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PH.D. THESIS

APPLICATION OF A NOVEL BALANCE TEST TO STUDY MOTOR LEARNING ABILITIES

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To my wife
Mojej żonie

ABSTRACT

The research carried out during the Ph.D. course regarded the application of postural balance tests to study motor learning abilities. Two protocols are used in this work: a novel divided attention (DA) test and the modified clinical test for sensory interaction in balance (mCTSIB). A total of 42 subjects participated in the experimental campaigns.

To provide experimental contributions to imitation learning, which is thought to be supported by the mirror neuron (MN) system, the DA test is administered to two groups of subjects, to which the information of the test is conveyed either through verbal instructions or imitation by observation. The results show that the imitation based learning approach only allows to catch the gross gestures, while the fine motor gestures are often not understood. Moreover, imitation requires a higher cognitive effort, thus resulting in slower gestures. This work points out that action understanding is not supported by the MN system, but instead, other brain circuitries are involved.

Postural tests are used in clinical analysis to diagnose neurological dysfunctions such as Parkinson's disease and fall risk in elderly. These tests are sometimes performed over multiple sessions to follow up the patient's rehabilitation. However, since the subject performance is analyzed by performing the test with only one attempt, the results can be biased by learning or adaptation effects which might lead to erroneous conclusions or diagnosis. In this work, the results of both DA and mCTSIB show that subjects need some practice trials to exclude any learning effect from the analyzed data. The number of practice trials depends on the test conditions and the considered parameters.

The learning effect should be taken into account also when validating models with data measured from subjects. Moreover, averaged results flatten the transient phase, which might mask important features. The results of this work show that the target pursuit movements of the DA test, which are achieved through 2D postural movements, follow the Fitts' model of speed-accuracy trade-off, whereas the choice reaction time follows the Hick's model. Both models show that the performance improves at each repetition with a power function. A modified model to account for learning is also proposed. In this work, postural models are analyzed by means of biofidelity and learning abilities with reference to behavioral motor models.

Vehicle collisions are mostly caused by driver's errors and are among the most causes of death in the world. Nowadays law enforcement faces the challenge to assess driving impairment that arises from multiple sources such as drowsiness and psychoactive substances. However, the current tools are not adequate to objectively assess driver's abilities. The features of this novel DA test seem suitable for a road test to assess driver's psychophysical conditions. Moreover, preliminary data on impaired subjects show that the learning trend might be used for assessment purposes.

ACKNOWLEDGMENTS

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Last but not least, I would also like to thank all those who have continuously and unconditionally supported me during my Ph.D. studies.

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List of Acronyms

A: target distance
Ae: effective target distance
AP: anterior-posterior
ASD: autism spectrum disorder
BAC: blood alcohol content
BESS: balance error scoring system
BMNS: broken mirror neuron system
BrAC: breath alcohol content
CARE: community road accident database (EU)
CDP: computerized dynamic posturography
CFF: critical flicker fusion

CNS: central nervous system
CoG: center of gravity
CoM: center of mass
CoP: center of pressure
CRT: choice reaction test
CS: correctness score
CTSIB: clinical test for sensory interaction in balance
CTT: critical tracking test
d.o.f.: degrees of freedom
DA: divided attention
DEC: disturbance estimation and compensation
DfT: Department for Transport (U.K.)
DUI: driving under the influence
DWI: driving while impaired (not to be confused with driving while intoxicated)
EC: eyes closed
EEG: electroencephalography
EMG: electromyography
EO: eyes open
EU: European Union (see Table 4.3)
FARS: Fatality Analysis Reporting System (U.S.)
fMRI: functional magnetic resonance imaging
HGN: horizontal gaze nystagmus
ID: index of difficulty
IDe: effective index of difficulty
INAIL: Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro
ISTAT: Istituto nazionale di Statistica (IT)
KP: knowledge of performance
KR: knowledge of results
LLE: largest Lyapunov exponent
LLR: long-latency reflex
mCTSIB: modified clinical test for sensory interaction in balance
MDO: material damage only
MEG: magnetoencephalography
ML: medio-lateral
MN: mirror neurons
MNS: mirror neuron system
MT: movement time
NAV: normalized average velocity
NAVM: normalized average velocity moment
NC: number of choices
NHTSA: National Highway Traffic Safety Administration (U.S.)
NIRS: near-infrared spectroscopy
NSAID: non-steroidal anti-inflammatory drugs
OLS: one leg stand
PBT: postural balance test
PCA: principal component analysis

PDO: property damage only
PET: positron emission tomography
PID: proportional-integrative-derivative
POMA: performance-oriented mobility assessment
PS: perturbed stability
PSEC: perturbed stability eyes closed
PSEO: perturbed stability eyes open
PVT: psychomotor vigilance test
RT: reaction time
rTMS: repetitive transcranial magnetic stimulation
SDA: stabilogram diffusion analysis
SFST: standardized field sobriety test
SLR: short-latency reflex
SUR: single-unit recording
TD: typical developing
tDCS: transcranial direct current stimulation
tLOS: theoretical limit of stability
TMS: transcranial magnetic stimulation
U.K.: United Kingdom
U.S.: United States of America
UNECE: United Nations Economic Commission for Europe
W: target size
WAT: walk and turn
We: effective target size

Chapter 1:

INTRODUCTION

1.1. SCIENTIFIC CONTEXT

In the last decade there has been much dispute over the role of mirror neurons in providing support for the neuronal process imitation. Being mirror neurons a new finding described for the first time in the 1996 by Rizzolatti et al. (1996), it has been subject for many research but its validity and role have not been acclaimed yet by the scientific community. Thus the theme remains very actual and vital.

Mirror neurons are a special class of neurons discovered in monkey's premotor-cortex brain area (Rizzolatti et al., 1996). Since this discovery in the middle of 90s, many studies have widespread researching on the role of mirror neurons and their possible appliance in many different fields. In particular, it is hypothesized that a particular mirror system manages the sensorimotor components involved in complex behaviors imitation (Arbib et al., 2000). This hypothesis has already led to new learning protocols based on the mirror neuron motor theory, substituting formal learning (top-down approach). For instance, Physical Apps©, LLC claims that pupil's math scores will improve by using a soccer size ball containing a calculator (the TheO™ Smart Ball).

However, only goal oriented actions seem to involve the mirror neuron system and thus the supported imitation mechanism. Hence, what if the subject does not know or recognize if the action is goal oriented? Kosonogov (2012) points out that there might be other brain structures that first understand the action, and only after motor areas are involved.

It is well known that posture control is a complex mechanism that involves various brain structures, such as sensory areas, motor areas and other areas not identified yet, and its performance is conditioned by cognitive load. Therefore, Kosonogov (2011) uses posture assessment to study the relation of mirror neuron system with speech, in which some subjects were listening either to object-related sentences or action-related sentences. Furthermore, Notarnicola et al. (2014) use balance assessment to compare performance of ballet students that had classes while they could observe themselves, thus stimulating mirror neurons, or while they could not look at themselves.

Balance assessment is dated back to the 19th century when the neurologist Romberg related neurological dysfunctions with posture control. Since then the posture assessment has been used in various situations, for instance to diagnose neurological disorders or to examine fall risk in elderlies. In general, such protocols require to perform the test only once and for 20-30 seconds, however in this way the results might be biased by transient effects such as adaptation and learning phase. This is a particular issue when the subjects are measured over various sessions since one might show improvement that is not due to clinical progress.

It is well known that subjects might need some practice before being comfortable with the experiment. Still, experimental studies which use repeated measures on postural assessment either neglect or vaguely perform some pre-trials to exclude the transient phase. For instance, Notarnicola et al. (2014) allow the subjects to perform two pre-trials, which might not be enough to adapt for complex tasks. Conversely, excessive pre-trials might cause fatigue; for instance in research of Kosonogov (2011) subjects were given 20 minutes of pre-trials to adapt to the test conditions.

Therefore, if such transient effects are not excluded or diminished, the averaged results might include several effects which bias the comparison between studies and sessions of experiments. Nevertheless, also the trend of the transient phase might provide useful information about subject capabilities or learning dysfunctions.

Hence, the issue of biased data by transient effects does not only involve clinical aspects but also models which are based on such experimental results. For instance, it has been demonstrated that the logarithmic model of hand pointing tasks, also known as the speed-accuracy trade-off or the Fitts' law (Fitts, 1954), is extendible to postural movements in frontal plane (Duarte and Freitas, 2005). However, the transient phase was not investigated, thus the model analysis might be biased according to the amount of practice one has experienced.

There have been several attempts to study human equilibrium control through mathematical models of human balance. Still with restricted practical turn-up as none of them managed to provide adequate biofidelity. In particular, controllers do not resemble the brain control nor its learning capabilities. Therefore, experimental studies with subjects are still required in order to understand different factors effect on human equilibrium and to provide data which can be used to set-up and validate the mathematical models.

Balance tests are also used by some police departments instead of just breath analyzers as any source of impairment increases risk of road accidents. Indeed, psycho-physical conditions influence equilibrium stability, in particular when the subject simultaneously performs multiple tasks (divided attention) (Liguori et al., 2002; Nieschalk et al., 1999; Uimonen et al., 1994). However, currently these roadside tests are assessed only by means of subjective judgments.

Hence, it is crucial to deploy a test that would allow to assess driver impairment for several reasons: first, because most of the road accidents are caused by drivers in deteriorated psycho-physical conditions and second, because just in the European Union every year over one million people are injured and over thirty thousand die in a crash (Elvik, 2000; *EU transport in figures 2013*, 2013).

This work's main aim is to investigate if an imitation learning based approach can lead to better results than a formal learning based approach by using a novel psycho-physical condition test that involves a posture assessment and a divided attention task. Other aims of this work are to research on the repeatability and learning phase of balance based tests and to study the feasibility of such novel psycho-physical test in order to be applied in the driver's impairment assessment.

1.2. OBJECTIVES AND CONTRIBUTIONS

This thesis has three objectives. The first goal is to investigate if a mirror neuron based training of motor-related test is effective to learn complex gesture tasks.

Trainings based on mirror neuron system have begun to be used in various fields, such as rehabilitation (Rizzolatti et al., 2009), sports, and class teaching, even though it is still unclear the role of MN in imitation and even if there is questioned an interpretation of MN measures correctness. There are already some research that compare imitation, but they mainly assess gross motor gestures, which are easier to mimic, neglecting the imitation of fine motor gestures. Moreover, there are works which by using similar approach either support MN theory (Cattaneo et al., 2007) or deny it (Pascolo and Cattarinussi, 2012). This work contributes to overall debate by providing experimental data on whether the MN paradigm can be used for training.

This first goal will be achieved by making a comparison between formal learning and learning by imitation, that is respectively top-down and bottom-up approach, by using a divided attention protocol, conceived to assess subject's psychophysical conditions, and a perturbed stability protocol; both based on balance assessment of quiet standing posture. The first protocol is used to compare learning approaches, while the second one aids to verify the uniformity of the sample, that is whether subjects present common quiet standing abilities and do not have neurological dysfunctions which consequently might invalidate the trial.

The second objective of this work aims to investigate whether tests based on balance assessment need some practice trials before they are capable of providing valid results. This is particularly important when the subject is tested over time in different sessions. If there is an adaptation phase, in which the subject gets used to the test conditions, or a learning phase, in which the subject tunes his/her balance mechanism, its influence will be included in the assessment score and thus the comparison might lead to invalid results.

For instance, currently the modified clinical test for sensory interaction in balance (mCTSIB), which is a perturbed stability balance test used by physicians to examine sensory and neurological dysfunctions, does not consider practice tests before initiating the evaluation phase. Conversely, for fall risk assessment, Horak (1987) suggests to provide the subject with other two attempts in case the first trial is failed, whereas others suggest to average the results of two-three repetitions to mitigate the effect of learning (NeuroCom International Inc, 2008). However, the trial repetition might cause fatigue in elderlies and in case of averaging performance, the learning effect although lessen, is still included. On the other hand, learning phase itself might provide valuable clinical information.

By this work it is contributed to determine the extent of the transient phase and its influence on balance tests comprising novel tasks. Indeed, it will be verified if this phase influences the postural pointing task modeled with the Fitts' law. However, this phase might be enhanced in this test since postural balance is a complex control activity. Therefore, the influence of the transient phase will be also investigated on a simpler model of a choice reaction test.

Last but not least goal of this work is to investigate if the divided attention protocol hereby proposed is suitable for further research in order to be used as a roadside impairment test. Currently, roadside tests consider only one or two sources of impairment (i.e. just alcohol or drugs) and neglect interactions with all other factors; while most of the vehicle accidents are due to a driver error such as distraction. A comprehensive impairment test seems to have a key role in reducing road fatalities.

Thus, this work contributes to laying the foundation of a novel methodology which would allow to assess overall impairment by means of objective judgments. The first steps toward this regard the validation of the proposed divided attention protocol by analyzing if the test and if the performance does not depend on the number of times that the subject has undergone it. Moreover, preliminary results on subjects in degraded psychophysical conditions are also presented.

1.3. SCIENTIFIC PUBLICATIONS CONNECTED WITH THE THESIS

Some parts of this thesis are based on papers published in journals or as conference proceedings during the doctorate.

In particular, the review of posture mathematical models in chapter 2 is based on the following book chapter:

- Pascolo P.B., Pagnacco G., Rossi R., *Human standing posture: mathematical models, their biofidelity and applications.* In: Posture: Types, Assessment, and Control, 99-136, 2011, Ed. Nova Press (NY).

Part of the experimental tests presented in chapter 5 is based on the following papers:

- Pagnacco G., Carrick F. R., Pascolo P.B., Rossi R., Oggero E., *Learning effect of standing on foam during posturographic testing – preliminary findings*; Biomedical Sciences Instrumentation 49, 219-226, 2012 (peer-reviewed).
- Oggero E., Rossi R., Pascolo P.B., Pagnacco G., *A novel methodology to evaluate the psycho-physical condition of individuals performing at-risk activities*; Biomedical Sciences Instrumentation 49, 15-22, 2012 (peer-reviewed).
- Rossi R., Pascolo P.B., *Long-term retention of a divided attention psychomotor test combining choice reaction test and postural balance test: A preliminary study*; Accident Analysis and Prevention 82, 126-133, 2015, doi: 10.1016/j.aap.2015.05.010 (peer-reviewed).

1.4. ORGANIZATION OF THE THESIS

The core part of the thesis is organized in six sections. Chapters 2, 3 and 4 lay the basis for the experimental setup developed later in Chapter 5 and thoroughly discussed in Chapter 6.

Chapter 2 provides a review of human posture and is divided in three parts. The first describes the mathematical models with their applications and limits based on their biofidelity and validation. The second part concerns the postural control and main types of controllers to retain it. The third part illustrates the contemporary balance assessment and in particular, tests used in clinical environment as well as in laboratory settings. Moreover, parameters and techniques to analyze posture are shown. This chapter serves as the basis for the balance based test used in the experiments.

Chapter 3 is as well divided in three main parts. The first describes motor learning at behavioral and neural level. Moreover, in the second part, the imitation learning process and in particular the role of the mirror neurons in supporting it is presented. Measurements of motor learning and performance that will be used to analyze experimental data are illustrated in the third part. Measuring techniques of brain activity that are used to support the mirror neuron paradigm are also illustrated together with their limits. This chapter serves as the basis for studying and elaborating the learning effect and performance of test administered to the subjects.

Chapter 4 is also divided in three parts and provides background for the psycho-physical driving conditions and their consequences in case of the driver deteriorated conditions. The first part describes the internal and external factors that can impair driving, while the second part reviews the current methods used to assess driver's conditions. The third part shows the impact that vehicle collisions have on society and thus the related economic costs. This chapter indicates the demand for the comprehensive impairment assessment protocol such as the novel balance test proposed in this work.

The experiments are reported in *Chapter 5* which is organized as follows. First, the experimental protocols used are described in detail. Second, the experiments regarding formal learning on the divided attention protocol, the related perturbed stability performance and the long-term memory retention are illustrated. Third, it is reported the experiment on the divided attention protocol with imitation learning as well as with the related performance of perturbed stability. Additionally, the results of a preliminary experiment on subjects measured before and after they participated in a university get-together party are reported.

The discussion on the experiments related to the objective of this thesis are thoroughly presented in *Chapter 6.*

Finally, in *Chapter 7* the thesis main conclusions are drawn.

Last section, *Appendix*, completes this work by providing tables with vehicle accident statistics, experimental protocol's details and the subjects' demographics.

Chapter 2:

HUMAN POSTURE

Human's posture is highly unstable due to erect stance. Even when not walking or moving, human stance is not immovable. Hence, adjustment movements are necessary to balance out internal variable forces and external movements. For instance, breathing involve shift rib cage thus comprising soft tissues, muscles and blood in the lungs; while heart beating involve contraction and haemodynamic forces.

Postural control is a dynamic process that operates both with feed-forward and feed-back control. Namely, it is a multi-input multi-output non-linear system, with optimizing functions that vary according to the situation, such as minimum energy, minimum jerk and maximum efficacy.

Sensory inputs are interoceptive (proprioception) and exteroceptive (tactile, auditive, visual) while output is neuro-muscular. Inputs' information have different importance in posture stance that varies also with environment conditions. For instance, on firm surface, posture relies mostly on somatosensory information, then vestibular and finally on vision, but in instable conditions the importance shifts to vision and vestibular information (Horak, 2006).

Afferent information is necessary to postural control in order to describe and monitor the neuro-muscular-skeletal system. Therefore, any sensory dysfunction or abnormality is likely to cause a poor posture.

More in detail, proprioception sensory system is composed of:

- Vestibular system is constituted of otoliths, sensitive to linear accelerations and gravity, and semicircular canals, sensitive to the rotational accelerations. Some medicinal drugs change the viscosity of the semicircular canal fluid, thus changing the system response;
- Muscle spindles, sensitive to changes in muscle length. High strain may damage them;
- Golgi tendon organ, sensitive to changes in muscular tension;
- Articular receptors, sensitive to joint position;

Tactile system is composed of cutaneous corpuscles, such as pressure receptors (Ruffini and Merkel corpuscles) and vibration receptors (Meissners and Pacinian corpuscles).

Postural control plan organizes and executes movements according to sensory inputs, strategies and stability constraints. Whereas neuromuscular outputs regard muscle length, stiffness, tone, and rate of shortening. Then muscle viscoelasticity and neuro-muscular delay are taken into account by the postural control and are verified through feedback.

Moreover, postural control can compensate loss of information such as vestibular disorder or blindness. Basically, it is mainly organized at the basal ganglia and cerebellum, with interaction at spinal level for fast reactions to perturbations. Cerebellum is also responsible for anticipatory postural adjustments, e.g. a body movement made to counterbalance an expected perturbation. For instance, when one shake somebody else hand, the activity which produces a perturbation due to a moving forward arm, the hip moves back to counterbalance it. A broad review on this and other anticipatory postural adjustments is provided by Massion (1992).

However, understanding exactly which nervous systems are involved in postural control and at which extend, is quite difficult because posture system is made of many subcomponents of sensory and motor functions (Hobeika, 1999). As usual in this field, brain functions can be located indirectly by analyzing subjects having posture control disorders, somatosensory-motor disorders, brain damage or aplasia, or by impairing posture control either using transcranial magnetic stimulation (TMS) or involving the subject in other tasks. In fact, even quiet standing requires cognitive functions to a certain extent depending on the postural task.

The stability area in which the CoG can move, depends on several factors such as personal physical features, feet strength and position, velocity of sway (as it increases momentum) and amplitude of sway (as it is more difficult to control).

Posture control is mainly exerted using ankle strategy or hip strategy (Figure 2.1) but in case of an excess of stability limits, a step can be made to prevent falling. Ankle strategy is used for small amplitudes of perturbations or for slow adjustments. Yet, the body inertia limits fast compensations or anticipatory adjustments, which have to be made at the hip.

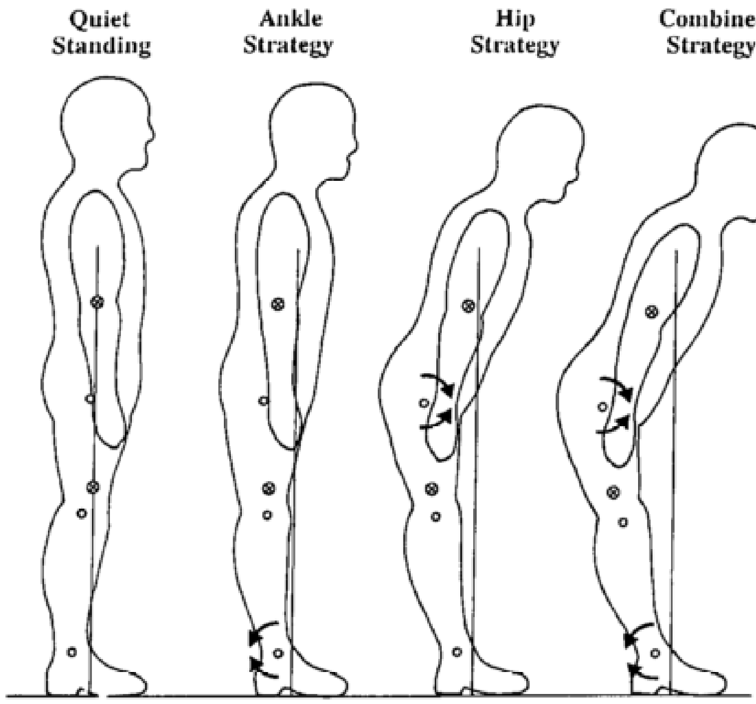


Figure 2.1: Postural strategies [reprinted with permission from (Winter, 1995)**].**

Postural control mechanism is stable (Ishizaki et al., 1991) and reliable (Forsman et al., 2007; Pagnacco et al., 2008) on healthy subjects, which allows to be used it in various fields, such as: neurological disorder (Ganesan et al., 2010; Reid et al., 2002), vestibular dysfunction (Jauregui-Renaud et al., 2013), fall risk in elderlies (Ozdemir and Kutsal, 2009), psycho-physical conditions (Nieschalk et al., 1999) and stroke rehabilitation (Mauricio and Reding, 1998; Yu et al., 2012). For each field of application some particular parameters have been determined to categorize population, however such indicators have usually circumscribed validity.

In order to study posture strategies, perturbations and control mechanism, mathematical models of human balance have been formulated over the years. The first deployed mathematical model is the single-link inverted pendulum. A simple model albeit its control has challenged researchers for a long time. However, as the simple inverted pendulum does not sufficiently describe the human kinematics, more sophisticated models have been developed, such as multi-link inverted pendulum and 3-D models.

Still, there is a general lack of model’s biofidelity which reduces their turn-up to study balance control. For this reason, experimental studies are required to study balance control and to investigate rehabilitation effects, psychophysical conditions (Nieschalk et al., 1999; Pascolo et al., 2009) and pathologies such as Parkinson's disease (Ganesan et al., 2010; Pascolo et al., 2005; Schieppati et al., 1999), or diabetes (Uccioli et al., 1995).

In this chapter mathematical models, with their advantages and disadvantages are illustrated as well as their biofidelity and validation. Furthermore, the main types of postural controllers to retain the erect stance are analyzed. Finally, the balance assessment is presented. In particular, tests currently performed in clinical environment and in laboratory settings are described as well as parameters and techniques to analyze postural ability are shown.

2.1. MATHEMATICAL MODELS

Human postural control has a high number of degrees of freedom (d.o.f.) to control. According to the task, yet in quiet stance (quasi equilibrium) just few d.o.f. can be considered. Usually the following joints are included (ordered from the most to the least used): ankle, hip, neck, and knee. Few models consider also the contribution of the upper limbs to the equilibrium maintenance, thus adding shoulder, elbow and wrist joints.

The very first one was the inverted pendulum, simple model but already complicated on controlling point of view. It appears to be not sufficient as it assumes that all the compensatory movements are made on the ankle (ankle strategy). The later multi-segment model takes into account hip strategy and considers also neck joint (Figure 2.2). Next, two multi-planar 2D model and 3D model get closer to the general human kinematics.

Even though more sophisticated models have been developed later on, still their biofidelity is not good enough to use such models for study purposes. In particular, fatigue of muscles, diseases and the neuronal control are not modelled, nor the compensatory action when the body segments move, e.g. when a person moves an arm forward the hip moves backwards (hip strategy).

2.1.1. 2-D models

2-D models assume that movements occur only on the sagittal plane (called also anterior-posterior plane) and that postural control is maintained by single joints torque control. Movements in the coronal plane or medio-lateral (ML) plane, which have less d.o.f. than the anterior-posterior (AP) plane, are consequently neglected. Of course, the more joints, the better the model describes human kinematics; however, also its complexity increase. Thus, in order to allow models to be studied with easier equations, some joints can be omitted.

First, usually the adults use mainly the ankle strategy to compensate perturbations and the displacement at ankle joint is higher than other joints. Ignoring the other joints such as hip, knee and spine and the rotation around them and also the effect of inertia and mass distribution, allow to deploy the simplest models by using just one link, one constrain and a lumped mass.

Secondly, assumptions can also be made on the internal and external perturbations. The internal ones come from movements or forces generated by organs such as heart, lungs, or body functions like blood activity and visceral/digesting activities. Their influence in general is quite difficult to simulate and measure with precision. Thus, the internal perturbations are often neglected or are implemented in very simple way (Hunter and Kearney, 1981). Whereas external perturbations come from the environment such as ground vibrations and surrounding noises and are more feasible to be imitated and measured. They can be applied to the model by making platform movements (Chagdes et al., 2013; Welch and Ting, 2008).

Even though the single link model is widely used, the ankle joint cannot be considered as sufficient d.o.f. to describe the erected stance. In fact, the hip strategy is often used to quickly counteract perturbations and is used by elderlies as a main control strategy (Alexandrov et al., 2005; Aramaki et al., 2001; Creath et al., 2005). To overcome the simplicity of one link, at least one joint can be added to simulate the hip movement.

Still, studies on the erect standing, on the muscular activity and experimental data have revealed that static erect posture is maintained by continuous movement of many joints, not just ankle and hip (Pinter et al., 2008; Stockwell et al., 1981; Wei-Li, 2008). Hence, adding more body segments controlled by more joints, would help to obtain more accurate results consequently reflecting more closely the natural human posture (Hemami and Jaswa, 1978; Stockwell et al., 1981).

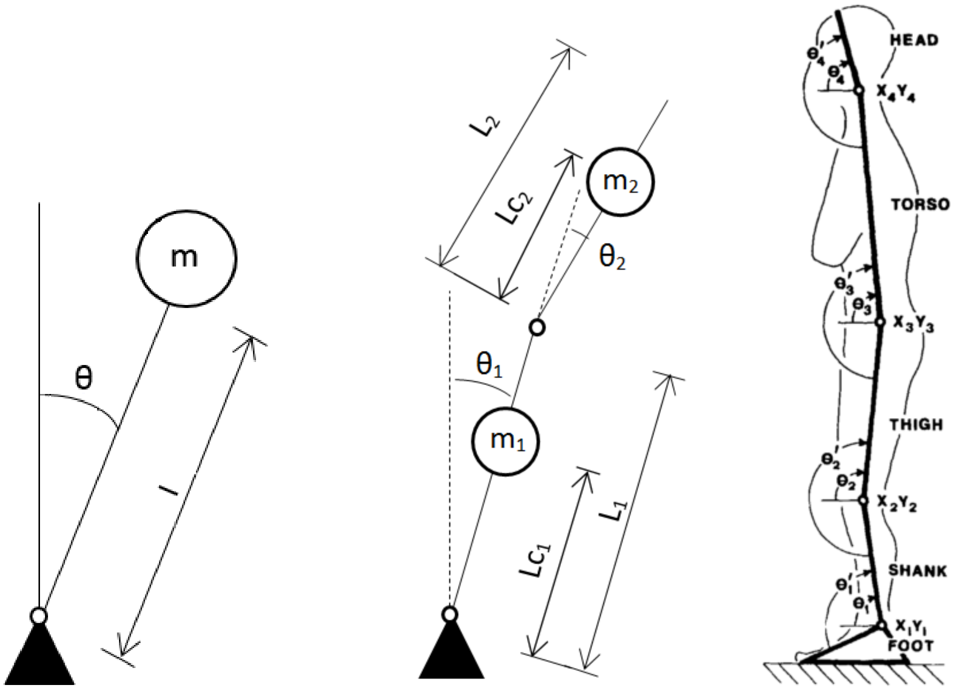


Figure 2.2: Example of sagittal 2-D models: simple inverted pendulum (left), double inverted pendulum (center), and multi-link model [reprinted with permission from (Stockwell et al., 1981)**] (right).**

As above mentioned, the single-link model is the simplest model (left Figure 2.2). It considers just a hinge joint to simulate the ankle strategy and a beam with a lumped mass on the tip (Smith, 1957). Such configuration can be described as an inverted pendulum because of one degree of freedom and the planar oscillation of rigid body around the ankle joint in the sagittal plane. Another variant incorporates also the feet as a contribution to the maintenance of erect posture (Pascolo and Carniel, 2009).

The two-link model incorporates the hip strategy and thus it divides the body into 2 links (below and above the hip), either with one lumped mass at the tip (center Figure 2.2) or with its own lumped mass, connected by 2 hinge joints, with feet belonging to the support (Hemami, 1978). This configuration can be described as a double inverted pendulum.

More accuracy can be attained by adding to the model joints such as: neck, knee, trunk, shoulder, elbow (in importance order). Consequently, the number of degrees of freedom and rigid bodies that is head, legs, thighs, and arms is increased. For instance, Hemami and Jaswa (1978) provide a model with 3 joints and Stockwell et al. (1981) provide a model with 4 joints and 5 links (Figure 2.2).

The single-link model torque control is described by the following Equation 2.1.

Equation 2.1: Example of single-link torque control on the ankle joint

$$M_c = J \cdot \ddot{\theta} - m \cdot g \cdot l \cdot sin\theta - M_p$$

Where J is the inertia with respect to the ankle, m is the lumped mass, θ is the rotation angle, l is the pendulum length, M_c is the torque control at the ankle used to stabilize the model and M_p represents the internal and external perturbations. The equation can be linearized for quasi static equilibrium ($\theta \approx 0$) by substituting $sin\ \theta$ with θ.

The double link inverted pendulum has two torques to control, at the ankle M_{ca} and at the hip M_{ch}, which are described in Equation 2.2 with reference of Figure 2.2.

Equation 2.2: Ankle M_{ca} and hip M_{ch} linearized torque control for the double-inverted pendulum. M_{pa} and M_{ph} regard the perturbation torque, respectively, at ankle and hip joint.

$$M_{ca} = \ddot{\theta}_1(J_1 + m_1 Lc_1^2 + J_2 + m_2(L_1 + Lc_2)^2) - \theta_1(m_1 g Lc_1 + m_2 g L_1 + m_2 g Lc_2) + \ddot{\theta}_2\big(J_2 + m_2 Lc_2(L_1 + Lc_2)\big) - \theta_2(m_2 g Lc_2) - M_{pa}$$

$$M_{ch} = \ddot{\theta}_1(J_2 + m_2 Lc_2(L_1 + Lc_2)) - \theta_1(m_2 g Lc_2) + \ddot{\theta}_2(J_2 + m_2 Lc_2^2) - \theta_2(m_2 g Lc_2) - M_{ph}$$

The main advantage of the one link model is its construction simplicity and easiness in implementation. The assumption that the body rotates just around the ankle joint allows on relatively simple modelling of mechanisms controlling the body stabilization. The system actuator is feedback based and it can be both linear and non-linear. It can be additionally stabilized by active or passive elements reflecting muscles and ligaments (Gurfinkel' and Osovets, 1972).

However, the one degree of freedom assumption neglects motor movements of other joints and the role of other body parts in the stability maintenance. Even though it has been shown that the oscillation frequency around other joints than ankle is often higher (Valk-Fai, 1973) they have an important role in upright posture (Pinter et al., 2008). In short, this model can be rather used to provide general understanding of the human postural mechanisms.

Some of those disadvantages are overcome by the two link model. The number of degrees of freedom is increased and the rigid parts is split into smaller ones. Yet, the closest simulation of natural human posture maintenance of all 2-D models can be achieved only by the multi-link model, so as major neuro-muscular control strategies can be simulated. Its complexity however, requires to linearize equations and to enhance the postural control, which in turn make more difficult to study the factors that influence balance control.

2.1.2. Multi-plane 2-D models

As already mentioned, the anterior-posterior plane movements are not detached but they go along with the lateral adjustments in order maintain the erected posture in equilibrium. In fact, planes differ by the type of joints and body mass distribution, which provides different reactivity to perturbations. In this way, internal perturbations can be implemented not just with their AP component, as in the 2-D model, but also on their ML component. In fact, while breathing mainly generates AP disturbance, other perturbations such as heart contractions, head movements adjustments, and coronary blood activity, provide perturbations both on sagittal and coronal plane.

Multi-plane 2-D models try to overcome the kinematic limits of the one plane 2-D models while maintaining some of their advantages. Winter (1995) proposed a model with AP and ML planes (Figure 2.3, left panel), but detached, while Roiatti (2001) proposed a coupled 2-D model (Figure 2.3, right panel). The latter approach has some characteristics of 3-D model although being still among 2-D panel model equations. With this model, both motions on the AP and ML plane interact one with another but they are not fully interdependent as each plane can have different number of joints and bodies.

For instance Winter (1995) provides a multi-plane model with 5 bodies in the ML plane (feet, lower limbs and trunk), connected by 4 joints, respectively ankles and hip. Three bodies are modelled in the AP plane (foot, lower limb, trunk) connected by 2 joints, respectively ankle and hip. Roiatti (2001) provides a coupled-plane model with 13 bodies in the ML plane, that is: feet, lower limbs, pelvis, trunk, head, forearms, arms and hands. The bodies are respectively connected by 12 joints, that is: ankles, hip, neck, shoulders, elbows and wrists. In the AP plane 8 bodies are modelled, that is: foot, shank, thigh, trunk, head, forearm, arm, and hand, which are connected by 7 joints, that is: ankle, knee, hip, neck, shoulder, elbow and wrist.

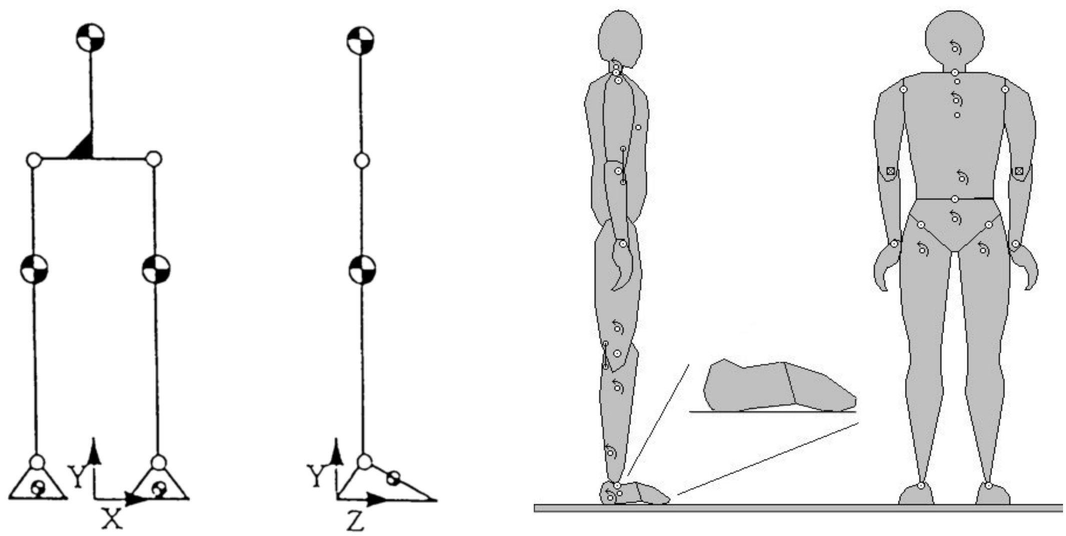


Figure 2.3: Detached multi-planar 2-D model [reprinted with permission from (Winter, 1995)**] (left) and coupled 2-D model [reprinted with permission from** (Pascolo et al., 2009)**] (right).**

The model considers the oscillations between two planes and thus it allows to describe the interactions between them. Still, in order to define the best coupling coefficients, the ‘trial and error’ approach must be used.

The main advantage of the coupled model is its possibility to define the SKG. The obtained plot from Roiatti (2001) is a good approximation with experimental one, except that real movements are characterized by higher frequency sway. Nevertheless, some of the movements are still neglected as model ignores the rotational movements around a vertical axis (like independent knee movements and the torsional motions of ankle and hip joints). It considers just the anterior-posterior movements in both planes. Although in reality rotational movements play minor role in the human balance equilibrium, they cannot be completely neglected.

2.1.3. 3-D models

In the 3-D model both AP and ML planes work with their unlimited interactions, such as axial plane rotation. However, joints and bodies are modelled as ideal. It means that the knee and elbow constraint are modelled as perfect hinges while the ankle and hips as perfect spherical joints. Additionally, body segments are modelled as rigid and with ideal geometries, for instance head is modelled with an ellipsoid, legs with cylinders or frustums, and chest with a plate. Still, some models consider just the main strategies (ankle and hip), while others consider more links segments.

The 3-D model can have different number of d.o.f. and thus different number of rigid parts and links. Each body part can have its own specific properties, such as mass distribution and inertia. An example of 3-D model is shown in Figure 2.4.

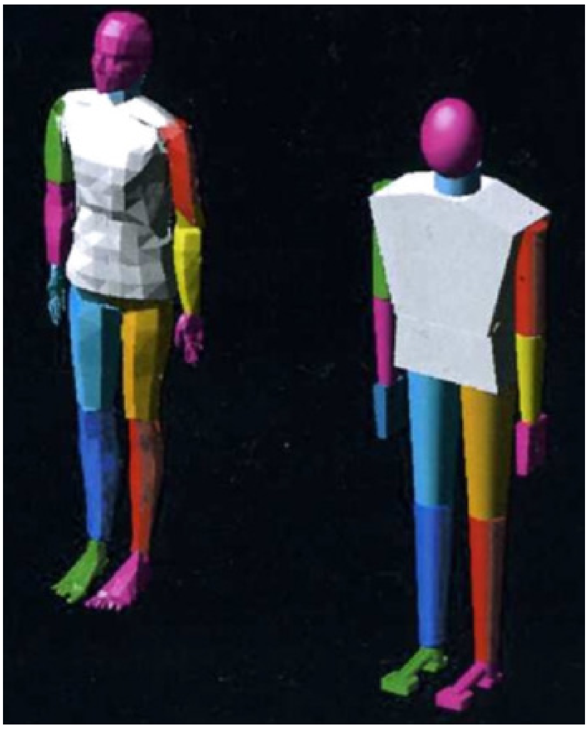


Figure 2.4: Example of postural 3-D model [reprinted with permission from (Pascolo et al., 2009)**].**

The 3-D model gives the closest resemblance of kinematics and dynamics of the human posture compared with previous models. The movements of the knees can be independent, with consequent introduction of the pelvic rotation and a multi-segmental spine. Moreover forces and displacements are properly deployed.

However, although the model is characterized by huge improvements comparing to its predecessors, some of the elements are still simplified. For instance, the complex rotoidal joint geometry of the knee mathematically is represented as cylindrical joint. Moreover, the model neglects the influence of some parts of body movements, internal organ movements, and changes in mass distribution connected to motions of soft tissues and live processes such as respiration, digestion and swallowing. In regards to the latter ones, probably it would be hard and pretty much impractical to measure experimentally their influence.

2.1.4. Models validation

Validation process requires a comparison of the COP, COG, or other indicators of the mathematical models with the ones obtained by subjects.

Giving the fact that one link model uses just an ankle strategy, in order to validate the model, the subject must be instructed or forced to avoid the other joints movements while keeping the postural balance. Moreover the subject must just move on one plane. This applies also to models having two or more links, in which the subject has to avoid to move non modelled joints. Furthermore it is also possible to validate the models by comparing the motion of the joints with experimental motion analysis by using opto-kinetic technique (Stockwell et al., 1981). Also model torque forces can be compared with muscle activation measured with electromyography (EMG) (Pinter et al., 2008).

