Electromyography (EMG) is an important tool to measure the muscle activity. EMG records electric activity released as muscle fibers contract. The major methods are needle EMG, also known as intramuscular EMG, which target single motor units [46] and surface EMG which records activity between pair of electrodes placed over skin on top of a muscle [66]. The signal of surface EMG is proportional with torque generated by muscle, although the opinions vary if the relationship is linear or non-linear [235]. EMG is usually normalized before doing comparisons between body sides [26]. The noninvasive detection of neural command, the efferent command to muscle, is an active research topic. Instrumentation using high density arrays of EMG is a promising approach [67].

2.2.6 Stimulation of motor system

The method of *neuromuscular electrical stimulation* (NMES) targets to cause response on a muscle with electrical current applied in peripheral nervous system. The stimuli is delivered using surface electrodes or implanted electrodes. A specific *motor point* is defined as a location, where electrodes on the surface of muscle giving the most robust response on the muscle [79]. In case afferent nerves are targeted the muscle response is a reflex. Receiving NMES, depending on dosage, can be an unpleasant experience [48], and it can also cause damage to muscles [162]. The application of generic NMES is used for strength training, testing, and post-exercise recover tool [136].

Functional electrical stimulation (FES) is a form of NMES, which targets

paralyzed or paretic muscles [172]. The applications of FES include neuroprosthetics and therapy [197].

2.2.7 Sensory system

Human sensory system includes the modalities of five classic senses: *vision*, *audition*, *gustation*, *olfaction* and *somatosensation*. Although all modalities form necessary bindings from the surrounding to CNS and in this way in setting up human cognitive state, our main interest is the ones which are directly contributing to motor behaviors.

The sensory element for vision is known as *retina*, which at inner rear surface of eye balls [113]. Retina consists of variety of light sensitive neuron cells, with an area high concentration, *fovea*. While retina has field of view of 180 degrees, the fovea is limited to few degrees. Eye balls can be moved in order to fixate the highly sensitive area to a particular target. The other mechanisms control the amount of light to enter eye by regulating the size of *iris* and the shape of the *lens* to provide focus. The optic nerve, a part of CNS, transfers the information out from the retina.

Proprioception is an essential sense for motor control as it is giving the sensory signal for feedback control of muscles. Muscle spindle, which is located in muscle belly parallel with fibers, can detect the stretch in the muscle. Golgi organ which is located in tendons detects tension on the muscles.

Vestibular sense uses semicircular ducts, located in inner ear, to detect changes in head rotation and gravity. The bending of the hair in inside the duct caused is perceived as acceleration. The organ has of three ducts oriented in a fashion that allows detection acceleration around three axes of rotation and on linear planes.

Somatosensation detects measures such as pressure, pain and temperature with a wide array of sensors [1]. The sense of touch is essential in dedicate manipulation tasks, e.g. handling fragile objects. In addition to collecting information about the environment the sensors also deal with perception of the states of the body itself.

2.2.8 Stimulation and observation of sensory system

Normally the sensors are stimulated with the stimuli in their natural modality, e.g. vision is stimulated with light and images. Sometimes, however, alternative methods are available. Proprioception can be affected by vibration on the tendons to cause sensation of lengthening muscle [184]. Vestibular system can be stimulated with electric signals [70], similarly, the afferent PNS can be stimulated with electricity [106].

Afferent signals can be potentially intercepted in the PNS before they meet CNS at spine. However, because generic non-invasive mechanism is not known for the coding the afferent signals, the more feasible approach in many studies and applications is to control the stimuli itself or obtain the information from measurements in the environment.

2.2.9 Central nervous system

Central nervous system is commonly divided in four sections: *cerebrum*, *cerebellum*, *brain stem* and *spine*. The nervous tissue consists of *white matter* and *gray matter*. White matter consists of myelinated (sheathed in tissue that allows a fast transfer of impulses) axons, functioning as relaying information. Gray matter is rich with cell bodies and synapses.

Spinal cord

Spinal cord, housed inside the spine, transfers efferent and afferent signals between PNS and other parts of CNS. It also connects sensors directly or with interneurons to motor neurons enabling quick reactions to stimuli when no other parts of CNS are involved in the processes. Interneurons are located in the gray matter of the ventral horn and the connections along the length of spine are connected so that neck and upper extremities are mapped at anterior part and lower extremities are mapped at posterior part.

In a stretch reflex an output of proprioceptive Golgi organ is connected to motor neuron making a muscle contract if it is stretched, making in effect muscle regulate a stable length.

At the same time there are inhibitory interneurons having connections from the Golgi organs to the motor neurons in order to protect the tissue being damaged by contraction. Some other reflexes use inhibitory interneurons during muscle contraction to relax antagonist muscle to relax. (Autogenic inhibition reflex, 1a inhibitory interneuron and 1b inhibitory interneuron). The presence of interneuron connections make possible to monitor or control the reflexes.

Central pattern generators are neural networks capable of creating periodic movement patterns in absence of rhythmic input. The rhythmic locomotion patterns has been observed in low spinal cats after complete dissection of spinal cord physically [73] or chemically [87]. Locomotion patterns generated in human spine has been found as well [51].

Brain stem

Brain stem, extending spine to superior direction, Figure 2.4 (a), is working as a gateway connecting the rest of CNS. It has vital importance in the regulation of many of the functions of ANS, such as heart rate and breathing [15]. It maintains consciousness and regulates sleeping, and eating.

Cerebellum

Cerebellum (Figure 2.4), also known as “little brain”, has a well-recognized function for the fine-tuning of motor control [137] and motor learning [104]. Also, non-motor learning, language processing and other cognitive processes has been proposed to be carried in cerebellum [25].

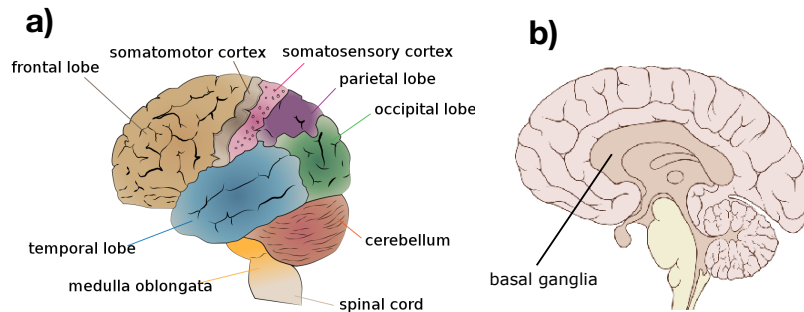


Figure 2.4: Cerebrum: (a) lateral view with lobes, and (b) sagittal view,

from (a) <https://commons.wikimedia.org/w/index.php?curid=51205157>,

and (b) <https://commons.wikimedia.org/w/index.php?curid=1496657>

Cerebrum

The cerebrum (the areas above cerebellum and brain stem in Figure 2.4 (a)) consists of two prominent hemispheres of cerebral cortex and organs below. The cerebral cortex is divided to lobes by surfacial features, ridges and grooves (gyri and sulci). See Figure 2.4 (a) for lobes and Table 2.1 for their associated functions. The associational brain areas of the cortex were initially found with patient with cognitive deficits related to cortical damages.

Table 2.1: Summary of lobes and associated functional areas

Name	Functions
Frontal lobe	Prefrontal cortex: executive function Motor cortex: motor function
Parietal lobe	Somatosensory cortex: sensing language
Temporal lobe	Auditory cortex Memory formation
Occipal lobe	Primary visual cortex: low visual processing

The hemispheres are highly symmetric by shape but to only some degree in function. The limbs are projected to somatosensory cortical areas at opposite side of the body. Similarly, visual fields are projected at contralateral cortical areas.

Prefrontal cortex the foremost part of frontal lobe is often associated with executive function [5]. This function includes tasks such as logical reasoning, planning, and regulation of cognitive processes. In this way prefrontal cortex presents very high level mental processes.

Basal ganglia (Figure 2.4 (b)) part of cerebrum is known its functions in motor control [85]. There is evidence that also non-motor reward based learning takes place in basal ganglia [85].

2.2.10 Observation of function of CNS

Functional neuroimaging methodology is measuring activity in CNS based on changes on parameters, primarily blood oxygenation and electrical activation.

Functional magnetic resonance imaging (fMRI) measures changes in blood flow in the brain [131]. The energy consumed by active neurons caused changes is primarily observed at the blood-oxygen-level-dependent (BOLD) contrast. For a non-invasive method fMRI provides high spatial resolution, less than mm^3 [80], with the cost of low temporal resolution, order of seconds, [111]. The typical fMRI experiment consists of repeated tasks or events and statistics is applied to contrast the difference between different conditions [78]. The applications involve brain mapping to identify functional brain areas and their connectivity [208]. A room-sized equipment able to generate strong magnetic fields and register the minute changes in the magnetic levels in brain is needed to conduct measurement. The strong magnetic fields and static supine position in tight cylinder limits the motor functional experiment designs.

Functional near-infrared spectroscopy (fNIRS) is measuring hemoglobin concentration, similarly to fMRI, but using optodes placed in contact with the scalp [68]. The method's ability to measure is limited to cortical areas near scalp. The features such as low cost, portability, safety, low noise make it feasible alternative to real-time applications [158]. fNIRS cannot measure anatomy so it has to be measured independently in order to locate the optodes with cortical features.

Electroencephalography (EEG) registers electric activity on electrodes placed on the scalp. The signals are subject to various forms of bad contacts of sensors, EMG signals, and electric noise in the environment [151]. The analysis of EEG signals can roughly split to two families: frequency analysis based and *evoked potentials (EP)* based methods. Frequency analysis are often dividing the signal to frequency bands and activity on a band is associated with the states of a brain, e.g. a certain phase of sleeping [20], neurological state [226], or functional connectivity of brain using methods such as phase-synchrony and coherence [13]. EP signals are recorded from nervous system following presentation of a stimulus, because of low signal-to-noise ratio the signals are usually averaged over several repetitions. There are various signals recorded for exogenous and endogenous stimuli of different modalities. Of particular cybernetics interest, for their use in brain machine interfaces, are:

Readiness potential (RP) , which appears in motor related cortical areas as subject is preparing motion

Event related potential, P300 , which appears as person is making decision or identifies certain stimuli to be exceptional

Error-related negativity (ERN) , which appears when subject has committed error during a task

Magnetoencephalography (MEG) is measuring the same fluctuating electrical sources as EEG, however it is observing the magnetic field caused by active neurons. Because the methods are based on same underlying physiological processes the results are somewhat similar and each of them has applications on which they perform better than other [35]. The MEG equipment needed to register the magnetic changes is much more voluminous than that needed to register EEG.

2.2.11 Stimulation of CNS

Transcranial magnetic stimulation (TMS) uses magnetic coil placed above targeted cortical area to induce current in the brain tissue. The caused electric field is sufficient to stimulate the neurons [12]. TMS systems are used for neurological therapy of depression [61]. TMS applied on motor areas can cause involuntary movements or sensation of movement even for paralyzed limbs [62]. *Repetitive TMS (rTMS)* uses stimuli pulses in repetition. High frequency (> 5 Hz) stimuli targeting muscles at primary motor cortex facilitates excitation [168] while low frequency (< 1 Hz) inhibits motor excitation. The same effect has been observed using *transcranial direct current stimulation (tDCS)* [161], a method that applies weak current between two electrodes on scalp.

2.2.12 Understanding the environment

The human sensory system is collecting a massive amount of information. In CNS there are several mechanisms working for abstraction or selection of stimuli for making sense of the environment.

Multi-sensory integration The brain is collecting information from the different modalities and assembling it to a coherent percept. In case of an arm grasping an object the collected information could be visual image of the arm and object, proprioceptive model of the articulated arm, somatosensation of the fingers touching the object and also a sound of the touch. Another example is a sense of heading in motion which is may not be constructed without vestibular and visual information [27].

Multi sensory illusions demonstrate human preference for the vision over other modalities. Ventriloquist illusion is an example of surprising outcome of multi sensory integration. Observer locates the sound source to a dummy which has mouth moving at the timing of the sound. Similarly, in McGurck effect [142] an observer hears wrong syllables when watching a prepared video with intentionally mismatched sound and lips reading syllables. Typical for the illusion to appear is the temporal and spatial proximity of the observed stimuli [212]. Other theories explaining how percept is conceived include weighting the sen-

sory cues in proportion to their reliability [65] or by detection of correlation of the signals from different modalities [167].

Body schema A person prior to entering a door estimates if the body can go through the hole or if it should be aligned to meet the observed dimensions. The spatial model the person is using is known as body schema. This model is adaptive. In case of driving a car through a small opening, the driver estimates the size of the opening against the model driver has of the car [138].

The body schema is updated as a result of multi-sensory integration. Incongruence in the cross-modal signals can cause unexpected sensations, as demonstrated in “Pinocchio” illusion. If a subject is touching nose with a finger with eyes closed and vibration is applied to flexor muscles on the arm, the vibration causes proprioceptor sensation of flexion of the arm and again sensation of extending dimensions of the nose as it is connected with the finger by touch and body scheme [119].

Mirror neuron system Single neuron recordings in premotor cortex of monkey indicated that same individual neurons activated with both observation and execution of movement [49]. This same behavior is found on human [153] and is known as *mirror neuron system* [182]. The existence of mirror neuron system is emphasizing the close connection between perception and action. Since its introduction the mirror neuron system has been in instrumental position on explaining learning by imitation [183], empathy [102], and human self awareness [164].

Attention The brain has been theorized to have serial bottlenecks [140] that limit the capability of processing information. Anderson [6] defines *attention* as a method to deal with these limitations.

Control of the selection of the target of attention may be exogenic or endogenic [175]. In exogenic control the attention is captured by stimuli, this could be salient features or in visual scene or an outstanding sound. The endogenic control is following the selection of target relevant to task a subject is performing. In case of overt (contrasted with covert) visual attention the gaze is oriented to direction of target of attention [30]. The orientation of gaze is helpful in cognitive studies are explaining human behavior [120].

Attention enhances perception on other sensor modalities, similarly as with vision. It allows an interested listener to focus to certain a speaker and filters out other sounds. Attention mechanisms has multimodal bindings [58] contributing to multi sensory illusions, discussed in the section on multi sensory integration.

Perceptual learning Eleanor Gibson defined *Perceptual learning* in 1963 as “Any relatively permanent and consistent change in the perception of a stimulus array, following practice or experience with this array, will be considered perceptual learning” [76]. In case of vision, training can improve detection of location in the visual field, spatial-frequency or orientation, and these changes

may be associated with neural plasticity in visual cortex [188]. The ability to learn to identify sounds used in speech not native to listener involves perceptual learning [192].

2.2.13 Generation of voluntary movement

As contrasted with involuntary movements, such as reflexes, where subject has no more than little control to stop them, voluntary movement involves complex networks in CNS allowing subject to at least some degree to control the action. Voluntary action is philosophically difficult term as it deals with concept of free will [177]. In his experiments, Libet [130] was able to measure cortical signals preceding the moment when subjects decided to make a self-timed voluntary act by hundreds of milliseconds. Although we will later investigate levels in voluntariness in action, here we consider practically voluntary action something subject chooses to do, not as something subject is forced to do.

In artificial motion control the dynamics of a controlled system is described with a set of differential equations. Such modeling is beyond capabilities of human CNS. The problem is known as degrees of freedom problem or Bernstein's problem, in reference to the investigator who postulated it [17]. The musculoskeletal system is built with redundancies. It has a big number of bones, each of which may be connected with several muscles to other bones at. The muscles are composed of abundant number of motor units. The CNS has infinite number of possible ways to generate same motion.

Motor behavior is proposed to be optimized to measures such as energy [92], smoothness [71] or accuracy [89]. Minimization of energy consumption is easily understandable in respect to organism's desire to survive. This economical approach is evident in the musculoskeletal system, which is evolved to be very highly efficient in locomotion. The smoothness based models can describe accurately trajectories in reaching tasks [99]. However, these optimization strategies cannot avoid the degrees of freedom problem [222].

In this section, we will consider movement generation to consist of planning, initiation, and execution. Planning involves generation and selection of potential movements. Initiation concerns about the decision to or not to execute planned action. Execution is the process of sending motor commands and controlling that the desired outcome is met.

Planning of movement

Experiments with deafferented monkeys [19], monkeys without proprioception, showed that even the subject was not aware of the initial position of a hand, the reaching movement was corrected towards target during execution of the movement. However, the displacements in the experiments were small enough so that the target was reachable by hand within biomechanics constraints. In order to action to take place the subject must believe that there is possibility to reach goal. James Gibson coined term of affordance to describe all perceived

transactions that are possible between an individual and the environment [77]. Affordances for a situation have to be learned before the come viable options.

In the process of planning a movement various cortical systems are active: goal decision and selection involve executive function and attentional mechanisms. When motor skill is learnt prefrontal cortical areas are activated, but as the skill is consolidated premotor, posterior parietal, and cerebellar areas of brain are activated [195]. Therefore, the planning of movement is more about recalling than generating a plan. Ideomotor theory proposes that brain registers sensory consequences of action and using bi-directional linking recalling the corresponding actions by the anticipated sensory expectations [100].

Evidence on monkeys suggests that premotor cortex is preparing several alternative movements in parallel [34]. The actual selection of competing programs is done at basal ganglia [150].

Initiation of movement

Startle reaction is a defensive mechanism, in which a human generates a quick response to surprising stimuli, e.g. abrupt audio of > 80 dB [179]. Startle stimuli can trigger a prepared motor plan earlier than subject would be willing otherwise [29]; it appears that human is delaying execution, even the motor plan was already prepared [88].

A rare neurological disorder, known as alien hand syndrome, makes the patient perform unconscious movements, for example as patient is closing buttons of shirt with one hand, the other hand is opening the buttons without the will of the patient. The syndrome can be a result of various neurological conditions and several brain circuits has been associated with it, including supplemental motor area [193].

Supplementary motor area has been proposed as a location where the decision when to act, or not to act is taken [39]. Measurements show [199,244] that before voluntary movements are elicited, there is a readiness potential in pre-supplemental motor area, followed with potential in supplemental motor area, before reaching the primary motor area.