Validation for the 2-D coupled model needs experimental data in which subjects are constrained or instructed appropriately in order to avoid axial plane rotations. However, by instructing the subject on allowed or not allowed movements he/she might act in a stiffer way, thus biasing validation. Still, as for the 2-D models, subject can be left free to move in order to study model's biofidelity.

For complete human 3-D models the validation process is easier since they give the closest replication of the human structure compared to previous models. However, in case of 3-D models with neglected joints, allowed movements must be taken into consideration in order to setup proper experiments.

2.1.5. Models biofidelity

On the contrary to models validation, comparing model data with subjects standing freely allows to make considerations on the model biofidelity.

It must be admitted that one-link model is quite reliable during the simulation of only ankle joint control mechanism but in general it resembles poor overall biofidelity. Even though the multilink model is improved by considering complex body interactions, the COP-COM plots result repetitive. COP in experimental conditions shows much more complexity and pseudo-random perturbations compared with the simulation. Nevertheless some randomness can be also included into the simulated internal perturbations.

Biofidelity of the coupled 2-D model is mainly limited by the lack of axial rotation at pelvis and trunk, by the shape of body elements, and by the imperfect description of body inertia.

The 3-D model is more suitable to embrace any factor with greater accuracy as it gives the possibility to apply on it forces coming from both, internal or external, sources of perturbations. That is, on their actual point of application, with their actual direction, and with their proper spatial distribution. In particular, 3-D models allow to describe with greater accuracy the body pressure applied to the feet and the resultant force.

A better simulation of the body oscillations in the AP plane is mainly due to spherical joints used by the model. Furthermore SKG results do not change substantially if trunk movements and trunk muscles contractions are neglected. This will also reduce model complexity, control complexity as well as reduce numerical instability.

Nevertheless, biofidelity is still an issue for mathematical models. Considering the complexity of a human body, it is still impossible to deploy an exact and comprehensive mathematical copy of it.

There are also kinematic issues, such as neglected degrees of freedom and joint simplification. For instance, most of the models consider the trunk as a one rigid body, but it can be improved by at least dividing it into two bodies (abdomen and thorax) connected with a joint. Moreover also body segments are shaped as ideal geometries, rigid and with constant density.

Some parameters, however, cannot be taken into account, because either they are difficult to assess or they will cause the model to be more sensitive to numerical instability.

Indeed, just the cardio-circulatory system provides numerous sources of perturbations: hearth systolic and diastolic, blood ejection, arterial muscular contraction, etc., which are difficult to measure and identify since they are not detached. For instance, heart contraction force is related to breathing as a systolic peak occurs during breath inspiration lungs (more blood is requested), and during expiration (back pressure). Meanwhile, the thoracic cavity expansion and contraction transfers blood mass forward and backwards generating perturbations. There are also some other internal activities that cause posture effects, such as ocular movements, digestion process, visceral movements, and muscle contraction. Upper limbs movements can either provide perturbations or contribute to equilibrium maintenance. Furthermore, environment as well can generate perturbations, such as ground stability, illumination condition and noises.

At a certain point, adding kinematic d.o.f. or shape fidelity will not result in substantial model improvements. Rather, it is preferable to improve the postural control mechanism by considering, for instance, a better biofeedback control and anticipatory actions.

2.2. POSTURAL CONTROL

The dynamics of a system are regulated through controllers that operate on the system inputs to obtain the desired output. Controllers that operate on postural models have the challenging objective to maintain the erect stance of intrinsically unstable systems. Generally, postural controls rely on the system state inputs (joint displacements, body displacements, CoM position) and strategies to provide stabilization torque at joints.

Various types of controllers are used in posture, from the simplest closed loop to the most elaborate that include learning capabilities. The most common are described below.

2.2.1. Closed-loop controller (feedback error correcting)

Feedback controllers are the simplest to implement, since their regulation does not require any representation of the controlled system; only the reference signal (y*) and outcome signal (y) are necessary. In this controller, the input of the system is corrected according to the output error e, which is calculated as the difference between the desired output (y*) and the actual output (y). The schema of a feedback controller is depicted in Figure 2.5. This is the case of proportional controllers (P), where the system input u is proportionally corrected according to $u = k \cdot e = k(y^* - y)$, with k as the feedback gain. High gains are desired as they allow to obtain fast reacting systems, but this in turn can cause instabilities to the system, in particular when the real nature of the signals is considered, such as signal delay and noise.

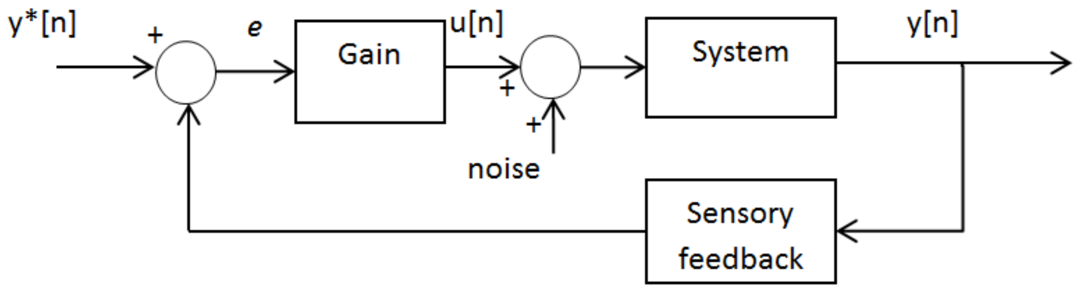


Figure 2.5: The schema of feedback controlled system.

However, there will always be some amount of error in the output since the error is corrected only after it has occurred, that is the error correction requires one time step. For this reason, in noisy systems the correction can occur when the system has already changed its state; therefore the proportional control is not sufficient to stabilize the inverse pendulum as oscillations might propagate due to perturbations. Only high ankle stiffness allows to reduce the oscillations but this is an unrealistic biological case.

The derivative control (D) is therefore necessary to stabilize the system as it introduces damping to the controller, which depends on the changing speed of error. Integrative controllers (I) consider the accumulation of error and thus controls low frequency errors, which might not be detected by proportional and derivative controllers due to their sensitivity threshold. Considering the proportional-integrative-derivative (PID) system, the control torque M_c for the simple inverted pendulum is calculated as in Equation 2.3, where the gains (K) of each controller are selected to optimize the system reaction to perturbations. The schema of a PID controller is depicted in Figure 2.6.

Equation 2.3: PID controller for the control torque M_c of the simple inverted pendulum

$$M_c(t) = K_P\, e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt}$$

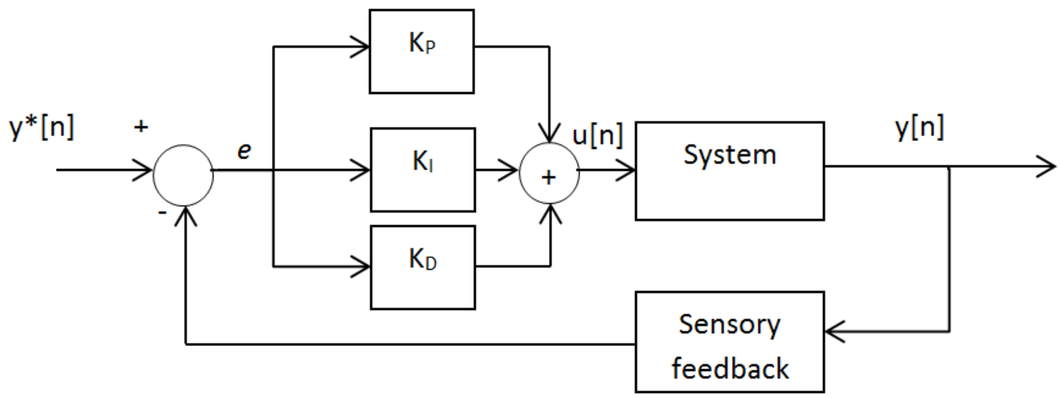


Figure 2.6: The schema of a feedback PID controlled system.

In a biological system the feedback is composed of many sources, which have different importance according to the situation and the task objectives. Error is calculated as the weighted sum of each sensory feedback. Moreover, since multi-link models require to control several joints, multiple sensory integration with different weights is necessary in order to provide to each joint a separate sensory weight (Figure 2.7). Gains of PID controllers (K_P, K_I, K_D) are calculated in order to provide a stable and robust control.

An example of a PID controller with three feedback channels proposed by Peterka (2002) is illustrated in Figure 2.8. This controller is applied to conditions where either the visual field is tilting or the platform is tilting. The feedback is composed of visual, graviceptive (from vestibular and somatosensory sensory) and proprioceptive signals, each with its weighting function to balance the importance between the sensory information (Equation 2.4). Function weights can change according to the task and conditions. For instance, for visual impaired subjects W_v=0 while W_g is reduced for vestibular dysfunctions.

Equation 2.4: Weighted sum of the sensory errors of Figure 2.8. Sensory contribution regards graviceptive sensory (g), visual sensory (v) and proprioceptive sensory (p) (Peterka, 2002)**.**

$$e(t) = W_g e_g + W_v e_v + W_p e_p$$

The controller proposed by Peterka (2002) also takes into account time delay in the control system. However, this is a generic time delay which occurs between sensory information and cognitive elaboration. This is a simplification of the sensory system since the neurotransmission speed is different for each sensory channel (e.g. vision 120ms, auditory 30ms). The model includes also the passive torque that is due to the muscle stiffness and damping which act locally and thus do not have any time delay.

This controller is able to provide stability for both test conditions (visual field sway and tilting surface), however it does not take into account sensory noise and only considers long loop reflex control that is the cerebral modulated control, while it does not consider the short loop reflex control at spinal level that modulates sudden perturbations. As a result, the model is verifiable only in the case of slow swaying visual field or slow tilting platform.

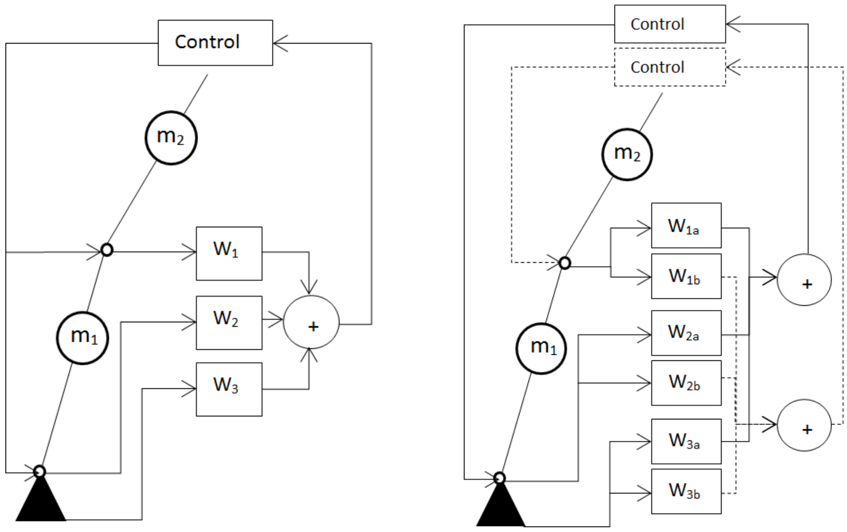


Figure 2.7: Comparison between the univariate (left) and multivariate (right) sensory integration and control. W is the sensory weight.

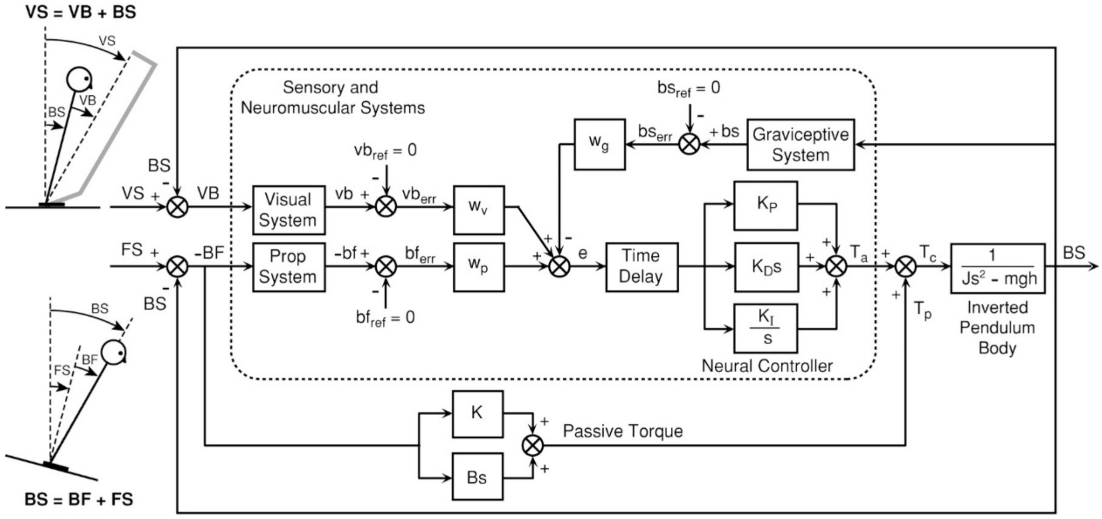


Figure 2.8: Feedback controller for sway referenced visual field (top left) or tilting platform (bottom left) [reprinted with permission from (Peterka, 2002)**]. BS is the subject tilt angle with reference from the vertical position, FS is the platform angle and BF is the subject tilt angle with reference from the platform perpendicular. VS is the tilt angle of the sway referenced visual field and VB is the relative angle between the subject and the visual field.**

The main limits of PID controllers regard the way the output is corrected and the parameters; better controllers are optimal controllers which though require knowledge of the controlled system.

Optimal controls do not use PID to regulate the system but they implement a control law that minimizes or maximizes a function cost $J(u)$ while considering system dynamics and boundary constraints. The optimal solution is found when the Hamiltonian H, which is function of the system and the cost function, is minimized or maximized with respect to the input u:

Equation 2.5: Minimization of cost function

$$\frac{\partial H(x(t), u(t), \lambda, t)}{\partial u} = 0$$

To optimize the cost function, it is required the description of the system dynamics. Typical function costs include energy expenditure, momentum, impulse, peak force, velocity, jerk, path length and process time. When the system dynamics are linearized, the cost function is quadratic, therefore the control operates on what is called linear-quadratic problem (LQ). In time-invariant systems the linear-quadratic regulator (LQR) is used to calculate an optimal control function that balance the need of fast error correction with the need to minimize the cost function.

However, when some of the system variables are not measurable, not available for feedback or when the control must operate with any incomplete state information, i.e. in noise conditions, the linear-quadratic Gaussian (LQG) control must be used. This last control is constituted by a LQR that operates together with an observer which provides an estimate of the feedback signal based on past observations (Figure 2.9). A linear observer used in stochastic models is the Kalman filter. This filter quantifies the amount of noise between the next state and the output to select the optimal observer gain.

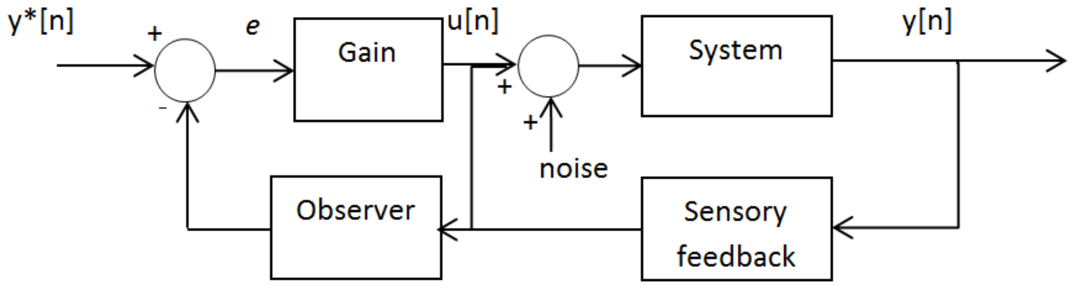


Figure 2.9: Closed-loop controller coupled with an observer to estimate the system feedback.

Even though this controllers have improved in the last decades, still it is not possible to perfectly model system dynamics and thus to obtain an effective optimal control. Further, finding an optimal solution requires high computational effort. For this reason human control is rarely based on optimal control but rather it uses sub-optimal controls (Haith and Krakauer, 2013).

2.2.2. Open-loop feedforward controllers

Although feedback controllers are capable to manage complex systems, they cannot be used when it is necessary to predict the future system state. For instance, with a feedback strategy a shooter would never be able to catch a moving target; the position error must be correct before shooting. In this case, only an open-loop strategy allows to predict the target trajectory and thus to set the necessary response anticipation. Further, open-loop control strategy is also necessary for the anticipatory posture adjustments, which counteract the unbalancing forces generated when an arm is extended and when a load is lifted. The balancing error is corrected before it actually happens.

Indeed, open-loop models are more complex to implement since they require an explicit inverse model of the system (Figure 2.10 without the dashed arrow). The desired outcome is fed to the inverse model, which simulates the system and provides the input that will generate the desired system output. No feedback signal is used to correct the output error, which is an issue in stability of closed-loop controls with delayed feedback. Therefore, the controlling signal can be preprogrammed in advance, which reduces the system reaction time. As a result, the control signal must be prepared at least one step in advance to affect the output signal at time step *n*.

On the other hand, the absence of feedback signal does not allow to correct environmental perturbations. This can be partly overcame by measuring the disturbances (Figure 2.10 with the dashed arrow) or by predicting the sensory feedback (Figure 2.11). Still, it not possible to perfectly correct output error since forward and inverse model are just an approximation of the system dynamics. For this reason mixed controllers that combine feedback and feedforward control are preferred.

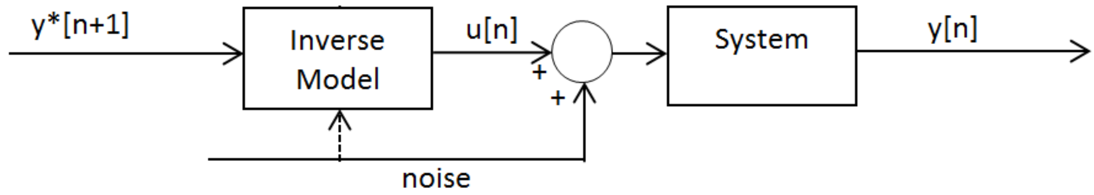


Figure 2.10: Example of an open-loop controlled system. Dashed arrow represents the measure of environmental noise to avoid error departure of output.

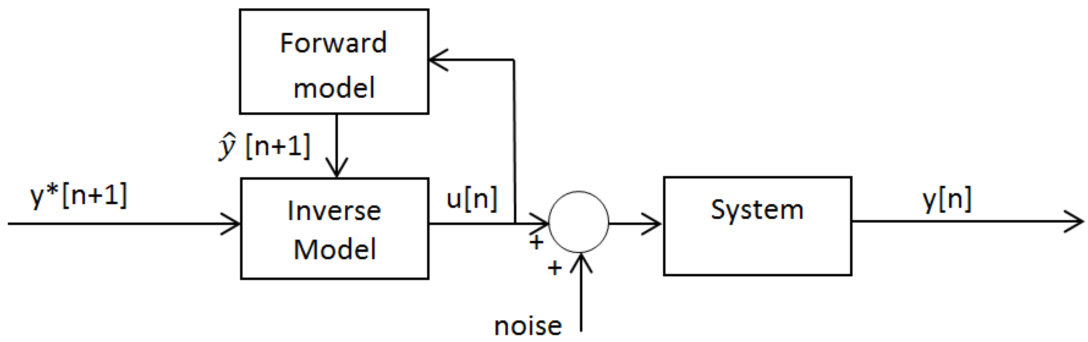


Figure 2.11: The schema of an open-loop controller with forward prediction of feedback ($\hat{y}$).

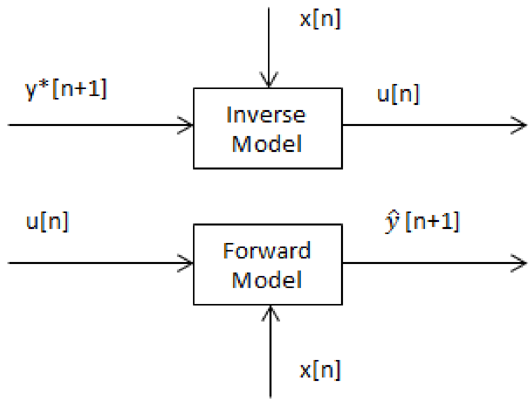


Figure 2.12: Comparison between inverse and forward model. Inverse model transforms the desired output (*y) to the system input (*u*), while the forward model transforms the system input to the estimated output ($\hat{y}$). *x*[*n*] represents the system state.**

2.2.3. Mixed controllers

Considering that the inverse model only tries to simulate the system to a certain extent, accurate issues can lead to summation of errors and departure of the outcome.

With mixed models the inaccurate action of the open-loop controller and the perturbations are later corrected with the effective feedback. Moreover, with closed-loop controllers the system state estimate is constantly reset which avoids output departure. Furthermore, with forward models it is possible to provide an estimated feedback to overcome the signal delay that would require to reduce the feedback gain.

The main difficulty in implementing this type of models regards the interaction of the two controllers. An example of mixed controller is illustrated in Figure 2.13.

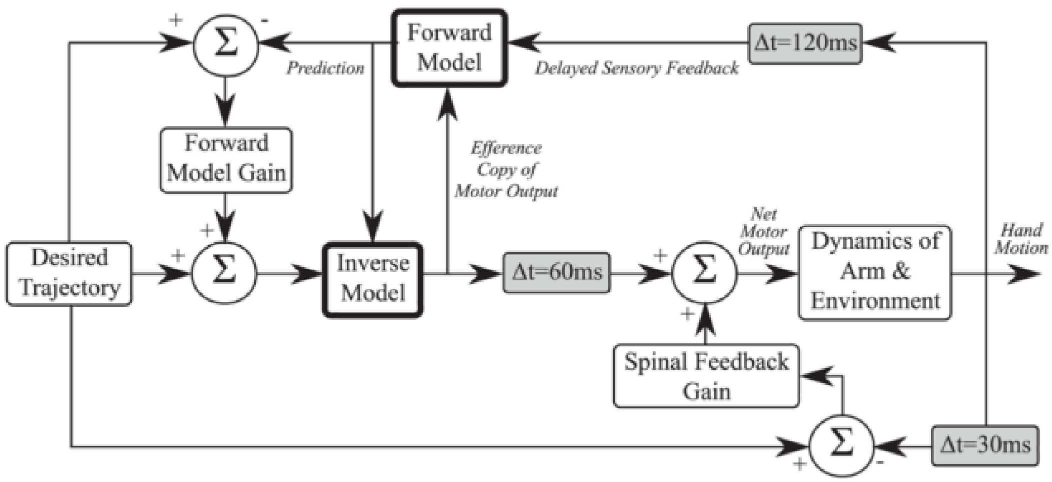


Figure 2.13: Example of a mixed feedforward and feedback controller for arm-hand motion [reprinted with permission from (Wagner and Smith, 2008)**].**

The above model includes forward prediction of sensory information, sensory and neural time delay, both short and long loop reflex which resemble the fast spinal feedback and the slower cerebral feedback. However, a biological controller does not have the desired trajectory as afferent signal to the spinal feedback, which is activated when the muscle spindles overstretch. The model includes also a time delay which takes into account the time needed for cognitive elaboration and to deliver the signal to the actuators. This might be used to test the model in conditions where subjects show higher time delays due to diseases or alcohol.

Conversely, this model (Figure 2.13) does not predict nor include in the control the environmental noise that can cause dynamics and sensory perturbation.

2.2.4. Learning controllers

The controllers above presented are made up of gain coefficients, signal weights and internal models which are setup with an analytic method. Learning controllers are mainly used to obtain the internal models when the system is not invertible (some unknown inputs) or it is hard to estimate the optimal control parameters (Jordan, 1996).

The inverse model is acquired either off-line or on-line through different methodologies but they all expose the controller to the system inputs and outputs. For this reason the open-loop controllers alone are not feasible to be used for on-line update because learning needs output feedback information, either intrinsic (sensory signals) or extrinsic (external observer).

Forward models and observers are capable to adjust from errors but they are reset when a different task is started. This means that they do not transfer the knowledge acquired on one task to execute with fewer errors a new task which limits the ability of the system to adapt to new conditions such as new perturbations or new situations.

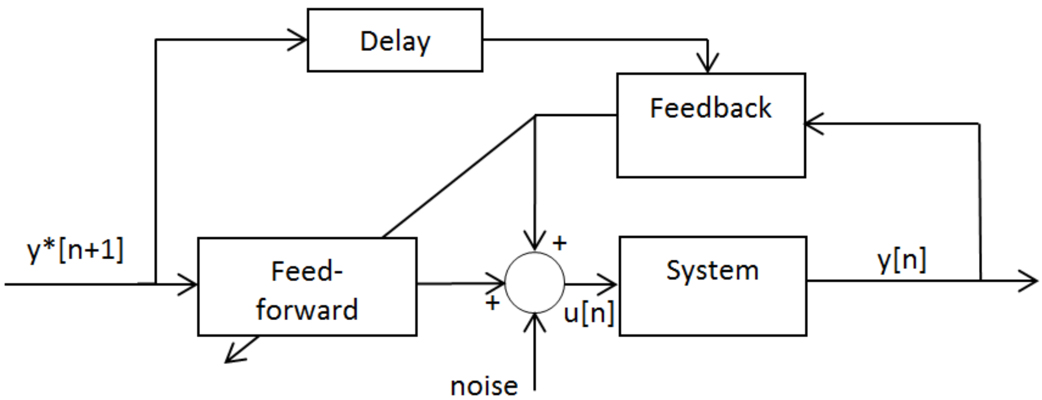


Figure 2.14: A schema of feedback error learning [figure adapted from (Jordan, 1996)**]. The crossing arrow symbolizes a learning signal.**

Feedback error learning (FEL) control is an indirect learning approach conceived to describe the cerebral motor learning control (Kawato et al., 1987). FEL acquires the inverse model of the system in the feedforward (open-loop) control by providing it with the error correction signal $\boldsymbol{u}_{fb}$ (Figure 2.14) from the feedback controller (that includes the cost function). The system input $\boldsymbol{u}$ is made up by the sum of the feed-forward $\boldsymbol{u}_{ff}$ and feedback $\boldsymbol{u}_{fb}$ output signals (Equation 2.6), but since this is an on-line learning control the feedforward controller adapts its input signal $\boldsymbol{u}_{ff}$ to reduce output error at each repetition. Therefore, the contribution of $\boldsymbol{u}_{fb}$ fades out with time according to the learning rate Γ. There is a time delay between the desired output $y^*[n+1]$ and the feedback controller to make it operate with the same time step of the system output $y[n]$.

Equation 2.6: Total motor command *u* in feedback error learning schema. Γ refers to the learning rate, *ff* and *fb* respectively refer to feedforward and feedback input signals.

$$\boldsymbol{u}[n] = \boldsymbol{u}_{fb}[n] + \boldsymbol{u}_{ff}[n];\ \ \boldsymbol{u}_{ff} = \Gamma f(\boldsymbol{u}_{fb})$$

FEL maintains the flexibility of mixed controllers where the motor command is planned in advance and error is later corrected. Moreover, FEL adaptation is goal directed because both controllers are supplied with the desired output y^*, contrary to the observers and forward models presented in the above paragraphs which stroll around to find an acceptable solution (Jordan, 1996).

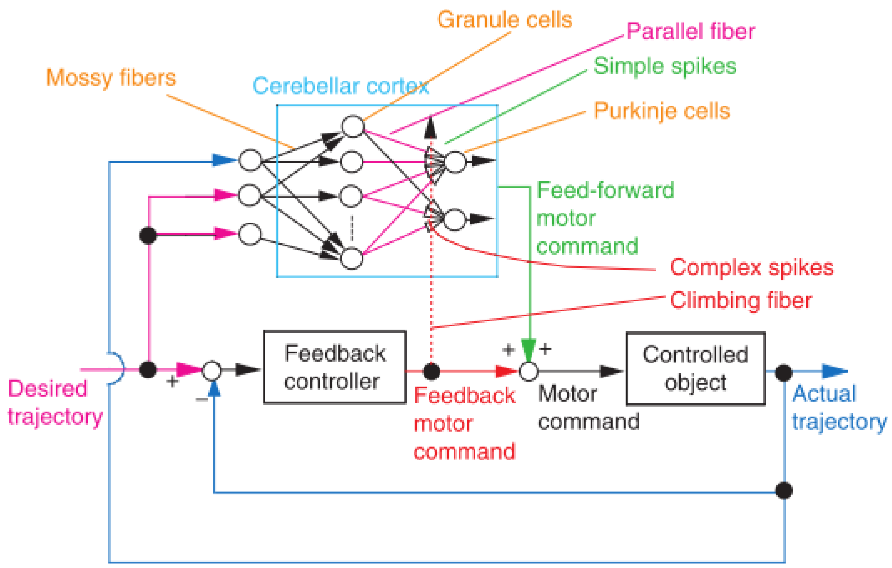


Figure 2.15: Feedback error learning model with feedforward neural network related to the cerebellar system [reprinted with permission from (Kawato, 2010)**].**

FEL controller can be used to learn the internal model of the system. However, in this work it is not the case of infants learning to control their motor system but subjects that have already an internal model which only has to adapt the controller to the new situation (pointing task through postural movements). Therefore, the internal model does not have to be setup from scratch but rather trained to adjust the internal parameters to achieve the new pattern of gestures (Braun et al., 2010).

This feedforward controller is constituted with a neural network that resemble the cerebellar cortex (Figure 2.15), which is the simplest controller in brain and is also present in reptiles. It is constituted with afferent sensory fibers (Mossy fibers), cerebellar granule cells, that elaborate simple signals, connected with Purkinje cells, that are capable of more complex elaboration, and efferent fibers that carry motor command through the pons and inferior-olive (not represented). Disruptions in this structure, such as the ones caused by Parkinson's disease, increases signal delay which consequently reduces control abilities (i.e. smoothness, stability, accuracy). However, in biological terms cerebellar controller is faster than cerebral cortex but it is less flexible in response elaboration. In fact, in mammals the motor control is mediated also by other cerebral areas that allow complex motor patterns.

FEL internal model does not have to be a perfect representation of the system because any inaccuracy is compensated by feedback controller and corrected at each repetition. However, the correction and adaptation of the internal model is sensitive to feedback delays, therefore the first repetitions must be done slowly to allow correct learning but also to avoid instability. This actually happens in subjects that have to learn a new gesture, the first attempts are slow but movement time is improved with repetitions.

2.3. BALANCE ASSESSMENT

Balance assessment can be traced back to the 19th century when the neurologist Romberg found the relation between some neurological dysfunctions and posture control. Although it is a simple test evaluated by means of subjective judgments it is still used as it is fast and does not require any expensive instrumentation.

Romberg test (Romberg, 1846) was originally developed to diagnose sensory ataxia and spinal cord damages, in which the subject is deprived of vision and has to rely only on vestibular and proprioception sensory information. Nowadays, the test is also used outside clinical circumstances, such as for drunk driving test. In Romberg test the patient stands with feet together and with arms crossed or kept along the body. First the test is performed with eyes open and then with eyes closed, each for 30 seconds. Excessive sway or loss of balance is interpreted as test failure. This is a simplistic test, however it is still in use for first discrimination because it is very rapid and does not need any equipment.

Many other balance tests have been developed since then. Some of the most used are summarized below.

Sharpened Romberg test (Lee, 1998) is a variant of the Romberg test made more demanding by reducing the base of support. Feet are positioned in tandem (heel to toe) with the dominant foot in front and crossed arms or hands at hips. First the test is performed with eyes open then with eyes closed. If the balance is lost or hands are moved from the hips before 30 seconds, it is interpreted as test failure. It should to be emphasized that this test has a learning effect, thus it ought be repeated at least three times to avoid false positive test.

Tinetti test (Tinetti et al., 1990), also called performance-oriented mobility assessment (POMA), and Berg test (Berg et al., 1992) are questionnaire item based tests used to assess fall risk in elderlies and patients with acquired brain injury, stroke or multiple sclerosis. Both tests assess the patients by their ability to perform some tasks, such as standing, turning and sitting.

Some balance tests are performed also on foam pads, such as the balance error scoring system (BESS) and the clinical test for sensory interaction in balance (CTSIB) (Shumway-Cook and Horak, 1986). Foam surface reduces the balance ability of the subject also because the instability perturbs feet plantar somatosensory system and general proprioception.

BESS balance test is used to evaluate balance ability and it is composed of three tasks, each performed for 20 seconds (sufficient to comprise three-four breathing cycles), first on firm surface and then on foam surface. In the first task, double leg stance test, the patient stands with feet together, hands at hip and eyes closed. The other tasks differ from the previous only by means of leg position. The second task is a single leg stance test, in which the subject stands only on the dominant leg, while the third is a tandem stance test, performed with feet as for sharpened Romberg. This balance test is assessed by counting the errors made during the performance, such as moving hands from hip, opening eyes, step, and excessive hip rotation. BESS balance test provides good reliability to assess balance ability (Bell et al., 2011).

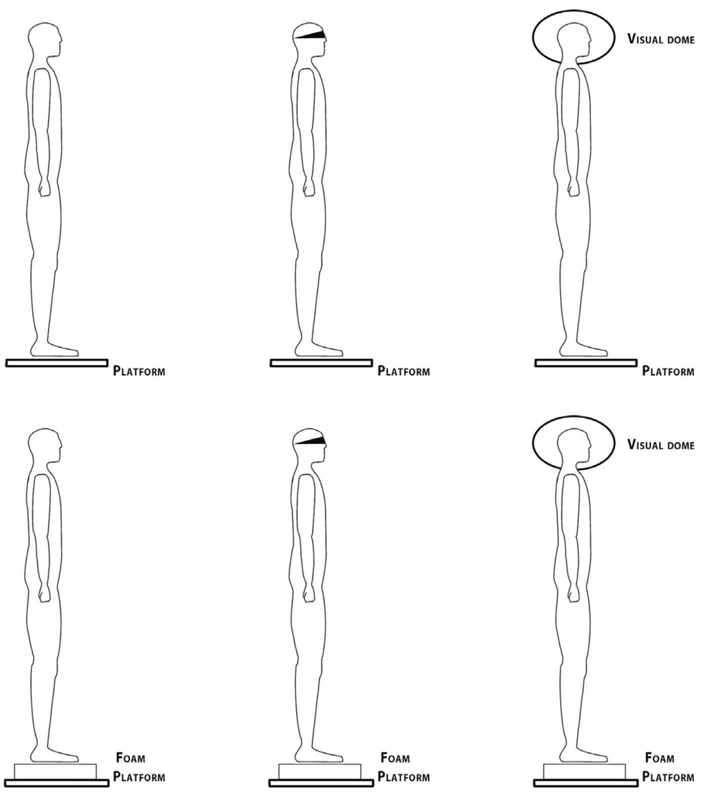


Figure 2.16: Conditions of the clinical test for sensory interaction in balance. Top conditions regard standing on a firm surface while the bottom ones on the foam surface. From left to right the conditions regard: eyes open, eyes closed and visual conflict.

In CTSIB balance test the subject stands barefoot with hands at sides in six conditions performed for 30 seconds. Figure 2.16 show the test conditions, which include vision (eyes open, eyes closed, visual conflict) and surface (firm or foam). In visual conflict condition the subject's head is covered with a dome in order to deprive peripheral vision and with a sway reference horizon. Test is stopped whenever the subject changes position of his/her hands or feet. However, if the failure happens at the first attempt, it might not be due to a balance disorder but simply because of learning phase. Therefore the subject should be allowed to have two additional attempts and then scores are being averaged (Horak, 1987). Assessment is done by subjectively evaluating the subject's sway.

CTSIB balance test is used to diagnose sensory conflict between vision and vestibular systems, somatosensory or vestibular dysfunctions. It has been found to be effective in displaying balance disorders (Cohen et al., 1993). Modified CTSIB (mCTSIB) differs from the original CTSIB by excluding visual conflict conditions. Therefore, four conditions are assessed in this balance test.

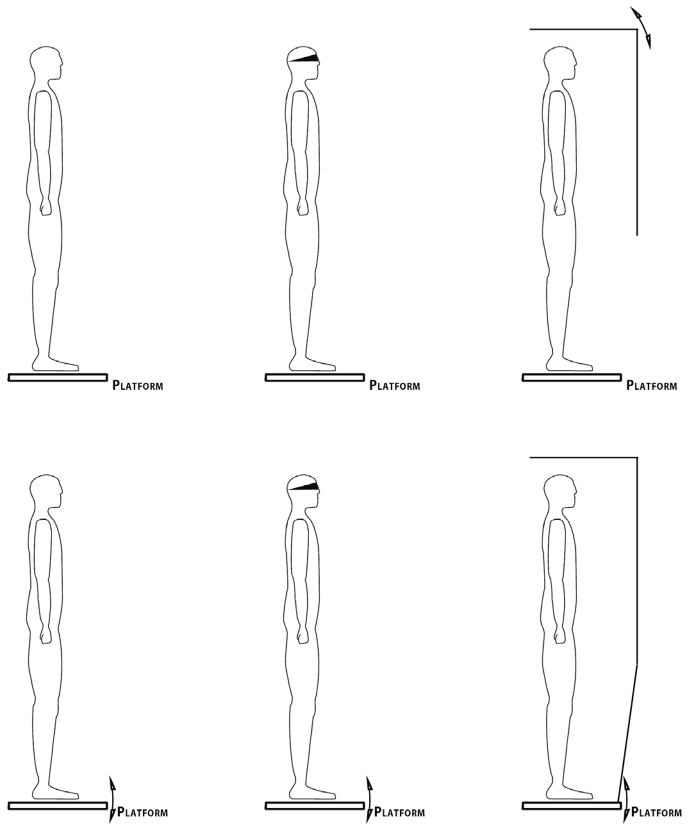


Figure 2.17: Conditions of the sensory organization test. Top conditions regard standing on a firm surface while the bottom ones on a tilting surface. From left to right the conditions regard: eyes open, eyes closed, sway referenced surround.

The sensory organization test has similar conditions tests of CTSIB balance test except that the visual conflict is realized by using a sway referenced surround and the foam condition is substituted with a titling surface (Figure 2.17). In addition, there are balance tests that use sliding surface or titling surface to disrupt the balance such as “motor control test” in which coronal plane slides, and “adaptation test” in which coronal plane tilts. However, tests that use moving platforms require more expensive equipment.

Other balance tests have also been deployed. Some examples might be the “star excursion balance test” (Gribble et al., 2012) and Y-balance test (Shaffer et al., 2013), which are dynamic tests used in sports; narrow ridge balance test (Curtze et al., 2010), used to assess lateral balance control; or laboratory purposes tests (see paragraph 4.2).

Among the above tests, the CTSIB seems the most suitable to be used with CDP because it uses a simple platform and comprises quite standing in unperturbed and perturbed conditions. This latter provide important information in the validation of a mathematical model. BESS would also be useful but patients with legs disorders find difficult to stand on one leg while postural controls are deployed for two leg standing.

The above tests are evaluated through subjective assessment which makes difficult to follow up patients and to compare conditions. Whenever quantitative measures are needed, it is necessary to use a computerized dynamic posturography (CDP). CDP requires a force platform having transducers (strain-gauges, piezoelectric), that by measuring vertical reaction forces provides the subject CoP position, an analogic-digital converter, and a computer or data-logger to record the signal.

Typically platforms have a firm surface, but they can be labile, allowing movements by pivoting, tilting, or sliding, or just with a cushion above the platform in order to generate instable perturbations that avoid mutual compensation by the dominant leg. Moreover, there are some double platforms that record separate forces for each foot. External perturbations can be also added such as a sudden slide of the surface or a sudden slightly hit on the back.

Platforms usually provide the forces of the transducers but some of them also directly calculate the center of pressure (CoP) positions, which later can be plotted into a graph called statokinesigram (SKG) (Figure 2.18).

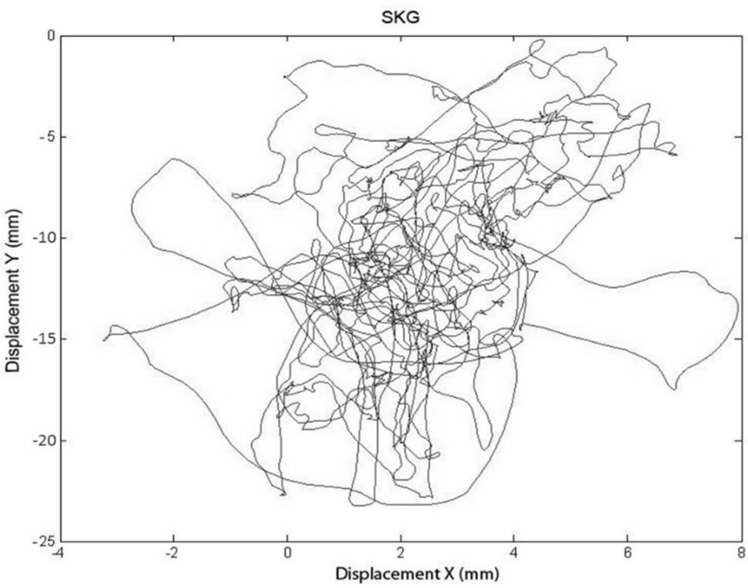


Figure 2.18: Example of experimental statokinesigram (SKG), also known as stabilogram, for a healthy subject [CAPS™ Professional, Vestibular technologies, LLC – Cheyenne WY, U.S.A.].

Usually only CoP is analyzed because the center of gravity (CoG) and center of mass (CoM) are not directly measureable and would require much more expensive equipment.

The CoG is the vertical ground projection of the CoM, although sometimes CoG and CoM are used interchangeably. CoG position have smaller frequency and amplitudes than the CoP and they overlap only in very static conditions. Some methods that correlate CoP and CoG have been proposed but usually they refer to single-link mathematical models. Already a two link model can provide multiple configurations for the same CoP position (Figure 2.1). For instance, zero-point-to-zero-point double integration method uses the assumption that in a single-link pendulum CoP and CoG overlap when horizontal forces are zero, the points between are calculated through double integration.

Other methods have been proposed such as low-pass filter (Caron et al., 1997) either fixed and sharp (i.e. 0.4Hz) or smooth depending on anthropometric features. This method hypothesizes that the high CoP frequencies are generated by dynamic forces while quasi-static forces account in low frequencies. Caron et al. compare such frequency filter methods but using only horizontal accelerations as a comparison indicator (Caron et al., 1997). Lafond et al. instead, provide a comparison of CoP-to-CoG methods with a direct measure of CoG (Lafond et al., 2004). The CoM of each body segment is calculated through the position of markers retrieved using an opto-kinetic technique, then the overall CoM and CoG are calculated. The result is compared with low-pass smooth filter method and zero-point-to-zero-point double integration method. The first method outcome is quite inaccurate, both in amplitude and frequency, whereas the second follows well the CoG position but it needs high sampling frequency to accurately find zero points (e.g. 200Hz).

Sample frequency is also important to get good quality data. Nyquist-Shannon sampling theorem must be considered when choosing the sample frequency. However, there are some works where the sample frequency is just 10Hz (Raymakers et al., 2005), that is only phenomena under 5Hz can be studied! To have a proportion, a simple reaction time is about 0.15-0.30s while Parkinson's disease cause about 3-7Hz muscle tremor. Moreover, it must be reckoned that the higher the frequency sample, the better the signal-to-noise ratio. Still, noise suppression is also important to reduce environment vibrations, otherwise they are overlapped on the SKG.

Measurements of postural balance

Statokinesigram (SKG) is a time series of the CoP coordinates, which displays non-linear and non-stationary pattern. It can be graphically analyzed by looking at some its characteristics. For instance, it might show direction prevalence of sway, small area of the CoP and short segments indicate fine control of the perturbations, long segments indicate sudden perturbation, and wide fluctuations indicate reduced balance ability. However, these evaluations are not adequate to provide objective data.

A wide variety of methodologies and parameters have been used or created in order to objectively analyze and decompose SKG. First of all, SKG is usually divided into medio-lateral (ML) component and anterior-posterior (AP) component as body d.o.f., stiffness and strategies differ between sagittal and coronal planes.

Traditional parameters directly analyze SKG in time domain, in frequency domain or in both. However, different approaches have been developed or excerpted from other fields, such as diffusion analysis and chaos theory.

In time domain some of the most used parameters are:

- Range, mean and root mean square displacement;
- Range and average sway velocity;
- Range and average areolar velocity also known as velocity moment;
- Sway accelerations;
- Total sway area, standard ellipse or circle, confidence ellipse or circle.

The confidence ellipse encloses the center of the SKG with about 95% probability and it depends on the sample size, while the standard ellipse encloses about 95% of the points (Rocchi et al., 2005). Therefore, comparing results of confidence ellipse must be done carefully. In order to have valid comparisons both sample frequency and time sampled must correspond.

Confidence ellipse is calculated as follows (Rocchi et al., 2005).

Equation 2.7: 95% confidence ellipse major semi-axis (a), minor semi-axis (b), and inclination (θ with reference to the x-axis).

$$a = \sqrt{\frac{2A}{s_y^2 + s_x^2 - \mathrm{B}}};\ b = \sqrt{\frac{2A}{s_y^2 + s_x^2 + \mathrm{B}}};\ \theta = arctan\left(\frac{2 - rs_x s_y}{s_y^2 + s_x^2 - \mathrm{B}}\right)$$

Where s_x^2 regards CoP variance points on x-axis (lateral), s_y^2 regards CoP variance points on y-axis (longitudinal), and r regards the correlation coefficient between x and y CoP coordinates. They are calculated as follows.

Equation 2.8: Coefficients s_x^2, s_y^2 and *r* of the 95% confidence ellipse.

$$s_y^2 = \frac{\sum(y_i - \bar{y})^2}{n-1};\ s_x^2 = \frac{\sum(x_i - \bar{x})^2}{n-1};\ r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}$$

Equation 2.9: Coefficients A and B used to calculate 95% confidence ellipse.

$$A = 2\frac{n-1}{n(n-2)} s_x^2 s_y^2 (1 - r^2) F_{\left(\frac{\alpha}{2};2;n-2\right)}$$

$$B = \sqrt{\left(s_y^2 - s_x^2\right)^2 + 4\left(-r s_x s_y\right)^2}$$

Cinematic SKG analysis is mostly in use for its simplicity and direct relation to physical quantities. However, such analysis is not always sufficient to assess the upright ability maintenance (Rasku et al., 2012) and other analysis needs to be performed in order to be able to find differences among groups (Deffeyes et al., 2009). For instance, frequency domain parameters, adopted from EMG analysis:

- Peak and median frequency;
- Mean power frequency;
- Variance of central frequency;
- Total power;
- Power spectrum ratio;
- 99% power bandwidth;

Other signal analysis comprises wavelet analysis, which can be used to extract significant features from the SKG signal. However, as this technique results in high dimensional vectors reduction, methods such as principal component analysis (PCA) must be used. In this way only the most significant features are considered and analyzed. For instance, using discrete wavelet decomposition, SKG can be divided first into a trend component and then using PCA into a low frequency component that "ramble" around the trend and a chaotic component that "tremble" around the trend (Maatar et al., 2013).

Another approach that has been recently used is stabilogram diffusion analysis (SDA). It is used to quantify the CoP stochastic and deterministic behavior (Doyle et al., 2008). It is calculated by varying the time span *m* of the square displacement (Equation 5.2), then the result is plotted for each time span.

Equation 2.10: SDA square displacement (Tanaka et al., 2002)

$$\langle \Delta x^2 \rangle_{\Delta t} = \frac{\sum_{i=1}^{N-m}(x_{i+m} - x_i)^2}{N-m};\ 1 \le m < N$$

Amoud et al. propose the use of entropy time series analysis, which is a signal regularity measurement (Amoud et al., 2007). In brief, the SKG signal is decomposed into its intrinsic mode functions. In other words, the signal is firstly decomposed into finite and simpler components. Then the overall entropy comes from the sum of each component entropy. With this method high frequency components are not suppressed by low predominant components. It is shown that this method can successfully discriminate between elderly and mid-adults by only analyzing the SKG.

Considering the nature of the SKG, chaos theory is also applied in posture analysis (Yamada, 1995). This technique is based on the Taken's theorem in which an embedding can be used to reconstruct the experimental attractor of a chaotic dynamic system (Cross and Gilmore, 2009). Attractor dimensionality and largest Lyapunov exponent (LLE) measure signal predictability (sensitivity to initial conditions) and allow to discriminate between subjects.

In Equation 2.11 it is represented the LLE calculation for discrete systems. However, since chaotic system usually does not allow to determine LLE through analytical calculations, thus numerical techniques must be used. A positive LLE denotes a chaotic system and the largest the exponent, the higher sensitivity of the dynamical system to initial conditions. That is, a small change in the initial conditions can cause a big outcome variation in high sensitivity systems (butterfly effect).

Equation 2.11: LE for discrete time series. x_0 refers to the starting point and n to the space dimension.

$$\lambda(x_0) = \lim_{n\to\infty} \frac{1}{n} \sum_{i=0}^{n-1} \ln|f'(x_i)|$$

Furthermore, some authors point out that SKG can be studied with fractal analysis (Baszczyk and Klonowski, 2001) and with fractional Brownian motions (Tanaka et al., 2002), while others use both chaos theory and fractals (Pascolo et al., 2006).

Postural indicators for particular applications have also been created in order to compare subjects. They can be classified into indicators that consider only SKG features, indicators that consider SKG features and anthropometric data, and composite indicators that consider many sources. The one of interest in this work is the stability score.

Stability score has been conceived to assess subject's ability to maintain balance during a quiet or perturbed standing test. It is calculated as the ratio between the 95% confidence ellipse and the subject's theoretical Limit of Stability (tLOS). It has to be borne in mind that in order to compare subjects with confidence ellipse trial sample size must coincide. tLOS is based on person's height. Basically, the subject COM can virtually sway inside a cone with up 12.5° of vertex aperture without losing stability (Parker and West, 1973). As the COM is generally assumed to be at 55% of person's height, the tLOS radius is calculated as shown in Equation 2.12.

Equation 2.12: Theoretical Limit of Stability (tLOS) radius. *H* is the subject's height.

$$tLOS = 0.55H \sin\left(\frac{12.5°}{2}\right)$$

Chapter 3:

MOTOR LEARNING

Learning is part of our daily life. Starting from birth till late adulthood one apprehend skills that range from social behavior to motor coordination. Motor learning involve many aspects such as playing, speaking, standing, writing, walking, etc.

One of the first gestures performed by babies while still able only to stay in supine position or rolling over, regard reaching and grasping, which are direction specific actions. With those activities there is the first learning in recruiting muscles with goal-driven approach that is without muscle modulation and optimization strategies. Between 4 and 36 months age optimization in muscle recruiting is implemented (de Graaf-Peters et al., 2007), in particular when muscles are strong enough to permit babies to start mastering crawling and sitting.

These positions require the development of a complicated postural control mechanism that reaches its full development in the adolescence. It can be divided into two levels of control which objective is to embed pre-structured recruiting patterns in spinal cord and brain stem, in order to allow the neural control in the brain to use motor synergies to keep erect stance (Forssberg and Hirschfeld, 1994; Turvey, 1990). The first level of control regards the direction-specific postural adjustments, while the second refers to the fine tuning of postural control with the consideration of sensorial information (Forssberg and Hirschfeld, 1994).

The implementation and development of those two levels are different from each other. The first seems to be innate and regards the actions to compensate body movements and internal perturbations. Babies that were suddenly perturbed demonstrate specific adjustment reactions (de Graaf-Peters et al., 2007). The second level of control starts developing from 4 months of age and regards the refinement and optimization of motor synergies. Strategies of muscle recruiting and modulation are created in order to i.e. minimize gesture energy, to improve coordination and accuracy.

Such strategies are tuned by using either a top-down or a bottom-up recruiting approach accordingly to the task (de Graaf-Peters et al., 2007) during a process called motor adaptation. For instance, top-down recruiting is preferred during reaching tasks but initial phases of standing show a preference for a bottom-up strategy that lasts also in adulthoods in particular for external perturbation adjustments (de Graaf-Peters et al., 2007; Mergner, 2013). Later top-down muscle recruiting becomes the dominant approach. During development not only does neuronal system improve but also muscles develop in strength, endurance and are more innervated by motor-neurons.

The same happens when an adult is exposed to a novel motor action; body coordination, movement smoothness and accuracy are object of change and improvement. Moreover, once the action is learnt, usually it will be retained for a long time. For instance, let's just think about PIN code typing: once the gesture is coded one retains it and is able to recall it for a long time, even when the code is changed to a new one.

In this work subjects undergo novel balance tests and a perturbed stability test whose learning phase will be analyzed. In this chapter behavioral motor learning related to the experiments of this work is reviewed. Then a separate paragraph is dedicated to the imitation process. Methods to measure motor learning and motor performance laws are investigated in the last section.

3.1. MOTOR LEARNING PROCESS

According to Bernstein, a Russian neuropsychologist, "*practice is a particular repetition without repetition*" (Bernstein, 1967), meaning that practice continually improve gestures. In fact, even after several years of practice and 10 million of products produced, hand workers at a cigar industry were still able to show time improvement in rolling cigars (Crossman, 1959).

However, why practice is needed to achieve a certain performance? The capability to acquire new gestures is best achieved with a motor control that use an exploratory behavior to search for the best solution that maps perception with action (Haith and Krakauer, 2014; Newell and McDonald, 1992). Moreover, learning also require time because it involves synaptic plasticity, which is strengthen or weaken over time.

The following paragraphs illustrate how motor learning evolves in terms of behavior and neural process. The last paragraph will present the motor program, which is a model that describes how voluntary actions are programmed and performed.

3.1.1. Stages of motor learning

Fitts and Posner have proposed that the motor learning of a new movement occur in three stages (Fitts and Posner, 1967). The first stage regards a cognitive phase where the subject understands the objective of the movements. It is also called the "what to do" phase. This phase is mainly based on declarative learning. Declarative learning can occur implicitly or explicitly. In the first case the learner unconsciously acquires the task relevant information.

For instance, a "serial reaction test" requires the subject to press one of four buttons according to the stimuli appearing on the screen. The pattern can be random or with a defined order of stimuli sequence. In the defined sequence the subjects are able to exploit the stimuli pattern by repeating several sequences of the test. They can understand the pattern also without being aware (Sanes, 2008). On the contrary, explicitly declarative learning is conscious and regards the attempt to figure out test goals, to retrieve from memory useful information from similar tasks performed in the past, and the representation construction of the motor task (Sanes, 2008).

Explicit declarative learning can be either acquired through verbal explanations or by directly looking at someone performing the related actions that is by imitation. Sometimes, however, it can be difficult to verbally explain some actions that is why the instructors say “do like I do now”. Still, they use verbal instructions to direct the learner attention towards the important information, otherwise the subject would have difficulty to perceive fine motor gestures or how some gestures have been achieved (which muscles, coordination of which body parts, etc.).

This first stage of motor learning is essential to gather the indispensable information required to understand the objectives and to achieve them and to take into account environmental factors that can influence the movement. This stage is characterized by full conscious control of movements although they appear rough and choppy and require high energy expenditure.

The second phase of motor learning proposed by Fitts and Posner is the associative stage. This is the phase in which is learnt how to achieve the intended gesture. This is the process in which the subject transforms declarative knowledge into procedural knowledge.

Procedural knowledge is learnt through experience and is defined as “know how to do” phase or just “know-how”. This knowledge is usually difficult to verbalize, i.e. describing a basketball shoot, and includes also non-motor learning, such as learning rules or habits (Knowlton and Moody, 2008).

Procedural knowledge requires to repeat the motor gestures several times in order to be acquired but its persistence differs according to several factors. For instance, intensive performing leads to short term retention (minutes to hours), while performing the gestures gradually and over several sessions leads to long-term retention (days to beyond) (Huang and Shadmehr, 2009).

In fact, the subject that performed a reaching task under perturbed conditions shows slower motor performance decay when the perturbations were applied gradually; perturbations applied suddenly demonstrated higher motor performance decay when practicing the same test after 2 hours (Huang and Shadmehr, 2009). Moreover, not only does the intersession resting phase improve motor persistence, but also intra-session breaks and night sleep, still usually there is a slight decay in performance between the session breaks (Luft and Buitrago, 2005).

Furthermore, sequencing the gestures in simple chunks improves motor retention although it will slower learning performance (Knowlton and Moody, 2008).

Learning pace is fundamental to consolidate memory as acquiring tasks one after another will disrupt consolidation and only the last performed task is retained. Such interference is gradually reduced according to the time passed between the acquisition of the two tasks and there is not any interference if the two tasks are performed with at least 4 or 5 hours break (Luft and Buitrago, 2005).

Yet, there are some other factors that reduce the motor memory persistence, like reward and focus of attention (Wulf et al., 2010). For instance, reward inducts offline memory reinforcement by increasing neuronal excitability through an increased dopaminergic activity. In fact, in the work of Abe et al. a critical tracking test was administered to three groups of subjects, that according to the accuracy of the gesture were either rewarded with an increasing amount of money, or punished by decreasing the amount of money, or nor rewarded neither punished (Abe et al., 2011). The rewarded group showed better long-term motor persistence than the other two groups.

When the gesture has been trained intensively and is well coded, it is not possible to transfer the motor action from one limb to another (Luft and Buitrago, 2005). For instance, a rookie basketball player find little differences to shot with one arm or another, but an experienced one would only be able to shot well with the dominant arm or with the one he/she practiced more. Perhaps this is possible only when the visuospatial coordinates information are encoded, while this transfer ability disappears when also the motor program is encoded, that is the procedure that recruits the muscles (Hikosaka et al., 1999).

This stage is generally characterized by small performance gains because the subject is refining movements, trying to interpret sensory information, trying to optimize the muscles modulation and recruiting, discarding to activate muscles that are not necessary to achieve the gesture. The focus is on temporal and spatial body coordination and proprioceptive information, which still requires the usage of working memory, even though with less extent than in the cognitive stage (Sanes, 2000).

The last motor learning phase is the autonomous stage, which takes years of trainings and is related to the ability to perform gestures with little or without conscious control. The gestures become automatic with very few or none utilization of working memory, movements are smooth and economic, gestures are well coded as he/she found the actions almost innate that do not almost need conscious control. For instance, an experienced karate player does not even have to think how to block a kick; once perceived, he/she will straight react with highly reduced reaction time. From the perception to action there is a straight neuronal mechanism.

Bloom and colleagues proposed a taxonomy of learning domains as follows: cognitive, affective and psychomotor (Flinders et al., 1996). At first the cognitive domain taxonomy was developed for teaching purposes and later the affective domain and the psychomotor domain were developed. Just the latter one is of interest in this work, however, it was only theorized in Bloom’s taxonomy. Other authors have provided developments and insights for psychomotor domain, but they differ from each other by the field of application and situation.

Simpson first proposed a version of the psychomotor domain with the following levels: perception; set; guided response; mechanism; complex overt response. Later a sixth category, adaptation and origination, was added (Simpson, 1972). The first category, perception, regards the ability to use sensory information to drive physical ability. That is, to use proprioception, vision and other sensory information to understand and interpret the situation, and to relate it to a motor action. The second category, set, is the readiness and adjustment preparatory phase for the action. It involves mental, physical and emotional aspects, which must be adjusted and prepared for the motor action. Guided response regards the early development of the motor psychomotor skill, which can be acquired by imitation or trial and error. This first three levels can be connected with the cognitive phase proposed by Fitts and Posner as all of them are required to understand "what to do" in order to achieve the problem.

The mechanism level regards the habituation of the learned response and can be related to the associative stage of motor learning, in which the gesture outcome is appropriate and the subject optimizes the energy expenditure. The last category, complex overt response, regards the ability to perform the motor act smoothly, finely coordinated, in an efficient manner and without hesitation. This level can be related to the automatic stage, in which the subject is able to perform complex skills almost without conscious control. Simpson provides another level which describes the subject's ability to adapt the acquired complex skill according to the situation or the specific problem. While the first five are being executed consequently, the sixth can take place at all levels (Simpson, 1972).

The taxonomy detail provided by Simpson seems more conceived for children education (Chapman, 2006), whose perception and arousal must be trained, than for adults who have already a developed perception mechanism and consciousness of their body.

Another taxonomy for psychomotor domain was provided by Dave, who proposed the following five categories: imitation; manipulation; precision; articulation; and naturalization (Dave, 1975). In this taxonomy the first two levels proposed by Simpson (perception and set) are missing.

The first category, imitation, regards the observation and replication of somebody's action. The subject initially has to watch the gestures, then understand the main goal, sequencing and patterning the actions, and finally try by himself/herself. The second level, manipulation, regards the performing an action from written, verbal instructions or from memory recall. It requires to code the related gestures before practicing. The precision level regards the calibration and mastering of the actions without the need of assistance or instructions, while the articulation level regards the adaptation of the actions to improve expertise and to satisfy new requirements.

These first two categories can be related to the Fitts and Posner's cognitive motor learning stage as they regard the onset of the motor action, while the following two levels can be related to the associative stage as both precision and articulation level regard an enhancement phase. The last one, naturalization, can be associated with the automatic stage, in which the subject is able to perform a high quality action that seems natural as little conscious control is required.

In addition, other psychomotor domain taxonomies were proposed by Harrow and by Thomas. Harrow's taxonomy is more connected with sports enhancement and children with special needs (Harrow, 1972). The following categories have been proposed: reflex movement; basic fundamental movements; perceptual abilities; physical abilities; skilled movements and non-discursive communication. Thomas' taxonomy is more connected with the learning outcome (Ken, 2004) and the following categories are proposed: perception, communication, movement, strength, dexterity, coordination, operation of tools and equipment, construction and art. These categories are more related to outcome assessment. The performance of each level can be evaluated in terms of cinematic parameters, such as distance, velocity, precision, and execution, such as sequence, procedure and technique.

Gagné et al. proposed in 1979 another comprehensive learning taxonomy which was not categorized as Bloom's domain (Gagné et al., 2005) and is more focused on the learning outcome than on the educational objectives (Ken, 2004). This taxonomy comprises intellectual skills, cognitive strategy and verbal information (corresponding to Bloom's cognitive domain), motor skills and attitude which can be respectively related to Bloom's psychomotor and affective domain. The instructions to achieve such skills should be designed in the following nine steps: gain attention, inform of the objectives, stimulate recall, present the content, learning guidance, elicit performance though practice, provide feedback, evaluate, retention and transfer to the job.

The Bloom's taxonomy was recently revised by various authors (Anderson et al., 2001; Krathwohl, 2002), but its main principles are still recognized and used. The taxonomies regarding psychomotor domain here reviewed are useful in a wide variety of fields. For instance, they can be used to train children motor abilities, athletes, hand-workers, teachers, and to improve meetings handling (Chapman, 2006).

3.1.2. Neural process

The learning process illustrated in the above paragraph involves brain adaptations that can be either temporary or permanent. Contrary to what was thought for many years that nervous system is hardwired, in reality brain continually change its connections due to its high plasticity properties (Wolpaw and Carp, 2006). However, there are still many brain mechanisms and neuronal properties that are not yet clear, in particular how learning is achieved at neuronal scale (Martin and Morris, 2002).

The complexity of the brain is due to its numerous connections that each neuron has with the others. In fact, an adult has about 100 billion of neurons each with an average of about 7 thousand connections but cortex neurons can reach over 100 thousand connections (Purkinje cell). For this reason, in order to understand some basic functions, animals having only few neurons, such as the seaslug and zebrafish, are sometimes studied instead.

Various types of neural cells and non-neural cells constitute the brain. This latter cells have supporting functions such as insulating nerve cells and supply nutrients. However, recently it has been found that such non-neural cells also play a role in signal neurotransmitting and synaptic plasticity modulation (de Pittà et al., 2011).

Neuron cells are generally composed of the soma (containing the nucleus), dendrites (input), and axons (output). However, their morphology, such as dendrite and axonal structure, and their cytoarchitecture vary according to the brain location.

Neurons are connected with each other through synapses, in which the electrical signal releases chemical compounds called neurotransmitters that are received by the other cell receptors. Axonal synapsis can be placed in a dendrite, another axon, directly on nucleus or another synapses. The information carried by that synapse vary its importance according to its width and location where the synapse is placed. Moreover, their size, connecting place and internal structure can vary according to the synapse activity and spike rate.

When a conditioned stimulus-response is presented it leads to a synapse creation and the repetition of the stimulus leads to an increased connection strength by growing in its size. This type of learning is the Hebbian learning theory, which seems to be the main mechanism in the cerebral cortex. For instance, research on rats learning to navigate inside a particular maze showed reorganization at synapsis level already after the first attempt. Synapses plasticity regards either creation or suppression of connections or receptor size. Still, is not yet fully proved the relation between plasticity and learning (Martin and Morris, 2002).

Learning that does not involve synaptic plasticity have also been found, such as anti-Hebbian theory which seems to be the main mechanism in the cerebellum. In this case there is a change in activation threshold, spiking frequency and modulation, as well as changes in neuronal pathway.

However, plasticity does not regard just neural cells. For instance, also other cells present in the brain, such as glial cells, can strengthen the synapses connections.

Moreover, brain plasticity varies during growth, being at its maximum during infancy when brain have wide unorganized areas. This seems to be an evolution advantage as computer simulations on learning proved that limited developed systems archive higher complex learning than fully developed systems (Meltzoff et al., 2009). During one's growth excessive synaptic connections and neurons are removed, metabolism is reduced and neuronal paths are optimized. The plasticity activity reaches its minimum during adult life.

Neuronal plasticity may be of short-term or long-term, according to the mechanism involved. Short-term plasticity mainly involves changing at synapses size or neurotransmitter modulation which last few seconds or minutes.

Long-term potentiation and depression is thought to be the main mechanism in supporting long-term memory and it involves the formation of new synaptic contacts, new sub-networks and modifications in intracortical processing (Sanes, 2008). These neural modifications last from hours to beyond.

Indeed, learning does not only involve changes in the central nervous system. Also motor-neurons show adaptation as repeated stimuli increase the innervation of the muscle and provide better recruiting of muscle fibers.

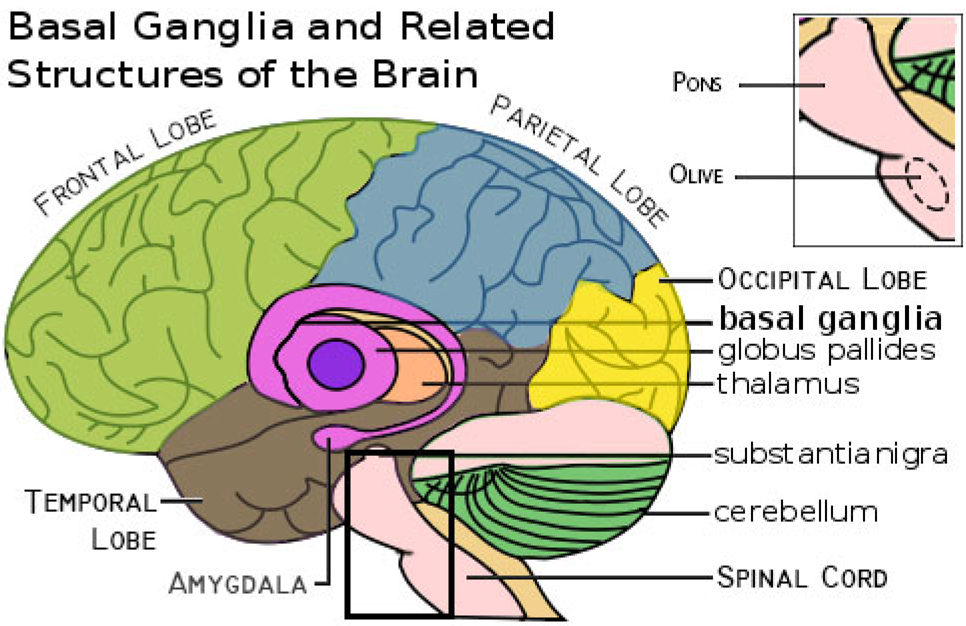


Figure 3.1: Brain neuroatonomy and cerebral lobes (modified from Wikimedia Basal_Ganglia_and_Related_Structures).

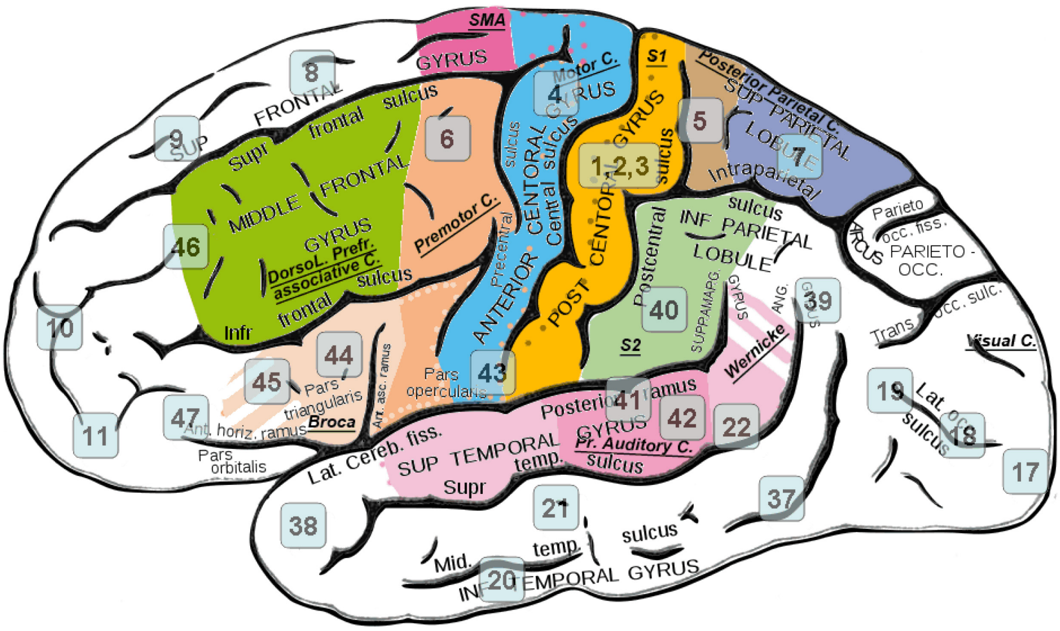


Figure 3.2: Brain motor areas and brain Brodmann regions (modified from superimposed figures of Wikipedia Brodmann_area and Wikimedia Gray726).

Motor learning seems to involve various parts of the brain, from the cerebellum to the brain cortex. Figure 3.1 shows the cerebral lobes and the limbic lobe while Figure 3.2 shows the brain areas related to motor functions with the cytoarchitecture cortex classification of Brodmann.

The cortical structures that subtend motor skills, which are Primary Motor Cortex (M1), Premotor Area (PMA) and Supplementary Motor Area (SMA), do not only have supporting functions, such as control and organize voluntary movements, but they are also involved in the adaption and retention of new gestures (Sanes, 2008). In fact, repeating a motor sequence such as piano playing, increases the cortical area related to finger movements, consequently speed and movement accuracy are found to be improved. Other brain parts are also involved in motor control and procedural learning, such as basal ganglia and cerebellum.

Table 3.1: Cortical brain areas related with motor skills.

Name	Location	Description
M1: primary motor cortex	Brodmann 4 (blue)	Its possible functions comprise voluntary movements control, movement coding and coordination. Somehow it shows the motor homunculus pattern, but the devoted area to a movement can increase with repetition.
SMA: supplementary motor area	Part of Brodmann 6 (violet)	Possible functions of this area include posture stabilization, control of movement sequence and movement coordination.
PMA: premotor area	Part of Brodmann 6 (pink)	This area possible functions contain movement planning, movement guidance in space and sensory feedback. That is the area where mirror neurons are located.
S1: primary somatosensory	Brodmann 1,2,3 (gold)	It is presumed to encode and process the proprioception input information. The amount of neural cells devoted to a body part depends on the innervation density of that body part, showing a pattern of the sensory homunculus.
S2: secondary somatosensory	Parts of Brodmann 40 (light green)	Possible functions comprise sensorymotor integration, attention and motor learning.
DLPFC: dorso lateral prefrontal cortex	Brodmann 46 (dark green)	It is a location for executive functions such as working memory, motor planning and organization, cognitive flexibility and abstract reasoning.
Somatosensory association cortex	Brodmann 5 (brown) Brodmann 7 (blue)	Possible functions of this area include somatosensory information processing and association (5), and space locating the object by using vision and proprioception information (7).
Broca's area	Brodmann 44, 45 (light pink)	This area possible functions contain language production and comprehension, including grammar sentence construction.

Brain activity measurements techniques

The activity of neurons can be measured by capturing electrical signals that they produce or indirectly by measuring the oxygen that they consume during their metabolism.

The most used techniques to measure neuronal activity comprise the functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), whereas to a lesser extent is used also the Magnetoencephalography (MEG) and single-unit recording (SUR). Also a new technique, near-infrared spectroscopy (NIRS) is becoming more popular.

The fMRI is among the most widely used techniques to detect the presence of neuronal activity in humans and nowadays it has almost replaced the positron emission tomography (PET). This measurements have a high spatial resolution but low temporal resolution. This characteristics set not negligible limits on fMRI as a method of experimental investigation (Logothetis, 2008), particularly in detecting the activity of groups of neurons.

In fact, it is necessary to repeat a gesture or an observation for several seconds in order to detect a change of oxygenation in single voxel. It is so as at the beginning of the stimulation, the neuron uses its internal energy sources and only then "feeds itself" from the blood vessels. This behavior delays the detection of oxygen consumption (blood-oxygen-level dependent - BOLD). Moreover the size of the analyzed voxel depends on the intensity of the magnetic field.

The electroencephalography (EEG) technique is characterized by good temporal resolution but poor spatial one. Moreover, it needs a zero signal as a baseline to which all other brain signals refer. This can consequently lead to erroneous interpretations if there are errors in the identification of the reference signal. In addition, the electrical signal is modified by the presence of cranial bone and eye movement, however, there are algorithms that reduce such noises.

The magnetoencephalography (MEG) has a good temporal resolution but similar like in the EEG technique, the signal is difficult to locate. Although algorithms allow a fair spatial resolution, it is not as good as the fMRI. Furthermore, in order to satisfactorily detect the magnetic activity, a relatively large area of neurons must be activated. The MEG moreover detects only the tangential magnetic waves but not distorted by crossing the skull. Still, it is the technique that combines the best spatial and temporal resolution.

The SUR technique provides microelectrodes inserted in the area to be measured, sympathetic to the skull. It allows to directly detect neuronal activation but it do not discern between the signals that are sent across synapses or the nucleus. Moreover the SUR technique has a higher signal-to-noise ratio but it detects the activity only of a single neuron.

The NIRS is a recent technique. It measures the first millimeters of brain activity (cortex is 2-3mm thick). Infrared waves are absorbed by hemoglobin and reflected waves are correlated with blood activity. The NIRS provides good temporal resolution but limited spatial resolution.

As this technique uses fiber optic cables it does not interfere with magnetic and electrical fields. Therefore it can be used for multimodal imaging. For instance it can be used with fMRI to couple the advantages of both techniques.

Apart from aforementioned techniques, there are some others that do not record neuronal activity but instead stimulate or inhibit neuronal activity by rising or reducing threshold at which neurons spike. The effects of inhibition or stimulation are then analyzed indirectly by recording subject response in various tests such as choice reaction time. For instance, tDCS (transcranial direct current stimulation) and rTMS (repetitive transcranial magnetic stimulation) are used.

tDCS uses microelectrodes that can be either placed in contact with brain or placed on the skull skin, while rTMS uses magnetic coils that are placed near the skull skin. Localization on the skin is more difficult as it is uncertain which region of brain is exactly beneath, therefore fMRI is sometimes additionally used in order to find the location of interest.

Table 3.2 summarizes the benefits and pitfalls of each technique here presented. Generally, the low signal-to-noise ratio (SNR) typical of these techniques forces to make numerous scans in order to separate the signal from background noise. Besides that, algorithms are necessary to correct the distortion effects of the tissues prepended to the area to be detected, which differ from person to person. The image analysis through sophisticated algorithms can also generate very different results depending on the setting of the operating parameters.

Furthermore, even non-invasive techniques might have a negative effect on the subject, for instance fMRI is very noisy and constrains the subject in confined space, while the EEG uses sensors in direct contact with the subject skin.

At present, there is not any sufficient technique that provides both temporal and spatial resolution at enough detail to allow in-depth studies of brain activity.

Table 3.2: Summary of pros and cons of neural activity measurement techniques.

Technique	Pros	Cons
EEG	Temporal resolution, non-invasive, economical device	Spatial resolution
fMRI	Spatial resolution, non-invasive	Temporal resolution, expensive device
MEG	Temporal resolution, non-invasive	Spatial resolution, activity threshold, expensive device
SUR	Spatial and temporal resolution	Invasive, records activity of one neuron
NIRS	Temporal resolution, economical device	Spatial resolution
tDCS	Measure behavior outcome	Invasive
rTMS	Measure behavior outcome, non-invasive	Location of interested area

3.1.3. Motor program model

The above paragraph describes the evolution of the learning of voluntary actions. In this paragraph the motor program model is illustrated, which is a behavioral model that describes how these actions are performed.

Originally the motor program model did not rely on feedback information and so there was not any control during movement. This means, that once the movement is started, the motor sequence is not modifiable until it is entirely accomplished.

This theory was firstly deployed as a feedforward control from the fact that feedback information requires some time in order to reach the brain. Therefore, such delay prevents it to be used to control movement execution and thus the motor program must be arranged before commencing the movement. For this theory, feedback is only necessary to initiate the movement, to have information about the state of the system (joint coordinates, muscle fatigue and tension) and only at the end, the movement is verified and error is corrected on the subsequent repetition. In fact, some movements are performed faster than the signal feedback (e.g. piano playing).

Hence, this theory mainly considered fast movements that are possible in the second stage (autonomous) of the three stages illustrated in the above paragraph. Conversely, in the first stage (cognitive) subjects movements are very slow not only because they need to organize the gesture, but also because they need to wait the feedback information. Moreover, movements once thought to be too fast to be feedback controlled, were later proved wrong by research on reaction time. For instance, the motor stimulus of a monkey hand movement reaches the brain in about just 10ms (Adams, 1976).

To overcome some limitations of open-loop (feedforward) motor learning Adams proposed a modified version of the motor program for simple, slow movements (Adams, 1971). In this theory the movement can be learnt through a motor program composed of two memory states, the perceptual trace and memory trace. The memory trace recall the program into memory that is necessary to initiate the movement, and once the movement is initiated, the feedback is available to be compared with the perceptual trace for error correction. However, this theory is constrained to limited motor circumstances (only-closed loop) and the two memory processes are supported by the same mechanism.

With the Schmidt's schema theory a generalized motor program was deployed (Schmidt, 1975). In this theory, the motor program is a movement plan stored in the central nervous system (CNS) that organizes complex movement patterns by assembling already available simple muscle commands (Schmidt, 1975). In this way, it is considered that motor memory limits do not allow to completely store every movement pattern.

The schema theory of the motor program, depicted in Figure 3.3, is constituted of two sub-schemas. The first, *recognition* schema, is related to the control of the movement while it is performed. The motor response is evaluated and corrected according to the motor schema. The second, the *recall* schema, is related to the production of the movement.

This theory is not confined to limited circumstances because it includes both closed-loop and open-loop controls. The sub-schemas play different roles according to the movement speed (Utley and Astill, 2008). In case of slow movements, both sub-schemas concurrently control the process, while in fast movements the *recognition* sub-schema is involved only at the end of the process.