Execution of movement

The problem of motion control is how to generate a desired trajectory on the body. A feedback controller in CNS (Figure 2.1 c)) is not sufficient controller for human body, because the latencies in feedback signal would make the control to be too late for the actual situation [105]. An open loop controller, with internal model, providing feedforward control signal is needed. A controller with inverse model is a physiologically valid model with cerebellum providing the needed functional neural circuits [201].

Figure 2.5 shows a scheme of inverse model. Motor command generates a trajectory of the controlled object. Inverse model is able to derive the motor command from the trajectory. The clear advantage of the scheme is that desired trajectory and realized trajectory can be processed in same dimensions

regardless of the presentation of the motor command. For practical considerations, however, we need more complex, adaptive model to deal with the noise in sensorimotor system and uncertainty in the environment.

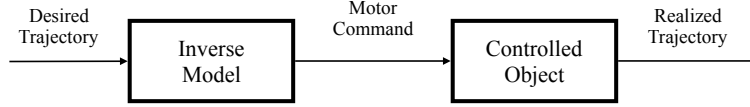


Figure 2.5: Inverse model.

A controller with learning model, Figure 2.6, supplements a feedback controller with an inverse model. The feedforward motor control and feedback motor control are combined to regulate motor command sent to the controlled object. Inverse model monitors the feedback motor command to adapt the feedforward motor command. In order to accommodate complexity of musculoskeletal system modular solutions containing multiple forward-inverse models have been proposed [242].

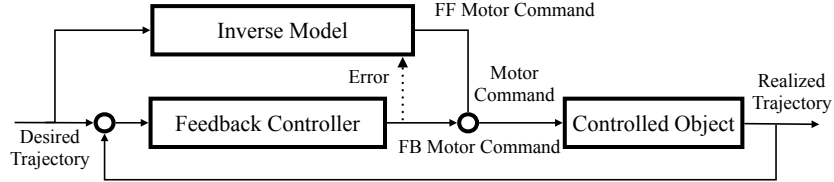


Figure 2.6: Generic feedback error learning model. (Based on [107])

2.3 Intelligent Behavior Control

We have laid the foundation on modeling natural and artificial behaviors with cybernetics. We reviewed the human control mechanisms in the light of cybernetics. In this section we will make some abstraction of human control models and discuss ways to augment, substitute and repair parts human controller.

2.3.1 Proficiency in motor behavior

The natural motion is generated in musculoskeletal system by nervous system. The musculoskeletal system with constraints of physics and abilities such as range of motion of joints, flexibility, and muscle strength define limits how

the motion can be expressed. Nervous system using motion control strategies generates and refines the dynamics.

In discussion concerning about motion control, we saw that outcome based approaches are not suitable for realization of movement. However, regardless of the method how they are generated, according to observations we can see some common features that characterize skilled behavior. The skilled movements generally tend to be accurate spatially and temporally, repeatable, smooth, and energy efficient. On a specific task the assessment of proficiency will be defined by the task constraints, e.g the measure might be hits on the target in defined time-frame.

These observable features are used to make assessments about the skill or ability to move. For children, several taxonomies of motor behavior has been devised to support for the assessment of the level of the development, e.g. Table 2.2.

Table 2.2: Taxonomy of psychomotor domain, according to Harrow [90]

Category	Example
Reflex Movements	involuntary reaction
Fundamental Movements	locomotion, manipulation
Perceptual Abilities	sensory discrimination
Physical Abilities	strength and agility
Skilled movements	adaptive skills
Nondiscursive communication	gestures and facial expressions

An artificial motion, as generated by robots or computer graphics, can be made to mimic human behavior to be more pleasant and acceptable for human observer [141]. When we look at behaviors we expect from us, the requirements go far beyond mimicking. The psychomotor taxonomy (Table 2.2) gives an overview of the richness that human motor behaviors can express. Artificial control has a lot of ground to catch on most of the categories. Particularly the robustness, gained by adaptability, in humans stands out as hard to replicate by machines.

2.3.2 Neural synergy system

Human interacts with the environment by sensing and acting as we discussed earlier in relation to intelligent agents. During introduction of neural system we saw the complexities related to sensing and acting. The human virtuosity in dealing with complex environment is illustrated here with a concept of *neural synergy system* [4], see Figure 2.7.

Neural command processing The human information processing capacity may be huge in comparison to that of machines [231], but it pales in comparison to the complexity of the environment. In order to be able to make sense

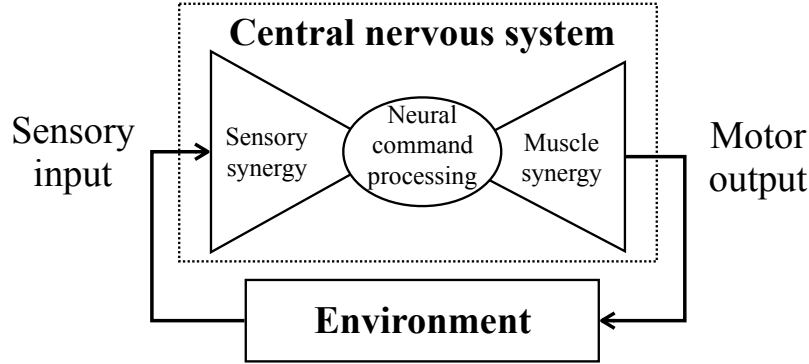


Figure 2.7: Neural synergy system

of the surroundings the CNS has to work on reasonable level of abstraction. This includes the updating of models environment and body schema.

In order to effectively to deal with complex environment, human must, be able to reduce the amount of data it obtains from the environment to processable units. *Sensory input* received from all the modalities is multidimensional containing redundancies and signals with variable quality of information. The transformation from wide array of sensory input to less is viewed as dimensionality reduction, a common method in machine learning [185]. Some sensory data may be refined with systematic approach, particularly proprioception considering the signals from all the muscles around the body [4] for multimodal information the rules of multi sensory information may be applied.

Muscle synergy is potential explanation to problem: how to deliver simple motor commands recruit multitude muscles to act on the environment. Figure 2.8 shows the composition of the muscle activations as linear sum of the weights as coded in spine [224] and commands sent from brain. The descending signals are hard to measure before reaching the PNS. Typical modeling approach [240] uses EMG measurable muscle activations, which are decomposed to weights and commands by means of non-negative matrix factorization [126].

2.3.3 Controller Hierarchy

In the concept of neural synergy system we saw how sensory input was turned to action using reduced dimensions. We refine this model further with details about interaction at various levels of abstraction. Figure 2.9 illustrates a concept of *controller hierarchy*. The abstraction increases as going higher, further from environment, in the same way as it did with the Neural synergy system. However, in this model the inputs and outputs of intermediate processes are interconnected.

As we saw in previous section, Biological behavior, the behaviors are initiated at several levels of neural system. Highest-level of behaviors driven by intention

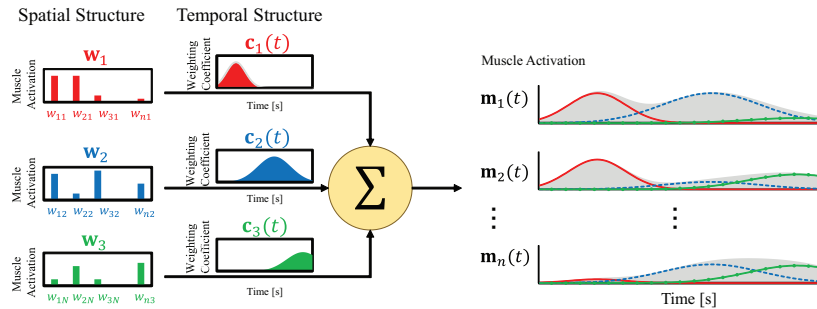


Figure 2.8: Muscle synergy,
Image courtesy of Dr An, University of Tokyo.

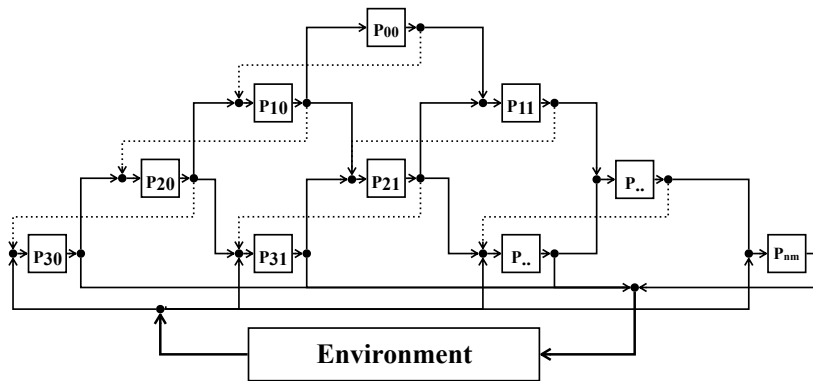


Figure 2.9: Controller hierarchy

involve all of the circuitry of voluntary motion. Intentional behaviors are often connected with executive function, which involves cognitive functions such as planning and problem solving. The executive functions are subject to slowing down in presence of a secondary task [169]. Automatization, an over-learning of a task to a level that processing can be efficiently time-wise and resource-wise, has been a way how to come over the controlled processing limitations [202]. Automatization, however, is not as robust as executive processing because it cannot be used in novel situation. When automatization fails, subject has to revert to executive control.

The low-level behaviors connect sensory signals to motor units at spine to make reflexes. Although, subject has little control on low level reflexes they are still integral part of controlled behaviors [159].

Human control is often viewed on the axis of top-down and bottom-up control. In top-down control the behaviors are originated and regulated by intention. Bottom-up control is originating from exogenous stimuli and is thus

regulated by environment. We consider skillful behavior to contain elements of both kind of behaviors, if not, the behavior would be either a reflex or a monotonic repetition without any respect to variation in the environment.

Table 2.3 summarizes behavior categories ordered from simple to complex. Reflexes are innate, a stimulus on a sensor triggers behavior inevitably. Habits and skill, are over learnt behaviors which have become automatic. An instinct is a bottom-up controlled behavior, driven by stimuli. An intuition is a behavior top-down controlled behavior, it is volitional but non-verbal. The intention is an explicit and reflective behavior, and thus expensive to process.

Table 2.3: Dichotomies in behavior, modeled after [181]

Intention	acquired	sense of control	top-down control	explicit
Intuition				tacit
Instinct				
Habit and skill	innate	automatic	bottom-up control	
Reflex				

2.3.4 Applications of intelligent behavior control

In this study we consider how to modulate imperfect human behavior for better. We do this in two experiments. The first experiment concerns about maintaining driving behaviors despite task demand, and the second experiment is about activating good motion patterns in post-stroke patients. Moreover, we introduce a software framework for building environments to apply biological control principle to modulate human motor behavior.

Driving

The extent to which drivers control their vehicles according to their intentions is a critical problem in driving safety. In the first experiment we quantify the difference between a driver's own intentions and the actual operations from observations of driver performance.

Typical driving is governed by two types of processes: proactive and reactive control. In Proactive control, the driver prepares and executes actions in a timely manner ahead of future events, whereas in reactive control the driver responds directly to environmental stimuli. A state in which the relative amount of reactive control is high implies that the driver is busy responding to the surroundings and has difficulty attending to future events.

Figure 2.10 (a) conceptualizes competent control of driving. The driver uses a high-level process P_1 dominantly for proactive control and controller P_2 reactively for minor adjustment. However, in a case of highly demanding task the driver is unable to use the process P_1 and has to revert to the reactive P_2 , making the control outcome inferior, Figure 2.10 (b).

In Chapter 3 we will theorize the driving behaviors that are causing the shift from top-down control to bottom-up control as consequence of increasing task demand. We analyze experimental data to derive a model to asses a driver's proficiency at a driving situation. We consider the use of the model to promote road safety.

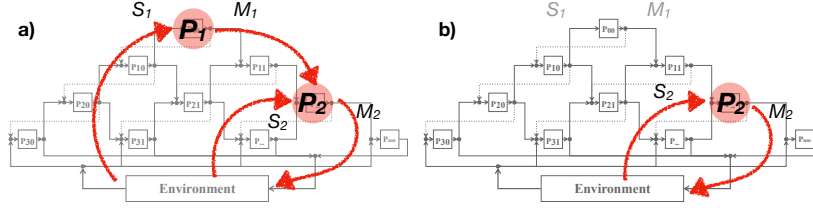


Figure 2.10: Control in (a) proficient driving, and (b) inept driving

Neuro-rehabilitation

Brain damage caused by strokes often leaves survivors with lateral functional motor deficits. The damage caused by stroke is focal to cerebrum, leaving musculoskeletal system and peripheral nervous system intact. Figure 2.11 (a) illustrates how a typical reaching task is controlled by a high-level process P_1 conveying the intended motion to lower motor processes, P_2 , to be recruited at the musculoskeletal system. However, in case stroke damage nervous system, Figure 2.11 (b), the motor signal from P_1 cannot reach lower processes, and the desired reaching movement cannot be realized.

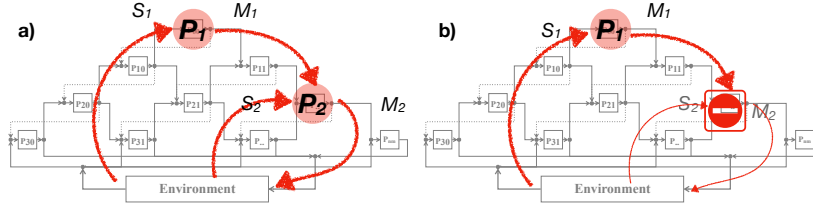


Figure 2.11: Control in reaching (a) in successful motion, and (b) stroke damaged system

Bimanual rehabilitation of the paretic arm is an active field of study for restoring normal functionality by making use of complex neural bindings that exist between the arms. In Chapter 4 we will make an experiment with post-stroke patients and healthy subjects using a bimanual training device. We develop evaluation tools to quantify the bimanual motor behaviors. On the

ground of acquired results we will discuss the suitability of different motion patterns for promotion of recovery. In addition, we introduce a new tool to evaluate the state of recovery in post stroke neuro-rehabilitation.

2.3.5 Generation of Environments

In behavioral studies, rehabilitation, or learning tasks, intelligent behavior control targets to modulate the behaviors of a subject. The subject is isolated from the natural environment and coupled with an artificial environment, Figure 2.12.

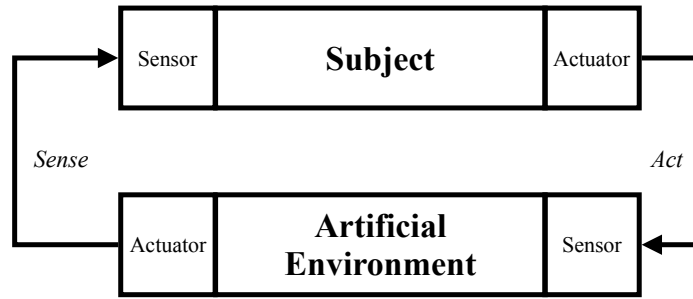


Figure 2.12: (a) Artificial environment making feedback-loop to agent.

In Chapter 5 we will investigate the problematics of generating a robotic rehabilitation environments for patients. The environments must be created flexible enough to accommodate both, the needs of sensitive patients, and also the changing needs of researchers. We design and implement a framework to build such environments. Special attention will be addressed to enable time critical feed-back loops to promote the recovery of the patients.

2.3.6 Limitations of modeling with controller hierarchy

During this thesis a conceptual model of control hierarchy, Figure 2.9, is used to illustrate abstract ideas of control-flow in human control processes. The illustrations are intended to portray the shift of control strategy during modulation of control: The shift along vertical axis in modulating driving behaviors between bottom-up and bottom-down controls and horizontal shift in functional control structures of bi-manual rehabilitation. However, one must recognize that the model cannot capture all aspects of human nervous and endocrine systems. Explanatory power of the model to generalize further control cases should be proven in the context of a larger number of cases than those discussed in the scope of this thesis.

Chapter 3

Driving

3.1 Intention in driving

For an experienced driver the driving is very natural, and many would agree, a pleasant, extension to ego-motion: the vehicle goes where the driver wants it to go without any noticeable effort: the vehicle follows driver's intention. We argue, however, that for inexperienced driver the driving is better described as reactive responses to the changes in the environment. In this section we postulate driving as a combination of these two kinds of processes, proactive and reactive processes.

3.1.1 Driving tasks

Driving is a multidimensional cognitive process. McKnight and Adams [143] analysed driving tasks and partitioned those to 45 major tasks, which are composed of more than 1700 elementary tasks. Michon [148] divided driving tasks to three categories: strategical, tactical and operational. Michon's model is illustrated in Figure 3.1.

The highest level, strategic level, is concerned about planning of the trip. It involves route planning according to the economical and motivational factors. Time window allowed for strategic decisions is long. A navigator is a device which provides help on the strategical level.

The tactical level realizes the strategy with maneuvers like lane-changing, obstacle avoidance and turning. Maneuvers are conducted in order of seconds. The control is considered to be a controlled process (as introduced in section 2.3.3).

The operational level is directly concerned with the steering and pedaling actions, that take place in milliseconds. Michon views these actions as automatic processing. The driving situation reflects the strategic decisions. If the task demands on the operational level get too high, the driver re-evaluates the strategy.

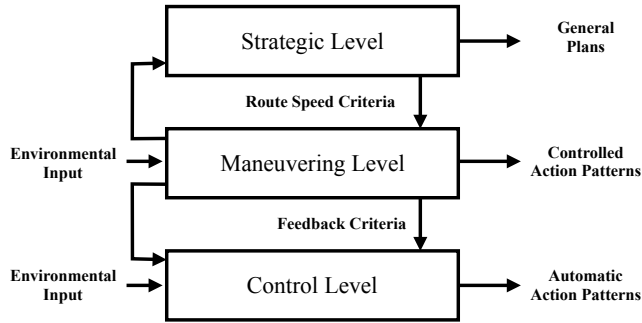


Figure 3.1: Three levels of driving tasks. (Modeled after [148])

3.1.2 Learning to control

Successive organization of perception (SOP) model which approaches human controller behavior in terms of servomechanisms [116]. Model was originally introduced in the context of artificial task of tracking sine waves, and later it has been applied to practical tasks such as driving [144]. SOP model explains control skill development with behaviors on three ascending levels.