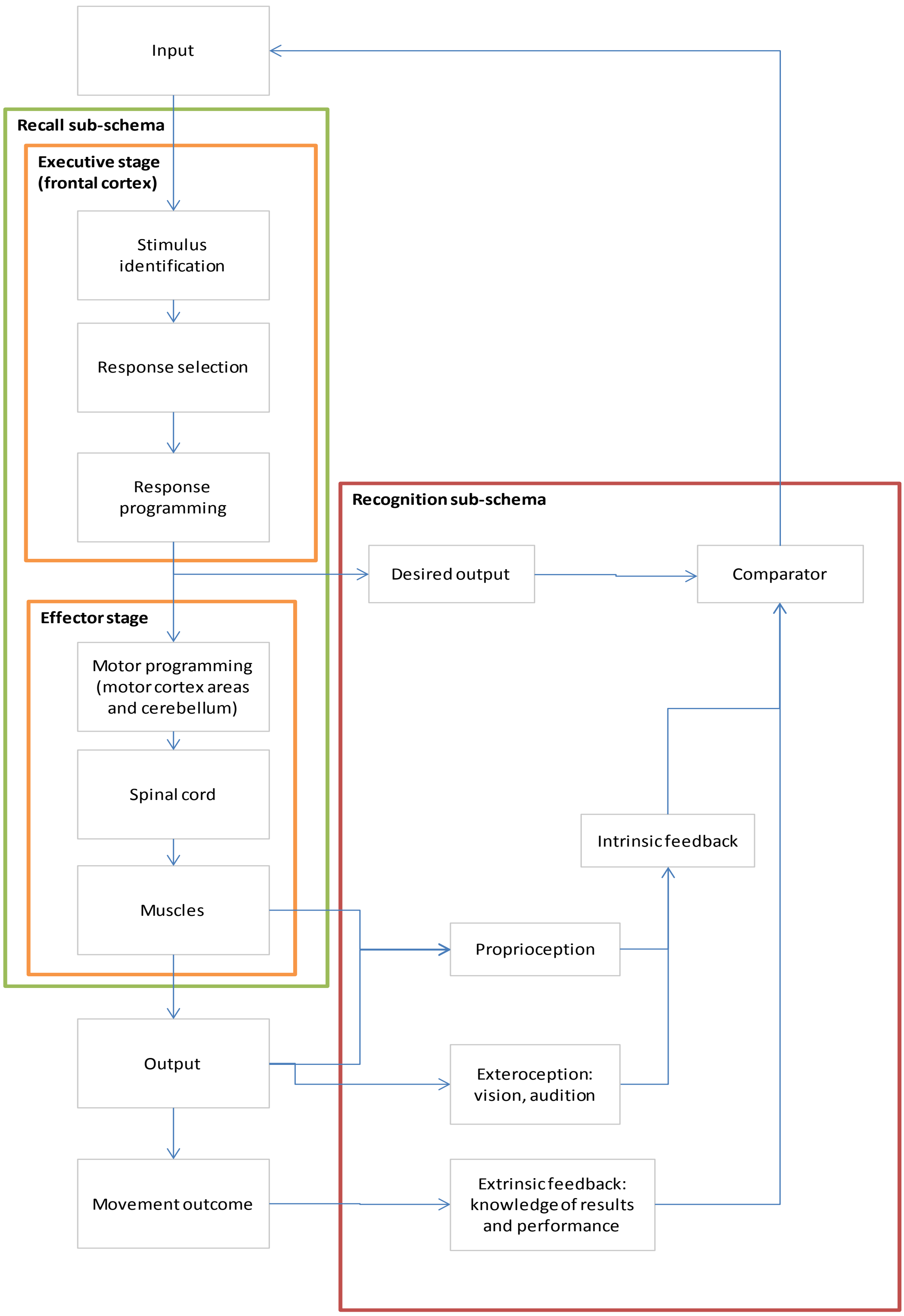


Figure 3.3: Motor program according to Schmidt's schema theory.

The *recognition* sub-schema compares the sensory consequences that the response produced and the outcome of the movement with the response specifications of the motor program.

The *recall* sub-schema process can be subdivided into the executive stage and the effectors stage. The first, executive stage, regards information processing coming from afferent information (i.e. proprioceptive, vision). At first, the stimulus is identified, then response is selected and eventually, response is programmed. The effector stage regards the creation of a motor program that is delivered to muscles through fiber nerves. The motor program according to the programmed response at the executive stage and to the system state (proprioceptive information) follows this steps:

1. selects muscles that are necessary to accomplish the response by composing simple subroutines (referred to simple coded movements);
2. arranges the sequence of muscle commands;
3. stores the program to motor memory;
4. forwards instructions to effectors.

Extrinsic information plays an important role in the feedback error correction process because it constitutes high order information. It can be divided into two main categories: knowledge of results (KR) and knowledge of performance (KP). KR regards information of goal outcome, for instance, the amount of hit targets or hit offset. KR can be redundant with intrinsic feedback as it might be retrieved directly by the subject. On the contrary, KP regards information of the quality of the movement kinematics, for instance, how the target was hit, and is important in fast or complex tasks (Utley and Astill, 2008).

One of the main limitations of the Schmidt's schema theory is that it is only based on supraspinal high cognitive processes, which allow the most flexible control but also the slowest. The processes involved in the motor control disregarded by the schema theory are the short-latency reflex (SLR) and the long-latency reflex (LLR) (Figure 3.4). The first, SLR or also known as M1 reflex, is a mediated by spinal processes and it is capable of fast reaction (20-50ms) but with fixed set of reactions. The second, LLR or also known as M2 reflex, is mediated by sub cortical areas (cerebellum, brainstem) as well as cortical areas (primary motor cortex). LLR is slower than SLR (about 80-150ms) but it has a wider variety of sets of reactions which can also be trained.

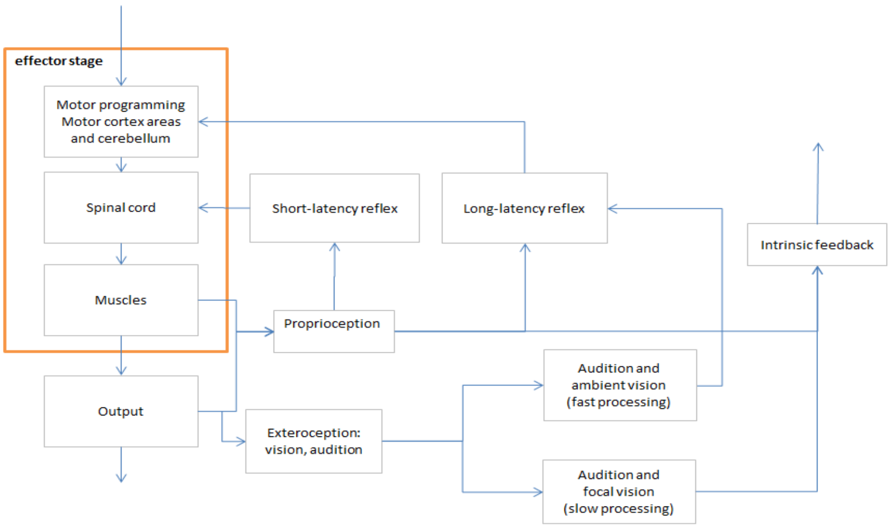


Figure 3.4: Reflexes not related with supraspinal high cognitive processes.

3.2. IMITATION PROCESS

The information acquisition stage to learn a new psycho-motor skill, either for Fitts and Posner motor learning or Simpson's taxonomy of psychomotor domain, can be achieved through many approaches such as trial and error, formal learning (called also verbal explicit learning), and imitation (Byrne and Russon, 1998; Stallings, 1973). The same approach can lead to different results depending on several conditions such as action goal, type of communication, individual characteristics and personal experiences. Feedback, although not necessary, usually improves the performance of learning process (Buchanan and Wang, 2012; Ivens and Marteniuk, 1997; Triano et al., 2006).

Additionally, all of these methods involve interaction of various and complex cognitive processes, albeit at different levels. For instance, formal learning is a top-down based process whereas 'trial and error' and imitation are bottom-up based ones (Sun and Zhang, 2004). Imitation seems to be an evolution advantage as it speeds up learning by using information from someone else, whereas 'trial and error' requires to individually figure out causal relations (Meltzoff et al., 2009). Formal learning provides abstract information that can be encoded through declarative knowledge. Imitation in animals is still debated but it has been proved that primates imitate conspecifics and even humans (Zentall, 2003). Emulation is common in animals but it should be distinguished from imitation as there is the attempt to reproduce the outcome by means of own strategies (Huang and Charman, 2005). For instance, a dog can emulate somebody opening the door by using his snout.

A subject that has to learn through observation initially gets the first idea of what is happening, then pays attention to the details of various body parts and motor sequences which he/she considers more significant (Elsner and Pfeifer, 2012). Later, when he/she has to reproduce the gestures, he/she adapts and corrects his/her movements to make them similar to what observed previously. However, only with the help of external corrections, one is able to verify the quality of his/her gestures and improve them. Indeed, fine motor gestures require more time to be learnt and are more difficult to be identified and observed than the gross motor gestures (Oxendine, 1967). Moreover, there is a difference in long term motor learning persistence; the gross movements last longer than the fine ones unless they are practiced regularly (Stallings, 1973).

In particular, learning by imitation involves observation, either voluntary or not, cognitive elaboration, and replication of one's behavior. The quality of imitation depends on the subject's personal background (Chartrand and van Baaren, 2009; Loras and Sigmundsson, 2012; Spilka et al., 2010) and its gender (Cohen et al., 2010). Indeed, the subject also shows selectivity both in the action reproduction, according to the importance he/she assigns to the observed gestures (Elsner and Pfeifer, 2012), and in the type of observed action (transitive, intransitive, communicative) (Liepelt et al., 2010). Besides, the subject can be conditioned by verbal communication in order to identify significant aspects to be observed (Elsner and Pfeifer, 2012; Southgate et al., 2009).

In light of the above, a question arises on what happens in the cognitive elaboration phase of imitation.

Byrne and Russon (1998) proposed a hierarchical approach for imitation learning. At low hierarchical level, action level learning occurs. The imitation regards the detailed specification of the small units of sequences of the novel actions. However, at action level 'trial and error' seems to be mainly used instead of imitation, because is more efficient to perform the detailed movements by using self-experience instead of copying each single muscle movement.

High hierarchical level is a program level learning where the imitation regards a broader description of the actions' and behavior structure and hierarchical layout. That is the main action goals and sub-goals of complex gesture organization are acquired by imitation. The gesture structures are then reassembled to achieve the action sub-goals and goals. However, the reassembly of the whole sequence could also be done by 'trial and error' approach, nonetheless this would work only for simple sequences where self-exploration still easily allows to figure out the right sequence (Byrne and Russon, 1998). Shon et al. have proposed that this imitation hierarchical approach can be computationally described by using Bayesian inference algorithms, which are able to handle incomplete and noisy data (Shon et al., 1998).

Meltzoff (2005) proposed the so called "Like me" hypothesis to explain how the imitation process works. In short, it is assumed that the imitation ability is innate and it allows to understand other's mental states. In this hypothesis imitation is developed in three stages. The first is the connection between observed and executed acts, then one's own acts are associated with own mental states and eventually the phase in which one projects his/her internal experiences onto someone else that is performing similar gestures.

The "Like me" hypothesis and the hierarchical approach have been submerged by the discovery of neurons that has fostered the simulation theory. In this theory the action understanding is innate and it allows to imitate others.

There are many variants of simulation theory but they all agree on the main idea that one does not need to use any mental state concept to understand someone else's actions or behavior. Instead, he/she uses his/her own mind as a model to predict other's intentions or behavior (Saxe, 2005). In other words, the other's behavior or intentions are understood, predicted or imitated by means of internal simulations.

Moreover, this theory considers that the internal simulation is carried out by being in the other's shoes. It means that one is able to simulate taking into consideration the physical and mental situations of someone else (Michlmayr, 2002). However, as the other can use different mental processes and reasoning, to adjust the simulation one needs to compensate for the differences by imagining an empirical information (Davies and Stone, 2000).

Furthermore, these internal simulations do not need to be carried out 'live' but they can be taken off-line. In this way, the simulation is supplied with pretend beliefs and desires of the other person, thus the produced output regards a pretended understanding, prediction or imitation (Davies and Stone, 2000; Michlmayr, 2002). Off-line simulation is consistent with delayed imitation.

In fact, the replication of the gesture learned by imitation at program level does not need to occur right when the gesture is seen; studies on infants and apes prove that the action goals can be acquired by imitation without practicing and they can be recalled later on (Byrne and Russon, 1998). Indeed, baby gorillas do not prepare the food by themselves but once they are wean, they already know what and how to do it (Byrne and Russon, 1998). Moreover infants were able to reproduce a novel gesture that they have just seen from an experimenter one week earlier (Meltzoff, 2005).

3.2.1. Mirror neurons role on imitation

Several studies argue that the simulation process is carried out by the same neural network that would produce such action or behavior, in particular that the imitation process is supported by the neural mechanism of the mirror neurons (Cattaneo et al., 2007; Southgate et al., 2009).

Rizzolatti et al. (1996) by using a Single-unit Recording technique, discovered a group of neurons in a monkey that are active either while performing an action or when looking at an action that is made by other people. They claimed that those neurons were active because they were mirroring the other's action, thus stating that a "mirror neuron system" (MNS) is dedicated to code and understand somebody's action.

Later, with fMRI measures, this neuronal system was found into the premotor cortex (PMA), supplementary motor area (SMA), primary somatosensory (S1) and somatosensory association cortex of human's brain (Figure 3.2 and Table 3.1). However, there were found two categories of MN: neurons that activate only to a specific action, either performed or seen, called highly congruent MN, and neurons that activate to several actions, called broad congruent MN (Rizzolatti et al., 1996).

Thus the mirror neurons are said to 'resonate' with the elementary motor acts. By virtue of this mechanism the observed actions can be coded by means of elementary motor components (Buccino et al., 2004). In this way the MNS supports the imitation process because if an elementary action of a gesture to be imitated is already coded, the MN 'resonate' and transfer the information to other structures that can either replicate or understand the gesture. On the contrary, when a novel gesture has to be imitated it is argued that there is a recombination of the 'resonating' motor acts that generates a new motor sequence (Buccino et al., 2004).

Some studies support this matter indirectly by claiming that the malfunctioning of this network is a cause of reduction or lack of imitation in subjects affected by autism spectrum disorders (ASD) (Cattaneo et al., 2007; Kana et al., 2011). In particular, the theory states that the broken mirror neuron system (BMNS) is related to the lack of understanding others and thus the deficit of imitation in autistic subjects.

However, recent works question those findings (Hamilton et al., 2007; Leighton et al., 2008). For instance some have found that many brain areas are activated in the imitative process (Molenberghs et al., 2009; Southgate and Hamilton, 2008), while others found that either the ASD subjects present difficulties in understanding what to imitate rather than the imitation as such (Southgate et al., 2008), or imitation performance of ASD subjects is different according to the type of feedback received (Ingersoll et al., 2003).

Nonetheless, there are experiments that show opposite results. For instance, Oberman et al. show that there are electroencephalogram (EEG) differences (mu-suppression, which is an index of MN functioning) in activities that require internal simulation between Typical developing (TD) children compared with children with ASD (Oberman et al., 2008).

However, the study does not differentiate results between gender (Proverbio et al., 2010) and does not investigate how the *mu*-suppression changes with task done repetitively (Aleksandrov and Tugin, 2012). Moreover, other studies show that there is a high variability in EEG *mu*-suppression both in TD and ASD (Fan et al., 2010), while Raymaekers et al. (2009) found no group differences in *mu*-suppression. Furthermore, EEG mu-suppression outcome in the Primary Somatosensory cortex (S1) differs according to whether a person has Positive Affectivity (enthusiastic, self-confident) or Negative Affectivity (poor self-confidence, lethargic) (Bell and Fox, 2003).

Electromyography was used to record facial muscles in TD and ASD subjects to record their reaction to pictures with happy or sad faces. ASD subjects show deficits in spontaneous mimicry when exposed to pictures of faces, thus providing support for BMNS theory (Oberman et al., 2009; Sims et al., 2012). On the contrary, Magnée et al. (2007) shows that ASD facial EMG are higher than TD, and Ekman et al. (1981) points out that ASD subjects do not respond to non-emotional smiles but they do respond to spontaneous smiles.

Another controversial experiment was carried out by Cattaneo et al. (2007) where TD and ASD subjects had to pick up a nut from a tray and eat it. Subjects' mylohyoid muscle activity was recorded with EMG and results were aligned on the moment the nut was picked up.

In that experiment ASD subjects demonstrate a delayed mouth opening compared with TD group. This was explained by the fact that ASD subjects are not able to understand the gesture that they see, thus proving the broken MNS. On the contrary, the same experiment, but carried out by normalizing the food position according to subject arm length, did not show group differences between TD and ASD (Pascolo and Rossi, 2011).

Moreover, there are also works which cast doubts on the existence of the mirror neurons or on the theory's experimental results interpretation (Dinstein et al., 2008; Pascolo et al., 2010).

Summarizing, the simulation theory seems a prominent theory in explaining the imitation process but it is still unclear whether the mirror neurons are involved in this mechanism. Moreover, also its validity in supporting imitation is still debated due to the simulation errors made when reasoning about someone else's mind (Saxe, 2005). Nevertheless, even though the mirror neurons and simulation theory are not yet fully proved, rehabilitation protocols based on this theory have been already devised and used.

However, the works demonstrating that MNS supports imitation have mainly used gross motor gestures or evident goals, which are easier to understand and copy. It is not clear if the subjects would be able to simulate and imitate fine motor gestures and when goals are not evident.

In this work, it will be compared formal learning approach with imitation by observation by administrating the subjects a test comprising both gross and fine motor gestures. The group of subjects involved in imitation will have to understand the protocol goals and gestures by looking at the experimenter that one time demonstrate the test.

The same balance tests will also be investigated in terms of motor learning for two reasons. First, to provide evidence that when used for clinical assessment the subjects might show learning effect, thus the result comparison over sessions might be influenced by such learning. Second, to provide the feasibility of one of the balance test to be used as psycho-physical condition test.

3.3. MOTOR LEARNING AND PERFORMANCE MEASUREMENTS

Learning is a process that optimize motor programs and automatize the identification of the stimuli and the selection of the related response. As a result, the performance increases with practice but its extent depends on several factors, such as training method, observed variable and its measuring criteria (Schmidt and Wrisberg, 2004).

Variables that are used to measure motor performance include: temporal quantities, such as time to complete the test, reaction time (simple, choice); accuracy quantities, such as response errors, distance from the target, movement compliance; magnitude quantities, such as distance realized, weight, strength, speed, height, articular movement; and coordination. Some particular tasks show relationships between those quantities.

In this work particular importance is represented by the Fitts' law, which describes the speed-accuracy trade-off of a movement, by the Hick's law, that defines the choice reaction time, and by the power law of practice, that describes the improvement rate in movement time.

3.3.1. Learning curves

Motor learning is mainly measured by analyzing the gesture performance over practice. By plotting gesture outcomes over attempts (trials) or training sessions, it is possible to visualize the performance improvements or persistence and to compare the effectiveness of different training methods. Performance can increase rapidly (in few trials) or slowly (needs many attempts), some examples of common learning curves are depicted in Figure 3.5.

Linear learning is mainly found in difficult tasks that are practiced in a short time or when the subject has already a good knowledge of the task. However, usually performance increase ratio is non-linear rather than constant. Complex gestures in fact involve a slow initial phase to comprehend the gestures and to code the related actions, but then the performance quickly raises. This is described by a positively accelerating curve.

Although performance improvements continue with practice, it is unlikely they show linear or positively accelerating patterns because they do not have any limit. This is of course an unrealistic case. Everyone, in fact, is aware that beginners usually achieve high improvements in short time but professionals' improvements rate is very low that a great effort needs to spend in order to achieve small performance improvements. This is typically described by a negatively accelerating curve (Figure 3.5), where the initial part is steep but later converges towards an almost horizontal asymptote. Such limit is not fixed but it can be moved forward, for instance with a more suitable training program.

S-shaped curve is perhaps the most general learning slope as it combines the positively and negatively accelerating curves. This curve considers the initial phase that corresponds to the Fitts and Posner cognitive stage, a steep phase that refers to the associative stage, and the last part that corresponds to the autonomous stage. The other curves can be obtained from this one. Positively accelerating might be the first part of a S-shaped but the amount of practice performed is not sufficient to show the entire learning curve, linear curves might be just a small window of the S-shaped curve with not enough trials recorded (Dubrowski, 2005), while the negatively accelerating curve is a S-shape with a short or not noticeable initial phase.

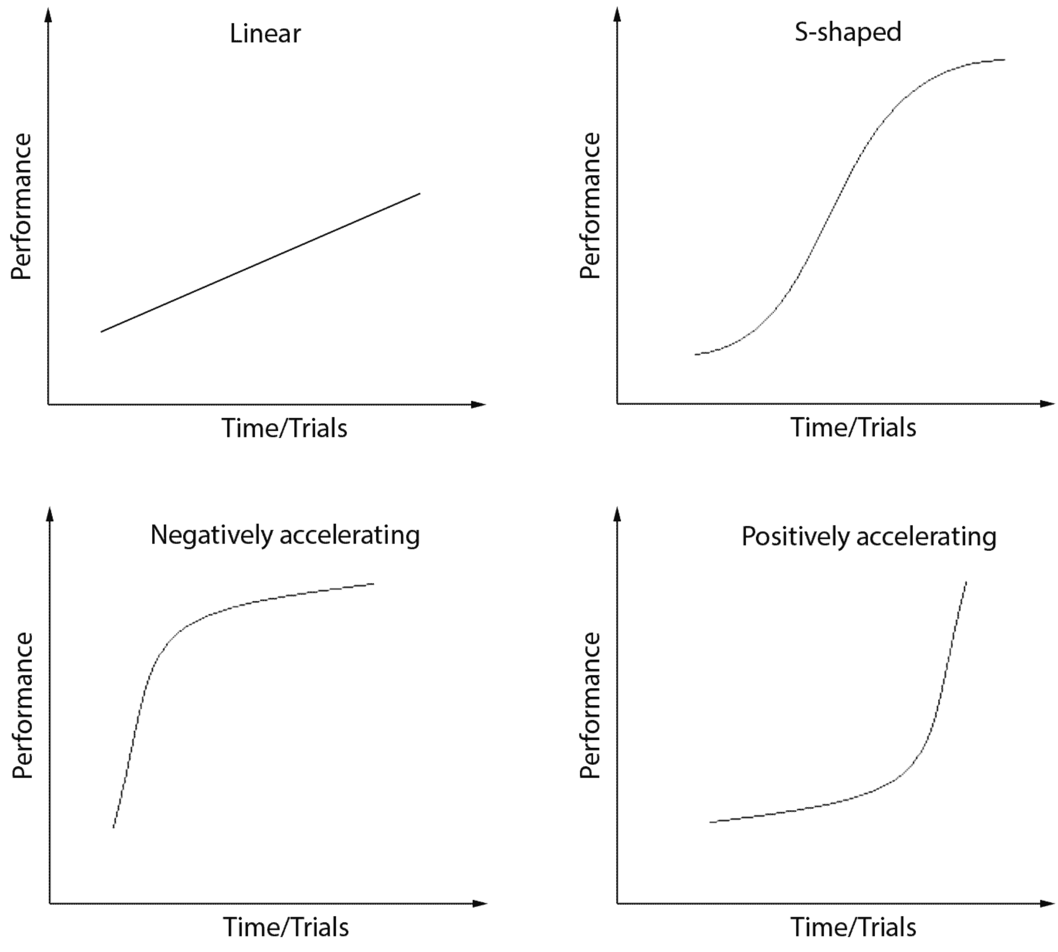


Figure 3.5: Typical learning curves for motor tasks.

However, since learning is directly measurable only at neuronal scale, behavioral learning must be inferred from performance outcomes. Therefore, the curves presented in Figure 3.5 should be regarded as "performance curves" rather than "learning curves" (Schmidt and Lee, 2005). For this reason, performance plateau in negatively accelerating curves does not necessarily indicate learning cessation. In fact, such plateau might originate due to the associative phase in which the subject optimizes gestures or finds new strategies (paragraph 3.1.1), it might arise due to fatiguing, or even low motivation and low attention.

Moreover, it should be considered that the test design might show an intrinsic or extrinsic limit in performance score, either at the top or at the bottom respectively defined as ceiling or floor effect. Such limits depend on the variable measured but also on the criteria used to measure the performance.

For example, regarding the first case, if in a simple choice reaction test only response errors are measured, the maximum performance is reached after a short time, however, measuring reaction time still shows improvement. In the second case, a wide tolerance error on a tracking test might not even show any performance difference over practice. In other cases, test limitations might be due to physiological issues, for instance, reaction time can improve up to a certain extent that depends on neural signal speed transmission and body inertia (limb, finger), or psychological limitations (i.e. Bannister's four minute mile) where kinetic analysis might indicate where to improve and thus moving the limit forward.

Retention tests and transfer tests

As just mentioned, there is not a direct relation between performance and learning, in particular near the performance limits. Therefore, the only way to prove that learning occurred is to perform retention tests, that is repeating the test after some rest period, or transfer tests, that is performing it in different situations or with different body parts.

Some gestures or movement patterns might be easy to acquire but not easy to retain, that is the case of fast acquisition movements in which the subject does not learn. Therefore, it is necessary to carry out retention test and compare the results with performance of previous training. If the performance is not reset, compared with the last training session, then learning occurred.

The retention of a motor gesture involves off-line motor consolidation, which is an improvement without practice, and regards neuronal organization, innervation of muscle fibers, memory consolidation and strategy optimization (Krakauer and Shadmehr, 2006). These tests can be carried out with short (hours to days) or long (days to months) intersession breaks. Moreover, multiple retention tests allow to evaluate the decay of learning over time. The performance of the repeated task usually shows some amount of decay that depends on the time break but also on what is practiced in the meanwhile. Practicing opposite movements interfere with the retention while performing different tasks improves retention (Huang et al., 2011).

Practicing allows also to generalize the internal motor schema that is to produce the gesture by using a combination of fundamental and simpler motor commands, which are already coded in the motor memory. This way, memory resources are optimized because instead of memorizing an entirely new motor schema, only the combination is stored and the simple motor commands are shared with multiple complex gestures.

Such generalization can be measured by making the subject to perform under different conditions, which consequently causes his/her capability of gesture transfers. For instance, it is possible to measure the adaptation of the motor strategies to variable environment (e.g. team sports), in perturbed conditions (e.g. noise) or uneven surface (e.g. cross-country running). Moreover, generalization allows to transfer the acquired skills to new situations, such as table tennis to badminton or tennis to baseball bat, or to other limbs, such as writing with the other hand or with foot.

However, gesture transfer to another limb is almost seamless only up to a certain generalization (Utley and Astill, 2008). In fact, the optimized motor schema is based on more innervated muscles and considers both, the noise of the specific sensory-muscles system and the characteristics of the limb (mass, inertia). Transfer abilities can be measured by comparing the learning curve of the transferred gesture with the learning curve of a group that did not perform the first gesture but only the transfer one.

3.3.2. Choice reaction time

In a choice reaction test (CRT) a subject must identify the stimulus, relate it to the right stimuli-response program, and in case executed it as fast as possible. The more responses one has to discriminate of, the higher the reaction time. Hick (1952) demonstrated that there is a logarithmic relationship between the number of choices (NC) one has to select and the reaction time (RT) (Equation 3.1).

The Hick's law depends on the $\log_2$(NC) because the cognitive process tends to be ecological by using a tree break down structure that halves the information at each step of elaboration. In fact, elaborating each possible combination would result in a larger amount of computations. Therefore, the reaction time is related to the amount of information (bits) that a subject has to elaborate, which depends on the probability (P) of the response $H=\log_2(1/P)$.

In CRT one has to select only one response, hence in a four choices test, each response has a probability of 25% to occur and therefore it requires two bits of information (two levels of choice), while an eight choice test requires just one more bit of information (Figure 3.6).

Equation 3.1: Hick's law of reaction time (RT) versus number of available choices (NC). *b* and *m* are curve fitting coefficients (Hick, 1952).

$$RT = b + m \cdot \log_2 NC$$

The coefficient *b* of Hick's law regards the reaction time having a test with one single choice ($\log_2 1=0$), whereas *m* regards the sensitivity to the task difficultness, i.e. the amount of presented choices, which depends on the subject's intelligence quotient (Roth, 1964), on the amount of practice and on the stimuli-response compatibility. For instance, top sport players are able to select the correct response in a complex environment (such as boxing, fencing, driving) with the same time as a double choice test. That is because they have overlearned the stimulus –response relationship which allows on a less conscious elaboration.

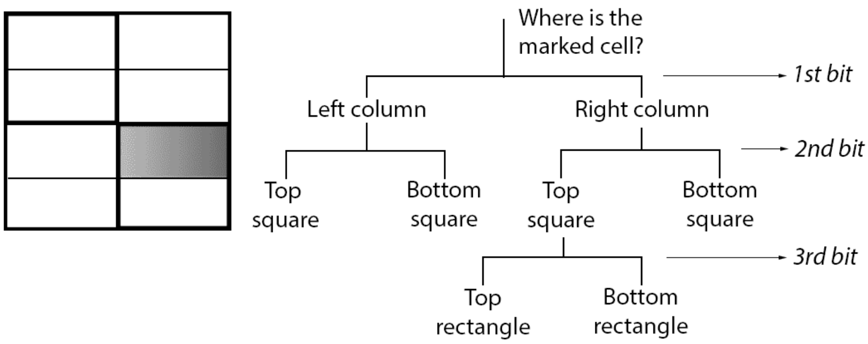


Figure 3.6: Example of eight choice problem that requires three levels of processing ($\log_2(8)=3$).

Compatibility of the stimulus-response also influences the *m* coefficient. Additional cognitive elaboration is needed to select the appropriate button when spatial disposition of the stimulus-choice is incompatible (Figure 3.7), that is when one has to press the left key if the top light is activated, and when the stimulus carries more than one information, which can be either congruent or not congruent (Stroop effect). In fact, one automatically associates with the stimulus to an abstract entity which of course can be described in various ways, for instance a shape can be described with its term definition or its depiction. Information which is not congruent (Figure 3.8) interferes with the response elaboration and as a result the reaction time is increased.

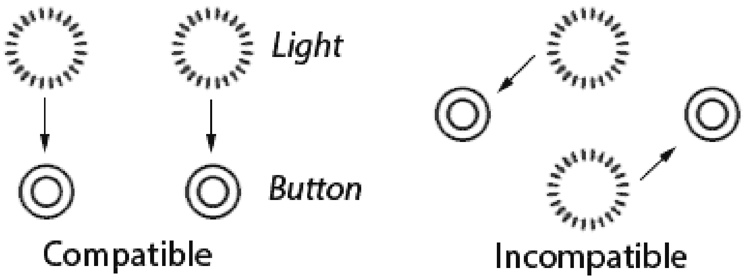


Figure 3.7: Stimulus-response compatibility influences the reaction time. Left panel shows compatible arrangement as the button to be pressed is aligned with the relative light. Right panel shows incompatible arrangement since the buttons and lights are not aligned.

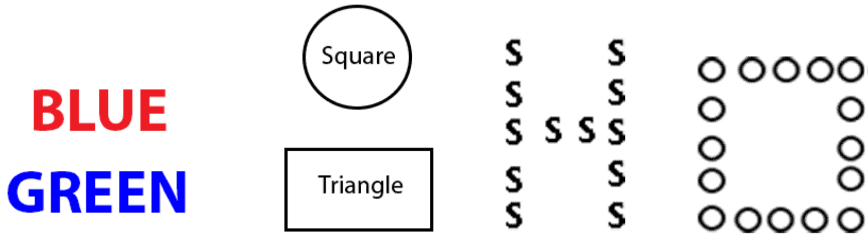


Figure 3.8: Stroop effect, examples of not congruent information (word-color, word-shape, letter-letter, and shape-shape).

3.3.3. Pointing tasks

Fitts (1954) found that there is a speed-accuracy trade-off between the time needed to reach a target with the difficultness of the task in subjects that had to move a stylus as fast and accurate as possible between two targets (Fitts, 1954). It is clear that the distance influences the time to reach the target, however, also the target dimension affects the movement time, since a small target size requires more movement precision. Fitts defined the index of difficulty (ID) as the distance over half of the target size (Figure 3.9) and found that if ID is increased, the movement time (MT) increases with a $\log_2$ relationship (Fitts' law, Equation 3.2).

Equation 3.2: Fitts' law for pointing tasks. Movement time (MT) depends on the $\log_2$ of index of difficulty (ID); A regards the target distance and W the target size.

$$MT = b + m \cdot \log_2 ID; \quad ID = \frac{2A}{W}$$

The coefficients *m* and *b* are similar to Hick's law; *m* coefficient regards the sensitivity to the difficulty index, while *b* regards the smallest movement time that is achieved when the target touches the starting point. In this case the subject has only to lift and lower the stylus with a small shift and as a result $\log_2$(ID) is equal to zero as A=W/2. Therefore *b* is related to the physiological neuronal signal transmission and muscular activation time delay.

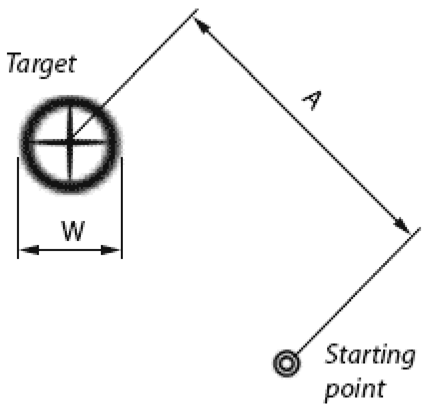


Figure 3.9: Target distance (A) and size (W) in single pointing tasks.

Fitts' law has been found to be valid also for one single attempt of target pointing (Schmidt and Lee, 2005) but it does not hold in pointing related situation. For instance, there is a linear relation in situations where there are temporal or spatial constrains, i.e. in which the gesture must reach the target in a certain time span or when the movement must follow a particular configuration (Schmidt and Wrisberg, 2004). However, since the Fitts' law holds on a wide variety of pointing tasks, situations in which it is not valid, are called "Fitts' violations".

Fitts' law has particularly practical implications in human-computer interaction design, such as in computer mouse pointing control, in application interface icons disposition and in touchscreen software (Bi et al., 2013).

Modified versions of the original Fitts' law have been also proposed. For instance, Crossman's equation (Equation 3.3) takes into consideration that the target can have different dimension in with (W) and depth (D) and thus considers its rectangular target area (Wallace et al., 1983).

Equation 3.3: Modified Fitts' law which takes into account the actual dimensions of the target.

$$MT = b + m \cdot \left(\log_2 \frac{A}{W} + \log_2 \frac{A}{D}\right) = b + m \cdot \log_2 \left(\frac{A^2}{W \cdot D}\right)$$

Moreover, the effective ID can be considered into the Fitts' law where the target distance is substituted with the effective path (A_e) executed by the stylus (either 2D or 3D), and where the target size is substituted with the effective target size (W_e) that considers the real endpoint spatial distribution.

Furthermore, Wallace (1983) proposed a variation of Crossman's formulation in which the target is considered with an ellipse shape because the distribution of the endpoints is usually wider on the movement direction and narrower in the perpendicular direction (Equation 3.4).

Equation 3.4: Modified Fitts' law that considers the effective distance (A_e) and the effective target area (ellipse shaped W_e, D_e).

$$MT = b + m \cdot \log_2 \left(\frac{A_e}{\pi \cdot \frac{W_e}{2} \cdot \frac{D_e}{2}}\right)$$

3.3.4. Power law of practice

In this section it has been shown that a learning phase is necessary to improve motor coordination, optimize gestures and to reduce perturbations. As a result, the time to complete the gestures is reduced with practice. The longest measure of practice seems to be made by Crossman (1959): operators measured over a seven year period have shown a continuous reduction of cycle time in making cigars (Crossman, 1959). The curve fitting of these results was better described with a power regression, which was later confirmed also in other experiments of movement time performance (Schmidt and Lee, 2005).

The power law of practice is illustrated by Equation 3.5, which describes the relationship between the movement time and the amount of practice. The regression coefficients b and m regard respectively the shift coefficient, that is the MT at the first trial, and the learning rate. According to m coefficient, different learning curves are obtained:

- $m>1$ positively accelerating;
- $m=1$ linear (line equation);
- $0<m<1$ negatively accelerating with ceiling effect (root equation);
- $m<0$ negatively accelerating with floor effect (hyperbole equation).

Equation 3.5: Power law of practice. Movement time (MT) is related to the amount of practice (P). b and m are regression coefficients.

$$MT = b \cdot P^m$$

Coefficients of Equation 3.5 depend upon various conditions and factors. First of all, individual motivation has a determined impact on learning, since it influences the willingness to accomplish the task, the attentional resources and cognitive capabilities. Low motivation reduces improvement rate (coefficient b tends to ∞ and m tends to 0) but it does not only depend on the subject.

Extrinsic factors that influence one's motivation regard also how the task is presented and organized. High motivated subjects might lose all the motivation if the task is not well prepared, if the equipment or tools are in bad condition, and if the personnel is unprepared.

Intrinsic factors of the task that influence one's motivation regard challenging conditions and how the task goal is set. Subjects might respond differently when challenged by others, for instance one can give up or get involved either when there is a competition or vice-versa when there is not.

Moreover, better performance is obtained when the task goal is either assigned by experimenter or set by the subject rather than an unset goal, unclear or vague, that is goals such as maximum effort or minimum energy expenditure (Boyce, 1992).

Another factor that influences learning concerns how the task information is conveyed to the subject. Initially it is fundamental to provide a general idea of the task, then detailed information on instructions and objectives but without flooding. Excessive information may not only confuse the subject, but it is also not taken into consideration.

In fact, the first instructions a subject is exposed to, persist more than the subsequent ones (Solley, 1952). Perhaps, that is because the subsequent instructions are delivered when the subject is already practicing and thus attentional resources are focused on the gestures. Hence, the task instructions and their amount must be carefully organized.

Information of the outcome of the test is also important to deliver high order information, in particular KP which provide information on the response programming and movement kinematics.

Another factor that affects learning performance regards the extent of practice. It is true that performance increases with practice but massive trial sessions are detrimental. Indeed, practice distributed over several sessions or with breaks between trials provides better motor learning and motor retention. Moreover, prolonged and uninterrupted practice causes muscular fatigue, which increases actuator's perturbations and cognitive fatigue, which reduces control capabilities.

Furthermore, practicing other similar tasks during intersession breaks can interfere with the performance of the main task, while practicing different tasks helps in improving the main task performance.

Chapter 4:

DRIVING WHILE IMPAIRED

Motorist condition is a major issue for driving safety. Already in 1872 the U.K. set up a law against riding horses or conducting carriages while drunk. At that time internal combustion engine were not yet applied into vehicles. And in 1964 the first campaign against "Drink and Drive" was broadcasted in the U.S. to persuade motorist to avoid alcohol drinking before getting to the steering wheel. But only the widespread usage of breath analyzers at the beginning of XXI century contributed to the sharp falling in figures of alcohol-related fatalities. However, vehicle accidents are one of the top ten causes of death, in particular among persons up to 40 years old.

Nevertheless alcohol is only one of the impairment causes. Other factors, such as fatigue and drowsiness, have even more impact on vehicle accidents, though they are usually being underestimated. In fact, most of the drivers stopped for allegedly impairment are found negative to psychoactive substances (*IMMORTAL (Impaired Motorists, Methods of Roadside Testing and assessment for licensing)*, 2005, *Prevalence of alcohol and other psychoactive substances in drivers in general traffic. Part I : General results*, 2011).

Furthermore, there are subjective factors that affect impairment extent. Hence, rather than fixing universal impairment thresholds, *per se* allowed limits are mostly being defined by authorities. For instance, alcohol limit in many countries is based on the average effects on driving and is set to 0.5g/L, despite the fact that with this amount a teetotal can already feel high.

In these latter years along with scientific research on road safety, the importance of motorist conditions has become a debated issue also among authorities and population. On the other hand, at this time there are still no practical tests that can effectively assess driver psychophysical conditions.