On the first level, named *compensatory*, the controller is stabilizing the difference between target and observed states in closed-loop mode.

On the second level, *pursuit*, more stable control is obtained by ability to predict future states of the vehicle with *internal models* of vehicle dynamics.

On the highest level, *Precognitive*, behaviors are executed in an open-loop control mode by applying knowledge of the controlled system and learned responses.

Driver's ability to model the vehicle dynamics has been elaborated in two-level theory on steering [56, 190]: at the guidance (pursuit) level, steering is based on the perceived geometry of the road; at the stabilization (compensation) level, any deviation from the desired trajectory is compensated with closed-loop control. In addition to error in guidance level such deviations may arise from disturbances in the environment, such as wind or an uneven road surface. The compensation level has been found to be more robust to decay in visual information in simulator experiments [74].

3.1.3 Proactive and reactive behaviors

Proactive behavior [7] is act happening in anticipation to a future event. On a reactive behavior act is happening in compensation to a change in the environment. Figure reffig:propreacttime illustrates the difference between these two kinds of behaviors. Let's assume a a pothole on the road. For a proactive driver sees the risky element in advance and steers to stay away from it. In case of reactive behavior the driver sees a alarming pothole and reacts quickly to stay

clear or after hitting the pothole restores the trajectory of the vehicle.

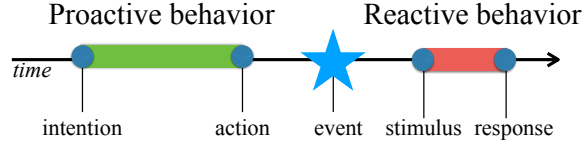


Figure 3.2: Proactive and reactive behaviors

The role of proactive and reactive behaviors is a common aspect in the two models previous models. In the Michon's task model the driver is eliminating need to rely on the time critical behaviors by tasks on the higher level. In higher levels of the SOP model the driver's ability to predict the changes in the environment enables proactive behavior. Figure 3.3

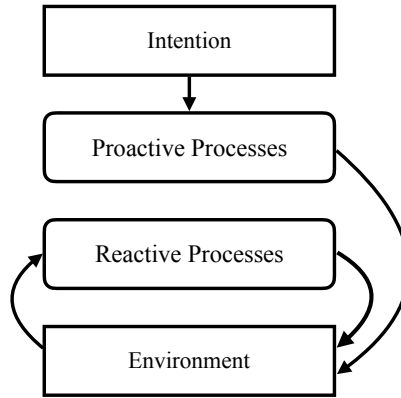


Figure 3.3: Proactive and reactive behaviors

Proactive behavior is regulated *top-down* according to internally maintained goals, whereas reactive behavior is *bottom-up* controlled and stimulus-driven [22]. These two kinds of behaviors, the ones driven by a need to change the environment and the ones adapting to the environment, can be identified in the context of driving a vehicle.

Generally, a person who drives a vehicle is motivated by a need to go to a specific destination, and driving provides a means of doing so. To reach the required destination, the driver controls the vehicle primarily by using the steering wheel for lateral control and the pedals for longitudinal control. These operations are conducted mainly according to the intentions of the driver to place the vehicle in a state beneficial for achieving the goal and sub-goals [211]. Reactive control, on the other hand, is needed in response to all manner of interactions

between the vehicle and the environment to keep the vehicle under control. Also the scope, how far consequences of proactive behaviors are predicted, is limited [233]. As a result of this limitation proactive behaviors need to be supplemented with reactive behaviors.

In novel or demanding driving scenarios, it is well known that drivers perform less well because of the higher mental workload [43,171,180]. This may be partly due to higher demand of executive function by proactive control [22]. We suspect that proactive processes are more sensitive to a stressful environment, and that control becomes more reactive in such an environment. Our approach in this paper is to assess the gap between driver intention and vehicle motion, not the intention itself, by quantifying the ratio of proactive controls to reactive controls based on observations of the vehicle and its driver.

3.1.4 Detection of driver’s intention

As long as there is driver’s involvement in the control of the vehicle, there is a need for the vehicle information system to understand the driver’s intention. In manual driving driver manifests the intention explicitly on the vehicles controls, mostly on steering wheel and pedals. The other reflexions of the intention are of great interest as they could provide information prior to control actions. Driver modeling [191] and machine learning [57,117] based approaches has been proposed to predict lane changing for driving support systems. Similarly brain potentials are for long known to be preceding conscious action [114], in his famous study Libet [130] measured brain activity 350 ms before the subject’s conscious decision to act. Electroencephalography (EEG) has been demonstrated in some driving settings to provide information about the drivers intent. Event related potential has been used to predict braking action before it can be detected in vehicle controls or even muscles [93,109]. However with current technology it is still difficult to associate the neural potentials to the events in the environment.

3.1.5 Quantifying the difference between intention and outcome

In this study we are extending the driver modeling discussion with the quantification of the proactive and reactive controls from the real driving data. It is well-known that the synergistic behaviors such as the proactive gaze movement and the steering are part of driving strategy [121]. We observe the drivers’ behaviors and operations, and the vehicle state under highly stressed driving situations and quantify the ratio of proactive and reactive controls from the relationships between gaze, pose, steering, pedaling and vehicle dynamics. We introduce the drivers to a high-speed slalom operation representing stressed driving situation and expect that the driver’s intentional control of the situation is expressed by his or her ability to maintain proactive control despite the stress caused by the task. We propose from the analysis results the ratio of

proactive to reactive control as an indicator of the state of driver proficiency at the task.

3.2 Materials and Methods

The driving experiments took place on a test track that was closed to other traffic. A Toyota Prius passenger car with automatic transmission was instrumented to record driver behavior and car dynamics. This research complied with the Declaration of Helsinki and was approved by the ethical committee at RIKEN. Informed consent was obtained from each participant.

Participants Thirty volunteers (18 women and 12 men) with a mean age of 57 years ($SD = 17.49$ years) participated in the study. All the participants were licensed and active drivers who drove at least several times per week; they included two professional test drivers. Each became accustomed to how the vehicle handled during various driving tasks done over a period longer than one hour before the experiments took place. The drivers were naive to the measured task, except for the two test drivers who were familiar with similar driving tasks.

Experimental Design As shown in Figure 3.4, six orange pylons were placed in a line at intervals of 15 m to provide a slalom course. From a standing start 40 m from the first pylon, the driver commenced at will, having been instructed to drive the course as fast as possible with the aim of reaching a speed of at least 40 km/h. The first pylon was to be passed on the driver's left, followed alternately by the others. At the end, 145 m from the start, the car was to be stopped on a given line. After the run, the driver drove around the track and returned the car to the initial position, repeating the entire cycle 10 times. The beginning of the slalom was marked by a blue pylon 15 m before the first orange pylon; 15 m after the last orange pylon, there was another blue pylon as an end mark.

The researcher who oversaw the driving experiments sat in the back seat of the car. Between runs, his role was to report the archived speed and encourage the driver to drive faster in spite of touching the pylons. He also asked the drivers to analyze aloud their own driving performance after each run as they returned to the start position. However, he did not give any advice to the drivers about how to improve his or her driving.

Data Recording The dynamics of the car and its status from the driver controls were recorded at a rate of 30 Hz on the control area network (CAN) bus of the vehicle. The position of the car on the track was acquired using a ProPak-V3 GPS receiver (Novatel Inc., Calgary) at a rate of 10 Hz. The driver's eye motion was recorded using an EMR-9 eye tracker (NAC Inc., Tokyo) at a rate of 60 Hz. This device provided horizontal and vertical orientations for both eyes separately. In addition, it recorded head-mounted video with the eye direction overlaid. This video was used to estimate head rotation; a

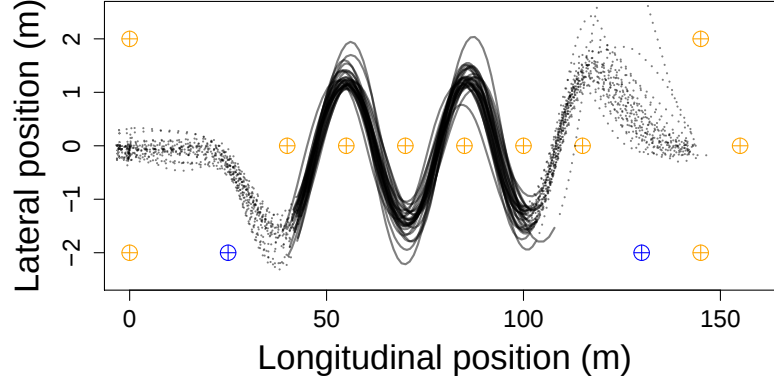


Figure 3.4: Pylon slalom course with the trajectory of the fastest run of each driver as recorded by GPS. Markers indicate pylons on the track. The solid part of each trajectory indicates the evaluated period.

machine-vision application tracked the position of an elliptically shaped part of the dashboard (see Figure 3.5).



Figure 3.5: Driver's view as recorded by head-mounted camera. The part of the dashboard marked with an ellipse was used to estimate the head motion. Cross and square shaped markers are the tracked directions of the eyes.

Performance Ranking Acuity in human motor performance is generally regarded as a trade-off between time and accuracy [69]. We emphasized the time aspect in the task design, so we ranked the drivers according to the time spent on the task. This was limited to the time between the two blue pylons to exclude the initial acceleration and final braking phases. Figure 3.6a shows the times of the drivers, in which the two professional test drivers were the fastest. The mean time on valid trials was selected as the ranking criterion. The optimal trajectory is the one that goes along the centerline as near as possible to the

pylons, so we defined accuracy as the standard deviation from the centerline.

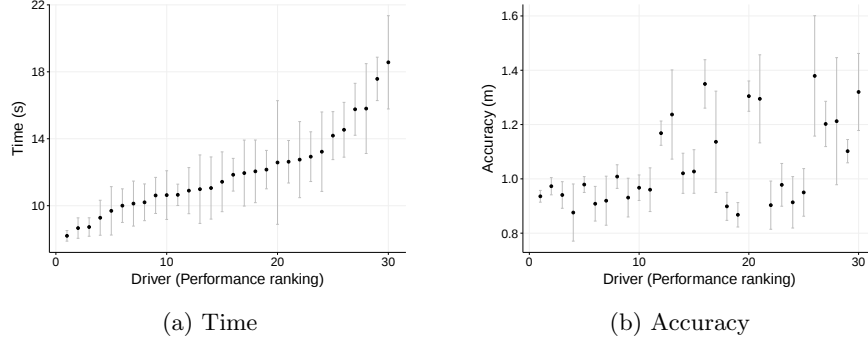


Figure 3.6: Two aspects of performance. The major index of performance is shown in plot (a), the mean time from the first to the last pylon. Plot (b) shows the accuracy measured as the mean lateral deviation (standard deviation) from the centerline (mean lateral position). Error bars are drawn at SD. Mean course time is used to rank the drivers by performance.

Excluded Trials Any trial in which the driver failed to steer the correct side of any pylon was excluded from the analysis. The driver with performance ranking of 13 failed on two trials, and the driver with performance ranking of 20 failed once.

Region of Interest The pylon course consisted of two and half cycles. The last half cycle was excluded because drivers might change strategy when detecting that they are at the last pylon. The remaining two full cycles were clipped at the onset of steering as described below.

Steering onset distance In a typical driving scenario, in which the vehicle is going straight and the driver wants to change the heading to another direction, the steering can be divided into two motions. In the first motion, the driver turns the steering wheel to the desired direction, and in the second motion the driver releases the wheel to the neutral direction. However, during the slalom, the steering angle is turned from one extreme to other without apparently stopping in the neutral position but rather staying longer in the extreme position (see Figure 3.7, which shows steering angle and velocity). For this reason, the onset of steering was registered as the driver starting to move the steering wheel from the extreme position. The longitudinal distance to the current pylon at the onset of steering toward the next pylon is used as the marker to indicate the onset of steering. A negative value indicates steering before passing the pylon.

Steering Compensation Meyer et al. [147] developed a method for studying the dynamics during pointing movements. The movement at the end effector

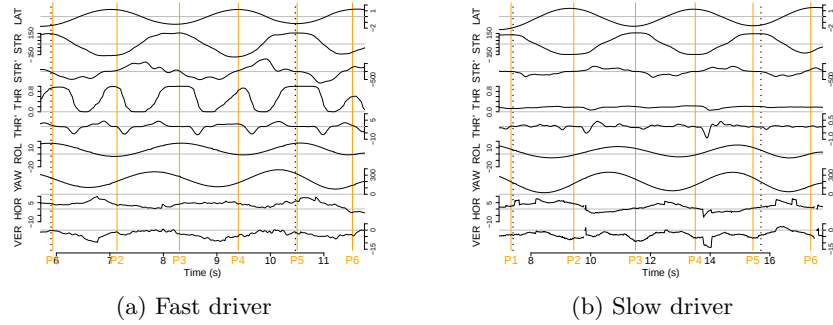


Figure 3.7: Extracts of time-series data for two drivers: (a) a professional test driver, ranked second in performance; (b) a regular driver, ranked second from last in performance. The vertical dotted lines limit the region of interest to contain two complete steering cycles. The parameters are LAT: lateral position (m); STR: steering angle, the position of the steering wheel (deg); STR': angular velocity of steering wheel (deg/s); THR: throttle position (arb. unit); THR': throttle velocity (arb. unit); ROL: roll angle of head (deg); YAW: yaw angle of head (arb. unit) ; HOR: horizontal eye angle (deg); and VER: vertical eye angle (deg).

is considered to be composed of bell-shaped overlaid sub-movements, which are observed in the velocity profile. Figure 3.8 illustrates this in the experimental data. The leftmost column in the figure shows a steering motion consisting of a single movement. The middle column shows a major movement followed by a sub-movement in the direction of the major movement. In this case, the car was not turning fast enough and the driver had to make the car turn more sharply. The third column consists of three sub-movements, the last one of which is particularly interesting: the car was turning too fast and so the driver made a corrective steering movement to make the car turn more slowly. The latter two cases, namely, under-steering and over-steering, caused additional zero crossings upon acceleration. These zero-crossings are quantified to detect the number of compensations to the steering.

Throttle–Steering Synchrony The prominent feature of the throttle signal in the time series of the fast driver in Figure 3.7a is that its frequency is twice that of the other signals. Throttle–steering synchrony represents the drivers’ synergistic behaviors of leg and arm motions, suggesting that smooth and natural combinations are used for driving in the situation. The relationships between throttle and steering angle are plotted in Figure 3.9. The correlation between the absolute value of the steering angle and throttling was quantified using Pearson’s coefficient of correlation. This value was multiplied by the mean of the throttle pedal position to reward use of the throttle.

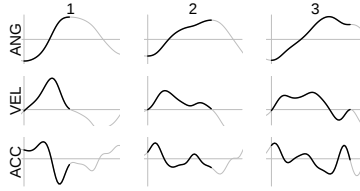


Figure 3.8: Examples of major steering movements. The first column shows a typical bell-shaped velocity profile, the second column presents under-steering, and the third one over-steering. The top row shows angular displacement (ANG) against time. The middle and bottom rows show the velocity (VEL) and acceleration (ACC), respectively, calculated as the first and second derivatives, respectively, of the displacement. The duration of each time axis is 2 s.

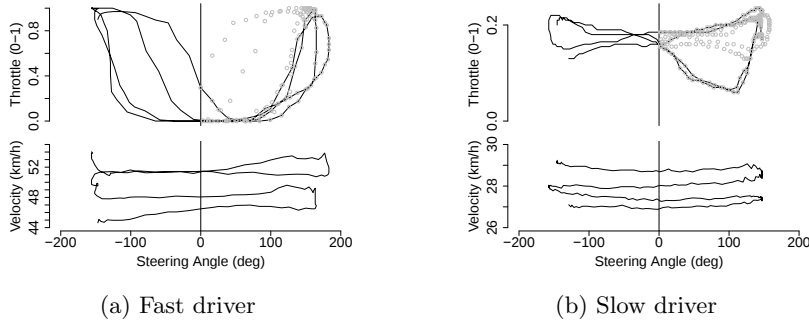


Figure 3.9: Correlations between throttle and steering: (a) second-fastest driver and (b) slowest driver in the performance ranking based on their fastest trials. The upper plots show throttle pedal position against steering angle, and the lower plots are the same for velocity. The throttle pedal position against the absolute value of the steering angle (plotted as circles) was used to quantify the throttle–steering synchrony using Pearson’s correlation coefficient. The correlation was 0.69 for the fast driver and 0.36 for the slow driver, both with $p < 0.001$.

3.3 Results

Performance The ranking of driver performance is shown in Figure 3.6a as mean time from the first to the last pylon. The performance of the drivers improved over the trials: 20 of the 30 drivers got their best time on the last trial. The accuracy on the first trial correlated strongly with the time in that trial ($r(28) = 0.78, p < 0.001$). During the later trials, as the drivers focused more on the time, the overall correlation decreased to moderate ($r(28) = 0.52, p < 0.003$).

Steering Compensation In an ideal slalom, one steering motion per pylon would be sufficient to steer through the course. However, uncertainties in the

environment and in visuomotor control caused the drivers to make adjustments to their major steering motion, as shown in Figure 3.10. The number of such adjustments correlated strongly ($r(28) = 0.96, p < 0.001$) with performance, with faster drivers producing on average less compensations.

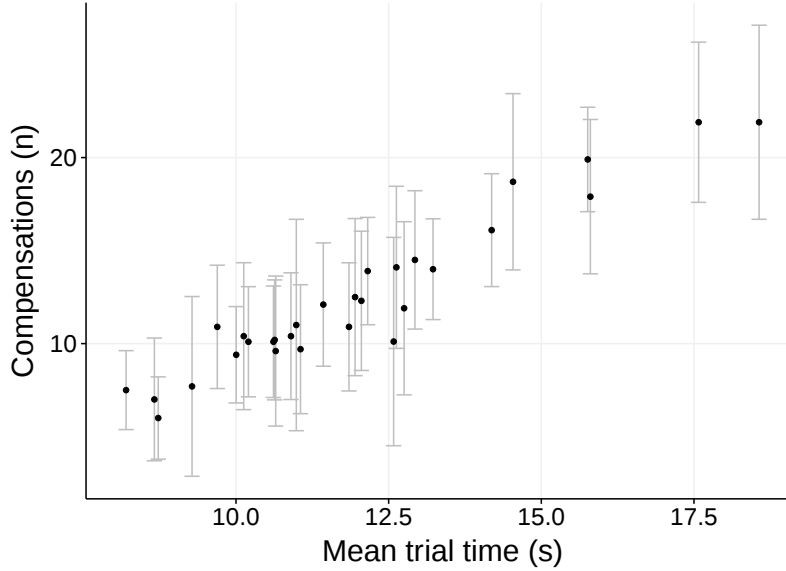


Figure 3.10: Number of steering compensations. Shown is the mean number of compensations during the evaluated portion of each trial, which consisted of four pylons. Error bars are drawn at SD.

Gaze and Posture Gaze is the summation of the directions of the eyes in the reference frame of the head, and again the head direction is taken relative to the driver’s trunk while seated in the vehicle. Human learns to turn the gaze to intended direction of ego-motion [83,121], the behavior is automatic as it is present even when eyes are closed [84]. The driver’s gaze during each experiment was observed using the head-mounted camera and was recorded as gaze overlay markers. For most of the drivers, head yaw was fixed to the centerline of the track at a certain distance in front of the vehicle and head tracking was a major component when supplemented with eye movement. All of the drivers except for one displayed typical [232,246] rolling of the head toward the inside of the curve. In analysis we could not find correlation between timing of the head or eye motion with performance. The proactive behavior in smooth eye movements and head movements seems to be helpful for the task without relevance to exceptional skill.

During the slalom, the driver’s eyes tended to fixate around the centerline

near or behind the pylon being steered around. This behavior is similar to that observed in bicycle simulations by [239], where fixation was observed on the future path between gates. Unfortunately, we were unable to register fixation times reliably from the eye-tracking signal because of noise caused by the difficult dynamic recording conditions.

Proactive Throttle The steering-to-throttle synchrony is shown in Figure 3.11. This strategy of pressing the throttle pedal in synchrony with steering is characteristic of many drivers. For drivers using the strategy, the ones with positive synchrony, proactive throttle correlated negatively with performance ($r(22) = -0.54, p < 0.007$).

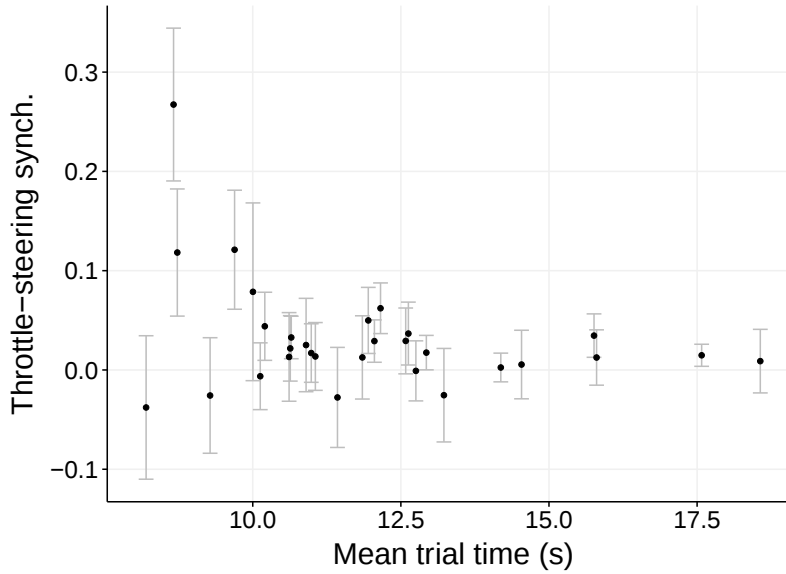


Figure 3.11: Throttle-steering synchrony. Mean value of correlation of throttle to steering angle, multiplied by throttle mean value. Error bars are drawn at SD.

The majority of drivers were accelerating as they passed the pylons. This choice is characteristic because the steering angle is at extremity and so the steering angular velocity is at a minimum. A larger steering angle causes more friction on the tires, which in turn causes the vehicle to slow down. It seems apparent that drivers prefer to throttle in anticipation to prevent the vehicle from slowing down. The coincidence between steering and throttling may be explained with proactive automatization: the drivers have learned to accelerate against the resistance caused by the turned wheels. Although this behavior may not be necessarily linked to superior behavior, as we saw with gaze and posture,

the distinct aspect is that for throttling in a stressful situation would most likely make the situation worse. For a driver, who is in distress over controlling the situation, pressing throttle to speed up the car is not a relevant option. Therefore the presence of the proactive throttling is an indication of driver's comfort in the driving situation. In case of braking, no regular braking pattern emerged for any of the drivers. During all the trials, 18 drivers used the brakes ($M = 4.6$ times, $SD = 2.7$).

Proactive Steering Figure 3.12 shows the steering onset distance. The higher-performing drivers started to steer earlier in relation to the pylons, showing moderate correlation ($r(28) = 0.50, p < 0.005$). This suggests that higher-performing drivers are better able to understand their environment and so act earlier despite of the stress caused by the environment.

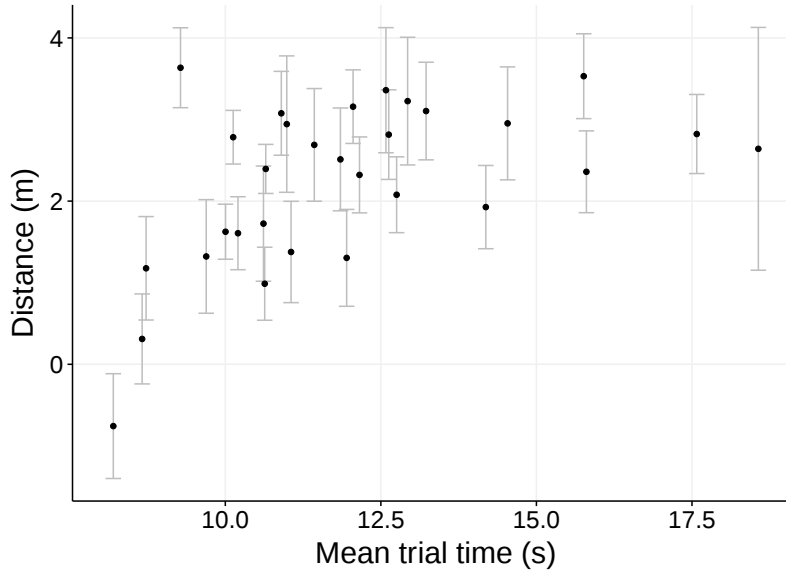


Figure 3.12: Steering onset distance. The dots represent mean location of steering onset in relation to current pylon for each driver. A negative distance indicates a location before a pylon. Error bars are drawn at SD.

3.4 Reactivity Index

We have presented driving as a mixture of two modes of control, namely, proactive control (acting for anticipated future events) and compensatory control (acting in response to sensory stimuli caused by past events). Proactivity is the crucial element in proficient driving. In a demanding driving task or an

unfamiliar driving environment, the driver cannot handle any more proactive processes and has to revert to reactive control.

In this study proactivity and reactivity in driving behavior were revealed in three aspects. Firstly, faster drivers steered more smoothly (see Figure 3.10). The second studied aspect was proactive automatization in throttling behavior (see Figure 3.11). Thirdly, the steering onset distance showed that faster drivers were able to act earlier (see Figure 3.12). In order to summarize these parameters, we normalized them linearly to range between zero and one, and averaged to obtain a model known as the *reactivity index*. The third parameter was inverted for the model so that each of the parameters showed more proactivity with lower values and more reactivity with higher values. The model correlates well ($r(28) = 0.81, p < 0.001$) with the mean performance time of the drivers. The modeled values for the drivers are shown in Figure 3.13. The importance of including several parameters in the model is to improve robustness against some behavior trait or quality that would otherwise bias the model. The different sensitivities of the parameters over performance ranges, as can be observed in Figures 3.10, 3.11, and 3.12, suggest that the model has potential to be tuned further with weighting of the parameters.

Higher-performing drivers show proportionally lower values of reactivity index compared with lower-performing drivers. A higher value of reactivity index means that a driver is less able to anticipate the required actions but instead is forced to use more reactive control to accomplish the task. The strong connection between driver skill and reactivity index, implies that less-skillful drivers, who show high reactivity index, have difficulty continuing to perform operations while responding to instantaneous control tasks, whereas more-skillful drivers have enough leeway to anticipate future events. These results suggest that the reactivity index quantifies the difference between the driver's intended state and the actual driving state. Stressful situations in natural driving, such as object avoidance maneuvers or negotiation of sharp corners, resemble behaviors in slalom and therefore we consider the model to be valid also for natural driving.

3.5 Driving assistance systems

The assistance systems in vehicles have gradually been replacing human operation in the driving [103,]. Some bottom-up control processes can be replaced safely with autonomous control. Advanced instrumentation in vehicles began with bottom-up instruments, working on closed-loop controls such as the anti-lock braking system (ABS) and cruise control to maintain a preset vehicle speed [16]. In contrast, more recent instrumentation uses open control to predict the state of the vehicle in relation to its environment. It also uses remote sensing to acquire information from the environment at a distance. For example, a lane-keeping assistant tracks the road ahead and adjusts the steering to maintain position in the lane. Adaptive cruise control adjusts the speed of the vehicle based not only on the desired speed but also on the speeds of the surrounding vehicles. This development can be seen as advancement from reactive

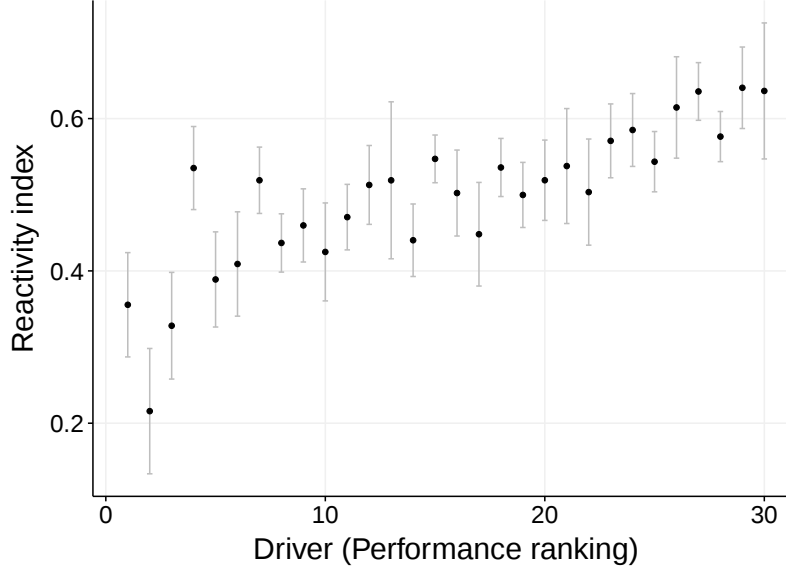


Figure 3.13: Mean reactivity index as computed for each trial from the steering onset distance, the number of compensations in steering, and the throttle-steering synchrony. Error bars are drawn at SD. Drivers with higher performance ranking show lower values of reactivity index. Mean reactivity index significantly predicts the performance time, $b = 21.52, t(28) = 7.430, p < 0.001$. The model also explained a significant proportion of variance in performance time, $R^2 = 0.6635, t(1, 28) = 55, p < 0.001$.

control towards proactive control.

One reason why autonomous controllers can replace these bottom-up controls is that it is easy to set the control target independently of the driver's intentions. It is still difficult to detect driver intention. Detection of the internal states of the driver is limited at present to applications such as alertness or inattention monitoring [55]. We argue that a driver, who is driving proficiently, is expressing intentions through the controls of the vehicle using proactive control. Driving that is full of reactive behavior tends to limit the driver's potential to drive safely.

An intelligent vehicle could use this information to decide the level of assistance to support with driving, or to inform the driver about potential risks in the current driving behavior. Figure 3.14 conceptualizes how the nervous system gets back to control of the driving situation using an assistance system. Measure such as reactivity index which decodes driver's capability to deal with driving situation can be valuable when deciding whether to intervene to provide driving assistance. Appropriate support based on the reactivity index could reduce the gap between driver intention and the actual driving state.

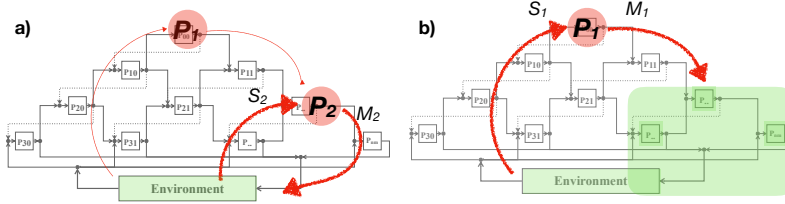


Figure 3.14: a) The driver is overloaded with tasks reacting to environmental stimuli, and b) some of the bottom-up tasks are handled by intelligent vehicle allowing the driver to control the vehicle according to intention.

Chapter 4

Neuro-rehabilitation

4.1 Bimanual post-stroke rehabilitation

The target of post-stroke rehabilitation is to restore damaged motor function so that patients can again perform tasks according to their will. We discuss the development of rehabilitation methodology to meet the individual conditions of patients targeting to restore bimanual function of the upper limbs, stroke survivors were relying in their earlier lives.

4.1.1 Stroke

Acute stroke is a medical condition caused by cell-death resulted from irregular blood flow in the brain [245]. In case of ischemic stroke the cell death due to failure of oxygen rich blood supply is a result of a blocked artery, often by a blood clot. The other kind of stroke is hemorrhagic, in which the brain is damaged by a pressure of leaked blood.

Stroke is one of the biggest causes of severe disability in welfare states [2]. Stroke survivors are often left with functional impairment of arms contralateral to their brain lesions. In daily tasks that they would normally perform using both hands, they use only the arm that is less affected by stroke [10]. The sensory deficits are directly related to motor function [207]. In addition stroke causes cognitive impairment [215], which on own part will complicate the motor rehabilitation.

4.1.2 Recovery

Recovery after stroke is connected to the reorganization of surviving neural structures [86]. The stages of ischemic stroke as manifested on brain imaging are: acute (24h), subacute (24h-5 days) and chronic (weeks) [18].

The spontaneous neurological recovery of stroke takes place in the first 6 to 10 weeks after stroke onset following a plateau on the motor recovery [118]. There is evidence from animal studies that after a stroke there is a certain

time-window with enhanced plasticity [156]. Also some studies indicate early intervention, in the sub-acute state of stroke, is for the benefit of recovery [40, 225].

Integrity of the corticospinal tract, intact connection from cortex to spine appears, to be important predictor for recovery [110, 214, 234]. The upper limb recovery can be predicted with presence of finger extension and shoulder abduction within 72 hours after stroke onset [160].

4.1.3 Intervention

Due to prevalence of the disability caused by stroke a number of therapies are actively practiced and investigated for improvement of motor function. Randomized controlled trial is the gold standard of evaluating outcome of an intervention [194]. The method involves dividing the subjects randomly to a group who receive the therapy and to a control group which does not receive the therapy. The outcome of the groups are compared with statistical methods.

Constraint-induced movement therapy Constraint-induced movement therapy [219] is targeted to overcome learned non-use of paretic arm associated with chronic stroke. The therapy restricts the use of less-affected hand by wearing a restraining mitt and thus forces the use of paretic arm in repetitive tasks or daily activities. In a randomized controlled clinical trial the therapy produced improvements in paretic arm motor function [241].

Repetitive bilateral arm training with rhythmic audio cueing Repetitive bilateral arm training with rhythmic audio cueing involves rhythmic movements using simultaneously both arms on a specific training device [236]. In a randomized controlled trial the therapy was found to have an advantage over dose-matched therapeutic exercises [134], however in larger trial [237] was not presented.

Mirror therapy Mirror therapy uses mirror to show patient the less-affected arm instead of paretic arm. Because of multi-sensory integration patient is liable to believe that the what he sees as the paretic arm is the paretic arm. The procedure is to execute requested movements on both hands while watching in the mirror. Controlled randomized trials [54, 243] conclude, that mirror therapy is promoting motor function recovery.

Hemispheric specialization with electrical brain stimulation Sensorimotor cortices are mainly controlling the contralateral extremities. However these cortices are not independent. In inter-hemispheric inhibition [45] during left arm motion: The right motor cortex activated for the movement inhibits left cortex. In case of right hemispheric post-stroke the left hemisphere does not get inhibited but instead possibly inhibits the right hemisphere leading to inhibition of the intended arm motion [53]. Inhibition on the stroke affected motor

cortex with repetitive transcranial magnetic stimulation (rTMS) has been found to advance motor recovery. Along with the improvement of methodology, brain imaging with targeted stimulation could enable therapy based on the individual damage on the brain networks [204].

4.1.4 Bimanual therapy

Bimanual training has been proposed as a therapy for rehabilitating the motor functionality of the paretic arm [91, 124, 227] with the aim of restoring normal life. Bimanual training seeks to employ many forms of bilateral neural coupling mechanisms to enhance the plasticity of the central nervous system [31]. This idea is expressed sometimes as the healthy hand “teaching” the impaired hand effective motion patterns.

Cauraugh and Summers proposed three mechanisms to facilitate the process of plasticity with using bimanual therapy [31]:

1. motor cortex disinhibition that allows increased use of the spared pathways of the damaged hemisphere
2. increased recruitment of the ipsilateral pathways from the contralesional or contralateral hemisphere to supplement the damaged crossed corticospinal pathways
3. upregulation of descending premotorneuron commands onto propriospinal neurons

Current bimanual therapy relies heavily on specific training devices [21, 228]. These devices are based on passive mechanics, in which the system is driven by forces generated by the patient [178, 236] or by active robotics [97, 205] to provide symmetric repetitive motion patterns for patient arm movement.