In this chapter sources of psychophysical impairment and psychophysical condition tests are first reviewed, then currently performed roadside measurements are analyzed. Eventually, road accident statistics are illustrated. The aim of this chapter is to raise awareness of the demand for the comprehensive impairment assessment protocol such as the novel balance test proposed in this work.

4.1. DRIVING IMPAIRMENT

Driving or riding requires skills such as proper reaction to internal and external stimuli, motor coordination and constant attention to several things. That is, driver or rider must keep attention to the external environment such as road, pedestrians, other vehicles and signals and to vehicle manoeuvre such as clutch, gear switch, indicators. All of this often together with talking to passenger, using or setting radio or mobile phone. Therefore, in order to handle simultaneously and with maximum attention all tasks connected to driving or riding, a person must be in excellent psychophysical conditions.

That is why most countries approved laws aimed to discourage “Drink and Drive” or “Driving While Intoxicated” and regulate professional driver’s shifts and rest time. However, over the years, awareness of driver conditions has been arisen and both diminution of alcohol permitted amount and higher enforcement have been made. In most countries a *per se* violation approach has been adopted, thus defining a BAC legal limit for motorists disregarding the subjective real conditions. It means that a teetotal drinking just a half-pint of beer might drive worse than social drinker. Subsequently, illegal drugs were also banned for drivers, hence the introduction of “Drive Under the Influence” (DUI) offence comprising both alcohol and illegal drugs, instead of “Drink and Drive” offence only. However, enforcement of DUI offence has been possible thanks to the launch either of proper testing equipment or reliable sobriety tests.

Nevertheless, not only do drugs or alcohol affect motorist psychophysical conditions but also internal factors such as fatigue, lack of attention, drowsiness, character, mood, diseases and external factors such as drugs, work stress, overexposing to flashing lights, loud noises/music or toxic substances might impact motorist abilities. In order to consider every factor having an effect on motorist psychophysical conditions, the term “driving while impaired” has been introduced. This term should not be confused with “Driving While Intoxicated”, therefore subsequent use of DWI in this thesis refers only to impairment, unless specified.

Sources of driving abilities impairment might be of different nature. In general, they can be divided into psychophysical factors and psycho-active substances that are analyzed below.

4.1.1. Psychophysical factors

Several factors influence the driving abilities, such as fatigue, medical conditions and environmental conditions.

With regard to fatigue, it has been demonstrated in professional drivers that shifts irregularity, work overload, insufficient rest between shifts are common factors that disrupt sleep patterns and circadian rhythms (Morrow and Crum, 2004). Moreover, those factors are more likely to increase crash severity.

A study to assess the effect of fatigue and sleepiness in motorists driving on open road from 9 a.m. to 7 p.m. was carried out (Philip et al., 2005). Inappropriate line crossings and simple reaction time were measured in control subjects and sleep deprived subjects. Results show that driving performance is strongly correlated with sleep deprivation and moderately correlated with fatigue. There is a drop in performance during mid-afternoon. In fact, the sleepiness has the bi-circadian rhythm that reaches its largest value around midnight and mid-afternoon (Reyner and Horne, 2002).

As mentioned, some medical conditions can impair driving. For instance, Parkinson's disease, epilepsy, cardiovascular disease and sleep disorder can have an impact on driving (Laddha et al., 2011). As well, vestibulopathy in both ears can lead to blurred vision on bumped roads and tinnitus disturbances interfering with multitasking ability, while reduced hearing will diminish perception of environmental and external sounds like honking. Vestibular system can be affected also by overexposure to ototoxic substances.

Table 4.1: Psychoactive drug categories and driving effects

Type	**Drugs**	**General effect** (Australian Drug Foundation, 2014) (Cusack et al., 2012)	**Driving effects** (NHTSA, 2014a)
Medications	Antihistamines, antidiarrheal, antiemetic, antiepileptic, painkillers, non-steroidal anti-inflammatory drugs (NSAID), painreliefs, travel sickness prevention, antibiotics	According to the drug amount: drowsiness, dizziness, poor concentration, sickness, slower reaction time	Lane control, steering stability, following distances
Anxiolytic	Benzodiazepine, Barbiturates, Valium®	Altered perceptions, slower reaction time, reduced motor coordination	Lateral deviation, reaction times, divided attention, increase effects of fatigue, reduce attention
Depressants	Alcohol, benzodiazepine, solvents, cannabinoids, and opioids such as morphine, heroine, methadone, oxycodone, codeine, cold medications	Reduced coordination, slower reaction time, judgment, blurred vision	Delayed reaction, lane travel, poor tracking, poor perception, impaired distance estimation
Stimulants	Cocaine, amphetamine, ephedrine, khat, caffeine, energy drinks	Lapses of attention, lack of coordination, increased aggression, overconfidence	Speeding, inattentive driving, impulse control, reduced divided attention, staggering
Hallucinogens	LSD, ketamine, mescaline, cannabinoids	Reduced motor coordination, impaired thinking, blurred vision	Weaving, slow reactions, lane travel.
Euphoriants	Ecstasy, alcohol, GHB, cannabinoids, Ritalin®	Risk taking, drowsiness, overconfidence, overreaction	Speeding, jumping red lights, erratic driving, lost peripheral vision

Prolonged expose to loud noises or music can lead to impairment similar to alcohol. Subject's balance in (Pascolo et al., 2009) were tested under sober conditions, sober and audio-visual stimuli, alcohol, alcohol and audio-visual stimuli. Results show that six minutes exposure to trance music and stroboscopic lights had similar balance impairment as three glasses of wine.

4.1.2. Psycho-active substances

In this paragraph main psychoactive drugs with their effect on motorists are shown (Table 4.1). Drugs are grouped by the effect they cause on central nervous system. Some drugs fall under several categories as the effect might vary according to the dose.

While illegal drugs are well known for their increasing crash risk, it is not the same for medications, even though they are more commonly taken by people. People mainly consider medications as safe.

Still, a group of medicines are based on opiates, cannabis or other substances that can cause driving impairment. For instance, codeine, an opioid, is used for its sedative properties, cough relief, painkiller and mild antidiarrheal. Indeed, according to the dose it may cause drowsiness, confusion, blurred vision and convulsions, thus driving should be avoided in particular with drug overuse. Also first generation of antihistamines drugs had side effects such as drowsiness and it was advised not to drive when taking medication.

It is also little known that some medications can be ototoxic, thus causing impairment as mentioned in the above paragraph. For example, some widespread used ototoxic medicines are aminoglycoside antibiotics (e.g. gentamicin, azithromycin), salicylates (e.g. Aspirin ®) and diclofenac (e.g. Voltaren ®). Moreover, it has been proved that high doses of non-steroidal anti-inflammatory drugs (NSAID), such as ibuprofen, can have an impact on driving abilities (Laddha et al., 2011). In addition, driving impairment can be caused by anxiolytics, such as Valium®, and euphoriants, such as Ritalin® used for sleep disorders.

Furthermore, among legal substances coffee and energy drinks are the most used stimulants. Such substances are sometimes used to prolong wakefulness, increase alertness and reduce fatigue, but at the expenses of impulse control and staggering, while during the drug elimination phase lack of attention and drowsiness may suddenly arise.

Reyner and Horne found out that after a single administration of one can of energy drink in sleep-deprived subjects, driving accidents on simulator decreased for up to 90 minutes, then accidents became again as in the control group (Reyner and Horne, 2002). Indeed, sometimes coffee is drunk in order to counteract alcohol effects. However, its effect regards alcohol levels up to 0.6 g/L and only brake latency is partially counteracted, not balance and not choice reaction time (Liguori and Robinson, 2001).

Some medicines are being abused above their therapy quantities or illegal substances are used in order to alter consciousness state. Undoubtedly, their usage causes driving impairment, from speeding and inattention as regards stimulants drugs to delayed reaction time and poor perception in terms of depressants drugs (Table 4.1).

4.2. CURRENT ROADSIDE MEASUREMENTS

Nowadays main road solutions used to assess psycho-physical driver's condition are: field sobriety test, breath analysis, sweat or oral fluid analysis.

Field sobriety tests mainly concerns divided attention tasks. Subject's physical coordination is evaluated while he/she has to count or follow instructions. The aim of these tests is not to identify which psychoactive substance caused impairment but only to assess if a driver is impaired or not. Therefore, in case of test failure, further investigations might be needed to discover if the source of impairment was legal (i.e. medications) or not.

Drug tests can directly detect the substance or the drug-metabolites using antibody binding. For example, alcohol, which is a volatile compound released with water and carbon dioxide, can be directly measured. Other drugs require, however, more complex analysis.

Moreover, metabolites testing is widely used because of the fact that parent drug quickly disappears. For instance, cocaine last about 15 minutes in the blood but its metabolites last about 2 days. However, the metabolite onset takes some time since the drug administration and its presence can be found for a long time even when the drug effect disappeared, thus not causing impairment.

Furthermore, the peak of the effect caused by the drug depends on many factors, such as the substance's fat-solubility, the route of administration, molecule size, and also on subjective characteristics, such as age, body mass, how recent food was eaten (Erowid, 2014).

In case of positive test, the sample must be verified with mass spectrometry and/or gas chromatography in order to avoid false-positive caused by non-impairing substances with cross-reaction to the antibodies. However, it might take some time before the specimen for confirmation analysis reaches the laboratory test and the specimen should be refrigerated right after collection (Walsh et al., 2008). Otherwise, in the meanwhile the drug may disappear and even added substances preventing degradation might be insufficient (Cusack et al., 2012).

Currently, there are no comprehensive tests that assess objectively all sources of impairment. In the following paragraphs typical roadside test are illustrated. Urine and blood sample result impractical and hassling in roadside test, therefore they will not be illustrated.

4.2.1. Standardized field sobriety test

The test is made of exercises that drunk person can make with difficulties, such as divided attention task and physical coordination. The standardized field sobriety test (SFST) is made of three exercises: the horizontal gaze nystagmus (HGN), the walk and turn (WAT) and one leg stand (OLS).

The first (HGN) requires to follow a horizontal moving pen or flashlight with eyes. Tracking smoothness, jerking and onset of nystagmus are being assessed. Alcohol and depressant substances can cause an early onset of pupil's nystagmus, i.e. within 45°, and jerky tracking.

The second (WAT) is a divided attention task. The person has to move on a line by putting the heel touching the toe: nine steps forward, then turning for nine steps backwards. While doing so, the person has to look at the feet, keep hand at side and count steps loud. Walking, balancing and following the instruction are being assessed.

The third one (OLS), is also a divided attention exercise. The person has to rise one leg with foot pointed out, while doing so, he/she has to look the raised foot and count loud "one thousand one", "one thousand and two", and so on. Balancing, counting and following instructions are being evaluated.

Rubenzer reports the Likelihood Ratio at 0.8g/L for each test: 3.6 for HGN, 1.9 for WAT, 3.7 for OLS and 4.4 for overall STFS (Rubenzer, 2008). Therefore, the most reliability is found only when all three tests are performed. Still, a near 1 Likelihood Ratio indicates poor evidence, while between 2 and 5 indicates only small evidence. Stuster and Burns provide evidence of SFST tests validity, reporting about 80% of true positives for BAC above 0.4g/L but lower than 0.8g/L and 91% of true positives for BAC over 0.8g/L (Stuster and Burns, 1998).

In general, this test does not require any instrument, thus it is inexpensive, and it is not easily tampered. However, weather conditions can limit the possibility to run the test and the test concerns mainly subjective judgments. Personnel must be properly trained and refresher trainings every two years are required.

Figure 4.1: Example of a standardized field sobriety test (WAT task) [modified from Maze Legal Group PC]

4.2.2. Other field sobriety tests

In addition to the SFST, other tests are used but they either have not been validated or have not been approved or they are impractical in roadside conditions.

In modified Romberg test, the subject has to stand with feet together, arms pointing straight forward and head tilde little backwards. The instructor then asks to close the eyes, count in head 30 seconds and then say stop. The head position produces little instability and makes the person rely only on proprioception and vestibular function as he/she will look towards the sky, thus loosing visual reference point.

There is another version of this test, called Sharpened Romberg, in which the subject has to place feet heel to toe while keeping hands at hips. This variant is made more difficult by reducing the base of support.

Both are a divided attention test and losing balance may indicate DUI. However, both tests can be used also to detect fall risk in elderlies, thus they can result false positive for DUI. Timing is being assessed because depressants stretch estimated time while stimulants shorten it.

Another test is Finger to Nose test. The person has to stand like in Romberg test but with arms extended laterally. Then he/she has to touch with the index finger the tip of the nose with the right or left hand according to officer's instruction ("Field sobriety test," n.d.). It is a balance and distance perception test and the failure in touching the nose may indicate DUI.

Other tests that involve divided attention, are alphabet recite and count down. Both can be done in position like in WAT or in OLS. The first requires the subject to recite the alphabet starting from a given letter, while the second requires to count backwards by numbers such three or seven. This latter one will be failed also by who has dyscalculia. Balance and counting or reciting mistakes are being evaluated.

The following tests involve motor coordination but not balance assessment. For instance, finger count requires the subject to use the thumb to touch each finger in sequence counting loud the finger number (forward and backward). Correct sequence finger touching, counting and smoothness are evaluated. Picking up several coins with one hand is also a motor coordination task, but it does not involve divided attention. Hand pat test requires the subject to put hands together with palms touching in front. Then the top hand is made rotate in order to touch with its back the palm of the lower hand. This process is being repeated with increasing speed while person is counting loud.

All of these tests are not reliable and a failure might indicate only the presence of alcohol but not its level (Bartell et al., 2012). For this reason, sometimes they are used only as pre-test before deciding whether to go through the "standardized field sobriety test".

There are many other tests or batteries tests aiming at general impairment assessing in laboratory circumstances. However, they result impractical for roadside conditions. Some of the most known are described beneath.

Stroop test (Liguori and Robinson, 2001) is a selective attention test. A word describing a color is presented to the subject, but the font color can be either the same of the described color or different (see paragraph 3.3.2). The subject has to press a button according to the congruity of described color and font. Recognition speed and errors are being assessed. However, colors can be mistaken by color-blind persons.

Critical flicker fusion test (CFF) (Liguori and Robinson, 2001) regards a light with increasing flickering presented a subject that has to indicate when the light becomes steady. The test can be made also in the opposite sequence, hence calling it fusion-to-flicker test. Stimulant drugs increase CFF while depressant and hypnotic drugs reduce it (Smith and Misiak, 1976) (Holmberg, 1981). Still, a subject can cheat on indicating light steadiness and other factors, such as personal suggestion and pupil diameter, can matter.

Trail making test (Army Individual Test Battery, 1944) is composed of two parts and requires the subject to connect a sequence of 25 dots. In the first part the dots are numbered, while in the second part dots have both numbers and letters and they should be connected alternating number and letter (1, A, 2, B, 3, C, etc.). Time to complete is assessed without counting errors as they already increase timing. This test can be used to assess general cognitive abilities and executive function.

Swedish performance evaluation system (Iregren et al., 1996) is a psychological battery test system that comprises tasks such as: simple and choice reaction test, grammar and mathematic operation tasks, memory recall and mood self-rating. This test has been initially used to study toxic effects of substances on the nervous system but sometimes it is also used to assess driver before the driving license renewal.

Cognitive drug research computerized assessment system (Wild et al., 2008) is a battery test used to assess drug effects. It comprises tasks such as: simple and choice reaction test, immediate and delayed word recognition, memory recall and non-verbal recognition.

Further used tests are: motor speed finger tapping test (Austin et al., 2011), symbol digit modalities test (How et al., 1994) and nonverbal memory Benton visual retention test (Helmstaedter et al., 1995).

4.2.3. Breath test analysis

Alcohol can be easily detected in breath, blood and urine as it is a volatile chemical compound. During blood gas diffusion in lung tissues, pulmonary alveoli expel both carbon dioxide and alcohol. The more alcohol in the blood, the more of it is being exhaled.

However, the ratio between the amount of alcohol in the breath (breath alcohol content – BrAC) and the amount of alcohol in the blood (blood alcohol content - BAC) is variable and depends on the alcohol metabolism phase, the amount of alcohol and the individual metabolism. For instance, (Jones and Andersson, 1996) found a mean ratio of 2395:1±193(SD), Confidence Variability of 9.1%, minimum and maximum respectively 1971:1 and 2800:1, while (Jaffe et al., 2013) found a mean ratio of 2267:1±246(SD), Confidence Variability 10.9%, minimum and maximum respectively 1214:1 and 2859:1. Therefore, there is a certain amount of false positives and false negatives, according to the real ratio of the person under investigation.

Moreover, the BrAC/BAC ratio differs according to the country (Table 4.2). This means that while France and U.K. have the same BAC limit (0.8g/L), the BrAC limit is 14% higher in France. Hence, when a reliable result is needed, blood analysis has to be done.

Breath analyzers can be made of chemical compound or electronic comprising an infrared spectrometry, a fuel cell or MEMS. The first devices used chemical compounds. A fixed amount of breath air must be taken into a bladder and then passed through the reagent. This will react with the alcohol and change color according to the amount of alcohol that might be contained in the bladder.

Table 4.2: Breath analyzer ratio (Jones and Andersson, 1996)

Country	BAC Limit [g/L]	BrAC/BAC ratio	BrAC limit [mg/L]
Austria	0.80	2000	0.40
Finland	0.53	2100	0.25
France	0.80	2000	0.40
Italy	0.50	2100	0.24
Netherland	0.50	2300	0.22
Norway	0.53	2100	0.25
Sweden	0.21	2100	0.10
U.K.	0.80	2300	0.35

Semiconductors analyzers measure the resistivity change of a metal oxide layer which the alcohol will change. However, the semiconductor reacts also to other substances such as acetone, hairspray, gasoline compounds and cigarette smoke. It is proved that diabetics expel high acetone quantities in breath (*Challenges and Defenses II*, 2013, *The Likelihood of Acetone Interference in Breath Alcohol Measurement*, 1985). Although semiconductor BrAC is very economical, it is limited to personal usage.

Fuel cell analyzers measure the electricity current coming from the alcohol oxidations in the cell. It reacts only to alcohol and analyzes deep lung breath, thus it is more accurate than the semiconductor one.

Infrared analyzer measures breathe alcohol by illuminating a chamber with sample breath. The alcohol molecules will absorb specific wavelengths which will be noticed by a detector. Other substances might absorb the same wavelengths, thus causing false positives. The instrumentation is quite accurate except at low limits but it is quite expensive.

Most law enforcement operators have instruments which implement both fuel cell and infrared analysis.

Moreover, the preliminary breath test (PBT) can be used to rapidly screen drivers while they are still seated in car. This instrument provides fast, easy and repetitive measures still being not expensive. Therefore it has been widely used to retrieve alcohol levels.

However, except for the infrared sensor, the other sensors' working life lasts for a certain amount of tests. Moreover, the operating temperature of the instrument is usually limited to above zero Celsius degrees. Even though there are some flaws, its wide spread usage creates a deterrent as people are afraid of the consequent fines and arrest (Gjerde et al., 2008).

Figure 4.2: Example of a professional breath analyzer (BACtrack® S80 Pro) [image courtesy of BACtrack®. All rights reserved].

4.2.4. Oral fluid analysis

Oral fluid is mainly made of saliva and some amounts of blood, food debris and gingival fluid. Only fat soluble metabolites, not ionized and not bounded to proteins can get into saliva fluid (Cusack et al., 2012). Therefore, drugs that do not have such chemical characteristics cannot be found in saliva.

Drugs in oral fluid are detected using antibodies preference binding. The test pads do not have to be moisten as saliva already provides water. Nevertheless, some drugs can cause dry mouth and very viscous saliva, consequently salivation must be stimulated. Though it is true that saliva stimulation increases the flow but it also reduces the drug concentration.

Moreover, oral fluid PH can change the saliva to blood ratio of the drug. For instance, cocaine saliva to plasma ratio at PH 5 is 273 but it is drastically reduced at PH 7.8 with only 0.44 ratio (Cusack et al., 2012). Opiates, cocaine and amphetamines can be found with ease, but it is not so easy for benzodiazepine and cannabinoids which have low secretion in saliva (Verstraete, 2005).

In order to avoid positive results due to passive contamination, such as cannabis passive smokers, cut-offs have been proposed (*Analytical evaluation of oral fluid screening devices and preceding selection procedures*, 2010).

Still, oral fluid can be adulterate taking in the mouth interference substances such as caffeine, vitamin C and cigarette smoke (*Preliminary Drug Testing Devices*, 2013). Moreover, its temperature allowed usage is usually above zero Celsius degrees and additional laboratory test is needed in case of a positive result.

Despite the mentioned limitations, its wider usage may become a deterrent for drugged driving, like breath analyzers became for drunk driving.

Figure 4.3: Example of an opto-electronic oral fluid analyzer and samplers (Dräger DrugTest® 5000) [© Drägerwerk AG & Co. KGaA, Lubeck. All rights reserved].

4.2.5. Sweat skin analysis

The mechanism of which drugs are included into sweat is not fully understood. Perhaps passive diffusion from capillaries into sweat excrete glands seems to be the main way (Brunet et al., 2010; Zlateva et al., 2007).

Similarly to oral fluid test, sweat analysis usually uses test strips containing antibodies which drugs will bind to. These tests analyze the most used drugs but not all. For instance, Securetec DrugWipe® K detects cocaine, opioids, cannabinoids, amphetamines and methamphetamines (Securetec AG, 2014), but not ketamine, benzodiazepines or medical drugs that can also cause impairment.

The test usage is not simple and it must be done by trained professionals. For instance the sampling pad of a sweat skin test has to be first moisten with water, then wipe the person's skin and put it in the test cassette. Next, part of the cassette test has to be immersed in water for some seconds and then left horizontally for some minutes until the result will appear in the form of red line. Moreover, the operators can misunderstand to interpret the result as sometimes there are faint red lines.

Furthermore, its usage is limited to above zero Celsius degrees and it must be carefully stored. Therefore it is not suitable in places where winter is harsh or in situations where it is very humid, raining or snowing. However, if well used, the test provides good preliminary results.

Still in case the positive test result, the sampling must be verified by a laboratory. Hence, the cost of the single-use disposable materials are more expensive than the oral fluid or the breath analyzers test.

Figure 4.4: Example of a sweat patch analyzer and its usage (Securetec Drug-Wipe® K) [image courtesy of Securetec AG. All rights reserved].

4.3. ROAD ACCIDENT STATISTICS

Vehicle crash is among the most frequent causes of injuries and death and it is the first cause of injury and death for accidents category (Bos et al., 2009). Consequently, it has a considerable impact on public services and economy. Indeed, vehicle crash involves national's health system, insurances, vehicle manufacturers (safety), safety research, road manufacturers, and is causing every year billions of economic loss.

Even though fatalities in EU28 have been halved since 2000, injuries and accidents still involve over 1.5 million people each year (*EU transport in figures*, 2011).

In this section statistics of road accidents in which at least a vehicle was involved are presented. The aim is to show the main figures of casualties, the main causes of road accidents and the burden of vehicle crashes on the society.

4.3.1. Main figures

Figures about vehicle accidents have been retrieved from national's databases and articles, namely in Table 4.4 used databases are shown. Analyzed countries are Italy, the United Kingdom (U.K.) because its population is similar to Italy, the European Union 15 countries (EU15) or more where available (Table 4.3), and the United States (U.S.) which country population is the nearest to the EU15.

The Italian Statistic Institute (ISTAT) collects information on vehicle accidents happened on public roads that caused injuries or deaths from three different police authorities: Carabinieri (Military Police), Polizia di Stato (State Police) and Polizia Locale (Municipal Police). However, each of them has different investigation procedures, which lead to report deficiencies. Another limitation is that crash figures do not comprise crashes that led to material damage only (MDO).

World Health Organization guidelines suggest that people died within 30 days of the accidents should be counted as traffic fatality whereas serious injured people should be counted only if there was at least 24h of hospitalization, while less than 24h of hospitalization counts as slight injury (*GLOBAL STATUS REPORT ON ROAD SAFETY*, 2013).

Table 4.3: European Union countries considered

EU15	EU25 (from 2004)	EU27 (from 2007)	EU28 (from 2013)
Belgium	EU15 plus	EU25 plus	EU27 plus
France	Cyprus	Bulgaria	Croatia
Germany	Estonia	Romania	
Italy	Latvia		
Luxembourg	Lithuania		
Netherland	Malta		
Denmark	Poland		
Ireland	Czech Republic		
United Kingdom	Slovakia		
Greece	Slovenia		
Portugal	Hungary		
Spain			
Austria			
Finland			
Sweden			

However, there is a certain amount of non-reported accidents, especially in low-mid income countries. It is so because police do not follow up accident victims, due to small injuries or no injuries (Derriks and Mak, 2007) or accident reports that are not complete thus failing to record (Gill et al., 2006). Gill et al. show that while from 1996 to 2004 the U.K. police reported a reducing injury and fatality rate, hospital admissions due vehicle accidents were almost steady (Gill et al., 2006).

Furthermore there is also an over reporting, as figures are altered by frauds. For instance, in U.K. 35% of personal injuries are suspected for “Crash for cash” (*Crash for Cash: Putting the brakes on fraud*, 2012), while in Italy 7% of car accidents are considered to be fraudulent (*Relazione Antifrode 2013*, 2014). Hence, in case of missing underreporting analysis correcting factors are suggested as follows: 1.02 for fatalities, 1.5 for serious injury, 3 for slight injury and 6 for material damages (Bos et al., 2009). Considering the last factor, the number of casualties non involving personal injuries is very high.

Looking at countries figures, reduction rate compared to 2002 is put in brackets. In 2012 in Italy the total injured people were over 250 thousand (-30%) (Table 8.1), while in U.K. less than 200 thousand people were injured (-35%). Whereas in 2012 EU15 and U.S. had respectively 1.07 million (-38%) and 2.36 million (-19%) people injured (Table 8.2).

Looking at 2012 fatalities, reduction rate compared to 2002 is put on brackets. In Italy over 3500 people died (-48%) and in U.K. died a half of this number (-50%). While almost 18 thousand (-52%) and 28 thousand (-48%) in EU15 and EU28 respectively and more than 33.5 thousand (-22%) in U.S. (Table 8.1).

Over a 10-year-period (2001-2011), U.K. injuries are slightly less (20% to 35%) while deaths are much less (40% to 55%) compared to Italy.

Table 4.4: Vehicles casualties' databases

Database	Information collecting	Data retrieved on	Link
Italian National Institute of Statistics (ISTAT)	Vehicle accidents happened on public roads that caused injuries or deaths from local police reports	15/10/2014	http://dati.istat.it
Italian government agency for work related injury insurance (INAIL)	Vehicle accidents happened while on duty or while commuting	20/10/2014	http://www.inail.it
U.K. Department for Transport (DfT), STAT 19 forms,	Police reports and hospital reports	21/10/2014	https://www.gov.U.K./ government/publications
U.K. insurance fraud bureau (IFB)	Surveys, investigations, anonymous reports	15/10/2014	http://www.insurancefraudbureau.org/
Eurostat	Information from EU countries	17/10/2014	http://epp.eurostat.ec.europa.eu
Community road accident database (CARE)	Information from EU countries	16/10/2014	http://ec.europa.eu/transport/ road_safety/index_en.htm
EU Injury database (IDB)	Information from EU countries	18/10/2014	http://ec.europa.eu/health/
US National Highway Traffic Safety Administration (NHTSA)	Fatality Analysis Reporting System (FARS) plus other sources	17/10/2014	http://www.nhtsa.gov/
US Department of Labour	Vehicle accidents happened while on duty	20/10/2014	http://www.bls.gov
US Census Bureau	Census and national databases	25/10/2014	http://www.census.gov/
UN Economic commission for Europe (UNECE)	Information from countries	20/10/2014	http://w3.unece.org/pxweb/

In order to make comparison with other countries, other indicators must be used. Death or injury rate per 100 thousand persons estimates the magnitude of society impact, respectively represented in Figure 4.5 and in Figure 4.6; fatalities or injuries per vehicle billion kilometer travelled indicates causalities occurred normalized on the traffic volume; and fatalities per 100 accidents indicate collision's severity.

Few databases provide information on vehicles kilometers travelled and Italy is not among them. However CARE database estimates in 2009 a 5.4 fatalities per vehicle billion kilometers travelled for Italy (*European Road Statistics 2011*, 2011), 4.5 for U.K. (Kilbey et al., 2010), whereas 7.1 fatalities per billion kilometers travelled for EU27 (*European Road Statistics 2011*, 2011), and 7.2 for U.S. (NHTSA, 2010). Considering population impact, the rate of fatalities per 100 thousand persons in 2012 is 6.80 for Italy, 3.10 for U.K., 5.21 for EU15 (*EU transport in figures*, 2011), 7.06 for EU28 (UNECE) and 10.67 for U.S. (NHTSA, 2013a).

However, analyzing statistics by age provided by Eurostat, average 2010 EU-28 death rate per 100 thousand inhabitants aged less than 65 due to transportation accidents, is 6.4, ranging between 3.0 to 12.8. Considering all ages transportation accidents is 7.0, ranging from 3.4 to 14.1.

Summarizing, Italy reports worst accident rates compared to U.K. and EU15, but still better rates than U.S. Only Italian fatality rate on rural roads is similar to EU15 average (Figure 4.8) while on urban and motorways, the rate is much higher, being in 2012 70% and 37% higher respectively (respectively Figure 4.7 and Figure 4.9).

Several factors may influence these differences, but as just mentioned Italian and most EU28 countries databases are not as detailed as the U.K. or the U.S. ones. Therefore an in-depth comparison is not possible. Nevertheless, some useful figures (either estimation or facts) can be retrieved from other sources such as World Health Organization (WHO) reports and International Traffic Safety Data and Analysis Group (IRTAD) reports. For instance, one of the reasons that U.K. has less fatalities might be due to safety restraints usage. In fact, Table 4.5 shows that U.K. has a higher safety belt and helmet usage.

In order to improve road security, in Italy in 2006 TUTOR system was introduced in some motorways. This system monitors average vehicle speed and after its introduction, from 2006 to 2012 a decrease of 45% of fatalities in motorways was observed, while in 6 previous years from 2000 to 2006 the reported decrease was of 23% (Figure 4.9).

Table 4.5: Safety belt and helmet usage (*GLOBAL STATUS REPORT ON ROAD SAFETY*, 2009) **and** (*Road Safety Annual Report 2014*, 2014)

Restrain system	**Front belts**	**Rear belts**	**Helmet**
Italy (2006)	65%	10%	76-99% according to region
United Kingdom (2009)	91%	84-90%	98%
United States (2009)	82%	76%	60%

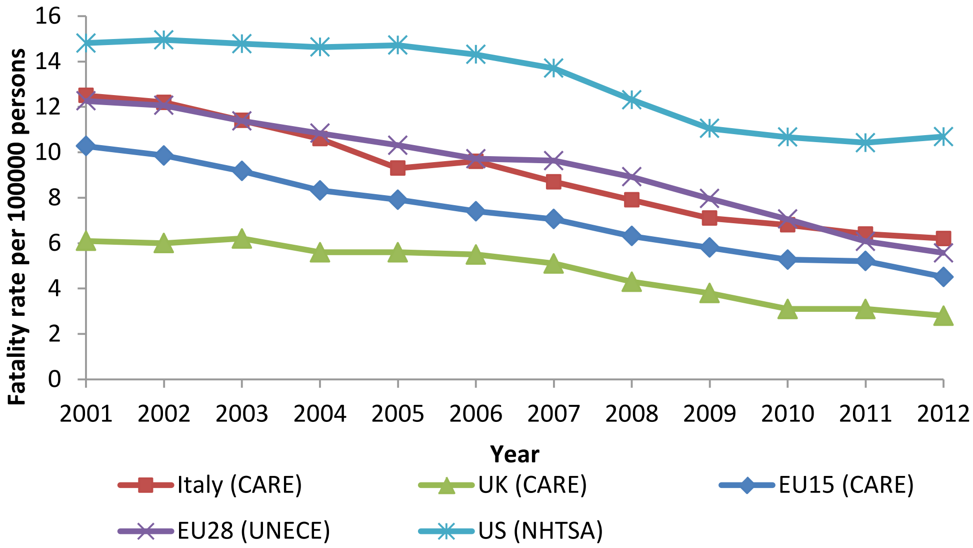


Figure 4.5: Fatality rate per year. Absolute figures are reported in paragraph 8.1, Table 8.1.

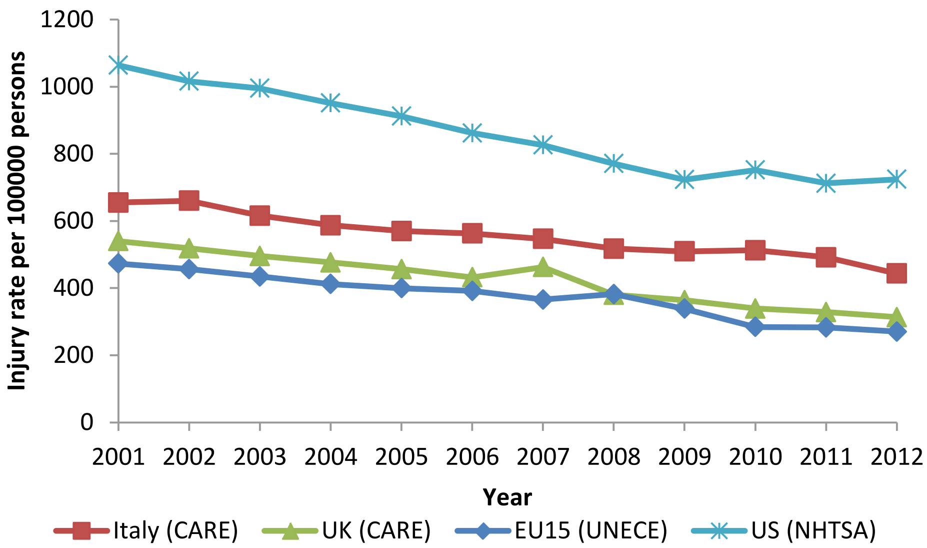


Figure 4.6: Injury rate per year. Absolute figures are reported in paragraph 8.1, Table 8.2.

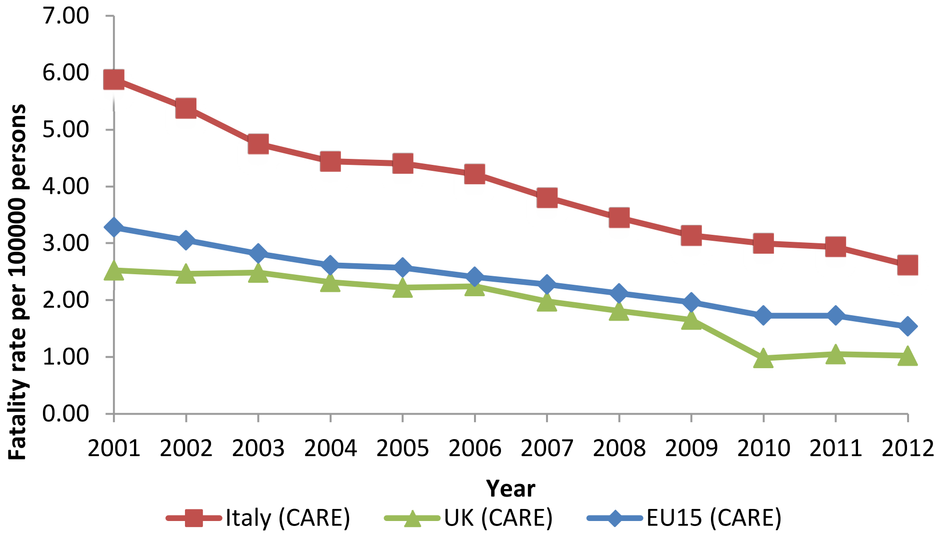


Figure 4.7: Fatality rate in urban roads

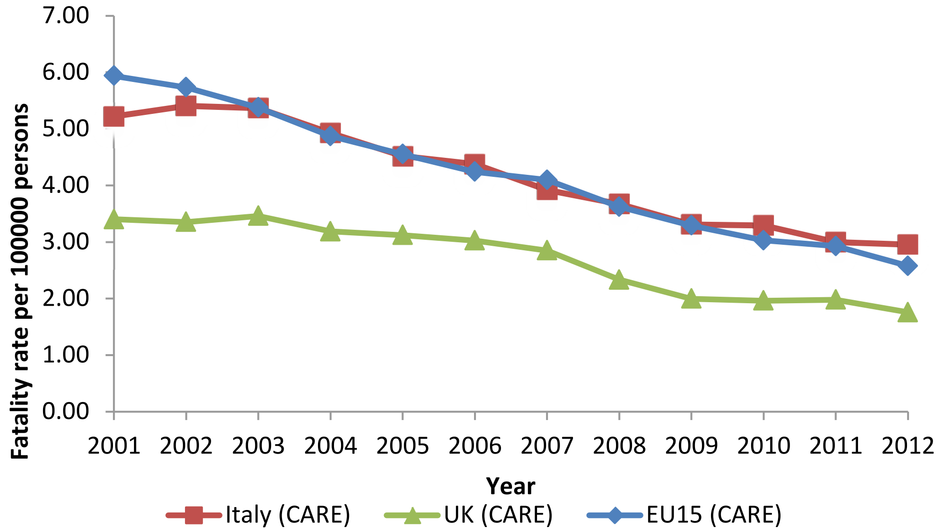


Figure 4.8: Fatality rate in rural roads

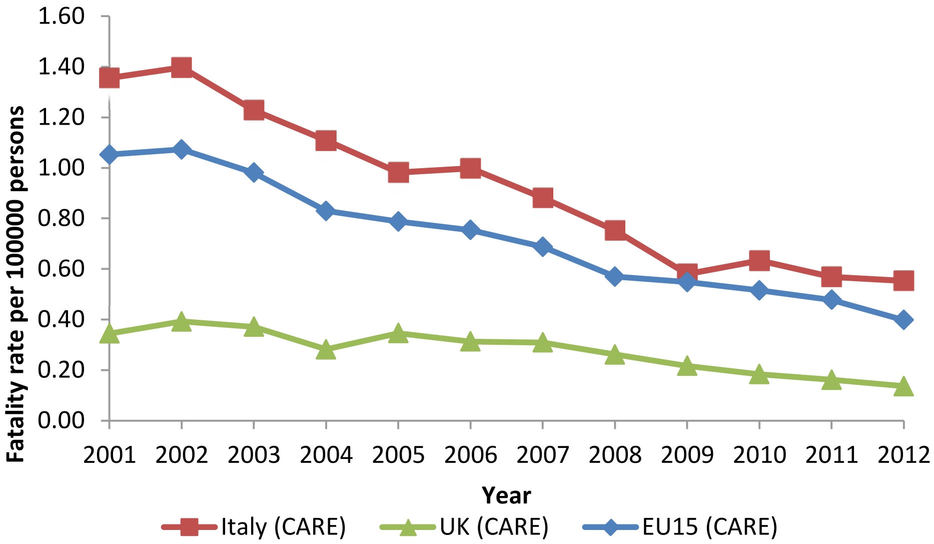


Figure 4.9: Fatality rate in motorway roads

4.3.2. Casualties on duty

Transportation is part of daily life and it is connected with leisure activities as well as work activities. Not only are professional drivers accidents considered as casualties on duty but also in some countries, like Italy and U.K., commuting accidents are part of labor accidents.

In U.S. in 2013, as much as 40% of total working fatalities are on transportation incidents and 36% of U.S. traffic fatalities are work-related (*National Census of Fatal Occupational Injuries in 2013*, 2014), while in Italy 6% of total working fatalities are on transportation incidents and 14% of Italian traffic fatalities are work-related, whereas in U.K. 39% of U.K. traffic fatalities are work-related (Figure 4.11). Regarding percentage of injuries, they are similar in Italy and U.K. (Figure 4.10), but looking at absolute values Italy has similar injuries while working but almost triple while commuting.

In U.K. killed are higher than in Italy, respectively 784 and 557 killed, not only because total fatalities are half of Italian ones, respectively 1960 and 3860, but also because there might be an Italian underreporting or misreporting of causalities. In fact, most of the vehicle accidents happen on working days during working hours, that is from Monday to Friday from 8 a.m. to 6 p.m. (*Incidenti stradali in Italia 2012*, 2013).