Despite the effectiveness of bimanual training, detailed analyses during bimanual motion training, especially electromyography (EMG) assays, have been less discussed so far. In this study, we detail EMG changes throughout different types of bimanual motions.

Phase, which refers to the movement of arms with respect to each other, is physiologically important. In-phase movement occurs when homologous muscles work simultaneously in both limbs [36]. Additionally, humans have a natural preference for in-phase movements over anti-phase movements [108, 145]; as frequency of motion increases, humans tend to switch from anti-phase to in-phase motion. However, this preference is not exclusive, as anti-phased motion patterns are a natural part of locomotion [170].

Mechanical coupling of arms is another common feature in many of the devices [206]. Mechanical coupling shares the load between arms, while loads would otherwise be divided between each arm independently. Furthermore, proprioceptive limitations associated with stroke-affected arms suppress the motor function of the stroke-affected arm [223]. Mechanical coupling [178] may increase sensory information needed to control the paretic arm [31].

4.1.5 Performance evaluation

Quantification of patient motor performance is valuable for the assessment of the current state and the prospect of functional motor recovery. Traditionally, such assessment is conducted by healthcare professionals using tools like Fugl-Meyer assessment [75]. Although, these assessments deliver a highly standardized score for clinical decision making, there is a need for diverse markers that can be measured via automatization. These scenarios include feedback that can be used to motivate the patient for better outcomes [216], rehabilitation done at patients' homes with digital connections to clinics [52], and proper adjustment of training level [163].

4.1.6 Evaluation of bimanual task performance with EMG measurements

In this study, we will quantify the immediate changes of EMG signals depending on the difference of bimanual motion type. We used the dual-steering rehabilitation system (DsRS) to create several types of bimanual motions. The DsRS consists of two wheels and a mechanical linkage that can change the connection between the two wheels among three training states: in-phase coupling, anti-phase coupling, and independent motion. Post-stroke patients were asked to perform four types of bimanual motions across two phase and two coupling states using DsRS. Phase, which refers to the movement of the arms with respect to each other, is physiologically important.

4.2 Experimental Setup

In this section, we introduce the device used to create the aforementioned types of bimanual motions. We also characterize the state of the post-stroke patients who participated in the study.

4.2.1 Dual-steering Rehabilitation System designed to create various types of bimanual motions

Patients with hemiplegia were asked to perform various types of bimanual motions using the dual-steering rehabilitation system (DsRS) shown in Figure 4.1 (a). This device consists of two steering wheels and a mechanical clutch that can change the state of the mechanical connection between the two wheels to one of three modes, in-phase, anti-phase, and independent modes, as shown in Figure 4.1 (b). While in the in-phase mode, the two wheels are mechanically connected, and when one is rotated by hand, the other rotates in the same direction. In contrast, while in the anti-phase mode, the second wheel rotates in the opposite direction when the first wheel is rotated by hand. While in the independent mode, the two wheels are free to rotate independently. This mechanism is useful for creating different phases of bimanual motions that enable

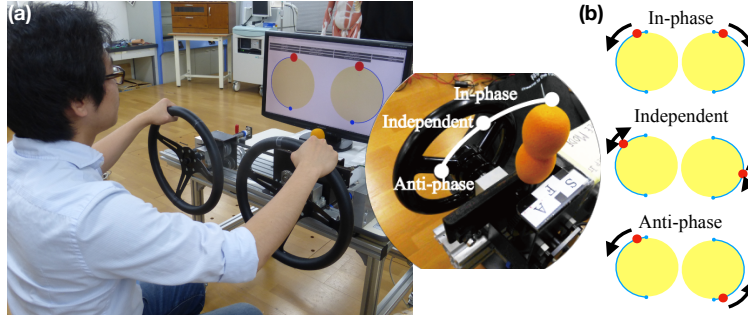


Figure 4.1: (a) Dual-steering rehabilitation system, the wheels of which can be mechanically uncoupled or coupled. (b) The movement patterns performed in the experiments: in-phase, where hands move in opposite directions; and anti-phase, where hands move in the same direction.

paretic motions to be supported by the non-paretic arm. The rotation of the wheels is measured by encoders.

4.2.2 Subjects

Eleven post-stroke rehabilitation inpatients (age, $M = 74.7$, $SD = 9.3$ years; sex, $M = 7$, $F = 4$) were recruited to volunteer for this study. All of the patients had been diagnosed with stroke (see details in Table 4.1). EMG recordings were made as the patients used the device over a mean of 76 days ($SD = 41$) post-stroke. The inclusion criteria were the ability to grip and rotate a steering wheel 180° independently with each of their arms. The patients were assessed using the Stroke Impairment Assessment Set (SIAS) [33] two times in total, once before and once after the experimental sessions. The SIAS scores of patient motor function performance on a scale from 0 to 5 were scored separately for proximal and distal function, which are measured by their reaching ability and voluntary finger motion, respectively.

All experimental sessions were conducted at the National Center for Geriatrics and Gerontology (NCGG) in Aichi Prefecture, Japan. All experimental protocols were approved by the ethics committee of NCGG.

4.3 Experimental Protocol

In this section, we introduce the experimental protocol for recording EMG data during DsRS training and introduce two indices to analyze the immediate changes in EMG among types of bimanual motion. One of the indices is used to compute the variance of EMG recordings among the different types of bimanual motions. The other is an index for computing similarities between the different EMG sets.

Table 4.1: All of the patients had paralysis contralateral to the side of the infarction-affected cerebral hemisphere. Legend: Side, affected hemisphere (left or right); SIAS Proximal and SIAS Distal, clinical assessments before and after all experiments, respectively.

ID	Sex	Age (years)	Side	Lesion Size (mm)	SIAS Proximal	SIAS Distal
P1	M	76	R	n/a	$4 \rightarrow 5$	$3 \rightarrow 5$
P2	F	81	R	$25.4 \times 7.0 \times 1.6$	$4 \rightarrow 5$	$3 \rightarrow 5$
P3	M	90	R	$8.7 \times 7.3 \times 1.6$	$4 \rightarrow 4$	$4 \rightarrow 4$
P4	F	79	L	$4.3 \times 5.7 \times 8.3$	$5 \rightarrow 5$	$5 \rightarrow 5$
P5	M	78	R	$7.4 \times 7.9 \times 1.6$	$5 \rightarrow 4$	$4 \rightarrow 4$
P6	M	68	L	n/a	$5 \rightarrow 4$	$4 \rightarrow 4$
P7	M	71	R	n/a	$5 \rightarrow 4$	$4 \rightarrow 5$
P8	F	72	L	$6.0 \times 2.9 \times 4.9$	$4 \rightarrow 5$	$5 \rightarrow 4$
P9	M	52	R	$7.0 \times 8.7 \times 3.2$	$3 \rightarrow 4$	$1 \rightarrow 4$
P10	M	73	L	n/a	$4 \rightarrow 4$	$4 \rightarrow 5$
P11	F	82	L	$8.5 \times 6 \times 6.6$	$4 \rightarrow 5$	$4 \rightarrow 5$

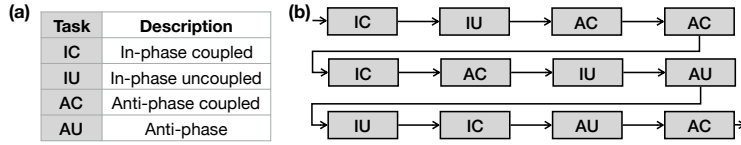


Figure 4.2: (a) The four task conditions defined as combinations of the phase and coupling conditions. For a given task, the same movement is repeated five times. (b) In the block design of the experiment, each of the four tasks was repeated five times in a pseudo-random order.

4.3.1 Experimental Protocol

Patients were asked to perform the four types of bimanual motions listed in Figure 4.2 (a) combining phase and coupling states. The experimental sessions followed a block design. As described in Figure 4.2 (b), each task block of 20 s was separated by 40 s of rest to avoid physical fatigue. Each session consisted of four tasks, which were repeated three times in a pseudo-randomized order. Prior to the experiments, subjects did light elbow flexing exercises as a warm-up and some rotations on the wheels to familiarize themselves with the device.

4.3.2 Method for quantifying EMG differences among bi-manual motions

EMG data recorded during the experiments were analyzed according to the following protocol:

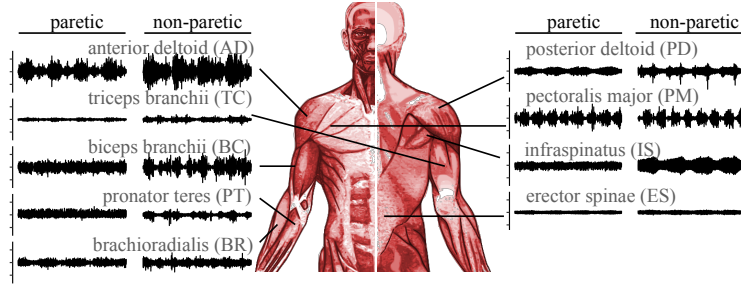


Figure 4.3: Placement of the EMG sensors and corresponding EMG signals during four cycles of in-phase motion. The EMG signal duration is 20 s and one tick in amplitude is 20 mV.

1. Activities of the nine muscles in each side described in 4.3 (a) were monitored in accordance with the guidelines of the Surface Electromyography for the Non-Invasive Assessment of Muscles Project [96].
2. The data that contributed less to creating the motions were removed [37].
3. The profiles were extracted for the selected muscles to represent the muscle activation in motion patterns.
4. The variance of the EMG profiles among the different types of bimanual motion were computed from the data.
5. The similarity between paretic and non-paretic arm EMG data for lateral activation similarity (LAS) was computed, and muscle activation similarities between different coupling states (MAS_C) and between the different phases (MAS_P) were also computed.

In the experiments, we monitored the activity of nine muscles, as described in Figure 4.3. Figure 4.3 shows an example of control muscle activities during DsRS use. In the case of this particular subject and task, the anterior deltoid was activated in response to DsRS control motion while the triceps was poorly activated. This result implies that the nine measured muscles are not always activated during DsRS use. In trials such as these, incorrect results can be derived from similarity and variance calculations if we use the EMG data based on muscles that did not contribute to the assayed motions [37]. The muscles activated by this motion depend mainly on the individuals assessed in our experiments. Therefore, we removed data on muscle activation for individuals in the first process of analysis using the method proposed by Costa et al. [37]. A flowchart describing this method is provided in 4.4 (b). In this method, the contribution of each muscle is quantified using the EMG amplitude and frequency.

The extraction of the surface EMG profiles started with preprocessing using a high-pass filter (4th-order Butterworth at 20 Hz) to remove motion artifacts. The filtered signals were rectified by taking absolute values of each datapoint

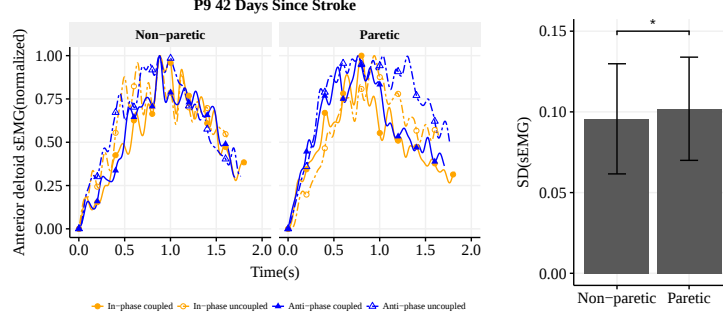


Figure 4.5: a) Example EMG profiles of the anterior deltoid muscles in different tasks during upwards motion. These profiles show that the anterior deltoid muscle of the non-paretic arm was activated in almost the same way across the four different types of bimanual motion, while the corresponding muscle of the paretic arm was activated in different ways depending on the type of bimanual motion. b) Statistical analysis of the variability of muscle activities on the non-paretic and paretic arms across all patients' trials. There was significantly higher dispersion for muscle activation of the paretic arms. The bars represent means, with whiskers representing $\pm$ SD.

4.3.4 Quantification of muscle activity variability between the different types of motions

First, we analyzed the EMG data to assess the variability in muscle activation between the paretic and non-paretic arms during the four modes of bimanual motion tasks. Figure 4.5 a) describes a prominent example of the difference in muscle activation between the paretic and non-paretic arms. The anterior deltoid muscle of the non-paretic arm can be seen to be activated in almost the same way across the four different modes of bimanual tasks, while the muscle activation of the paretic arm differed among the four modes, especially between the in-phase and anti-phase motions. This result suggests that the muscle activity pattern changes across different motions.

To quantify the variability of the muscle activities among the different types of bimanual motion, we used the following equations:

$${}^*D = \sum_{j=1}^l \left(\frac{1}{k} \sum_{i=1}^k \sigma({}^*m_{ij_{IC}}, {}^*m_{ij_{IU}}, {}^*m_{ij_{AC}}, {}^*m_{ij_{AU}}) \right) \quad (4.2)$$

$$\sigma^2 = \frac{1}{4} (({}^*m_{ij_{IC}} - \mu)^2 + ({}^*m_{ij_{IU}} - \mu)^2 + ({}^*m_{ij_{AC}} - \mu)^2 + ({}^*m_{ij_{AU}} - \mu)^2) \quad (4.3)$$

$$\mu = \frac{1}{4} ({}^*m_{ij_{IC}} + {}^*m_{ij_{IU}} + {}^*m_{ij_{AC}} + {}^*m_{ij_{AU}}), \quad (4.4)$$

where $*$ can be P or N , as described for the data matrix above.

4.3.5 Muscle Activation Similarity

Another index we use in this paper is activation similarity (AS). AS is used to compare the similarities between the two data matrixes represented by $*M_+$ in (4.1). For example, the similarity between the paretic and non-paretic arms for in-phase coupled motion can be quantified as follows:

$$AS(^PM_{IC}, ^NM_{IC}) = \frac{1}{l} \sum_{j=1}^l (r(^Pm_{j_{IC}}, ^Nm_{j_{IC}})) \quad (4.5)$$

$$r(^Pm_{j_{IC}}, ^Nm_{j_{IC}}) = \frac{\sum_{i=1}^k (^Pm_{i_{j_{IC}}} - \overline{^Pm_{IC}})(^Nm_{i_{j_{IC}}} - \overline{^Nm_{IC}})}{\left(\left(\sum_{i=1}^k (^Pm_{i_{j_{IC}}} - \overline{^Pm_{IC}})^2 \right) \left(\sum_{i=1}^k (^Nm_{i_{j_{IC}}} - \overline{^Nm_{IC}})^2 \right) \right)^{1/2}}, \quad (4.6)$$

where $r(*^1, *^2)$ is the Pearson's coefficient of correlation between the vectors $*^1$ and $*^2$ and $\overline{^Pm_{IC}}$ and $\overline{^Nm_{IC}}$ describe the averages of the elements of the vectors $^Pm_{j_{IC}}$ and $^Nm_{j_{IC}}$, respectively.

The muscle activation similarity AS between the paretic and non-paretic arms under the same condition can be used to assess how much the motion of the non-paretic arm is controlled in a healthy way throughout that motion. In contrast, AS for the paretic arm between the different conditions can quantify muscle activation differences among different conditions. In this research, we define AS between the paretic and non-paretic arms in the coupled condition as *lateral activation similarity (LAS)*, while that between the different conditions is defined as *muscle activation similarity (MAS)*.

4.4 Experimental Results

In this section, we analyze the experimental results with seven patients using the indices introduced in the previous section. We show that the variance of the EMG patterns for the paretic arm among the different types of bimanual motions are larger than those for the non-paretic arm. Furthermore, EMG patterns during coupled in-phase bimanual motion exhibit higher similarity with the EMG pattern of the non-paretic arm.

4.4.1 EMG pattern variance

As described in Figure 4.5 a) in the previous section, the muscle activation patterns differed among the bimanual motion conditions. We quantify the variability in muscle activation pattern using the index $*D$ introduced in Section 3. Figure 4.5 b) summarizes the statistical analysis for variability of muscle activation. To compute the variability, we applied the mean of Equation 4.2 on

the selected muscles that contributed to generating the motions, as discussed in the Experimental Protocol section; the selected muscles for each patient are summarized in Figure 4.6. The variability in muscle activities for the paretic arm was significantly higher than that for the non-paretic arm, suggesting that muscle activation of the paretic arm differs considerably across the bimanual motion types.

100	100	50	50	100	100	0	0	0	P1
100	75	100	25	100	100	0	0	0	P2
100	100	50	50	100	100	0	0	0	P3
100	100	100	25	100	50	25	0	0	P4
100	100	100	100	100	0	0	0	0	P5
100	100	100	100	100	0	0	0	0	P6
100	100	75	50	100	75	0	0	0	P7
100	53	65	25	65	81	90	18	0	P8
100	100	72	44	41	100	38	2	0	P9
100	91	41	50	8	83	75	50	0	P10
100	100	25	75	100	75	25	0	0	P11
B	L	B	P	Q	P	M	S	S	

Figure 4.6: Probability of each patient’s muscles being used to represent a task according to the muscle selection method [37]

4.4.2 Muscle activities of the paretic arm depend on the type of bimanual motion

Another research objective is to determine which bimanual motions create the most appropriate EMG patterns with respect to patterns distributed among the different types of bimanual motions. We assessed this objective using the index described by Equation (4.5) to determine which bimanual motion type among the four is most suitable for bimanual training.

LAS can quantify the degree of similarity in muscle activations between the paretic and non-paretic arms during the tasks. Figure 4.7 shows LAS according to phase condition in the experiments. LAS takes significantly lower values when measured in anti-phase compared with those measured during in-phase motion. LAS, however, fails to characterize higher similarity in either coupling condition, as illustrated in Figure 4.8.

MAS is a unilateral comparison of muscle activations according to coupling condition. Figure 4.9 illustrates that the similarity of activations in the paretic arm is reduced under coupling. This result, together with the previous result (Figure 4.8, indicates that coupling affects the paretic side, but neither the coupled nor uncoupled condition does not systematically increase the similarity. Instead, there is variation between trials; for some trials, coupling hinders similarity, while for others it enhances the similarity in the activation patterns.