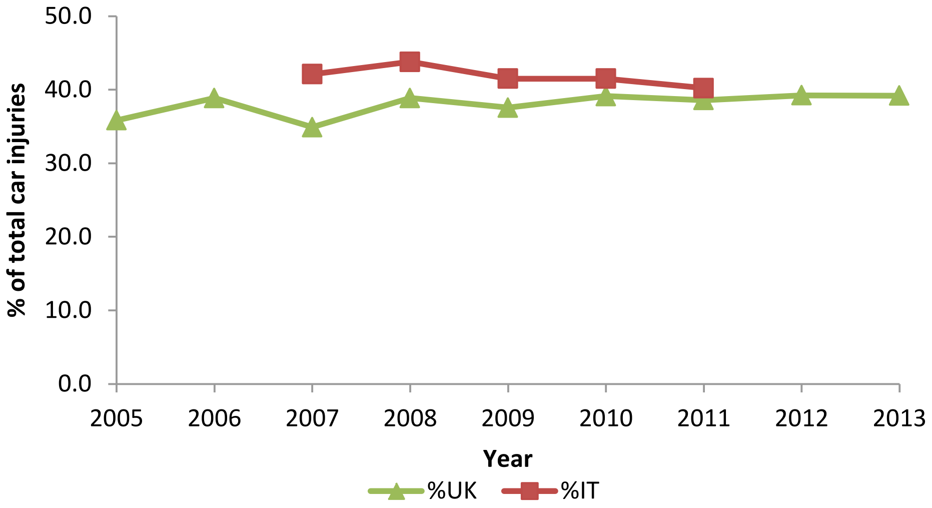


Figure 4.10: Vehicle crash injuries while working or commuting

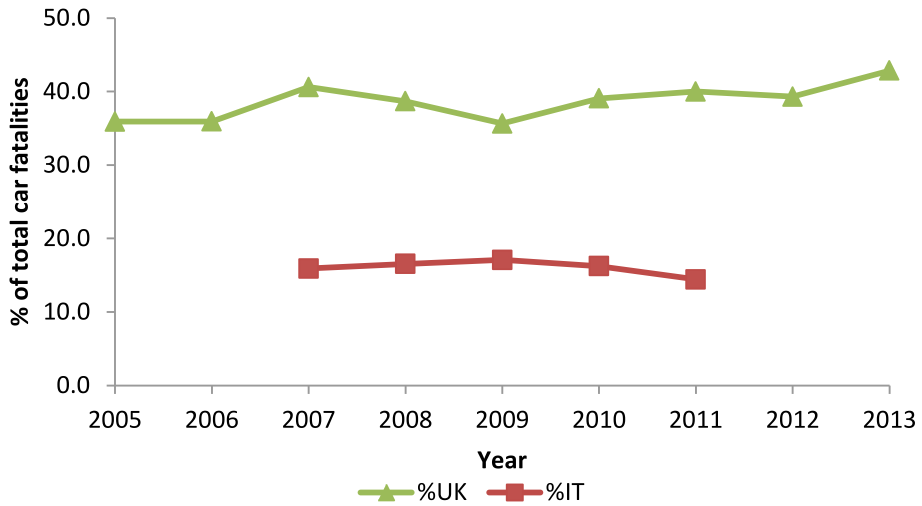


Figure 4.11: Vehicle crash fatalities while working or commuting

4.3.3. Causes of vehicle accidents

Most of vehicle accidents are caused by human errors (Petridou and Moustaki, 2000; Rumar, 1986; Wiegmann and Shappell, 2001) such as driver error (overestimation, distraction, driving under the influence, fatigue) and infrastructure design (monotonous roads, guard-rails, maintenance) (Larue et al., 2011). Very few vehicle accidents are due to vehicle issues or objects-animals present in carriageway.

Many studies assess the relation of alcohol and vehicle accidents, but very few consider distraction or drugs (both legal and illegal); even though alcohol is not the first cause of vehicle accidents but just among the most causes. Also road safety policies mostly act to reduce “drink and drive” but do not put the same effort for “drive slow” campaigns.

Figures on drugged driving can be found in national databases but more detailed figures are described in specific works. Papers examined in this paragraph are shown in Table 8.3.

Alcohol is the most psychoactive substance found in drivers but illegal psychoactive substances have increasingly been reported and there is an increasing abuse of legal medicines such as pain-killers containing opioids or cannabinoids and anxiolytics containing benzodiazepine (Jones et al., 2009). Also over-the-counter medicines such as antihistaminic and anti-emetics can cause impairment.

Regarding alcohol limits, they vary by country (between 0.0 to 0.8 g/L (*Road Safety Annual Report 2014*, 2014)) and in many there are tighter limits for professional or novice drivers. Also in the past, those limits were slightly higher. However, studies proved that alcohol impairment begins already between 0.2-0.5 g/L, while between 0.5 and 0.7g/L the risk of a fatal crash increases from 4 to 10 times (Fell and Voas, 2006).

Admittedly, alcohol is estimated to cause fatalities of 22% in U.S. (NHTSA, 2010), 15% in U.K. (*Road Safety Annual Report 2014*, 2014) and there are no data available for Italy and some other EU countries. Moreover, mid to low income countries show higher percentage of drink and driving (*GLOBAL STATUS REPORT ON ROAD SAFETY*, 2009). For instance, comparing random stopped drivers, Thailand has 2.5 times more DUI’s than Norway, even though enforcement reported by (*GLOBAL STATUS REPORT ON ROAD SAFETY*, 2009) is considered little better in Thailand (5/10) than Norway (4/10). Italian ISTAT does not record anymore data on accident caused by vehicle defects or by DUI. That is because it is not easy to report such cause for officers.

Looking at Table 8.3, a case control study carried out in south-eastern Norway found out that of about 200 drivers killed in accidents between 2003-2008, about 35% had alcohol or drugs in their blood samples, including psychoactive medicines (Gjerde et al., 2011). A study conducted on about 1.4 thousand blood samples divers killed between 2003-2007 in Sweden found out that 17% had taken alcohol, about 5% alcohol and other drugs, almost 3% illegal drugs, about 13% legal drugs and 2% illegal and legal drugs. Totally, about 40% of drivers involved had taken psychoactive substances (alcohol or drugs) (Jones et al., 2009). Drummer et al in Australia found that 49% of over 3.3 thousand drivers killed during 10 year time span were positive to alcohol or drugs (Drummer et al., 2003).

Although during the years alcohol prevalence decreased from 33% to 28%, drugs prevalence rose from 22% to 30%. In particular almost 50% more cannabis and almost 100% more opioids (comprising legal medicines based on) were found. Probably this is also due to the increasing use of drug control. DRUID report (driving under the influence of drugs) shows the results of oral fluid and blood samples over thousand random stopped drivers in the Veneto region (Figure 4.12). Results show that 15% of drivers was found positive to alcohol, drugs or both.

There is also a high alcohol prevalence because any BAC>0.1 g/L was considered. Considering only equal or over BAC legal limit (0.5 g/L), alcohol prevalence was 5.2% (*Prevalence of alcohol and other psychoactive substances in drivers in general traffic. Part II : Country reports*, 2011). The highest prevalence among psychoactive substances was alcohol only or alcohol combined with drugs (64.0%), followed by cocaine (8.3%) and cannabis (7.7%).

A research from the Irish Medical Bureau of Road Safety has shown that the prevalence of cannabis and benzodiazepine are the most prevalent drugs after alcohol (Figure 4.13). Between 2007 and 2011 blood and urine samples from 7776 Irish drivers suspected of intoxicated driving were tested. An average of 23.5% were negative, 31% were positive for one drug and 45.5% to more than one drug (Cusack et al., 2012). However, as drugs remain in blood and urine for some days, the drivers might not have been impaired when tested. Indeed, there are high positives of DUI as only suspected drivers were tested.

M.-C. Li et al. provide a good review of Marijuana effect on driving (M.-C. Li et al., 2012). It is pointed out that the odds of having a collision is in average of 2.66 as tetrahydrocannabinol (THC) decreases driving performance within 4 hours of in taking, especially when combined with other psychoactive substances. Basically, the odds should be even higher but THC user behavior compensates sensory and motor impairment, such as slower driving.

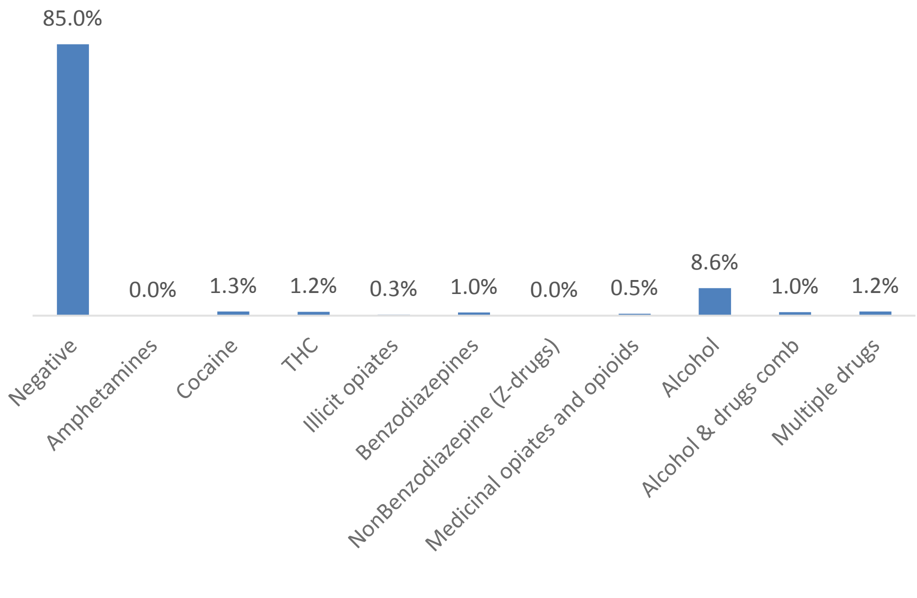


Figure 4.12: Average drug prevalence from Veneto random stopped drivers between February 2008 and August 2009 (n=1310) (*Prevalence of alcohol and other psychoactive substances in drivers in general traffic. Part II : Country reports*, 2011)

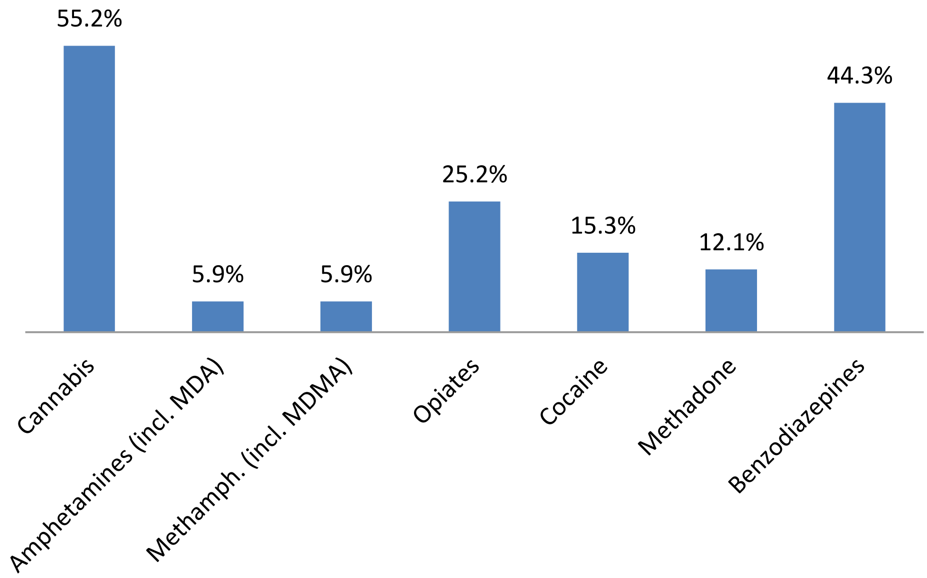


Figure 4.13: Average prevalence of drugs from Irish suspected drivers between 2007 and 2011 (Cusack et al., 2012)**.**

Another study from the same Norway area mentioned above, found that of over 10 thousand random drivers only 4.5% of them had taken alcohol or drugs (Gjerde et al., 2008), while 11.5% of Thailand random stopped drivers were positive to alcohol or drugs (Ingsathit et al., 2009). The main drugs found were psychoactive medicines (3.4% of drivers) then illegal drugs (1% of drivers). Augsburger et al. show an 89% of Swiss stopped drivers with alcohol or drugs in their blood or urine samples (Augsburger et al., 2005) while Appenzeller et al show an 92.4% of positive drivers to Alcohol or drugs (Appenzeller et al., 2005). Though, such amount is just because only drivers suspected of DUI were analyzed by police. Also, Augsburger et al. conclude that such high percentage correlates with police abilities to suspect DUIs. However, this only means that there are few suspected drivers that are false positive (11%) but it does not comprise the DUI drivers as an object of suspicion.

Looking at injury reports, a study conducted in France (Mura et al., 2003) found out, that 17% of injured drivers admitted to hospital emergency units were positive to alcohol and 9% to legal or illegal drugs. The same investigations made in a control group with an age and sex match, found that 5% of persons admitted to hospital emergency unit for non-traumatic reasons were positive to alcohol and another 4% to drugs. The latter percentage excludes people admitted to hospital as intoxicated of analyzed drugs.

The NHTSA database also provides data on alcohol-related fatalities per hour of the day (NHTSA, 2011). Results show that between 9 p.m. to 6 a.m. more than 50% of crashes are related to alcohol with a peak of 66% between midnight and 3 a.m. Yet the fatalities between 9 p.m. to 6 a.m. are just 35% of the total fatalities. The lowest rate is found between 9 a.m. to 3 p.m. (about 10%), which is accounted for 23% of the total fatalities. 48% of the crashes happen during working hours and commuting (6 a.m. to 6 p.m.), of which only 14% are alcohol related. The percentages are also quite steady between 2000 and 2009.

Other main causes of vehicle accident not related to DUI are distraction, driver error and speeding.

In 2005 the U.K. Department for Transport started to record contributor factors to accidents. Even though the report is only about accidents where a police officer attended, and it is based on opinions depending on officer's skills and they are reluctant to record factors where there is not full evidence such as impairment or DUI, the report gives a good indication of accidents causes.

In Figure 4.14 percentages of main categories are shown and in Table 8.4 total accident figure factors are presented. Similarly to what stated in the paragraph introduction, the report shows that driver error is responsible for 72% of vehicle accidents. In particular, fatalities are mostly due to loss of control 34%, failed to look properly 26%, careless-reckless 20%, impairment or fatigue 16%, speeding 15%, distraction 9%. All accidents are mostly due to failure to look properly 42%, misjudgment of other's path or speed 22%, careless-reckless or hurry 17%, distraction 5%, whereas impairment 6% (alcohol, drugs or fatigue) (Graves et al., 2014).

That is to say driver is responsible in the most collisions. Non-driver related fatalities responsibilities are on road conditions 10%, which is still an anthropic factor, and reduced visibility 5% such as dazzling headlights, dazzling sun, or rain, fog, blind spot.

Similar results are found in Italian's figures (Table 8.5), where the most causes of accidents are due to driver or pedestrian responsibility 80% or road environment 15%. Driver error causes almost 28% of road accidents, while distraction or hesitance cause about 17% of accidents and the same amount is due to disobedience of road rules.

As has been mentioned in the previous paragraph, Italian accident contributing factors due to vehicle defects or DUI are not recorded because of notice difficultness for officers.

The U.S. NHTSA's Fatality Analysis Reporting System (FARS) estimates that vehicle accidents caused by distraction in U.S. are 14% of fatalities and 20% of injuries (average 2005-2009), while speeding is 31% (*Speeding and distraction-Related Traffic Fatalities in 2009*, 2012). Furthermore, distraction caused by mobile phone usage, like dialing, calling, texting, in U.S. is estimated to be accounted for 5% of drivers in 2012 (NHTSA, 2014b). Speeding in Canada in 2011 is estimated to be accounted for 20% of vehicle accidents (*Road Safety Annual Report 2014*, 2014). In Italy the distraction is accounted for 17% of the crash injuries (*Road Safety Annual Report 2014*, 2014).

Indeed, two types of driver distraction can be distinguished: in and outside vehicle. In-vehicle distraction means drivers involved in secondary tasks, for example a glance to the radio takes from 1.5 to 3 seconds according to the radio layout (Perez et al., 2013), at 50km/h the distance travelled not looking at the road varies between 21 meters to 42 meters! Other in-vehicle distractions are eating or drinking, picking up food or fallen beverages, cleaning food crumbles from clothes, talking with passengers or with mobile phone, smoking, using mobile phone or GPS, etc. Thus, outside vehicle distraction comprise, for example, looking at people-animals-landscape, looking at previous crash, searching street names, looking at signs.

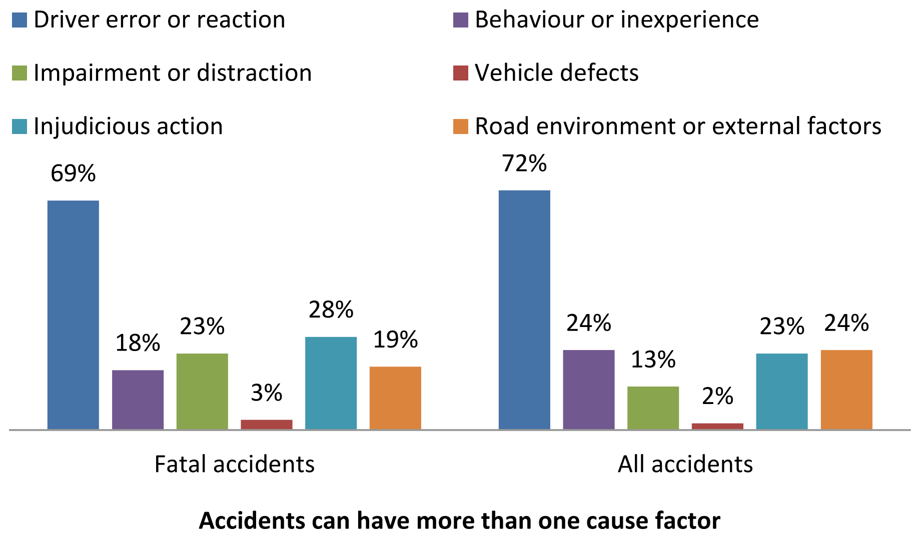


Figure 4.14: Contributing factor for accidents in the U.K. in 2012 (Graves et al., 2014)**. Absolute figures are reported in paragraph 8.1, Table 8.4.**

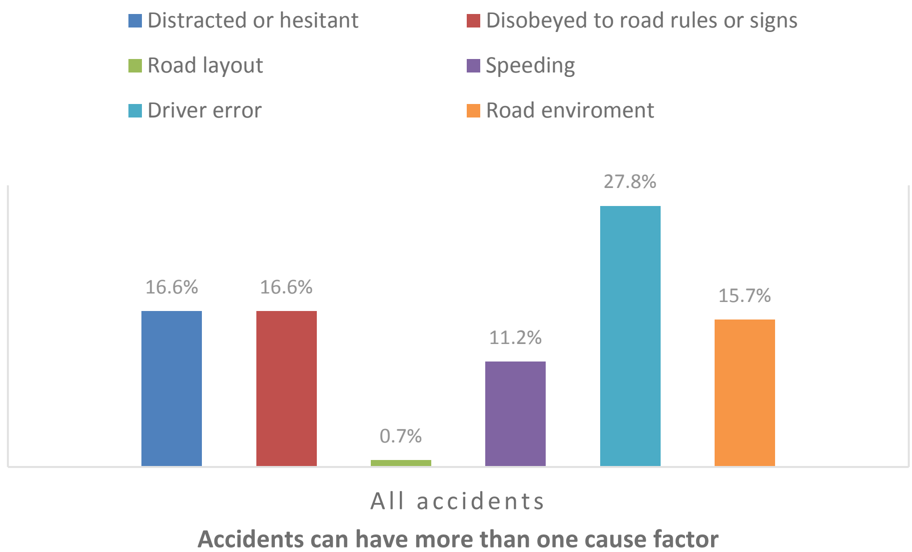


Figure 4.15: Driver responsibility contributing factors for accidents in Italy in 2012 (*Incidenti stradali in Italia 2012*, 2013)**. Absolute figures are reported in paragraph 8.1, Table 8.5.**

4.3.4. Road accidents costs

Vehicle accidents comprises at least one of the following costs: insurance claim, material damage, loss of productivity, traffic congestion, police, settlement cost, hospitalization, reduction or loss of working abilities, moral damage.

Table 4.6: Casualties cost retrieved for some regions, in brackets original currency value (exchange rate date according to the reported year price)

Study	Region	Fatality	Serious injury	Slight injury
(Vodden et al., 2007)	Ontario (2004)	€9.430m (C$13.6m)	€0.194m (C$0.280m)	€0.012m (C$0.018m)
(Lloyd et al., 2012)	U.K. (2012)	€1.448m (£1.743m)	€0.242m (£0.196m)	€0.018m (£0.015m)
(*Road crash costs*, 2014)	Netherland (2009)	€2.612m	€0.281m	€0.009m
(*Studio di valutazione dei Costi Sociali dell'incidentalità stradale*, 2012)	Italy (2010)	€1.503m	€0.197m	€0.017m

In Ontario Canadian region (about 12 million inhabitants) total fatalities costs are estimated to be about C$11billion, while injuries C$5billion and property damage only (PDO) C$1billion (Vodden et al., 2007). Alcohol-related crashes account for 24% of the fatalities cost and 3% of the all crashes cost, for a total of C$3billion. In Netherlands (about 16 million inhabitants) the total amount of socio-economical cost is about €12.5 billion, €2.6 billion for fatalities, €4.7 billion for hospitalization and €3.9 billion for material damages (*Road crash costs*, 2014). In U.K. in 2012 fatalities are estimated totally to cost £3.14billion, while injuries totally £4.58billion to £2.9billion respectively for serious and slight injury, while PDO £4.53billion; for a total of £15.2 billion (*Road Safety Annual Report 2014*, 2014). In Italy in 2010 fatalities total cost is estimated as €6.2billion (*Studio di valutazione dei Costi Sociali dell'incidentalità stradale*, 2012).

In U.S. total economic cost due to crash in 2000 is $230.6 billion, of which $51.1 billion are alcohol related and $40.4 billion are speeding-related (NHTSA, 2010). Traffic accident costs are high considering that in U.S. it is 2% of GDP and in Netherland is 2.2% GDP. To have a comparison U.S. agriculture is 1.12% GDP and Netherland agriculture 2.8% ("List of countries by GDP sector composition," 2014)!

As mentioned in paragraph 4.3.3, road design is one of the most anthropic causes of car accidents after driver error. Table 4.7 shows an average of savings for each euro spent on road safety interventions. The most effective seems alcohol control but this is because alcohol leads to more serious accidents and therefore to more cost. Nevertheless, summing road design savings, for each euro spent 8.9 euro are saved, on higher visibility 7.5 euro are saved and 22.5 euro on helmets usage. How much euro spending on traffic control or driver education will lead to savings? These figures are neither reported nor assessed.

Table 4.7: Cost effective interventions on road safety (*Road traffic injuries among vulnerable road users*, 2005)

Measure on which €1 could be spent	Savings (€)
Road design	8.9
Simple road markings	1.5
Upgrading marked pedestrian crossings	14
Pedestrian bridges or underpasses	2.5
Guard rails along the roadside	10.4
Removal of roadside obstacles	19.3
Median guard rail	10.3
Signing of hazardous curves	3.5
Area-wide speed and traffic management	9.7
Conspicuousness	7.6
Daytime running lights (normal bulbs)	4.4
Roadside lighting	10.7
Alcohol control	
Random breath testing	36
Helmets	22.5
Cycle helmets	29
Motorcycle helmets	16

Chapter 5:

EXPERIMENTAL TESTS

In this chapter the experiments related to the thesis objectives drawn in the introduction are illustrated. Since some experiments are relevant to more than one objective, their results are not aggregated on the objective level, but instead, each test results are separately reported, according to experiment campaigns.

The first aim of this work is to investigate whether an imitation by observation, which mechanism should be supported by mirror neurons, is more effective than a formal learning approach. Notarnicola et al. (2014) used balance assessment to compare performance of ballet students that had classes while they could observe themselves, thus stimulating their mirror neurons, or while they could not look at themselves.

In this work subjects are instructed either by verbal explanations or by observing the experimenter who performs one trial. A divided attention (DA) test comprising gross motor gestures (balance test) and fine motor gestures (choice reaction test, CRT) is used to compare the two learning approaches. Consequently, learning trend and absolute task performance of both approaches are compared in order to understand which method in this test is more suitable for conveying the information to the subject (DA formal learning - set 1, DA imitation learning).

However, since the balance tests might be biased by subject's equilibrium abilities, a perturbed stability test (PS), similar to the mCTSIB illustrated in paragraph 2.3, is used to compare the two groups (PS - set 1, PS imitation group). Besides, this PS test is used to confirm if subjects are free from neurological dysfunctions, which consequently might invalidate the DA experiment.

The second objective of this work is to investigate if tests based on balance assessment show learning effect and if so, at which extent. Balance tests for clinical purposes usually last 20 to 30s and are performed just once; but some studies suggest to average the results of two-three trials to mitigate the effect of learning (NeuroCom International Inc, 2008), or to provide the subject with other two further attempts in case the first trial is failed (Horak, 1987). However, the trial repetition might cause fatigue in elderlies and in case of averaging performance results still include learning effect. Moreover, as usually subjects are tested over time in different sessions it is important to compare unbiased data not altered by learning phase.

The tests above mentioned (DA and PS) are used to identify whether subjects need some practice trials before they are capable of providing valid results in balance tests. Further, if so, to identify first how many repetitions are sufficient to have data with limited learning effect (DA formal learning - set 1, PS - set 1), and second, if the learning effect appears also when repeating the test after about six months (DA formal learning - set 2, PS - set 2). Subject adaptation phase to the test conditions is not considered in the experimental data as the subject was given the time and opportunity before the test to adapt his/her posture to the equipment. Namely, the subject stepped onto the platform 20s before initiating each trial.

The third objective of this work is to examine if the novel divided attention test here proposed is suitable for further research in order to be used as a roadside impairment test. The divided attention test with balance test require attention and motor-coordination, and is commonly used in the U.S. to evaluate if a motorist is driving under the influence of alcohol or drugs (driving under the influence offence). However, such tests are usually assessed by subjective judgments and require *ad-hoc* trained personnel. Although the standardized field sobriety test (SFST) provides fair to good correlation with DUI, it is the case of laboratory conditions not roadside conditions. On the contrary, the currently available objective roadside tests reveal only illicit drugs or alcohol, with the limits as illustrated in paragraph 4.2, although alcohol and illicit drugs are not among the most causes of vehicle accidents (see paragraph 4.3.3).

The first steps toward the validation of the divided attention test, above mentioned, involve the analysis if the test is easy to perform and understand (DA formal learning - set 1), if there is a short learning phase (DA formal learning - set 1), and if repetitions over time do not provide better results (DA formal learning - set 2), and if degraded psychophysical conditions influence performance and learning (DA impaired subjects).

The Table 5.1 provides a summary of test usage according to the objectives.

Table 5.1: Tests interrelation to objectives.

Test/Objective	Imitation training based on mirror neurons	Learning phase in balance tests	Novel methodology to assess impairment
DA, formal learning - set 1	X	X	X
DA, formal learning - set 2 (repetition)	X	X	X
DA, imitation learning	X		
DA, impaired subjects			X
PS, set 1	X	X	
PS, set 2 (repetition)		X	
PS, imitation group	X		

Regarding ethical aspect of the carried out experiments, the Ethical Commission of the University of Udine does not require formal approval for the protocols here proposed but just a notice. Therefore such a notice has been submitted.

Moreover, informed consent was always obtained from the subjects before initiating the tests and anonymity of the subjects was maintained by using an ID code. Participants were voluntary and not paid nor rewarded in any form. Subjects' compliance to the experiments was made by the experimenter on the base of the administered self-declaring questionnaire. Both informed consent and questionnaire can be respectively found in paragraphs 8.2.3 and 8.2.4.

Prior experience of postural assessment, injuries, diseases or psychophysical conditions that might influence on equilibrium would exclude the subject from experiments.

In the following sections the experimental protocols are first described (paragraph 5.1), then the results for each test are presented (paragraph 5.2). The discussion and conclusions regarding experiments are drown separately in order to allow on thorough analysis, respectively in chapter 6 and chapter 7.

5.1. EXPERIMENTAL SETUP

In the two following paragraphs the protocols used in the experiments, divided attention (DA) test and perturbed stability (PS) test will be illustrated.

5.1.1. Divided attention protocol

The instrumentation of the divided attention protocol presented in Oggero et al. (2012) comprises a posturographic platform (CAPS™ Professional – Vestibular Technologies, LLC, Cheyenne WY, U.S.A., left panel of Figure 5.1), a P.C. with proprietary software (VTImpair - Vestibular Technologies, LLC, Cheyenne WY, U.S.A) and a hand-held trigger (a one button modified computer mouse, right panel of Figure 5.1). The protocol set up is depicted in Figure 5.2. Sampling frequency of platform force is 64 Hz, sufficient to capture in detail postural sway characteristics. The first natural frequency of the platform is 92 Hz and its force resolution is 0.2N.

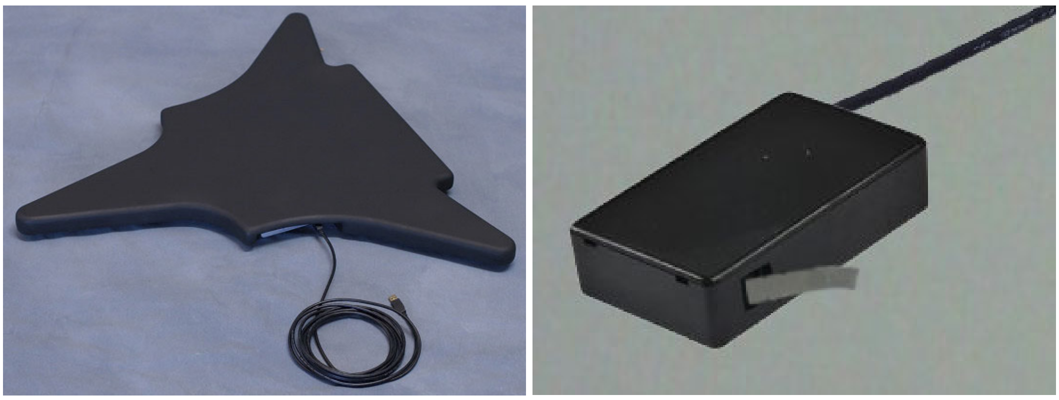
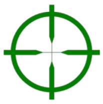
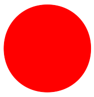
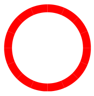
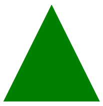
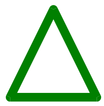


Figure 5.1: Instrumentation used in this test. Left panel depicts the platform [Copyright © 2001-2015 Vestibular Technologies, LLC. All rights reserved] and the right panel the hand-held trigger.

Before initiating the test, its protocol was described and informed consent was obtained from the subject. The experiment was setup as follows. The subject was centrally standing on the platform in front of a computer monitor with the screen positioned at subject's eye level and at a distance of 40º of horizontal field of view. The subject then underwent two types of test: 10 trials of a divided attention test and later 10 trials of a psychomotor vigilance test (PVT).

Table 5.2: Symbols used for the divided attention protocol.

Symbol	Correct (follow or react)	Dummy (ignore)
Subject's CoP		
Critical tracking test		
Choice reaction test		

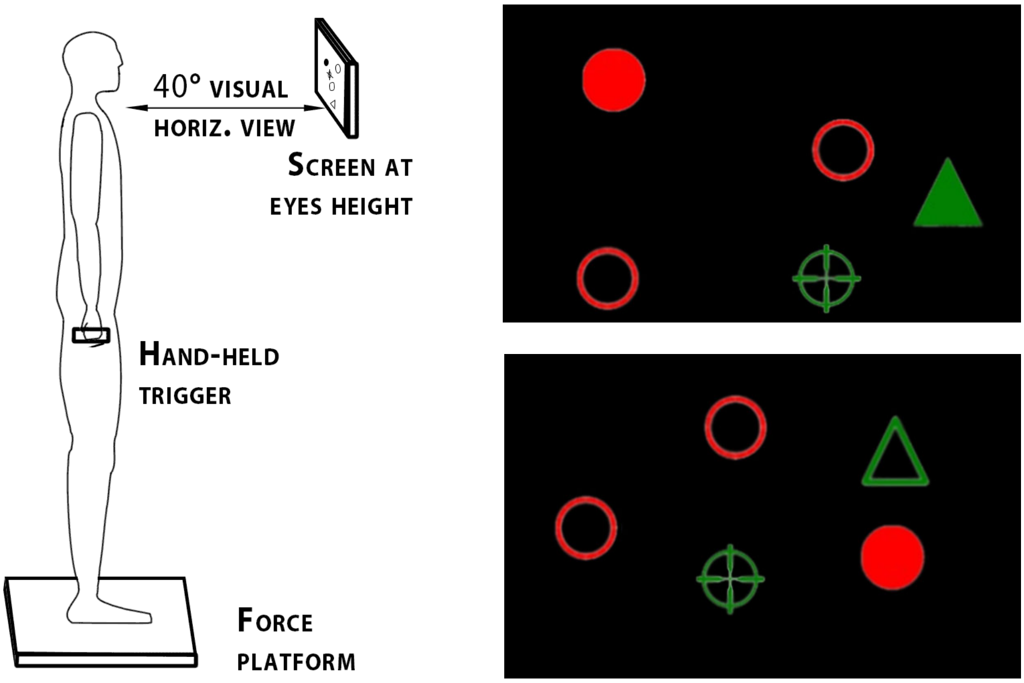


Figure 5.2: Left panel shows test setup: subject, force platform, trigger and computer screen. Right panel shows test screenshots (black background provides a higher contrast) [modified from (Oggero et al., 2012)**]. Right panel up represents a condition in which the subject should press the trigger, right panel down represents a condition with a false vision cue symbol that the subject should ignore and should not press the trigger [reprinted with permission from** (Rossi and Pascolo, 2015)**].**

The divided attention test measures the ability to perform two tasks at the same time; it combines a critical tracking test (Jex et al., 1966) and a choice reaction test. The first measures both psychomotor coordination and balance ability, and is achieved through a posturographic balance test (PBT). The tracking test requires the subjects to follow a target displayed on the screen as a red solid circle by moving their CoP presented as a cross-hair marker (Table 5.2). Moreover the target can either remain still or be translating with straight movements. Dummy symbols are always displayed along with the target symbol in order to increase the task difficulty level and thus favor the divided attention (see right panel in Figure 5.2). Dummy symbols are displayed as a red empty circle that is with shape and color similar to the target. Furthermore the targets are displayed within the 50% of the subject's theoretical Limit of Stability (tLOS) radius, so individuals are not pushed towards falling limits and thus to guarantee the task safety performance. The tLOS was adjusted by providing the height of the subject to the software (Equation 2.12).

The choice reaction test requires to react appropriately according to the visual stimuli (visual cue) that is appearing. In this task the false reacting symbol is displayed instead of the correct symbol. Once the trigger is pressed, the visual cue, either correct or dummy, disappears from the screen. If the trigger is pressed when there is no visual cue on the screen, a reaction to absent cues indicator is incremented. Symbols of both tasks are presented in random locations and with random pace (from 3s to 5s). However, here CRT is assessed while the subject is performing a divided attention test, which causes the reaction time higher than as it would be done alone.

The duration of each test was 60s which in total gives 28 minutes of testing time, keeping constant pace of the repetitions (one test every 3 minutes with 85s seating between). Between tests subject stayed out of the platform and seated in order to minimize the possible fatigue. Moreover, subjects had 20 to 30s before starting the divided attention protocol to get acquainted with the equipment (platform and trigger) and with the sensibility of the CoP displayed on the screen.

The tests are designed in order not to be too complicated and thus to be easily understandable for most of the individuals. Symbols are designed in order to be well perceived also for dyslexia and for daltonism: they do not comprise numbers or letters and shape is different for each task (Table 5.2). Moreover they are displayed on black background which provides high contrast.

In order to obtain the reaction time of the subject in rest conditions, at the end of the DA test the subject undergo a psychomotor vigilance test (Dinges and Powell, 1985) which measures the ability of a subject to sustain attention. Usually the test lasts 10 minutes, however, for the purposes of this experiment test time is shortened to 1 minute.

This test is achieved by a simple visual reaction test, where the subject has to press a trigger with the dominant hand whenever a screen switch color from black to white, repeated 10 times. The stimulus pace was randomly chosen between 1s and 3s and it is measured as the time passed between the stimulus and the action.

Divided attention performance analysis

The DA test performance is analyzed considering the results of the single tasks. The CTT task is defined by the accuracy and delay of the subject's tracking movement, which are calculated respectively through the cross-correlation coefficient and lag between the subject's CoP and target coordinates.

The cross-correlation function shifts the two signals for each data sample k and calculates their sum (Equation 5.1). The maximum cross-correlation coefficient c_k is considered as the accuracy of the subject's movements to pursuit the target, whereas the amount of shift regards the lag of the two signals (measured as k times sample frequency), which is considered the delay between the change of target position and the subject movement.

Equation 5.1: Cross-correlation coefficient, normalized with its maximum values so the result is 1 for identical input signals. *N* refers to the signal length, *k* to the signal shift, *x* to the CoP signal and *t* to the target signal.

$$c_k = \frac{\sum_{i=1}^{N-k} x_{i+k} \cdot t_i^*}{\max(x) \cdot \max(t)} \quad 0 \leq k \leq N$$

The cross-correlation was considered as a whole and subdivided into its medio-lateral (ML) and anterior-posterior (AP) components. The higher accuracy of target tracking, the cross-correlation coefficient is closer to 1. The smaller the lag between CoP and target signal, the lower delay of tracking movement as the subject's movement matches the target in greater extent. On the contrary, the larger the lag, the worst the subject's reaction time as his/her movement falls behind the target and thus it takes more time to reach the target.

The largest Lyapunov exponent (LLE) is also obtained from the CoP signal in order to verify the performance trend in another analysis domain. LLE is numerically calculated through the Matlab (MathWorks – Natick MA, U.S.A.) routine provided by S. Mohammadi, using an embedding dimension of 2 and 4 respectively for the single CoP component and for the whole CoP signal.

The reaction time was a time difference between the appearance of the right stimulus and the button pressing. Reaction to incorrect stimulus was only marked as "reaction to incorrect cues" and reaction time was not considered. The correctness score (CS) of the choice reaction test was calculated by considering correct responses, missed and/or wrong reactions (Equation 5.1). It was possible to achieve the maximum score (value equal to 1) only if the subject always reacted correctly, that is if always responded correctly to appeared stimuli. Any wrong response such as the reaction on dummies, when not needed or missed response, reduced the score. Such kind of "penalty" was assumed upon to prevent pressing the trigger continuously in order to obtain the maximum of CS.

However, there should be taken into consideration also the fact that the trigger device was made by using the electronic system of a computer mouse. Therefore, there could be some additional delay due to the computer software click event handling. Nevertheless, such possible delay was minimized by allocating the entire operating system resources to the test purposes.

The dependent variables used in the analysis are summarized in Table 5.3, while the independent variables regard the CTT target coordinates and the appearance of the CTT and CRT visual cue. Protocol instructions can be found in paragraph 8.2.1.

Equation 5.2: Correctness score (CS)

$$CS = \frac{ReactionToCorrectCues}{TotalCorrectCuesPresented} * \left(1 - \frac{(ReactionToIncorrectCues + ReactionToAbsentCues)}{TotalIncorrectCuesPresented}\right)$$

Table 5.3: Parameters used to analyze the performance of the divided attention test (dependent variables).