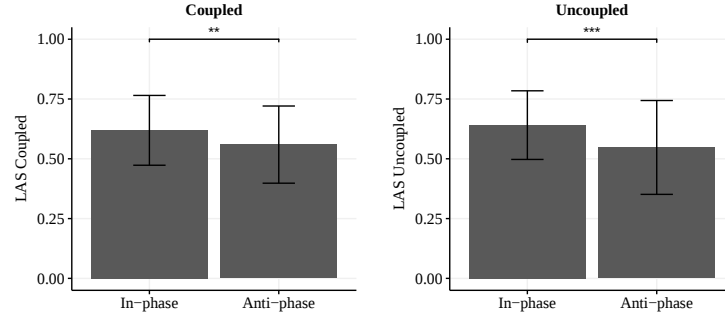


Figure 4.7: Lateral activation similarity (LAS) indicates that the contralateral similarity in EMG signals measured for anti-phase motion is lower than that measured for in-phase motion in both coupled and uncoupled tasks. The whiskers represent $\pm$ SD.

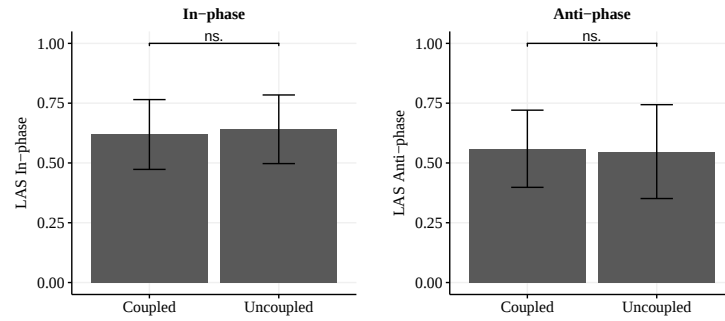


Figure 4.8: Lateral activation similarity (LAS) indicates that the contralateral similarity in EMG measured under coupling is from the same as that measured under uncoupled tasks. The whiskers represent $\pm$ SD.

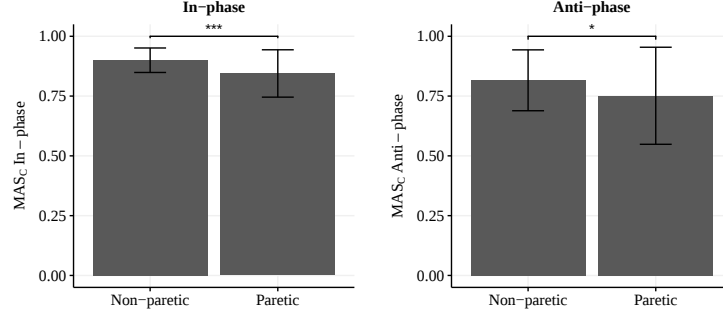


Figure 4.9: Muscle activation similarity (MAS), a parameter comparing EMG similarity between coupled and uncoupled conditions, indicates lower similarity among tasks for the paretic side. The whiskers represent $\pm$ SD.

4.5 Influence of Motion Pattern to Performance

Bimanual training is a widely practiced method to promote recovery from post-stroke motion paralysis, but the mechanism of recovery remain poorly understood. To identify the mechanism behind motion recovery through bimanual training, we introduced two indices to analyze EMG signals associated with four types of bimanual motion.

*D in Equation (4.2) represents the dispersion of the EMG pattern among different types of bimanual motions. The experimental results described in Figure 4.5 show that muscle activation patterns differed among the types of bimanual motion. This result implies that the muscle activation control is tuned automatically, even though the same motions were performed. This muscle activation tuning may be responsible for triggering recovery from motion paralysis.

The analysis using index AS in Equation (4.5) suggests the preferential bimanual motion creates similar EMG patterns between paretic and non-paretic arms. Figures 4.5 and 4.7 suggest that for in-phase motions, muscle activations are closer between the paretic and non-paretic arms.

One of the important reasons why muscle activities of the paretic arm differ according to bimanual motion type could be the signal processing that occurs in biological control systems. This type of signal processing can be modeled like the neuro-synergy system described in Figure 4.10 [41, 166], where information acquired from the environment is gradually symbolized to reduce its dimensions, while control signals are created from this symbolized information to create behaviors. The notions of sensor synergy [4, 123, 221] and muscle synergy [38, 47, 82, 200, 217] represent the input and output processes of the neuro-synergy system, respectively.

We can consider that a stroke damages the middle of this signal processing flow, and the signal accordingly becomes stuck at some intermediate point,

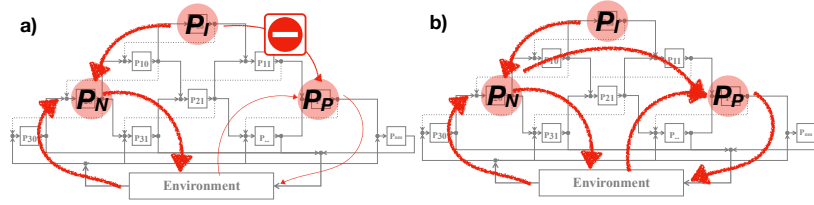


Figure 4.10: a) Represents a stroke affected bimanual behavior. The non-paretic process P_N is successfully regulated by the intention P_I , while the stroke affected process P_P fails. In b), the part of the control is gradually shifted from the process P_P to P_N , and the desired flow of control from the intention until the environment is achieved.

thereby causing motion paralysis. The results of this study suggest that appropriate bimanual motion can stimulate improved muscle synergy by circumventing the damaged or damage-affected circuitry.

These results also suggest the importance of careful observation in creating a bimanual rehabilitation exercise menu best suited to each patient's condition. Statistical analysis suggests that in-phase motion can enhance the appropriate muscle activity changes for the majority of patients. However, there were patients for which anti-phase motions better elicited the appropriate muscle activities. Rehabilitation must be designed to meet each patient individually.

Chapter 5

Generating Environments for Behavior Control

5.1 Artificial Environment

When interacting with the surroundings, a human uses all the sensory modalities to make sense of environment. In neuro-rehabilitation, or behavior research in large, the environment has to be crafted carefully to elicit the desired behaviors, see Figure 5.1. Various devices are in key role of generating the environment. The orchestration of devices to work together for task is essential in order to build functional environments.

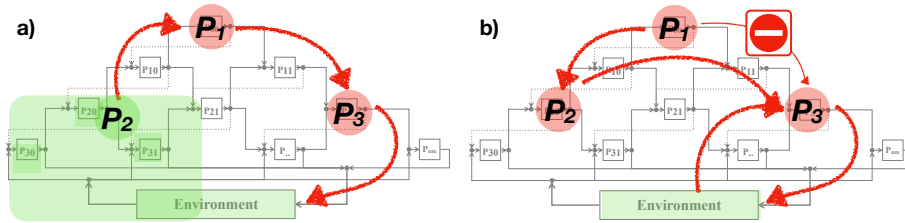


Figure 5.1: Examples of changing the environment in robotic neuro-rehabilitation. a) some sensory-motor tasks are done by a robot, and b) the stimuli to CNS is generated in a way to activate dormant circuits or establish new neural connections.

5.1.1 Scene of Rehabilitation

In typical neuro-rehabilitation settings a patient is surrounded by rich instrumentation of sensors registering and actuators modifying the state of the patient aiming to restore damaged neural functionality (Figure 5.2). Clinical staff

observe the patient safety, while scientific and technical staff supervise the instrumentation. All of the instruments must be orchestrated promptly so that the desired behaviours, intended to transfer the state of the patient towards recovery, can take place.

Conventional rehabilitation relies little on instrumentation [11,213], however the field of robotic rehabilitation [101,135,146] is based on control technology. The sensory instrumentation includes kinetic, kinematic sensors for determination the kinesiological state and brain imaging to sense the neural state. The actuators stimulate central or peripheral nervous system by electric, magnetic, visual, auditory stimuli and act physically to move the patient and in this way induce somatosensation. Feedback loops are a specific considerations, where the patient output, as observed by sensory devices, is modulated and reflected back to a patient to influence the internal state of the patient.

Because of the various conditions of the patients, it is impossible to create a sophisticated rehabilitation system that fit to all patients. We should develop the flexible systems that can respond to many requests of the patients not only the predictable ones but also the sudden events such as not to move shoulder this time because of the pain from this morning, and skip measuring back muscle EMG because of pain relief patch treatment. The patient conditions are always changing. We must fit the experimental systems to the patient condition at that time. Furthermore, the limited time is available for clinical experiments to reduce the patients' loads for joining the experiments. For effective clinical tests, therefore, the flexible operations that can tune the system configuration to fit to the patient conditions within the limited time is required.

5.1.2 Device Integration

Integration of medical devices is common activity in clinical settings. There are initiative such as Integrating the Healthcare Enterprise (IHE) [203] and Medical Device Plug-and-Play (MD PnP) [81] targeting at interoperability of the medical devices. For the purpose of integrating sensors and actuators to build robotic systems there are a plenty of platforms, such as ROS [176], providing tight integration. An interesting approach taken in Bonsai framework [133] makes possible to create applications and prototypes for empirical experimentation by drawing data flows between components of a system. Industrial automation is based commonly on fieldbuses [220], such as Controller Area Network (CAN bus) used in automobiles, in tasks requiring high precision timing, however these systems are hard to integrate with other systems [59].

Lacking application level protocols to build systems, integrators for a rehabilitation laboratory, or similar undertaking, are to work on mixture of analog and digital signals and various application programming interfaces provided by vendors. The aforementioned integration approaches, all provide the basic infrastructure needed for building communication in the system. However we were unable to find a framework that would support the diversity of platforms our devices and components needed to run on.

5.1.3 Purpose

In this paper, we will discuss the suitable framework to orchestrate the operation of the various kinds of instruments for rehabilitation applications. In order to be able to implement flexible applications on rich variety of platforms we wanted to build on existing technology using component based design. We will examine configuration of applications in respect to performance of the framework and the role of Internet of Things (IoT) devices in rehabilitation oriented cyber-physical systems in the presence of the constraints given by feedback loops.

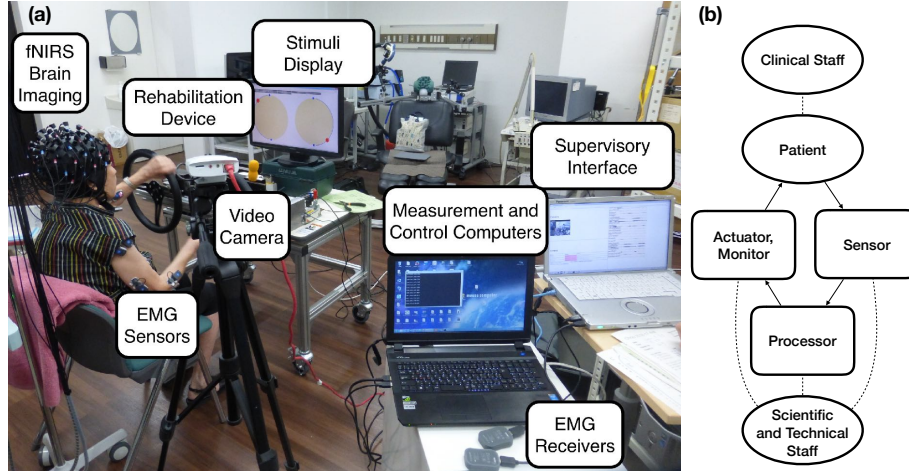


Figure 5.2: (a) Environment of neuro-rehabilitation and (b) the roles of people and devices in the environment.

5.2 Integration Framework

In this paper we consider a rehabilitation system as an ensemble of devices and, depending on circumstances, personnel working on a rehabilitation task. The same combination of devices and personnel can form several tasks, therefore we need a flexible way to build software applications that support the functions of each of rehabilitation systems. An application framework is a method, where an application skeleton is furnished to required functionality. Modularity, reusability, extensibility and inversion of control are typical benefits associated with the method [14].

One core function of any application is to register data produced by sensors so that the things that happened during a patient session can be reconstructed and analysed afterwards. The actual rehabilitation applications with specific feedback loops are to be extended on this basic functionality. In this section we discuss how to implement the data-flow between devices, implement common timing for the data, and state machine needed to keep the devices synchronised.

Architecture

Events and data stream are well suited for modelling the messaging between the scientific devices [133]. Component based development is an approach where software is composed in runtime of components running on heterogeneous platforms, which are connected with events and data-streams as well as conventional method calls [23]. In addition to preferred modes of messaging the approach provides means to configure software applications in a similar flexibility as expected from combining hardware devices.

We want an software application to resemble as much as possible the actual rehabilitation system. For this reason the components of an application are modelled after devices of the system, however in case a device has several independent functions, it may be reasonable to split a physical device to logical devices by functions. Computational modules, which carry significant processing tasks, which do not belong to a domain of a specific device, are considered as functional components of a system.

Figure 5.3(a) gives overview of the system architecture. Main communication method is event based. All components in the architecture are connected with Message-oriented Middleware (MoM). MoM defines communications according to publish-subscribe pattern [42]: when a client sends a message on a topic, it will be broadcasted to all clients which have subscribed to that particular topic.

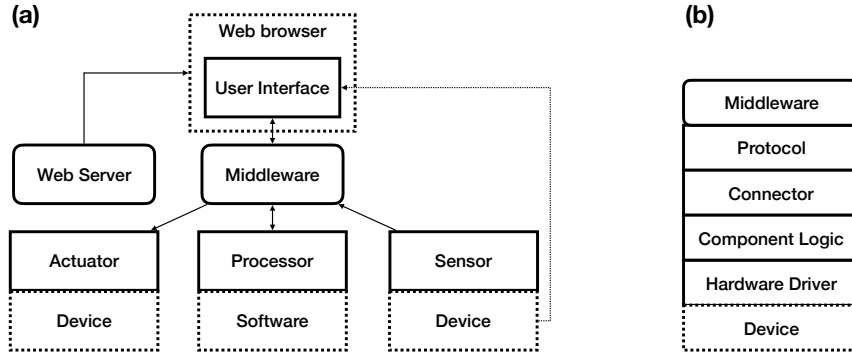


Figure 5.3: (a) The architecture of an integration system and (b) a detailed software stack to connect a device to the middleware.

In the system architecture we implemented the middleware with Message Queueing Telemetry Transport (MQTT), standardised as ISO/IEC 20922:2016. MQTT is a lightweight for client, in respect to processor load [32] and network load [72]. Several broker implementations and client libraries on various programming languages and operating system environments are available for the protocol. Importantly MQTT uses internet protocols for communication making possible to build the network backbone connecting devices on standard wired and wireless local area networking hardware.

A web-server provides user interfaces (Web UI), which are interacting with MoM. The connection from a device to Web UI is a exceptional case, where camera's device drivers are providing a live video stream to application using refined protocols defined in internet standards. Connecting video through MoM would overload the system with inefficient streaming without delivering any functional gain for the current applications.

The design of a component

The task of a component is to expose the functionality of a device or processing, it is representing, to the rest of the system. Middleware is the major communication channel, thus the component is connecting the device to the middleware as seen in Figure 5.3(b).

In practice the *protocol* layer consists of a ready made MQTT library implementation for the target platform. It is providing a robust communication with the MQTT broker. Each component instance in an application must be identified uniquely when registering to MoM. Nodes, which are connected to hardware, can have only single representative instance. Instead monitoring nodes, which can have many simultaneous instances, such as web client, a unique identifier must be generated for each instance.

Connector layer is a base class or library implementing the framework specific behaviours, which are same for all components. These include state machine implementation and methods for status reporting. *Component Logic* layer deals in response to events from the middleware and from the hardware. In object oriented design it may be implemented as a subclass to *Connector*. *Hardware Driver* is interfacing library to access the physical hardware. The processing components, which do not need dedicated hardware, do not implement this layer. The decision of which programming language to use for implementation of a component depends directly on the language's ability to communicate with hardware driver and it's capability to implement the algorithms needed for computations.

Timing

When combining data streams from different sources care has to be taken that the timing of the data is comparable. This is done by detecting common data points in time-series. A generic MoM does not provided automatic way to provide synchronisation of messages [94], timing issues has to be dealt depending on the capabilities of the devices. The synchronisation methods can be classified (in descending order of preference) as follows:

- Sampling in devices is driven by *a shared clock*.
- Sampling is started by *a common trigger*.
- *A recorded trigger* is fetched from the stream.

- Recording is *started at same time* on the devices, manually or automatically.

A complex application will normally involve several of these synchronisation methods. Often at some stage there will be resampling of two or more streams to a common timing to simplify analysis. The applicable solution for synchronisation depends on the capabilities of devices and application requirements.

Message

The communication needed to build applications using the components is shown as hierarchy of messages in Figure 5.4(a). A message is an associative array, a collection of key-value pairs. All the messages share few core fields and fields specific to type of the message. The sender of message is declared in the field *client_id* and the associated timestamp, *time_utc*, in reference to a clock identified by *clock_id*.

In the proposed architecture the messages are coded as text using JSON, a standardised subset of ISO/IEC 16262. An example of a status message is given in Figure 5.4(b). The status message contains only elementary values of string and numeric types, however a value may also contain ordered and associated arrays. The obvious advantage of the chosen approach is that the messages can be extended to application needs without breaking compatibility to previously implemented software.

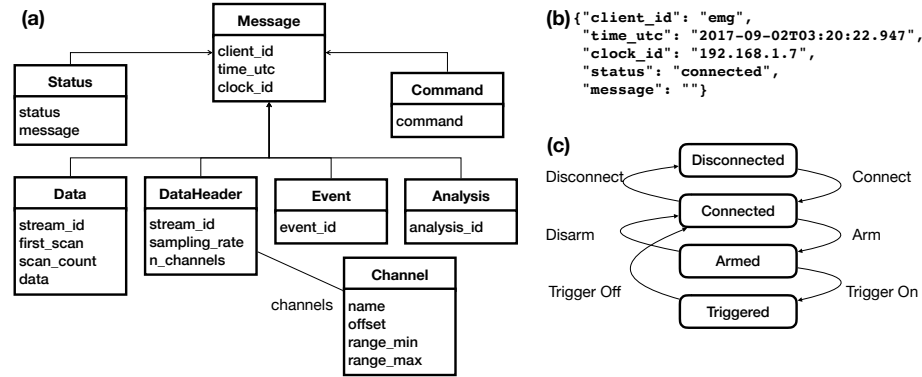


Figure 5.4: (a) Message class hierarchy, (b) a Status message and (c) state machine implemented in components.

State Machine

Temporal orchestration of the devices is guaranteed with a common major state-machine, see Figure 5.4(c). Supervisory application controls the state of the components by issuing commands, i.e. *command* messages on *command* topic.

After receiving a command a component has to report its state on *status* topic. The success of commands is not self evident when components are dealing with real-world hardware and so a supervisor cannot assume that commands are always successful. If the state transfer fails, then information related to failure specified in *message* field of the *status* message.

The major states are summarised in the following:

- Disconnected: A component is listening to the middleware, but disconnected from associated hardware.
- Connected: A component is connected to hardware.
- Armed: A component is streaming data between middleware and the hardware and is ready to use actuators with minimal delay.
- Triggered: Actual trial is in progress. A component is acting on patient and recording.

Event-messages are created as a mechanisms to implement application specific substates. For example an orchestrated calibration sequence between devices can be implemented with events.

Streaming and Analysis

A stream is a form of continuous signals carrying information concerning states of patient and instrumentation. When sending data in message structures care has to be taken so that the amount of information to message size ratio is kept high. Messages *Data Header* and *Data* are designated for the streaming. *Data Header* message is sent before first package of stream in *Data* stream and when a streaming component is requested for status to allow new clients to join after stream has been already started. Fields in *Data Header* describe the channels in stream. The following *Data* messages contain economically little other information than the actual data values. Regulation of the duration of data per each message makes the data update rate predictable. Client can be designed to work on specific data length without need to buffer or realign data before processing or displaying.

Sporadic observations and observation with irregular shapes are transferred as *Analysis* messages in JSON structures. This mode of transfer is suited for both observations done directly on patients and analysis derived from streams.

5.3 Issues and applications

We have used the integration frame in various applications in various experiments [3, 37, 38] in our premises and in several hospitals. The core kit we have been using consists of a notebook computer working as the MoM broker, web server and a host for components. The notebook computer and other computers depending on the applications have been connected by a network switch with

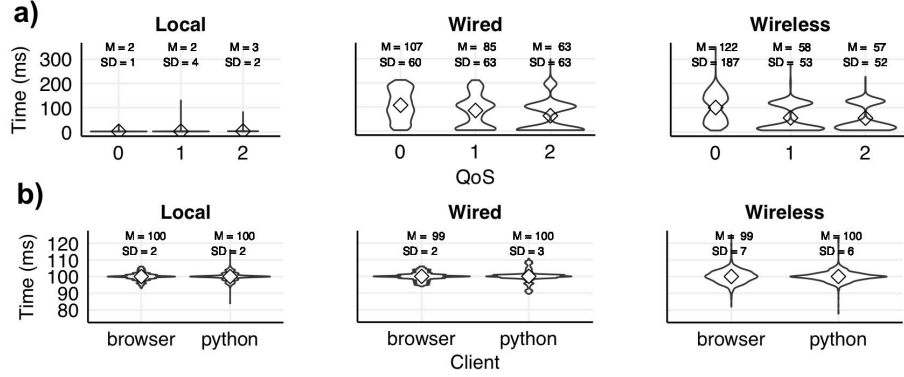


Figure 5.5: a) Duration and variation in messaging in different networking and quality of service conditions. The time is roundtrip time from sending to receiving a reply for $n=1000$ in 100 ms interval. b) Jitter in streaming. The time between arrival of stream packets sent at interval of 100 ms. Legend: M= mean and SD= standard deviation. On the violin plot the diamond shape is placed on mean and the curve represents kernel density.

WIFI access point. The formed network is not connected to internet, to regulate unwanted traffic.

Client and component implementations

The component based design proved to be very successful. In the framework a device can be replaced by other providing the same functionality, e.g. wireless EMG can be changed to wired system if the band-width is congested. Components can be relocated to run on another computer, which is an advantage when a system governed by a component needs special attention or additional processing capacity.

The wide availability of MQTT protocol implementations on different platforms, helped us to implement the components on various programming environments including: python, C#, java and javascript. Importance of richness is that the components can be written in tools implementors are proficient with or which provide features hard to get otherwise, e.g. MATLAB to use its mathematical libraries and Unity3d to create virtual environments.

Particularly the web interfaces that could be run on tablets, smartphones and laptop computers, were helpful for clinical staff and researchers as well so that they could monitor and analyse the data in real-time.

Messaging performance

MQTT protocol defines quality of service (QoS) in three levels:

- Level 0: Message is received at most once.

- Level 1: Message is received at least once.
- Level 2: Message is received exactly once.

As the QoS level increases more communication in the network has to be done to guarantee the service [128]. Also the physical network structure, how the client nodes are connected to the broker, is an defining factor in the performance of the infrastructure. Despite of being well aware that system performance has many factors in software and hardware components [187] and transferred content [155], we wanted to get some estimate of the system throughput performance using consumer class hardware under the conditions of QoS and client connection.

Figure 5.5 (b) summarises the performance measurements, that we did using ActiveMQ broker [209] running on a Apple Notebook and python clients for the platform. Client A, residing on the same computer as the broker, sent a message with payload of 10 characters to Client B. Upon receiving the message Client B answered with a message containing same payload. Client A registered the time span between these two messages. The client connection condition was defined as the connection of Client B in respect to the broker: in local condition it was running on the same computer as the broker and in wired and wireless conditions on Windows computer connected via network switch using LAN or WIFI connections respectively.

No lost messages were observed during performance testing. The results indicate that for clients which need fastest possible response times should be running in same computer as the broker using QoS level 0. The low performance of QoS level 0 in networked conditions is due to different internal message handling strategies of ActiveMQ broker in default configuration. In the test configuration wireless network was performing better than the wired. Implementor must accept that there will be delays in the network transmission when using hardware and software which has not been optimised for the traffic.

Streaming performance

The information in electrical signals in brains and muscles is up to 600 Hz, with the highest frequencies obtained at facial muscles elsewhere 300 Hz [157]. In case of optical motion capture a range [210] typically hundreds of Hz is needed to capture human motion [210]. Kinematic and kinetic biomechanics measurements generally show similar sampling rates. According to Nyquist-Shannon sampling theorem the sampling rate should be two times the highest frequency component in the signal in order to reconstruct the original signal. From this we can conclude that 2000 Hz sampling frequency should be sufficient on most applications. The streaming of the time-series to the components for processing in timely manner is a crucial aspect of the platform.

In order to evaluate the streaming performance, using the same hardware configurations as when measuring messaging performance, we set Client A to stream simulated data of 50 channels at 2000 Hz signals refreshed in 10Hz, thus sending 200x50 matrix of values ten times per sec. The values were 32 bit precision floats sent in base64 encoded string. Client B was subscribing to the

data stream and registering the difference between arrival times, see Figure 5.5 (b) for the results. Client B was running two configuration: one in java script inside of Chrome web browser and the other as a python implementation. The noticeable feature is that in wireless transmission mode there was more variance compared to two others, while in all configurations the mean interval remains same. Therefore time sensitive streaming should be placed in single computer or connected with wired network. During performance testing we could also confirm that a realtime plot on a web browser was able to promptly display time series without excessive processor load.

Wireless Sensory Networks and Internet of Things

Wireless Body Area Network (WBAN) consists of miniature devices placed on or implanted in the body and connected to network [125]. Plenty of affordable wearable WBAN sensors have been implemented for the purpose of registering physical activity [154]. The practical advantage of wearable wireless sensors in rehabilitation is the ease of placing on the patient because the wiring, together with earthing related noise and safety issues, can be ignored. The advantages of wireless sensors become evident when instrumenting layers of sensors on patients having impaired motor function possibly relying on a wheelchair.

A WBAN has a specific node, a personal device, which works as a gateway to outside of the WBAN [152]. This is usually a personal computer or a smart-phone. WBANs are closely associated with IoT concept, where all devices are connected to internet and in this case all collected data is stored on a cloud server. Ideal place for integrator to intercept the sensory data is at personal device as the observations are physically near and so to avoid the latencies caused doing transaction with a cloud computer. In addition to accessibility of data stored on the cloud also data ownership, what and how the cloud data may be viewed, may place constraints on the use of IoT devices [149].

In majority of the healthcare IoT where data is accessed through cloud service [44,115], the feedback loops become inevitably slow to modulate signals in time to be of valuable feedback to patients during rehabilitation sessions. In rehabilitation already sub-second delays in feedback become a hindrance. The way human integrates different sensing modalities into consistent percept needs fidelity in order of 100ms to take place [196]. Neurofeedback effect is enhanced by quick feedback [64] the order 250-300 ms [198]. The applications built on the proposed framework can provide this required performance. However the problems arise with the delays in wireless transmission on a congested bandwidth. On a device group, e.g. electromyography of 20 channels, the processing of signal group must be delayed until the instant the all packet of data on all of the channels is received and the packets may be received correctly in a random temporal order. The issues regarding a coexistence of several WBANS and other wireless networks are recognised and an active research topic [112,189] and so there is hope for improvement. Meanwhile the selection of devices, which can deliver signals properly is essential for building feedback loops.

In a fields of rehabilitation, where environment is more predictable than

working with demanding inpatients, design of rehabilitation systems can have different targets. Models of neural recovery suggest that while a big dose of rehabilitation is needed but this is not met in practice [122]. Similarly patients receiving more therapy have better changes to recover than patients who received less [132]. The framework provides also means to build less labor intensive methods to increase the amount of therapy for patients.

Chapter 6

Critical assessment

In the past three chapters we discussed ways of modifying human performance in form of three studies. This chapter unifies those discussions using the framework for the discussion was based on the theoretical constructs formed and described in the second chapter, Background. This chapter is closed with reflective discussion of the previous studies and their consequences and opportunities.

6.1 Top-down and bottom-up controls

In this study we have considered bottom-up controlled behaviors as adaptation of human to environment and the top-down control as human's act to change the behavior. Human nervous system uses needs both systems for effective interactions with its environment. We examined the realization of behaviors in two contexts. In the first context, we considered how to identify and deal with lack of skill in driving behaviors. On the second context of neuro-rehabilitation we were considering how to repair disease broken nervous system to enable the patients to return to normal life.

Driving Essentially driving is about getting to a destination. Driver has some kind of plan with waypoints, which may be added or adjusted as the driving goes on. The execution of such plan is top-down controlled.

Obtaining perfect driving skills that would enable driving virtuously using top-down control alone is not realizable because of unpredictable features in the environment. Therefore the top-down control has to be complemented with environment stimuli driven bottom-up control to compensate for the error between desired and actual vehicle state caused by error in control.

The vehicle technology has taken incredible steps in recent few years targeting autonomous control. Now in the transition situation, before the vehicles can handle any kind of driving situation equally or superior to human driver, the human and the vehicle has to share the driving tasks. The bottom-up processes

have been easier to automatize and the top-down controls still need human supervision.

Neuro-rehabilitation Neuro-rehabilitation deals with recovering function of damaged nervous tissue. In this thesis the focus was in post-stroke rehabilitation. Stroke survivors are often left with little damage to higher mental processes, but instead with various level of hemiparesis, a impairment of motor function on one side of the body. Activities of daily living involve bimanual motions, and the recovery of hemiparesis is essential to lead normal lives.

Bimanual therapy is one of the widely practiced forms of therapy. Complex neural connections between the hands are proposed to help to restore the neural connections so that the stroke affected arm could be controlled voluntarily. The actual mechanisms are not known. In order to design suitable rehabilitation study aiming to find motion patterns which could facilitate the recovery was conducted.

The post-stroke patients showed different level of impairment in the tasks which were equally simply for healthy subjects. Phase condition, where the wheels were rotating to opposite directions was harder for patients. The results related to the other condition mechanical coupling did not open as clearly. It appears that for some patients the coupling is helping and for others hindering. This important finding has a consequence that the suitable therapy to correspond state of the patient must be selected.

The neurological substrates that define impairment in the behavior need to be addressed in more detailed study. However, during the experimentation, we found out that several sever patients were helped with the mechanical connection: a training session after mechanical coupling improved their performance. This suggests that those with minor impairment would be hindered by feedback loops caused by the mechanical interactions of the coupling at the device.

Altogether the findings advance the big goal of connecting the intention to behaviors. The underlying strategy in this endeavor is to make top-down and bottom-up work together for the realization of a common behavior, and this way make the state of nervous system more favorable for reinforce the connections needed to relay intention to action. This is achieved by exciting the good bottom-up processes, such as afferent sensory signals, and suppressing the bottom-up processes, such as reflexes which are would work against the goal.

Facilitating Top-down Behaviors by Changing the Environment Purpose of driving, the reason why people drive, is concerned about getting to way-points. Similarly the target of rehabilitation was to restore the lost motor functions, that patients are able to do the things they wanted to do in the way they wanted to do. Common the approach to these two is to help to align the control processes at different levels to work together for common goal. They way how this can be accomplished is by changing the environment. In case of driving we proposed to adapt the environment by driving support systems so that driver can concentrate on the main task of directing the vehicle to the

waypoints. In case of rehabilitation the approach is to modify the environment show that patient is in favorable state for the neural recovery to take place.

The intelligent vehicles have internal communication infrastructure well established. Introducing a parallel network is not feasible. Instead the proposed enhancement to monitor and support driver's behavior should be incorporated to the existing infrastructure. However, in case of neural rehabilitation no such a sophisticated infrastructure is available.

Making a neuro-rehabilitation environment for a patient is a delicate process. The medical and mental state of patient may need special attention. In the core of neuro-rehabilitation, the cybernetic feed-back loops from signals measured at patients are modulated back to the environment available for the senses of the patient. We created a framework to generate environments by integrating neuro-rehabilitation laboratory devices. The framework was based on open-source technologies so we saw as natural to share our contributions to those who are working on similar undertakings.

6.2 Modulating behaviors

The control in human motor system is layered and redundant, as we have seen in the past chapters. The controller hierarchy, introduced at Section 2.3.3 and Figure 2.9, has been the major theoretical vehicle to discuss how the control flow in driving behaviors and motor control in post stroke patients. Controller hierarchy as modeling tool has the ability to describe mechanisms how control is carried in behaviors.

Generally all human behaviors are interactions with the environment. These interactions form loops through the environment and some controllers in the hierarchy. The major emerging pattern in behaviors include been the interplay between top-down and bottom-up control. Top-down control involves higher level neural circuits, including those with executive function. The bottom-up control involves *local loops*, loops which are weakly, if at all, connected to higher level. These local loops may be reflexes, very quick reactions to environmental changes, which may not even be conscious to subject. Wellbalanced adaptive behaviors such as driving or reaching tasks have components of both as we saw in chapters 3 and 4 respectively.

The reflective nature of higher control, control loops that involve also the controllers higher in the involve even symbolic processing. The dichotomy of controlled and automatic processes [202] can be described with the model. In this case the novel control is handled on the higher level, while after learning through repetition the processes can handled to greater degree on the low level controllers.

In the discussion on the recovery mechanisms of stroke, the model was used to theorize how plasticity, the ability in neural system to reorganize itself, can be applied to restore the function lost because of medical condition. The principle of modulating behaviors is to change the environment. There are two generic approaches: First approach being by substituting of some components of sensory-

motor system with artifacts and the second one is by making environmental stimuli in a way that encourages changes in desired parts of nervous-system.

6.3 Substituting components of behavior

In the driving related study, chapter 3, we established quantification for the degree how much driver was in control of the situation. By using that measure, we proposed that when a driver was loosing the top-down control by overwhelming needs of bottom-up control an intelligent vehicle could overtake some of those tasks.

In case of physical disabilities e.g. amputated arm, the parts of body can be replaced with prosthesis. However, the process of introducing replacements for components of which were original parts sensory-motor system are much harder in comparison to a vehicle. There is ongoing progress on replicating the dexterity in human limbs, which allows the low-level control of the tasks. The issues to integrate with high-level control are more profound. Feeding the afferent sensory signals to the central nervous system is difficult and so is the decoding of the intention so that the prosthesis would behave fast enough so that wearer would accept it.

Some help might be provided by anticipatory behaviors, preparatory behaviors happening before the action itself. In the driving context we saw that steering actions preceded with rolling of head in anticipation to gravity effect and similarly gaze was turned to future path of the vehicle. Decoding of the intention from CNS signals remains very hard. While the technology improves these signals might give a clue to improve the acceptance of prosthesis.

6.4 Targeted changes in the nervous system

In order to accommodate prosthesis nervous system has to adapt to the differences to the body parts that were replaced. Sometimes this plasticity is used in order to learn control mechanisms. Neuro-rehabilitation, particularly stroke motor rehabilitation, takes, however, another approach. The goal of the rehabilitation is to modify the structures in the CNS to be able to carry out behaviors that were lost due to medical condition.

The study of neuro-rehabilitation, chapter 4 was concerned about finding rehabilitation exercise tasks, which would promote recovery of paretic arms. The bimanual control mechanisms in central nervous systems made grounds to assume that some motion patterns would target such circuits and further that training would enable independent motions of paretic arms.

The reorganization can be attributed to revoke use of dormant circuits, and creation of new connections according to Hebb's rule. Initial state and organization of nervous system is different over individuals and therefore similar physical damage can be hugely different deficit on the functional properties. Therefore, it is impossible to provide one generic solution helpful to all patients. In or-

der to systematically load the neural circuits, we developed a framework which enabled creation of patient specific applications.

6.5 Driving

In this section we outline the progress of the study from initial hypothesis to the use of The driving is seen primarily as interplay between higher and lower processes. We tried to use these models to see if activation of different circuits would be for benefit in stroke recovery, however the different state of stroke and initial conditions of patients, however, made hard to collect statistically significant data. The consequences and applications of the findings in this research are discussed followed with the future work.