Parameter name		Parameter definition
Critical tracking test	Accuracy	Cross-correlation coefficient between the center of pressure path described by the movement of the subject and the path of the target.
	Delay	Cross-correlation lag between the center of pressure path described by the movement of the subject and the path of the target.
	Sway pattern variability	Largest Lyapunov exponent of the center of pressure path described by the movement of the subject.
Choice reaction test	Correctness score	Correct responses against missed and/or wrong reactions as described in Equation 5.1.
	Reaction time	Time difference between the appearance of the right stimulus and the pressing of the button.

Motor performance models analysis

The outcome of this DA test is also analyzed to investigate whether a two dimensional postural task follows the performance laws presented in paragraph 3.3, if according to these laws, the learning effect is shown and if so, if they follow the power law of practice.

The Hick's law learning curve is investigated through its *m* parameter (dependent variable) for the double choice reaction test (independent variable) of DA protocol (Equation 5.3). The coefficient *b*, that is the reaction time in which a single choice is presented to the subject, is obtained from the PVT. To avoid bias of the learning effect of PVT results, the *b* coefficient is calculated as the average of the last six PVT trials. Since the CRT task presented to the subject is a two choice test, one only bit of information is necessary to elaborate the response ($\log_2(2)=1$). As a result, the *m* coefficient is the simple difference between RT_{CRT} and RT_{PVT}.

Equation 5.3: *m* coefficient calculation of Hick's law.

$$m = \frac{RT_{CRT} - \overline{RT_{PVT}}}{\log_2 NC}$$

The learning curve of speed-accuracy trade-off is calculated for the original Fitts' law, for a modified law that considers the effective index of difficulty (IDe), and for a IDe that takes into account the maximum tilt angle that the subject performs during the target tracking.

The target size displayed on the screen (W1) is chosen according to the typical CoP sway in rest conditions, which is about 5 to 10mm over few seconds. Additionally, since ID depends on the target dimension (W) it might show ceiling or floor effect (Schmidt and Lee, 2005). Therefore, the learning curves are obtained considering four different cases of target size.

Along with W1, three smaller targets (W2, W3 and W4) are used to calculate movement time (MT), the minimum of them (W4) is chosen considering that the subject's ability to pass through small areas is reduced due to postural sway. For instance, for a subject of 1.70m, the tLOS is equal to 102mm but screen displays targets up to 50% of tLOS to avoid to push the subject towards, W1=5.1mm, W2= 4.1mm, W3=3.4mm, W4=2.0mm.

The parameters analyzed are summarized in Table 5.4.

Table 5.4: Parameters and conditions used to analyze the speed-accuracy trade-off (Fitts' law).

Parameter name	Parameter definition
Movement time (MT)	Time to reach the next target. Calculated as the time between the appearance of the new target and reaching its boundary. It is the only dependent variable.
Distance (A)	Distance between the two target centers.
Effective distance (Ae)	CoP path length between the position at the onset of the new target and the position where the boundary of the new target is reached (Figure 5.4).
Target size (W)	Dimension of the target, which is normalized with the subject's theoretical limit of stability (tLOS - Equation 2.12). Three target sizes are used to calculate movement time and distance: W1=tLOS/20, W2=tLOS/25, W3=tLOS/30 and W4=tLOS/50 (Figure 5.3).
Effective target size (We)	Diameter of the 95% confidence circle of the CoP positions distribution after the target is being reached.
Index of difficulty (ID)	Ratio between target distance and target size (A/W).
Effective ID (IDe)	Similar to ID but calculated with the effective distance and effective target size (Ae/We).
Tilt angle (T)	Subject tilt angle with reference to vertical position. It is calculated as the inverse tangent between the target distance from the CoP center and the subject's height.

Since one trial comprise multiple targets, in order to calculate the parameters in the above table, CoP signal is chunked into blocks comprising only a single target.

The Fitts' law is also calculated considering the maximum tilt angle performed during the tracking with reference from the perpendicular (Equation 5.4). It is supposed that the difficulty of the task increases when one has to move near the tLOS.

Equation 5.4: Modified IDe that considers the maximum tilt angle (T). k refers to an arbitrary constant calculated to maximize the R^2 of regression.

$$ID_{et} = \frac{ID_e}{\cos(\mathrm{k} \cdot \max(T))}$$

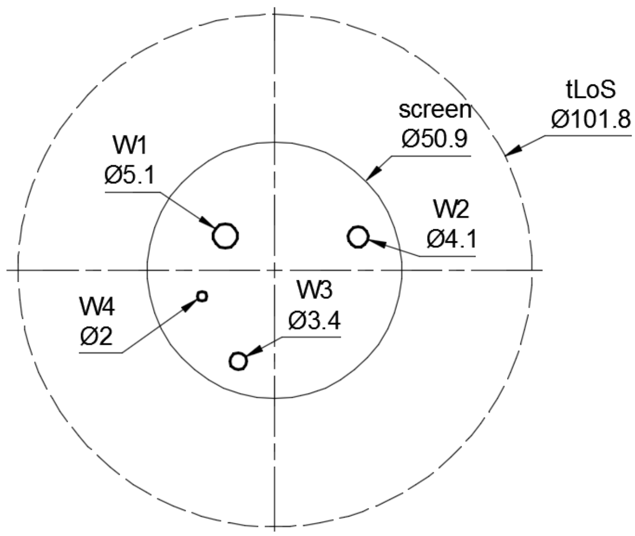


Figure 5.3: Example of target sizes (W1, W2, W3, W4) for a 1.7m tall subject. To avoid reaching postural stability limits the CoP positions and targets are displayed up to a diameter of 50% of tLOS. Drawing measures are in millimeters.

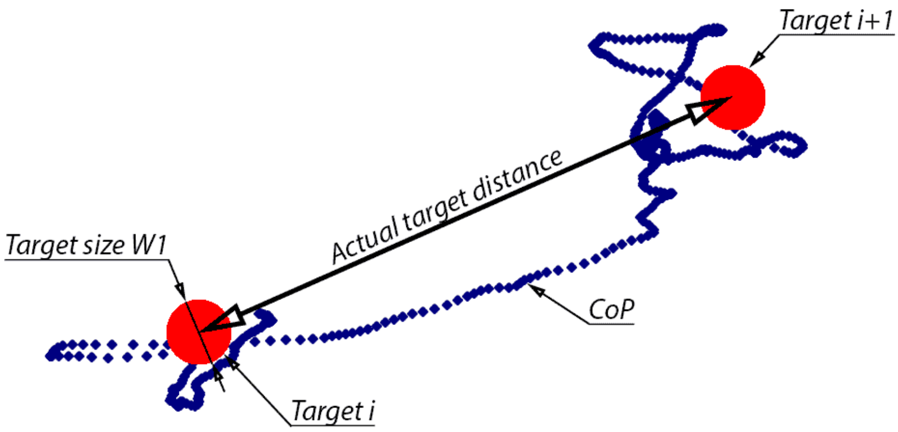


Figure 5.4: Example of a CoP path from the onset of the next target.

5.1.2. Perturbed stability protocol

The protocol of the perturbed stability test comprises of a posturographic platform (CAPS™ Professional – Vestibular Technologies, LLC, Cheyenne WY, U.S.A.), a 100mm thick foam cushion (medium density foam) placed on the platform above described (Figure 5.5), and proprietary software (CAPS™ EQ software – Vestibular Technologies, LLC, Cheyenne WY, U.S.A.).

Figure 5.5: Platform with the foam cushion used in the PS test [Copyright © 2001-2015 Vestibular Technologies, LLC. All rights reserved].

The perturbed stability test measures the ability to keep the erect stance under the perturbed conditions of the mCTSIB protocol, illustrated in paragraph 2.3. mCTSIB has been preferred among other protocols because it includes perturbed tasks, it is suitable to use with computerized dynamic posturography and it does not require very expensive equipment.

Perturbations are generated by the foam cushion on which the subject stands. The height of the cushion (100mm) is sufficient to provide separate perturbations for each lower limb and thus to oblige separate compensatory movements. Moreover, since the standing surface is not firm, also the tactile pressure sensory of the feet is disrupted. Additionally, in the eyes closed conditions the stability is even more challenged as the available sensory information is further reduced and subjects must rely only on the proprioception information (vestibular, muscular and articular).

Before initiating the test, its protocol was described and informed consent was obtained from the subject. The experiment was setup as follows. Subjects stand on the foam cushion and perform the test either with eyes open (perturbed stability eyes open – PSEO) or with eyes closed (perturbed stability eyes closed - PSEC). Subjects perform 4 trials each of 60s, which in total gives 7 minutes of testing time keeping the constant pace of the repetitions (one test every 2 minutes). Between tests subject stayed out of the platform and seated in order to minimize the possible fatigue (40 seconds). The test pace was constant of one test done every 2 minutes with the total of 7 minutes testing time. Subject could stabilize his/her posture by stepping onto the cushion 20s before initiating each test. The time duration for the single trial is longer than usual clinical tests (which is 20s to 30s) in order to allow the study of possible learning effect without being biased by stepping off the force platform. Four trials were performed in order to evaluate a possible slightly increasing trend after a likely initial sharp performance improvement.

Perturbed stability performance analysis

The PS performance is measured by analyzing the CoP path characteristics. Three kinematic parameters are obtained from the CoP: the stability score, the average sway velocity and average velocity moment. All of them measures the ability to counter react to the perturbations. The first regards the amount of the theoretical stability area is used to control the perturbation, a high stability score means that the CoP area is small. The second and the third parameter measure the ability to control stability with the minimum input. Both are normalized with the height of the subject to provide comparable measurements. The learning effect is also investigated through the largest Lyapunov exponent, obtained from the CoP.

Data analysis included the subject's individual height-normalized posturographic results provided by the CAPS™ EQ software. The measured parameters (dependent variables) are summarized in Table 5.5, while the independent variables consist in the mCTSIB conditions (eyes open or closed, compliant surface). Protocol instructions can be found in paragraph 8.2.2.

The trials are subdivided into blocks of 20s as this includes enough breathing cycles and because it is a common clinical test duration. Therefore, for each subject a total of 16 measures were analyzed: four 60s long trials and twelve 20s long blocks. Sampling frequency of platform force was 64 Hz, sufficient to capture in detail sway characteristics.

Table 5.5: Parameters used to analyze the perturbed stability test (dependent variables).

Parameter name	Parameter definition
Stability score (SS)	Subject's ability to maintain balance during the test. Calculated as the ratio between the 95% confidence ellipse (Equation 2.7) and subject's theoretical limit of stability (Equation 2.12).
Normalized average velocity (NAV)	Calculated by dividing the total distance of the CoP with the total acquisition time, then the result is averaged with the subject's height.
Normalized average velocity moment (NAVM)	Calculated as the average of the areal velocity of each point, that is the average of the cross product between the CoP velocity vector in one point and its distance from the 95% confidence ellipse center. The result is then normalized with the subject's height.
Largest Lyapunov exponent (LLE)	Subject's variability of sway movement patterns. Calculated numerically with the routine provided by S. Mohammadi using an embedding dimension of 4.

5.1.3. Data analysis

Data analysis is presented with the distinction between test protocols and motor performance laws.

DA and PS protocol

The trials of one single group are analyzed by using the analysis of variance (ANOVA). This method compares the population groups by analyzing their means and their variations. The key outcome is the *p*-value, which indicates how much the populations' measures overlap. The null hypothesis can be rejected (i.e. the groups are not similar) when the *p*-value is smaller than a significant level α, which represents the type I error. This error refers to the chance to find a false positive result, i.e. to find a difference that is due to random chance; the threshold of α is usually set at 5%.

Comparisons between trials are carried out with Helmert's contrast, which compares one trial mean with the mean of the subsequent trials. However, when a large amount of multiple statistical comparisons on the same population are performed, type I error can rapidly rise causing an increased likeliness to find a false positive. For this reason, adjustments methods are used to correct the *p*-value. In this work the Tukey's honestly significant difference test is used when the results of a single group are compared while the more conservative Holm-Bonferroni's correction is used when the results of two or more groups are compared. On the other hand, such corrections increase the type II error, also called β error or error of the second kind, which refers to the chance of missing a true positive result. In short, it is considered that the two populations have statistically different mean when $p<.05$. To compare the results of a single group, data are usually normalized to avoid type I errors that might arise with small variances and high means.

When the same variables are measured several times in different conditions (e.g. separated sessions of practice) it is required to use the general linear model (GLM) - repeated measure, as it takes into account also the correlation between the dependent variables. GLM univariate and multivariate is a broader statistical method which comprise ANOVA and regression analysis. While the ANOVA is straightforwardly carried out with Matlab function *anova1*, multivariate analysis is carried out with IBM SPSS (IBM – Armonk NY, U.S.A.), a statistical software which also provides more detailed analysis such as sphericity test and its violations corrections. An example of raw recorded data and analyzed data is reported in appendix in paragraph 8.4.

In this work, together with *p*-values, GLM results are presented also with *F*-test and the effect size (partial η^2). *F*-test is the ratio between the between-group and within-group variability and it is used to calculate the *p*-value. If the variability between the groups is larger than the variability within the groups, then the means of the groups are different and therefore *p*-value is diminished; the larger *F* the smaller *p*. *F*-test results are reported as *F*(*df*, *error df*)=*F*-value, where *df* stands for the degrees of freedom.

The effect size indicates the strength of the statistic. High effect size is considered for partial η^2>.26, medium for partial .08>η^2>.13 and low for partial η^2<.08. GLM repeated measures is sensitive to sphericity violations as it assumes that the repeated measures have homogeneous variances. When sphericity is not verified, adjustment methods allow to correct the statistical results. In this work the Mauchly's test is used to verify sphericity assumption and when it is violated the conservative Greenhouse-Geisser correction is used.

Data are depicted by its mean and error bars, which indicate the 95% confidence interval (CI). Non overlapping error bars in results from a single group indicates that the two trials are statistically different at the 5% level. However, in GLM repeated measures (group comparison) overlapping CI do not necessarily indicates that two means are statistically similar (null hypothesis cannot be rejected) (Wolfe and Hanley, 2002).

Motor performance laws

The goodness of fit of the model (Hick's law, Fitts' law, power law of practice) is represented by the squared Pearson coefficient R^2 of the regression, calculated with ordinary least squares method. Results of R^2 here are interpreted as follows: very good fit for R^2 above 0.8, moderate fit for R^2 between 0.5 and 0.8, fair fit for R^2 between 0.2 and 0.5, and poor fit for R^2 below 0.2. Regression trend coefficients (m and b) of the analyzed parameters are calculated with Matlab routine *polyfit*, adapted to provide logarithmic and power regressions.

5.2. EXPERIMENTAL RESULTS

The experiments illustrated in this work and the group of subjects involved are summarized in Table 5.6. Moreover, Table 5.7 shows the subjects involved in the perturbed stability test according to test conditions (eyes open or eyes closed). A total of 42 subjects were assessed several times, whose demographics (age, gender, anthropometric data and group test) can be found in paragraph 8.3. To study motor learning in DA and PS the subjects repeat the test respectively ten trials and four trials.

Since the tests carried out involve different sample sizes, in order to obtain the finest statistical significance it is necessary to analyze each set of Table 5.6 separately.

Table 5.6: Group relation with tests

Group ID	N° of subjects	Divided attention test			Perturbed stability test		
		Formal learning		Imitation learning	Set 1	Set 2	Imitation group
		Set 1	Set 2				
01 - A	25	X (only 16)			X		
02 - B	17		X (only 10)			X	
03 - C	16			X			X
04 - D	3	X			-		

Table 5.7: Number of subjects related to perturbed stability test (PS) conditions.

Group ID	PS eyes open	PS eyes closed
01 - A	14	11
02 - B	10	7
03 - C	-	16
04 - D	-	-

Regarding the analysis of motor performance laws presented in paragraph 3.3, the speed-accuracy trade-off (Fitts' law) is obtained analyzing the CoP of DA test, while the Hick's law is obtained from the CRT reaction time and PVT reaction time. The subjects tracked an average of 7.5 targets for each trial they performed, that is about 75 targets for each session (Table 5.8). The target size W4 was excluded from the investigation of floor and ceiling effect in Fitts' law due to excessive targets not reached by the subject (>5%, almost one miss for each trial). A total of 3447 targets were displayed, which distances (A) ranged from 5mm to 109mm and tilt angle up to 50% of tLOS.

Table 5.8: Summary of the targets performed by the groups and the targets not reached for each target size (W).

Group	Total targets	Targets not reached			
		W1: tLOS/20	W2: tLOS/25	W3: tLOS/30	W4: tLOS/50
Group A	1192	12 (1.0%)	17 (1.4%)	26 (2.2%)	105 (8.8%)
Group B	1057	7 (0.7%)	11 (1.0%)	17 (1.6%)	81 (7.7%)
Group C	1198	9 (0.8%)	25 (2.1%)	35 (2.9%)	103 (8.6%)
Total	3447	28 (0.8%)	53 (1.5%)	78 (2.3%)	289 (8.4%)

5.2.1. Divided attention test: first set

In this experiment subject will perform the divided attention test described in paragraph 5.1.1. The purpose is to verify if there is a learning effect and how long it last. Moreover, these results will be compared later in paragraph 5.2.3 to verify if imitation by observation (paragraph 3.2) is more effective than formal learning approach (this experiment).

Materials and methods

Sixteen healthy subjects (8 females and 8 males, age=28.2±9.6 years; height=1.71±0.08m; weight=72.17±11.36kg) participated in this test.

The experimental data were elaborated in the Matlab statistical package (MathWorks – Natick MA, U.S.A.). Each test result was normalized in order to permit the comparison across subject and test types. Normalization was done by dividing the result by its average of the last 6 trials which do not comprise any learning effect.

The one-way analysis of variance (ANOVA) was calculated using the Matlab *anova1* function, then these results were used in the function *multcompare* (alpha level 0.05 and Tukey's honestly significant difference criterion) to identify the columns that are significantly different from the others. Output of the function *multcompare* allows also on graphic analysis as means and confidence intervals are plotted. In this case, two means are significantly different when confidence intervals do not overlap each other (p<.05).

Motor performance laws are analyzed through regression coefficients *b, m* and R^2, respectively the shift coefficient, the learning rate, and the goodness of fit of the model. Learning effect is analyzed with the power law of practice on data normalized with the average of the last six trials.

Results

Table 5.9 shows the subject's overall average performance (mean and standard deviation) for each parameter considering the last six trials in which the learning effect is exhausted. Additionally, in this table, the results of the one-way ANOVA (p values) on the normalized data are reported.

From Figure 5.6 to Figure 5.17 it is shown the graphical output of the function *multcompare* for each parameter (with prior data normalization by the last six tests average). Comparison results are differentiate by using three colors. The blue color represents the test taken as a reference to which all other samples are compared. Red colored columns indicate data which are significantly different from the reference sample while grey columns mark data not significantly different.

Table 5.9: Mean values (average and standard deviation) calculated across all subjects on the last 6 trials to exclude any learning effect and the *p* values obtained from the normalized data.

Parameter		Cross-correlation	
		Coefficient	Lag (s)
Critical tracking test (CTT)	**ML component**	.916±.047, p<.001	1.179±.157, p<.05
	AP component	.921±.032, p<.001	1.228±.160, p<.001
	Whole signal	.842±.055, p<.001	1.205±.145, p<.001
Choice reaction test (CRT)	**Reaction time [s]**	.702±.136, p<.05	
	Correctness score	.977±.052, p<.001	
Psychomotor vigilance test (PVT)	**Simple reaction time [s]**	.217±.050, p<.001	
CTT largest Lyapunov exponent (LLE)	**ML component**	78e-3±2.7e-3, p<.001	
	AP component	78e-3±1.6e-3, p<.001	
	Whole signal	71e-3±1.8e-3, p<.001	

In the following figures is presented a graphical trial comparison for the considered parameters.

Cross-correlation coefficient	Cross-correlation lag

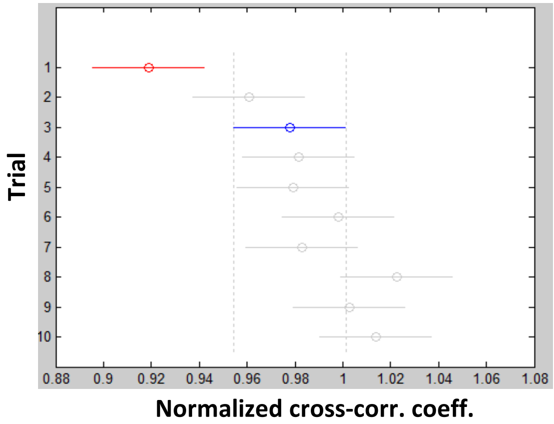


Figure 5.6: CTT Cross-correlation coefficient for the ML CoP component

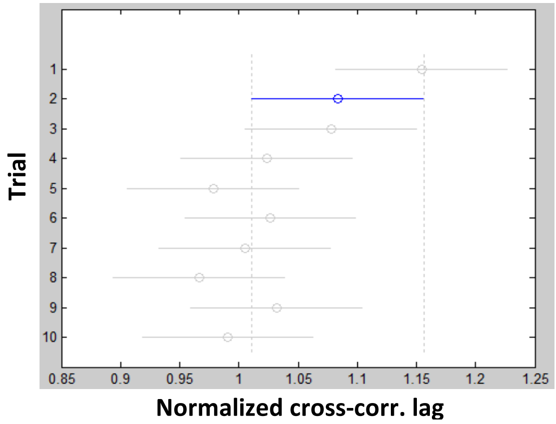


Figure 5.7: CTT Cross-correlation lag for the ML CoP component

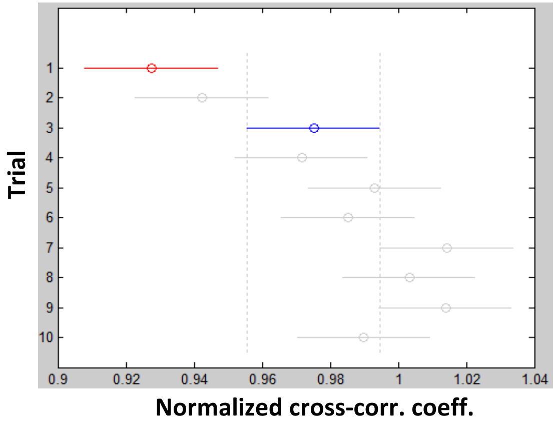


Figure 5.8: CTT Cross-correlation coefficient for the AP CoP component

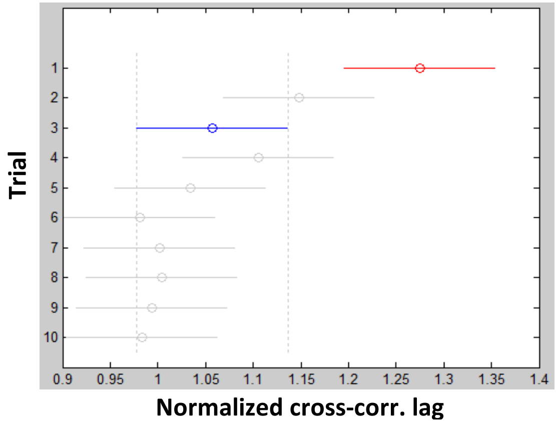


Figure 5.9: CTT Cross-correlation lag for the AP CoP component

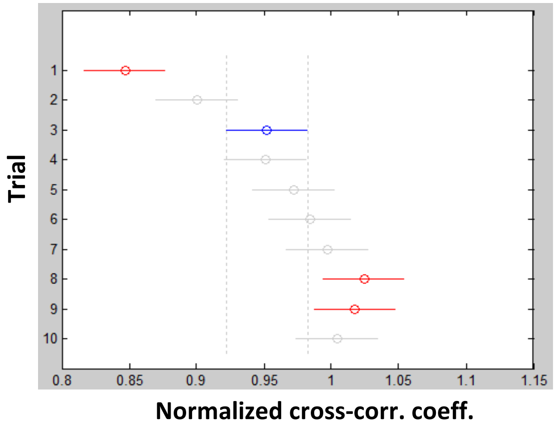


Figure 5.10: CTT Cross-correlation coefficient for the whole CoP signals

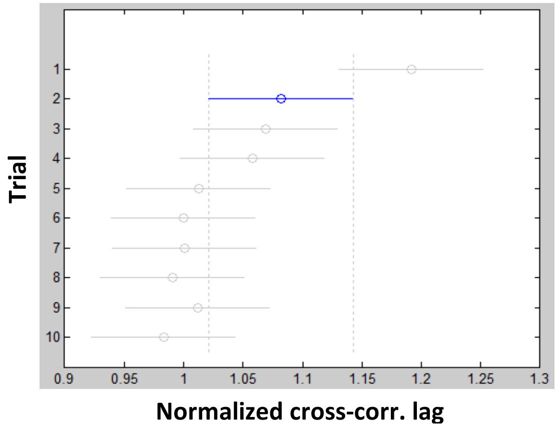


Figure 5.11: CTT Cross-correlation lag for the whole CoP signals

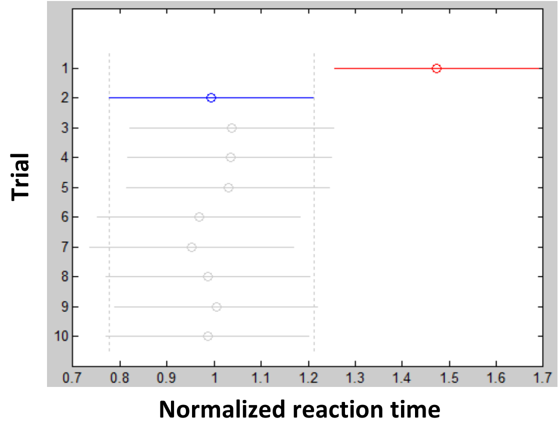


Figure 5.12: CRT reaction time

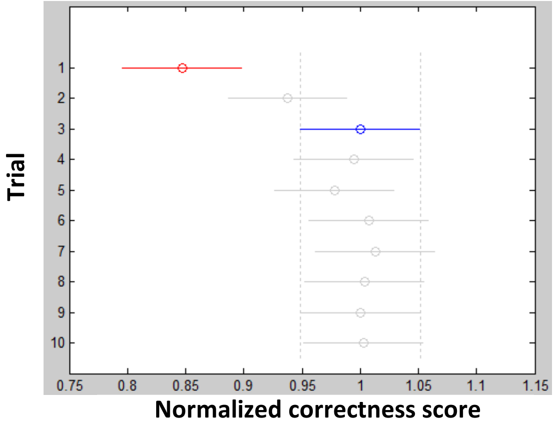


Figure 5.13: CRT Correctness score

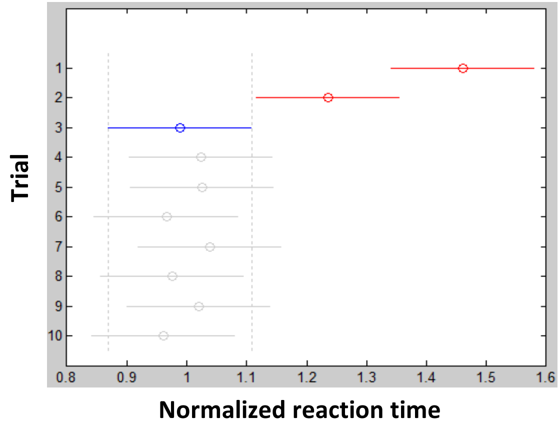


Figure 5.14: PVT Simple test reaction time

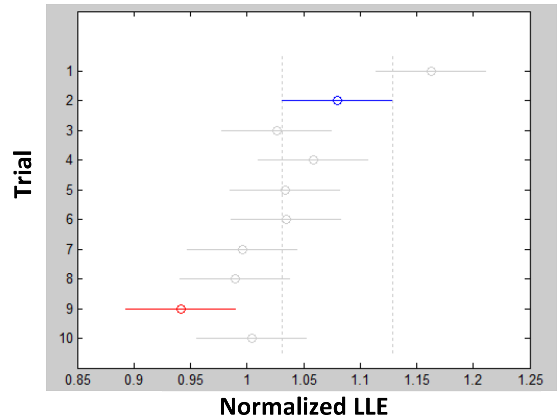


Figure 5.15: LLE for the ML CoP component

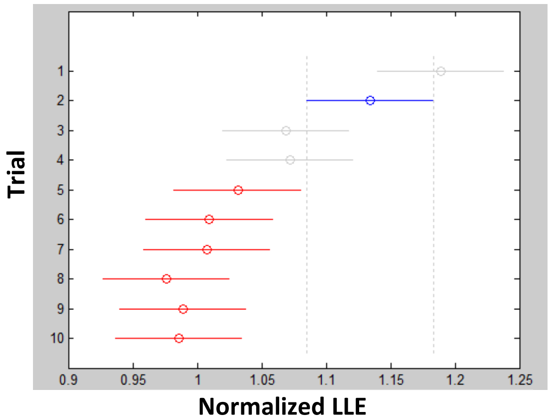


Figure 5.16: LLE for the AP CoP component

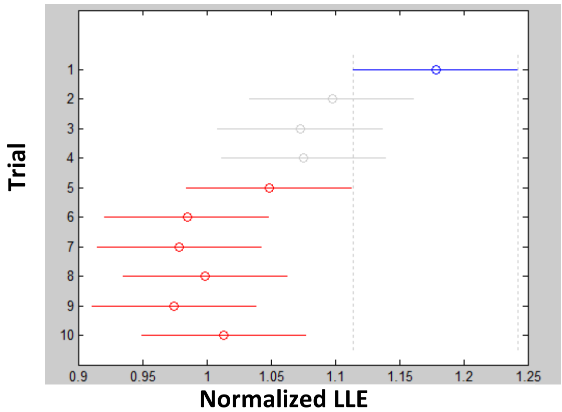


Figure 5.17: LLE for the whole CoP signal

For future implementations of this protocol it is proposed a single parameter which should simplify the psychophysical conditions. It comprises all of the previous parameters and it is calculated as the general accuracy over general reaction time (Equation 5.5).

Equation 5.5: Performance parameter for the divided attention test

$$PerformanceScore = \frac{CrossCorrelationCoefficient * CorrectnessScore}{CrossCorrelationLag * ChoiceReactionTime}$$

The performance score can be subdivided into its ML and AP plane components, in the same way as it was done for the previously analyzed parameters. Figure 5.18 to Figure 5.20 show that the performance score shows the same learning effect like the parameters it is composed of.

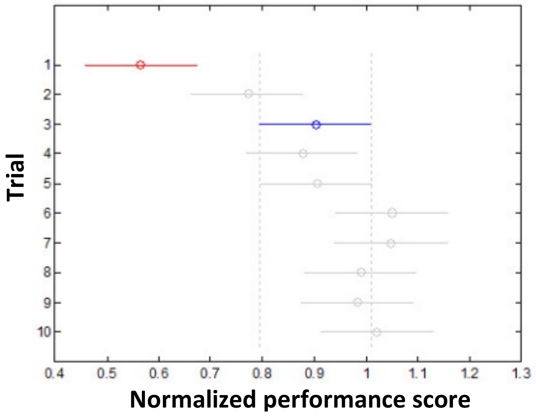


Figure 5.18: Performance score, ML component

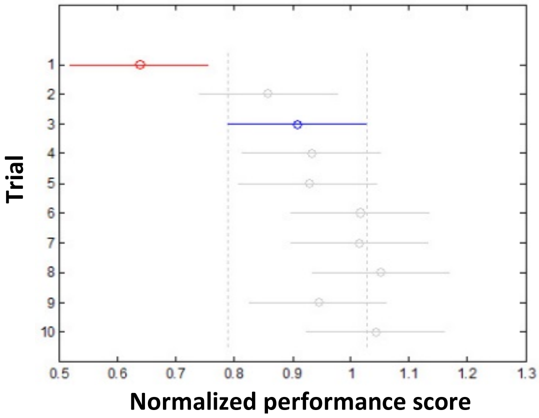


Figure 5.19: Performance score, AP component

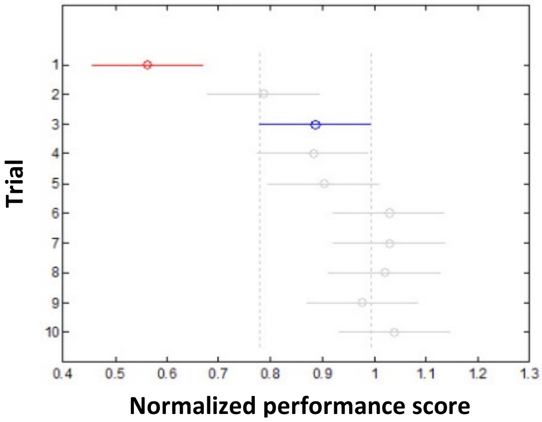


Figure 5.20: Performance score, whole signal

The following figures and table show the results of the motor performance laws.

The learning trend for *m* coefficient of Hick's law is depicted in Figure 5.21, normalized with the average of the last six trials.

Figure 5.22 illustrates for each target size the goodness of fit (R^2) of speed-accuracy trade-off (Fitts' law), which is calculated for the original index of difficulty (ID), for the effective ID (IDe) and for the effective index of difficulty calculated considering the tilt angle (IDet, Equation 5.4). In this latter case the R^2 results are shown across trials.

Figure 5.23 illustrates the learning trend of movement time (MT) to reach the target for each considered target size. The MT results regard an IDe and an IDet equal to 5, and they are normalized with the average of the last six trials. The regression coefficients of the learning trends are reported in Table 5.10.

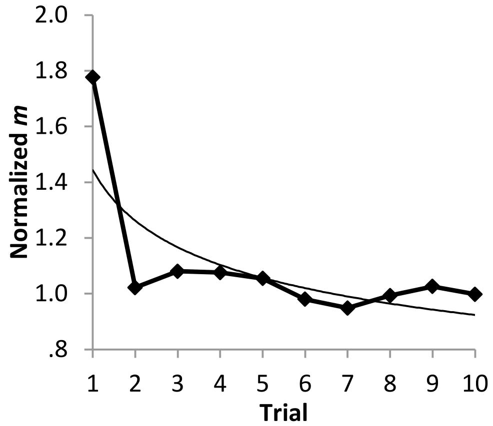


Figure 5.21: Hick's normalized *m* coefficient. Power law of practice regression coefficients: *b*=1.444, *m*=-0.194, R^2=0.62.

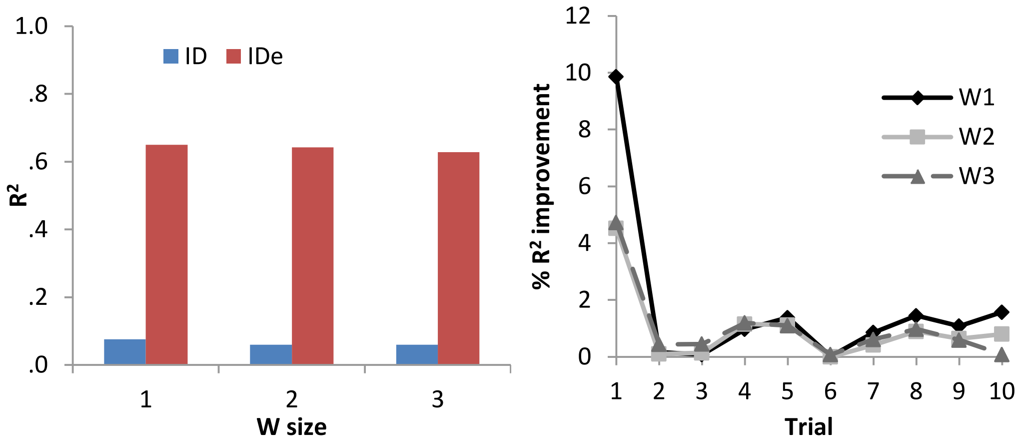


Figure 5.22: Comparison of regression R^2. Left: comparison between the original Fitts' law (ID) and effective ID. Right: influence of the maximum tilt angle on the modified Fitts' law.

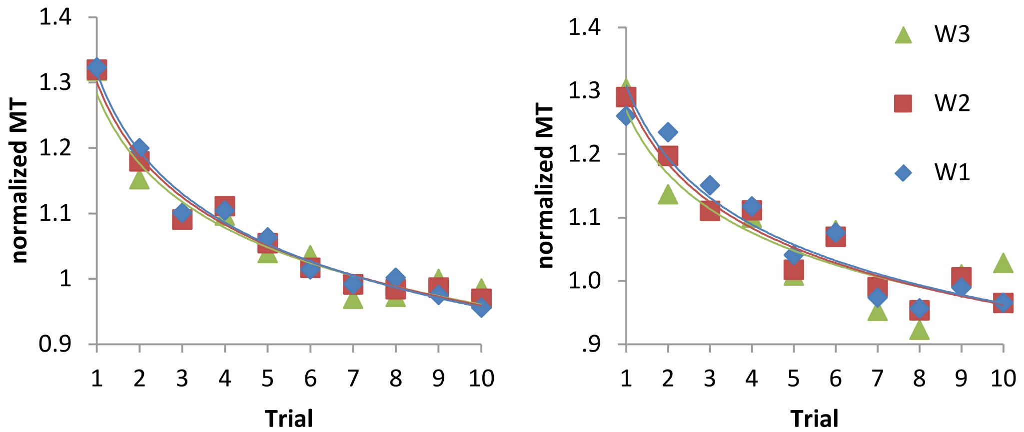


Figure 5.23: Learning trend for Fitts' law for each target size (W). Fitts' law is calculated with IDe=5 (left) and with IDet=5 (right).

Table 5.10: Regression coefficients for power law of practice calculated on Fitts' results (normalized data).

Target size	Regression for IDe=5			Regression for IDet=5		
	b	***m***	**R^2**	***b***	***m***	**R^2**
W1	1.316	-0.138	0.98	1.309	-0.133	0.91
W2	1.301	-0.132	0.97	1.295	-0.129	0.93
W3	1.283	-0.126	0.94	1.283	-0.123	0.77

Discussion

Results summarized in the Table 5.9 are homogeneous across all samples which points toward the consistency and reliability of the conceived methodology to measure DA performance. This test can be considered as a not impaired state giving the fact that all subjects declared to be free from impairment of any condition that would influence their equilibrium abilities.

Considering the learning trend shown in Figure 5.6-Figure 5.11 and Figure 5.12-Figure 5.13 there is a noticeable improvement between the first trials and last ones except for the medio-lateral cross correlation lag. The learning trend is exhausted after the second trial although there is a not significant slight improvement till about the forth trial. In fact, at the beginning the subjects familiarize themselves with the equipment and test protocol by practicing their movements in target pursuit, discriminate between symbols and appropriately react by using the trigger device. Similarly, the performance score shows a learning trend that is exhausted within two trials. Moreover, LLE shows a weak chaotic dynamics since the degree of sensitivity to initial conditions is close to zero. Still, LLE is reduced across the trials.

Comparing the reaction time of the two tests, it is apparent that choice reaction test (CRT) reaction time is about three times higher than psychomotor vigilance test (PVT) simple reaction time (0.697s against 0.212s). That is because there are different neural mechanisms involved in the two tests as described by the Hick's law, and also because in the CRT the subject is moving in order to follow the target while in the simple reaction test the subject stays still.

Furthermore, the tests are also different by the kind of stimuli used. In the PVT simple reaction time, it is very easy to identify the event when the screen switches from black to white color as it is a strong visual stimulus. Whereas in the second test the subject has to involve cognitive mechanism to discriminate between the two symbols. Therefore, the first case facilitates the possibility of a straight reaction with little delay as the motor neuronal mechanism can be pre-activated for this particular movement.

Moreover, looking at the critical tracking test (CTT) cross-correlation lag, which is connected with the delay of the subject's tracking movement, it is found an about two times higher reaction time comparing with the CRT reaction time test (1.211s against 0.697s). In fact, as the subject usually adopts an ankle strategy to pursuit the target, the neuronal signal has a longer path to cover. It also should be taken into account the higher inertia as the full body must move while in the first case just the finger is involved. Furthermore, there is a mutual influence between target pursuing and triggering because by being performed at the same time they slow down each other.