6.5.1 Progression

The starting point for driving study was a corpus of on track recordings of driving. The initial purpose of the study was to model the driving behavior with the conceptual model of neural synergy system, in section 2.3.2. This model aims to explain how human can perform complex interactions with the environment by using only limited processing resources in the central nervous system. Using the model, I laid out initial hypothesis that:

1. A skillful driver is better at finding and modeling the cues from the environment data needed for driving
2. A skillful driver is able to modulate the cues to steering commands

When analyzing the driving data, I found soon that for most of the driving data the tasks were too much dictating the driving behaviors, e.g. the drivers were paying excessive attention to speed or precise tracking of the lanes. Furthermore the repetitions of few trials could not give base for statistical analysis. A particular task, pylon slalom, in the data was different in intensity and number of repetitions, so this was my task to focus on.

While registering the behaviors and categorizing behaviors by hierarchy, in Section 2.3.3, the two kinds of interactions became visible: top-down controlled and bottom-up controlled. Top-down controlled behavior seemed to be associated with preparatory actions, such as gaze leading the steering motion. While bottom-up controlled behaviors seemed to come out from nowhere: the evidence to map actions to sensory stimuli was not strong. This led to the hypothesis of the roles of top-down and bottom-up control as laid out in Chapter 3.

Generally the driving data is very hard to analyze. Based on the literature there was high expectations on the analysis of eye movements. However the efforts to refine the data was in vain, there was no way to judge, if the detected eye movement was originated by subject. The precise eye movement recordings should give deeper insight to mental processes of driver.

The lack of structured queries of the driver’s state was an other regret related to data records. It would be valuable to validate the assumption about driver’s anxiety in relation to performance.

Validation of the model could not be done by contrasting it to some other driving task by same drivers. Despite having the data from several other tasks by the same drivers. The nearest candidate of curve driving data was contaminated with the task definition of tracking of speed and position.

6.5.2 Simulated driving after stroke

We had an opportunity to use driving simulator with post-stroke rehabilitation patients. We instrumented the patients with fNIRS and EMG. In that case the hypothesis was formed:

1. The strong neural connections by over-learned driving behaviors should be resistant to stroke, easy to recover
2. Strong compensatory behaviors in should evoke big muscular responses

The major problems with driving was that the initial conditions were not easy to define. Many of the patients had no recent driving experience or no experience at all. Furthermore the drivers could neglect the use of paretic hand completely, for which we cannot tell how they behaved before the stroke. There was cases which seemed to be supporting the hypothesis, but the number of cases could not overcome my subjective bias.

We tried the simulated pylon slalom as well. In addition to base various baseline of driving skill the problem was with the realism with our simulator. We could not furnish the simulator to detail that the patients would immerse to driving.

The strong compensatory behaviors hypothesis has the issue that it is difficult to obtain decent number of repetitions. A driver may react very strongly to a certain driving situation. But would it happen it may happen only once, and it makes demanding to collect data for analysis, particularly brain imaging data needs a number of repetitions in order to overcome the noise in the system.

Observed spatial neglect in driving was causing further complications. Neglect is a failure to report, respond, or orient to contralateral stimuli that is not caused by an elemental sensorimotor deficit [95]. We observed that many patients had a lot not orient with simulated driving including the slalom. Some patients were steering always from the same side of gates regardless of the instructions. These issues at high level sensory processing makes it much harder to evaluate the motor performance which was our target.

6.5.3 Applications and Consequences

We evaluated the vehicle dynamics and driver actions on the vehicle controls to quantify the top-down and bottom-up controlled processes. Based on the analysis, we modeled driver’s proficiency as difference between of intention and

outcome. We established an index, proactivity index, by evaluating the ratio of the two modes of control. High ratio of top-down control indicates that driver is able to manifest her intention on the control of the vehicle and in this manner is performing proficiently, bring in control of the driving situation.

The driving is a learnt skill. Learning of the driving skills involves building internal models in the central nervous system for accommodating vehicle dynamics, a high speed version of ego-motion and the effects of controls on the vehicle motion.

The feeling that driver is in control of the situation makes premises for a comfortable driving experience. The other direct consequences of loosing control can cause accidents. We suggest that the proactivity index can be used in advance driving assistance systems (ADAS) to decide if driver should be discouraged to continue driving or if further assistance should be provided by vehicle to ensure safe driving.

Today when auto-pilot functions have been introduced on consumer vehicles (Tesla Inc, Palo Alto) the overall control of the driving situation must still be handled by the human driver. However the detection of proactive behaviors, the attendance to future events, can be as a token that driver is supervising the vehicle operation.

6.5.4 Future Work

The major contribution of my work on driving analysis was the modeling of drivers proficiency in the task. In order for the model to be fully exploited and taken to application, it has to be validated with other driving tasks. This validation would be a signification undertaking, most likely involving tasks in simulated environment and driving a predefined route on a highway. Without this validation the model, cannot carry effective value, and remains a conceptual model.

We discussed the use of model for data source fo the driving assistance systems to support decision making. The implementation of such a system was out of the scope of this study, and thus remains as future work.

Evaluation of driver's ability to drive a vehicle, is an acute problem. Aging and health conditions are known to impair driving ability. An automatic tool which could be used in driving task should be able to give a realistic view of fitness to drive. The merits include that with simple instrumentation it can be used as daily tool as it does not need an expert's subjective assessment, which appears to be the standard [50].

6.6 Bimanual post-stroke rehabilitation

Bimanual rehabilitation was modeled with interactions between the arm specific controls and the common control to both of the arms. In this section we discuss the progress of the study, how to identify the good task promoting recovery.

6.6.1 Progression

The driving simulator experiments with the post-stroke patients indicated that to get statistically significant results the experiment conditions must be much more strict in order to get statistically significant data. On the wheel we used for driving simulator, we had additional functionality to couple a seconds wheel. With this two wheels we had the opportunity to experiment with the conditions of symmetry and phase.

We based the hypothesis of the study on these conditions:

1. In-phase motion, where homogeneous muscles in the arms work simultaneously, is easier than anti-phase motion, where hands move to opposite directions, for patients.
2. Mechanical coupling improves the movement of the patients.
3. Healthy subjects are indifferent to the conditions.

Initially the purpose was to use muscle synergies (Introduced in Section 2.3.2) to characterize the motion. Although seemingly very simple tasks, it seemed that each subject was taking their own approach how to rotate the wheels. Individuals had different strategies how they generated the movement and this included different set of muscles. It seemed very difficult to establish the number of synergies required by the approach with healthy subjects. Lacking the reference with healthy subjects did not encourage to continue the work on patients. Instead some other approach was needed. The starting point for the work was the finding that muscles on the same side of body shared much more similarity despite of the tasks condition to the contra-lateral similarity in muscles working at same time. This led to implementation of the various similarity parameters.

6.6.2 Applications and Consequences

In order to evaluate the bimanual performance we developed a set of markers, that are composed by comparing electromyography envelopes registered during different modes of bimanual motion. We used a specific training device, which had two wheels operated by each hand of a subject. The wheels could be operated by two task condition: phase and coupling.

One particularly promising marker, named MAS_C , was found to correlate with the recovery of patients. This marker was computed by comparing the EMG recording done in a mechanically coupled and uncoupled modes. A high value in MAS_C implied by similarity of EMG signals in the two modes, thus indicates interdependency of the mechanical coupling to the other arm.

The proposed markers have many applications in rehabilitation and related fields. Assessment of recovery is done by subjectively by clinician using various tool sets. Markers, which can be measured automatically, can be used in various training devices inside and outside of hospital to monitor the progress of rehabilitation.

6.6.3 Future Work

The study could reveal the complexity of the role of the coupling in bimanual therapy. The effect of brain damage is not same on all patients. In order to provide more detailed information more data is needed that would allow segmentation of the patients to groups. Again in order to get more data the task has to be simplified to more basic reaching or aiming tasks. A robotic bimanual training tool which would minimize the resistance or load to the hands, this would overcome the need to work against the weight of the limb the patient had to do with these experiments.

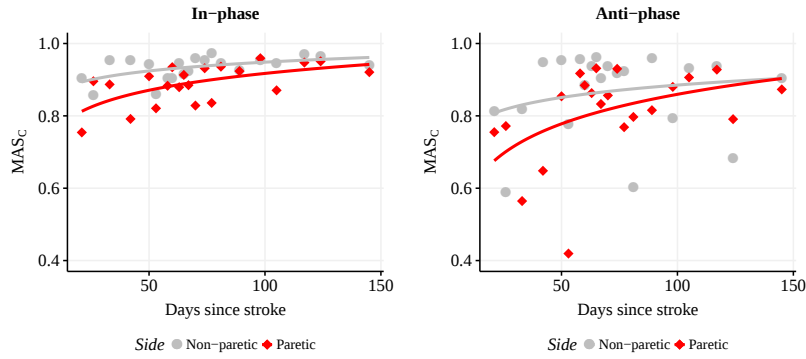


Figure 6.1: A parameter comparing the similarity of muscle activations over coupling condition, MAS_C , correl.

Quantification of patient motor performance is valuable for the assessment of the current state and the prospect of functional motor recovery. Traditionally, such assessment is conducted by healthcare professionals using tools like Fugl-Meyer assessment [75]. Although, these assessments deliver a highly standardized score for clinical decision making, there is a need for diverse markers that can be measured via automatization. These scenarios include feedback that can be used to motivate the patient for better outcomes [216], rehabilitation done at patients' homes with digital connections to clinics [52], and proper adjustment of training level [163].

The second finding of the work was the introduction of the comparison of EMG over a condition. In case of coupling condition, parameter MAS_C , this is interpreted as independency of coupling. This might be a very helpful tool with assistive robotics or conventional rehabilitation following an operation on a limb. The parameter might give an answer to problem how much load the limb can support without reflexes caused by pain or otherwise uncomfortable motion.

6.7 Generating of Environments for Behavior Control

6.7.1 Progression

The integration of laboratory devices, the topic of Chapter 5, started as an engineering solution to practical a practical problem with the hardware which we needed to run together. The solution was based on architectures I had applied in some industries to build distributed measurement systems with update on the technologies available with modern web-browsers. After good response from visitors to our lab, we understood that there must be other people having the same problems. We wanted to make our solution available to those.

The issues related with using the internet-of-things and wireless-body-area-networks are still quite new. The affordability of these systems makes the users more tolerant for their weaknesses. When building systems with several of such systems the problems with compatibility and reliability are multiplied. In the research of the integration we wanted to focus on these issues.

The importance of special requirements of given by the rehabilitation context are not to be ignored. The patient work needs flexibility to configure systems for patient needs. We could answer this with the framework approach.

6.7.2 Applications and Consequences

The orchestration of instrumentation in a neuro-rehabilitation laboratory for experimentation is demanding. The environment consists of a number of sensory and actuator devices, behavior of which has to be co-ordinated in a prompt manner in order to invoke desired effects on the patients.

We designed and built an integration framework providing tools to orchestrate the behavior of devices, and in this way enable building of rehabilitation systems and processing pipelines. We designed the framework on lightweight readily available open source technologies to provide lightweight bindings that make devices work efficiently together. We discuss the design considerations for system architectures using the framework to deliver the performance needed for rehabilitation tasks, which often require properly timed feedback from sensors to patient.

Because of achieved simplicity and robustness in the framework, we expect that created applications will be deployed in diverse environments including laboratories, hospitals and homes. The introduced framework is available for download at: <https://github.com/riken-ibcu/bclab>.

6.7.3 Future Work

When we started the work on the integration framework there actually was no contender. We wanted to employ and be prepared to employ the system on platforms that were not supported by other approaches. Today a particular

robotic operation system, named Robotic Operation System (ROS), has establish a good position as a platform to integrate sensors and actuators. The design requirements for robotic systems are very much similar to those of implemented using our framework.

The popularity of ROS platform is promoting the need of evaluation of its suitability to either build components on or to use as a platform for the framework. The anticipated high learning curve of ROS system and need to use tools and run architectural components on certain operating systems are potential challenges. The performance comparison is of big interest as ROS may be inferior in performance as some results indicate.

Anyway the synchronization issues with the various devices are a continuous nuisance. This is highlighted when working in different modalities: different wired and wireless, and digital and analog media. The low level synchronization issues has to recognized and solved in order to make high level integration easier.

Chapter 7

Summary conclusions

In this thesis we discussed about modulating human behaviors with artificial control. While mimicking human, or biological behavior in large, has been inspiring for research and development of artificial control, the approach we take is quite the opposite. The application of biological control principle is rooted in the way how cybernetics describes and modulates behaviors.

This thesis builds on concept of controller hierarchy, introduced in 2.3.3. On the high level controllers deal with intentional behaviours, and when going lower on the model the more dependency to environment increases. The control flow in this model can be described as top-down control and bottom-up control. A proficient control in any system of complexity is a well-balanced act of both modes of control.

This thesis exploits the dimensions of efficiency and robustness. Efficiency is depicted in the hierarchy *vertically* by means of abstraction. The processing of abstracted information can be executed with less resources on the elevated levels of the hierarchy. In the driving study the proficient driving was contributed to sophistication of processing on the appropriate level. The second quality, robustness, is realized in the hierarchy *horizontally* with redundancy of controllers; the functionality of damaged or failing controllers is redirected for execution on similar controllers on the same level. The concepts of recovery in bimanual training in neuro-rehabilitation is attributed to activation of alternative circuits.

On the other hand, the application of behavior control in humans folds into two categories: augmenting and training. Augmentation is concerned about enhancing the behaviors with artificial components, while training targets to improve the behavior by inducing changes in the functions of central nervous system. One may argue that both of approaches are based on neural plasticity, this may be true because it may impossible to augment human behaviors without need of adaptation from the nervous system. However, the training approach avoids introducing any physical artifacts. Augmentation approach, on its part, tries to introduce artifacts with minimal rejection from the host system. Driving with ADAS system is clearly augmentation and rehabilitation is training.

7.1 Driving

The extent to which drivers control their vehicles according to their intentions is a critical problem in driving safety. We quantified the difference between a driver's own intentions and the actual operations from observations on driver performance.

Typical driving is governed by two types of processes: proactive and reactive control. In Proactive control, the driver prepares and executes actions in a timely manner ahead of future events, whereas in reactive control the driver responds directly to environmental stimuli. A state in which the relative amount of reactive control is high implies that the driver is busy responding to the surroundings and has difficulty attending to future events. The vehicle dynamics and driver actions on the vehicle controls were analyzed to quantify the proactive and reactive processes.

Based on three indices related to amount of compensation in steering, proactive automatization and steering timing, we showed that the ratio of proactive to reactive control could be computed from the driver's operations. The linear summation of the three indices, referred to as the proactivity index, can quantify the difference between driver intention and actual operations.

The quantification of driver's behavior based on a new theory has value for driving researchers. There are many potential implications for these results to be applied. Quantifying a driver's ability to control the driving situation would be highly useful for deciding whether the driver should continue driving. The proactivity index can be used in various advanced driver-assistance systems (ADAS) to monitor driver status.

7.2 Rehabilitation

Brain damage caused by strokes often leaves survivors with lateral functional motor deficits. Bimanual rehabilitation of the paretic arm is an active field of study for restoring normal functionality by making use of complex neural bindings that exist between the arms.

In a search of an effective rehabilitation method, we introduce a group of post-stroke rehabilitation patients to a set of bimanual motion tasks, with conditions of inter-manual coupling and phasing. We compare similarity in surface EMG profiles in order to understand the effect of the conditions.

The paretic arms of the patients were more influenced by the task conditions in comparison to the non-paretic arms. The results suggests that in-phase motion may be activating neural circuits that trigger recovery. Also the coupling condition has an effect on behavior, but the response of the patients was divided whether coupling was helping or hindering.

Results from the study can be used in designing patient specific rehabilitation programs, on bases of decisions what kind of exercises or tasks a rehabilitation should be composed of. The novel indices may are capable of describing the the similarities between different motion conditions. Automatic quantification

of patient motor performance is valuable for the assessment of the current state and the prospect of functional motor recovery. Outside clinical domain the quantification may be used as feedback on adjusting the training level properly or motivating the patient to carry on with the rehabilitation. The quantification of motor performance may be applied also on assistive robots in order to decide how much support patient needs.

7.3 Controlling behavior

In the third part of the study we introduced a solution to build environments for learning, particularly in the demanding neuro-rehabilitation context. The settings consists of a number of sensory and actuator devices, behaviour of which has to be coordinated in a prompt manner to evoke desired effects on the patients.

We designed and built an integration framework providing tools to orchestrate the behaviour of devices, and in this way enable building of rehabilitation systems and processing pipelines. We designed the framework on lightweight readily available open source technologies to provide lightweight bindings that make devices work efficiently together.

In the related study we validated different design considerations for system architectures using the framework to deliver the performance needed for rehabilitation tasks, which often require properly timed feedback from sensors to patient. Importantly, our study is concerned with Wireless-body-area-networks, and their applicability as research tools as low cost alternative to high end scientific instrumentation in the point of view of system integration.

Although, there are several alternatives to implement interaction with a group of devices, recognising the well established efforts in industrial automation and also robotic operating systems which both share similarities with our framework. Our framework is a unique endeavour specialising on orchestration of distributed systems specialized on neuro-rehabilitation. Because of achieved simplicity and robustness in the framework, we expect that created applications will be deployed in diverse environments including laboratories, hospitals and homes. In order to encourage the use of the framework we share it as open source.

7.4 Conclusion

In this study we saw that human performance was enhanced for robustness and efficiency. The conceptual tool of controller hierarchy was used to illustrate the controllers in human behaviors. In the conceptual model, the robustness is realized as redundancy on horizontal axis, and efficiency is seen in abstraction of information dimensionality on the vertical axis. The methods of augmentation with technology and alternatively training was introduced to modulate the processing flow in the controller hierarchy. We expect the scope of applications

to extend beyond the driving and neuro-rehabilitation, discussed in this thesis, to variety of complex problems in situations, where human behaviors are under performing due to exogenous and endogenous causes.

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