With regard to the motor performance laws, both Hick’s and Fitts’ law show improved performance with trials. Figure 5.21 shows that learning in Hick’s law results lasts one trial, which is of course consistent with the results of CRT of Figure 5.12, but the power law of practice fits moderately well. On the contrary, power law fits generally very well for Fitts’ results, with the exception to IDet - W3 in which it fits moderately well. Table 5.10 shows a decrease of *m* coefficient which means that learning phase increases according to the target size. This can be considered a floor effect of the measured parameter as with W2 and W3 MT increases respectively with an average of 3.5% and 5%.

Figure 5.22 allows to draw considerations also of the index of difficulty. Regarding the original ID the goodness of fit is quite scarce, conversely a great improvement is found considering IDe, which is about 15 times better than ID with constant trend across target size and trials. This means that the model of modified Fitts’ law describes quite well the speed-accuracy trade-off also when pointing tasks are executed through postural movements.

A further improvement is found when the maximum tilt angle of the subject is considered, but it influences R^2 in a different extent across the trials: at the beginning there is more influence, then the improvement ranges from 0% to 2%. This means that tilt control is involved in the learning of the task. Moreover, the goodness of fit is not reduced if the tilt angle is incorporated into the model of Fitts’ law, but it slightly reduces the fit of power law of practice model, in particular the data points spread out in the last trials (Figure 5.23). Other tilt angles have also been considered (initial, final, mean angle) but the maximum angle value provides the best improvement in R^2.

5.2.2. Divided attention test: second set

In this experiment, some of the subjects that underwent the first set are reassessed. The purpose of this experiment is to verify long term motor memory retention of the gestures related to the protocol proposed in paragraph 5.1.1, to verify if there is a learning phase and if the overall performance is different from the previous set. The results of the cross-correlation, the choice reaction test and the psychomotor vigilance test of this set are also reported in Rossi and Pascolo (2015) (permission obtained).

Materials and methods

Eleven healthy subjects participated in this study but one was excluded due to technical problems, therefore only ten subjects are considered (5 females and 5 males, age=30.1±11.2 years, height=1.69±0.08m, weight=67.1±9.4kg). All participating subjects denied pathologies or being under the influence of psychotropic substances before one set on trial and declared that they did not use or trained on any stabilometric platform between the two sets. Participants were voluntary and were not paid.

The protocol, materials, methods and analysis used here in this work are presented in paragraph 5.1.1, except for what is reported below.

The subjects firstly went through the protocol test (first set) and then after about six months (180 days) they repeated it again (second set).

Before starting the second set, informed consent was obtained and each subject was asked if he/she remembered the protocol and if so, he/she was asked to describe it. Still, the experiment was re-explained and subjects could take again confidence with their body movements and the sensibility of the CoP displayed on the screen.

The IBM SPSS statistics software (IBM – Armonk NY, U.S.A.) was used for all statistical analysis as it provides useful tools to analyze repeated and dependent variable data.

The learning effect of the singular set was analyzed using univariate GLM repeated-measures (interaction model, type-3 sum of squares, alpha level 0.05, Helmert's contrast, Holm-Bonferroni's correction) with normalized data. If Mauchly's test indicated a violated sphericity, conservative the Greenhouse-Geisser's correction was chosen. To compare the results of the two set of trials multivariate GLM repeated-measures analysis (interaction model, type-3 sum of squares, alpha level 0.05) was performed between the last four trials of the first set and the first four trials of the second set. Partial η^2 is listed for effect size.

Motor performance laws are compared through regression coefficients *b, m* and R^2, respectively the shift coefficient, the learning rate, and the fitting goodness of the model. Learning effect is analyzed with the power law of practice on data normalized with the average of the last six trials.

Results

The performance of the divided attention test is evaluated by the cross-correlation of the subject's CoP signal and the target signal, both as a whole data set as well as divided into its medial-lateral plane (ML) and anterior-posterior plane (AP) component. The coefficient of the cross-correlation represents the quality of which the subject CoP overlaps the target signal, while the lag of the cross-correlation represents the delay of the subject's movement to reach the new target. The choice reaction test performance is assessed by the reaction time (combined reaction time) and the correctness of the response (correctness score).

Table 5.12 first set results shows learning effect similar to the results of set 1 (DA – formal Learning, set 1), except for whole signal cross-correlation lag, correctness score and choice reaction test reaction time, in which there is not significant learning effect. However, for the first two (whole signal cross-correlation lag and correctness score) the significance is near the alpha level (0.05) and the effect size level is respectively high (partial $\eta^2 \approx .26$) and medium (partial $\eta^2 > .13$).

This suggests that there is not a significance difference due to limited number of subjects involved. In other words, a larger sample size may lead to a significance difference. The choice reaction test reaction time shows a decline trend between the first and the second trial (Figure 5.30) but the null hypothesis cannot be rejected even though there is a medium effect size (partial $\eta^2 \approx .13$).

Learning effect in the second set of trials is absent (Table 5.12) in all parameters but in LLE. Moreover, in the PVT simple reaction test the Helmert's contrast results for "trial 1 vs later" ($F(1,9)=8.13$, corrected $p=.152$, partial $\eta^2 \approx .475$) shows high effect size (partial $\eta^2 > .26$) suggesting that non-significance might be due to small sample size. The initial trend is comparable with the first set (Figure 5.32).

Except for the medio-lateral component of the cross-correlation coefficient, results reported in Table 5.11 show no significant difference in performance between the first set last four trials and the second set first four trials.

In the second set all subjects but one remembered the test execution and approximately also the meaning of symbols appearing on the screen. Furthermore, right at the end of the first trial all subjects already reported good confidence with the protocol.

The absolute results of the two sets (average and their confidence interval) are shown in Figure 5.24-Figure 5.35. The data are grouped by test (x-axis) and set. The first set is identified by black squares and solid line while the second set of trials are identified by grey diamonds and dashed line.

Table 5.11: Multivariate repeated measures comparison between the last four trials of the first set and the first four trials of the second set [modified from (Rossi and Pascolo, 2015)**].**

Parameter	Cross-correlation	
	Coefficient	Lag
CTT ML component	$F(3,7)=5.52$, $p<.05$, partial $\eta^2=.703$	$F(3,7)=0.74$, $p=.563$, partial $\eta^2=.240$
CTT AP component	$F(3,7)=1.11$, $p=.406$, partial $\eta^2=.323$	$F(3,7)=0.16$, $p=.918$, partial $\eta^2=.065$
CTT Whole signal	$F(3,7)=1.93$, $p=.213$, partial $\eta^2=.453$	$F(3,7)=0.50$, $p=.692$, partial $\eta^2=.177$
CRT Correctness score	$F(3,7)=1.38$, $p=.326$, partial $\eta^2=.372$	
CRT reaction time	$F(3,7)=0.09$, $p=.962$, partial $\eta^2=.038$	
PVT Simple reaction time	$F(3,7)=1.37$, $p=.328$, partial $\eta^2=.370$	
CTT LLE ML component	$F(1,9)=0.49$, $p=.502$, partial $\eta^2=.052$	
CTT LLE AP component	$F(1,9)=1.11$, $p=.320$, partial $\eta^2=.399$	
CTT LLE Whole signal	$F(1,9)=0$, $p=.110$, partial $\eta^2=.02e-3$	

Table 5.12: Comparison of the learning effect. For each parameter and set it is indicated the trial at which there is no more statistical difference (Helmert's contrast) and the set within-subjects results (*F*, *p* and *η*) [modified from (Rossi and Pascolo, 2015)**].**

Parameter	First set		Second set	
	Cross-correlation		Cross-correlation	
	Coefficient	Lag	Coefficient	Lag
CTT ML component	2nd, $F(2.94,26.50)=4.48$, $p<.012$, partial $\eta^2=.332$	None, $F(3.28,29.59)=1.24$, $p=.315$, partial $\eta^2=.121$	None, $F(1,26)=1.90$, $p=.157$, partial $\eta^2=.174$	None, $F(3.29,29.62)=0.90$, $p=.461$, partial $\eta^2=.091$
CTT AP component	3rd, $F(3.49,31.45)= 6.57$, $p<.001$, partial $\eta^2=.422$	2nd, $F(1.93,17.42)=6.71$, $p<.01$, partial $\eta^2=.427$	None, $F(9,81)=0.86$, $p=.563$, partial $\eta^2=.087$	None, $F(2.60,23.37)=0.62$, $p=.589$, partial $\eta^2=.064$
CTT Whole signal	3rd, $F(9,81)=9.71$, $p<.001$, partial $\eta^2=.519$	None, $F(2.31,20.83)=3.13$, $p=.058$, partial $\eta^2=.258$	None, $F(3.24,29.17)=1.49$, $p=.237$, partial $\eta^2=.142$	None, $F(3.62,32.56)=0.58$, $p=.665$, partial $\eta^2=.060$
CRT Correctness score	None, $F(9,81)=1.99$, $p=.052$, partial $\eta^2=.181$		None, $F(4.48,40.36)=0.38$, $p=.840$, partial $\eta^2=.041$	
CRT Reaction time	None, $F(9,81)=1.03$, $p=.422$, partial $\eta^2=.103$		None, $F(9,81)=0.84$, $p=.516$, partial $\eta^2=.085$	
PVT Simple reaction time	2nd, $F(4.16,37.49)=4.70$, $p<.01$, partial $\eta^2=.343$		None, $F(2.95,26.57)=1.10$, $p=.366$, partial $\eta^2=.110$	
CTT LLE ML component	3rd, $F(9,135)=7.20$, $p<.001$, partial $\eta^2=.324$		None, $F(9,117)=1.42$, $p=.189$, partial $\eta^2=.098$	
CTT LLE AP component	5th, $F(9,135)=9.95$, $p<.001$, partial $\eta^2=.399$		3rd, $F(9,117)=6.05$, $p<.001$, partial $\eta^2=.318$	
CTT LLE Whole signal	3rd, $F(9,135)=5.03$, $p<.001$, partial $\eta^2=.251$		3rd, $F(9,117)=3.40$, $p<.01$, partial $\eta^2=.207$	

Cross-correlation coefficient	Cross-correlation lag [s]

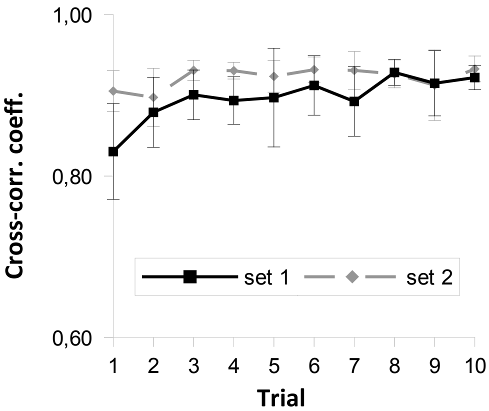


Figure 5.24: CTT Cross-correlation coefficient for the ML CoP component

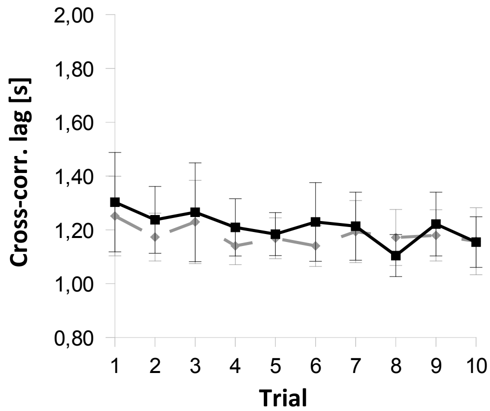


Figure 5.25: CTT Cross-correlation lag for the ML CoP component [s]

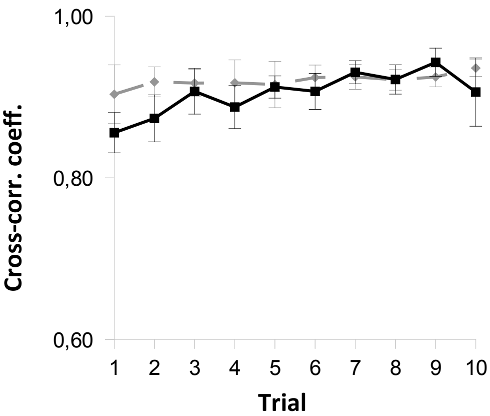


Figure 5.26: CTT Cross-correlation coefficient for the AP CoP component

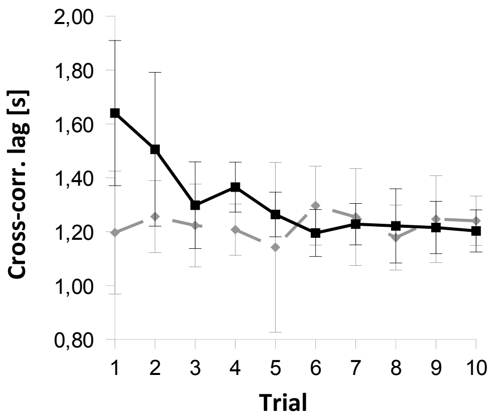


Figure 5.27: CTT Cross-correlation lag for the AP CoP component [s]

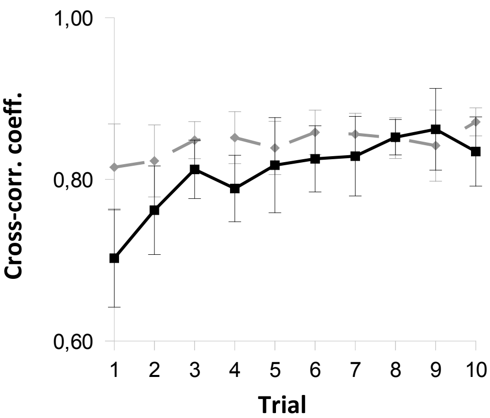


Figure 5.28. CTT Cross-correlation coefficient for the whole CoP signals

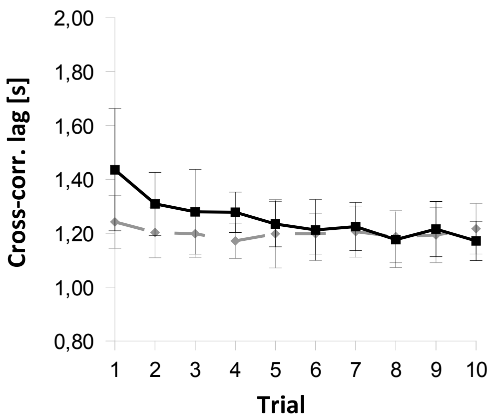


Figure 5.29: CTT Cross-correlation lag for the whole CoP signals [s]

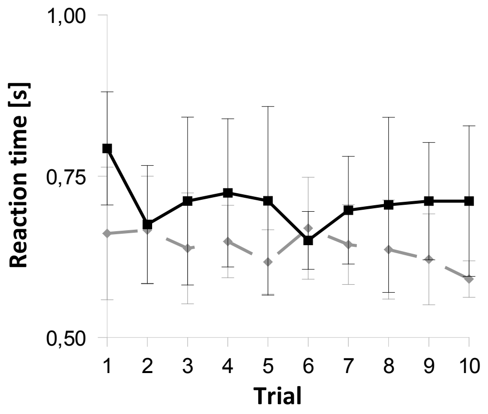


Figure 5.30: CRT reaction time [s]

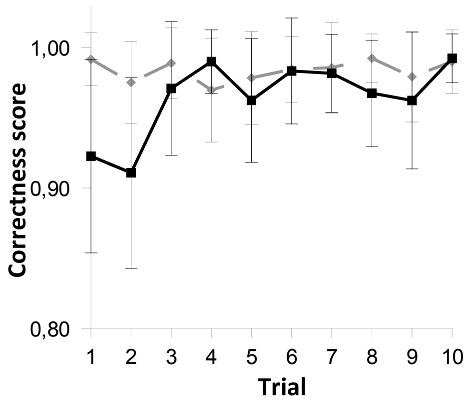


Figure 5.31: CRT correctness score

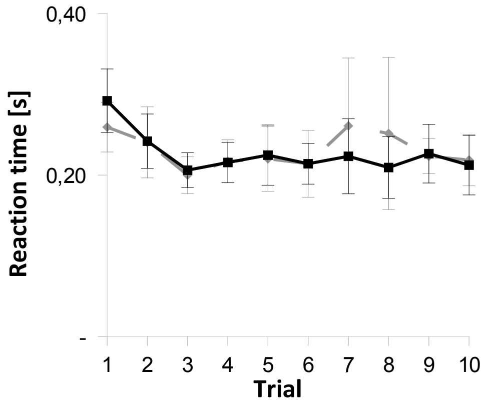


Figure 5.32: PVT Simple test reaction time [s]

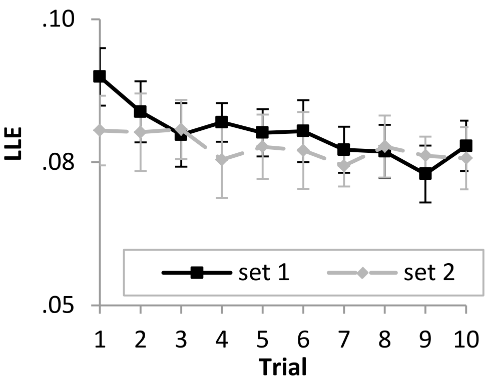


Figure 5.33: LLE for the ML CoP component

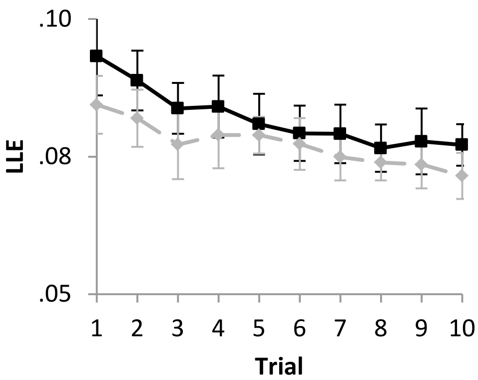


Figure 5.34: LLE for the AP CoP component

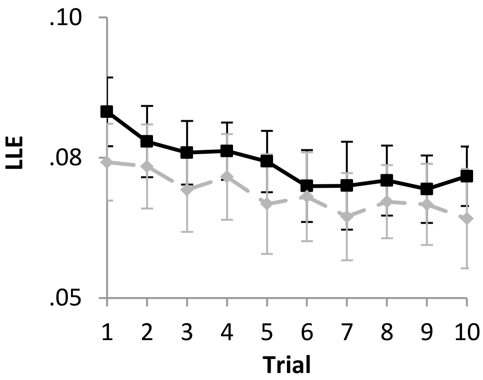


Figure 5.35: LLE for the whole CoP signal

The following figures and table show the results of the motor performance laws.

The comparison between the two sets for *m* coefficient of Hick's law is illustrated in Figure 5.36, which depicts also the best fitting regression: power for set 1 and linear for set 2. Learning trend is illustrated through the regression coefficients calculated on the *m* normalized data. The coefficients are compared in Table 5.13.

Figure 5.37 illustrates for each target size and trial the goodness of fit of speed-accuracy trade-off (Fitts' law) calculated considering the tilt angle (IDet, Equation 5.4), while Figure 5.38 illustrates the Fitts' law results for each set. Also in this case the best fitting regression is linear for set 2 and power for set 1. Table 5.14 shows the regression coefficients for the learning trend of the Fitts' law.

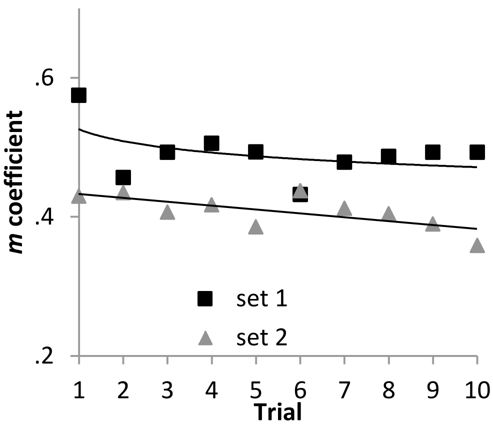


Figure 5.36: Comparison of *m* coefficient between the two sets.

Table 5.13: Regression coefficients for power law of practice calculated on Hick's results (normalized data).

Set	Regression coefficients		
	b	***m***	R^2
Set 1 (power)	1.445	-0.194	0.62
Set 2 (linear)	1.121	-0.017	0.73

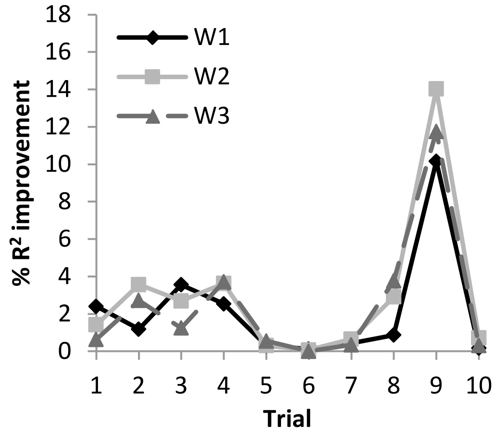


Figure 5.37: Comparison of influence of the maximum tilt angle on the modified Fitts' law for set 2.

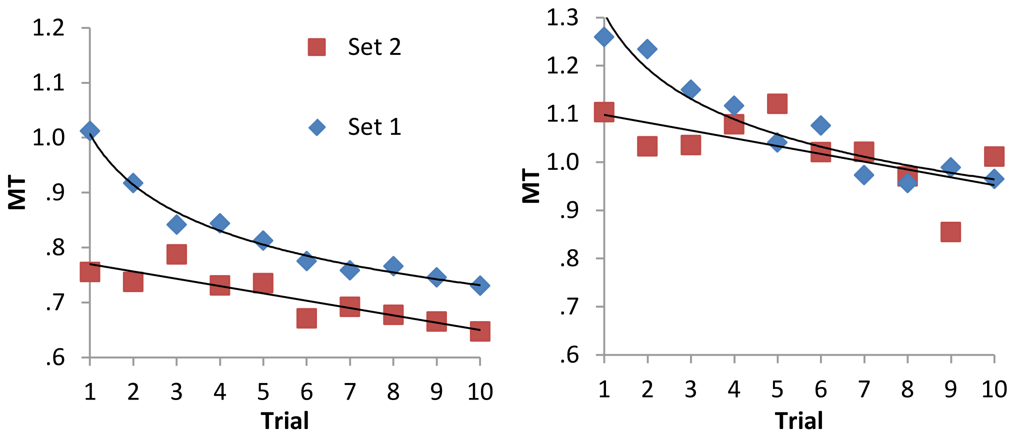


Figure 5.38: Learning trend for Fitts' law for each set with W1 target size. Fitts' law is calculated with IDe=5 (left) and with IDet=5 (right).

Table 5.14: Regression coefficients for power law of practice calculated on Fitts' results (normalized data).

Set	Regression for IDe=5			Regression for IDet=5		
	b	*m*	R^2	*b*	*m*	R^2
Set 1 (power)	1.316	-0.139	0.98	1.309	-0.133	0.91
Set 2 (linear)	1.150	-0.020	0.79	1.114	-0.016	0.43

Discussion

Similarly to the results shown in paragraph 5.2.1, the first set learning effect does not last beyond the second repetition. Therefore, also in the set 2, where the sample size is smaller the third trial can be considered as effective. Even though three parameters do not show statistical learning effect like in DA - Formal Learning set 1, their effect size suggests that non-significance is probably due to limited sample size. In fact, this experiment considers a subset (10 subjects) of the subjects previously involved (15 subjects).

In the second set, despite the subjects only approximately remember the actions related to Driving while Impaired assessment test (Figure 5.24-Figure 5.30), they do not show any performance gain. Therefore, the subjects have learnt the gestures as they preserved gross and fine motor strategies and the coordination between the two tasks. Also the performance of the first four trials of the second set is similar to the last four trials of the first set (Table 5.11), except for a little higher performance in the medio-lateral component of the cross-correlation coefficient.

On the contrary, motor memory retention is disputed in LLE and in reaction time baseline test (PVT simple test reaction time). With regard to LLE, Table 5.12 demonstrates that even the second set subject show an improvement that lasts up to the third trial. This means that the subject still needs some trials to adapt to the postural perturbations involved in the target tracking movements. With regard to the PVT reaction time, although the null hypothesis cannot be fully rejected (Table 5.12), second set learning trend and first trial high effect size (partial $\eta^2 \approx .475$) indicate that there might not be motor retention for this parameter.

Comparing the performance reached in the two sets, Figure 5.24-Figure 5.35 show that the subjects do not achieve better results when they repeat the test after six months. Considering that the subjects self-declared they did not undergone posturographic tests meanwhile, the results are found to be repeatable when the divided attention test is conducted over time.

Regarding the motor performance models, it is interesting to notice that in set 2 both Hick's law and Fitts' law are best fitted with linear regression. Therefore, it seems that when the subjects repeat the test, the power law of practice is not valid anymore. However, due to the small *m* coefficients of set 2 the repeated trials are not sufficient to display a full negative accelerating curve, therefore this should be just a window of the last part of a power curve which is almost linear. In fact, Table 5.13 and Table 5.14 show that set 2 learning trend (*m* coefficient) presents a slower improvement rate than set 1.

Also the tilt angle influence on IDe has a different trend compared with the first set. Again the fitting improvement ranges from 0% to 4%, but the peak is on the ninth trial not on the first. Few reasons can explain this trend. First, the subject retained the motor gestures, which comprise also the tilt control, and thus there is not an initial improvement peak in R^2. Second, also in the first set R^2 trend is rising in the last trials, which means that the controller is searching for new solutions or is adapting to the fatigue.

5.2.3. Divided attention test: imitation group

In this experiment subjects underwent the DA protocol, but instead of verbally explaining the test (formal learning), the experimenter performed it once and the subject had to replicate it (imitation). The purpose was to compare the two learning approaches in regard to gross and fine motor gestures.

Materials and methods

The materials, methods and the protocol used here in this work are presented in paragraph 5.1.1, except for what is reported below.

30 healthy students participated in this study. The methodology of protocol explanation differed between two distinct groups of subjects. The group A was composed of 14 subjects (7 males and 7 females, age = 24.8 ± 3.7 years, height = 1.71 ± 0.09m, weight = 68±11.8kg), while the group C was composed of 16 subjects (9 males and 7 females, age = 22.3 ± 3.2 years, height = 1.74 ± 0.09m, weight = 79 ± 15.6kg). Note that in this work group B is related to other experiments.

The participants declared that they had never undergone posturographic tests before and were free from any disease or pathology that could affect their equilibrium. Informed consent to the testing was obtained from all the participants. Subjects in group A had shown and verbally explained the instrumentation, the symbols that would appear on the screen and their function as well as the objective of the test. The test instructions were given to them only verbally and no motor gestures that they should perform were either mimicked or shown. To the subjects in group C the test was demonstrated one time at the beginning of the set of trials by the experimenter and no verbal instructions on how to execute the test were given. The subject was positioned so that he/she could observe both the motor gestures of the experimenter and what was happening on the screen.

The test was introduced to the subject by the following words: "This is a balance platform and this is a button (which was held in the hand). Now I will perform the test once. You have to watch what I am doing and what is happening on the screen, then you will have to repeat it 10 times". No further indication was given to the subject and the investigator did not comment on the exercise quality. Before starting the repetitions of the test, both groups could familiarize themselves with the instrumentation. At the end of the set of 10 repetitions, the group C was asked to explain the meaning of the symbols that appeared on the screen and the actions associated with them. Informed consent was modified according to this methods.

To compare the results of the two groups the n-way analysis of variance was performed. The function *anovan* (with the interaction model and type-3 sum of squares) of the statistical package available in Matlab (Mathworks - Natick MA, U.S.A.) was used. The data for each parameter and for each subject were first normalized according to the average of their last six repetitions. The *anovan* results were used in *multcompare* Matlab function (with the Tukey's honestly significant difference criterion, alpha level of .05) and its graphic output was reported.

The IBM SPSS statistics software (IBM – Armonk NY, U.S.A.) was used to compare the two groups. Univariate GLM repeated-measures analysis (interaction model, type-3 sum of squares, alpha level 0.05, between subjects factor: group) was performed between the data sets of the two groups.

Motor performance laws are compared through regression coefficients *b, m* and R^2, respectively the shift coefficient, the learning rate, and the goodness of fit of the model. Learning effect is analyzed with the power law of practice on data normalized with the average of the last six trials.

Results

The comprehension of the two tasks varied among subjects according to the task. Both groups properly understood the first task (target following) but one subject from group A did not understand how to follow the target on the anterior-posterior plane. None of the subjects had confused the target signal with the dummy signals. The second task (visual cue) was properly understood by group A and by 62.5% of group C (10 subjects). In fact, 37.5% of group C (6 subjects) either did not perform properly the second task or deduced a different goal for it.

The first task performance was evaluated by the cross-correlation of the subject's CoP signal and the target signal, both as a single data curve as well as divided into its medial-lateral plane (ML) and anterior-posterior plane (AP) component. The coefficient of the cross-correlation represents the quality of which the subject CoP overlaps the target signal, while the lag of the cross-correlation represents the delay of the subject's movement to reach the new target. The second task performance was assessed by the visual cue reaction time (combined reaction time) and the correctness of the response (correctness score).

The learning effect of the group C is shown by the graphical result of the *multcompare* function (Figure 5.39-Figure 5.50). The red color rows indicate results that are statistically different from the blue colored row, which are selected as a test parameter reference. Results for the combined reaction time (Figure 5.45) and correctness score (Figure 5.46) regard only subject that understood trigger functionality. Otherwise the data would be invalidated by a non-sense triggering.

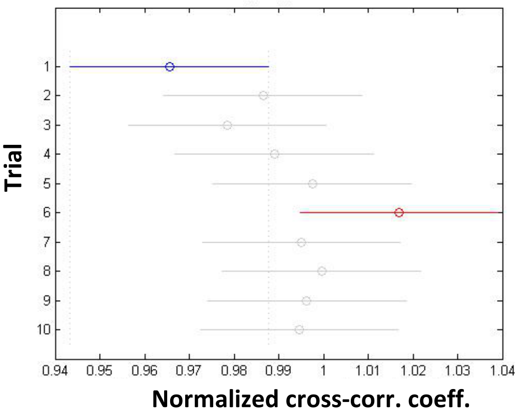


Figure 5.39: CTT Cross-correlation coefficient for the ML CoP components

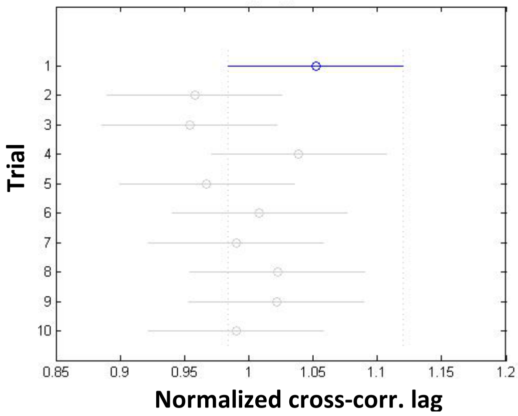


Figure 5.40: CTT Cross-correlation lag for the ML CoP components

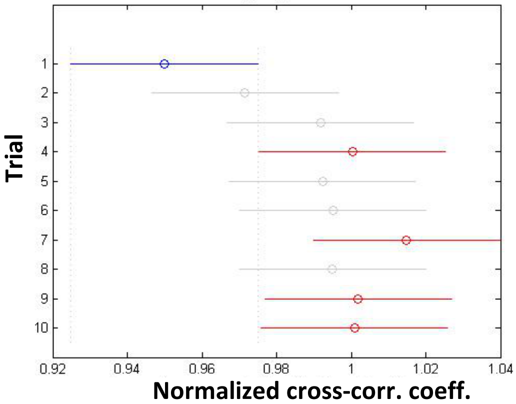


Figure 5.41: CTT Cross-correlation coefficient for the AP CoP components

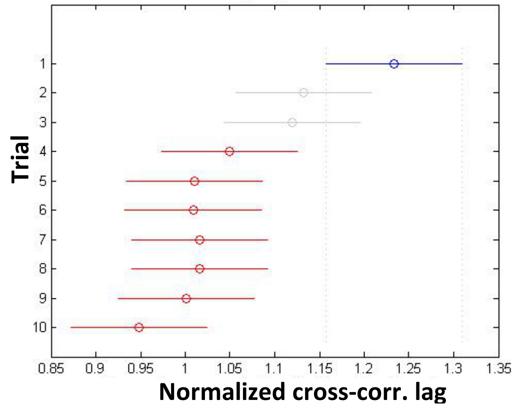


Figure 5.42: CTT Cross-correlation lag for the AP CoP components

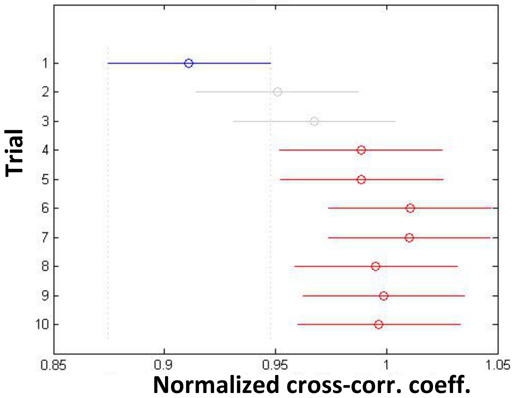


Figure 5.43: CTT Cross-correlation coefficient for the whole CoP signals

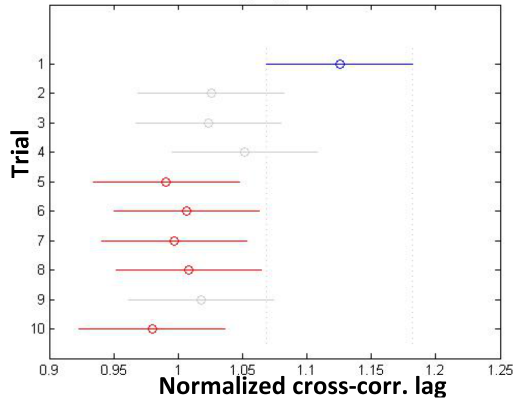


Figure 5.44: CTT Cross-correlation lag for the whole CoP signals

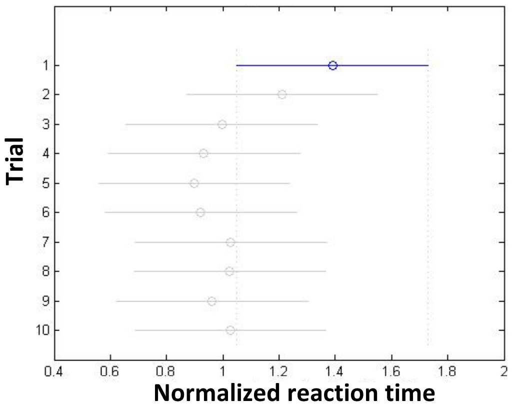


Figure 5.45: CRT reaction time (only subjects that understood the trigger functionality)

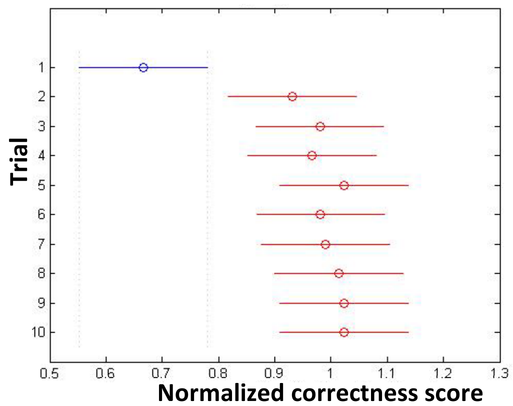


Figure 5.46: CRT Correctness score (only subjects that understood the trigger functionality)

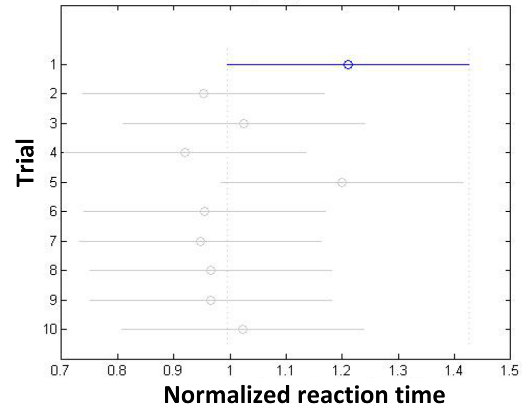


Figure 5.47: PVT Simple test reaction time

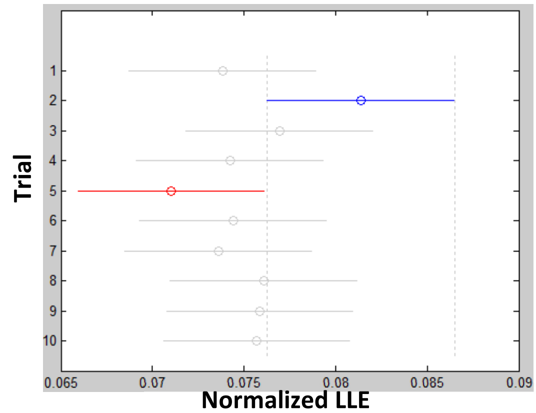


Figure 5.48: LLE for the ML CoP component

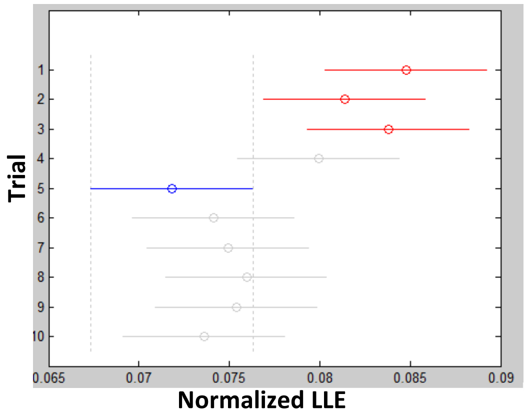


Figure 5.49: LLE for the AP CoP component

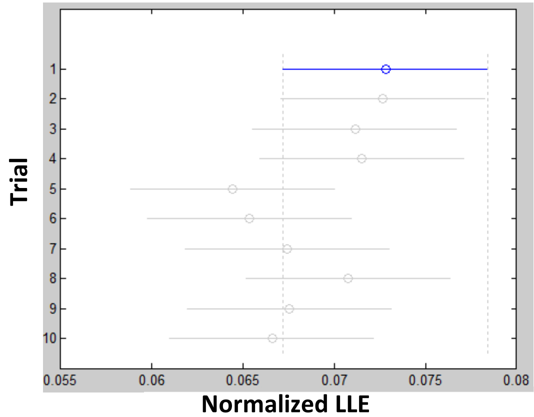


Figure 5.50: LLE for the whole CoP signal

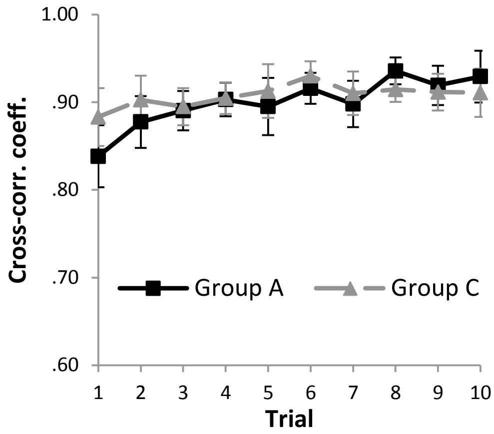


Figure 5.51: CTT Cross-correlation coefficient for the ML CoP components

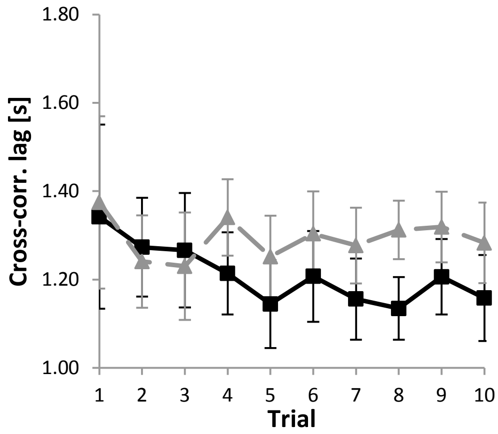


Figure 5.52: CTT Cross-correlation lag for the ML CoP components

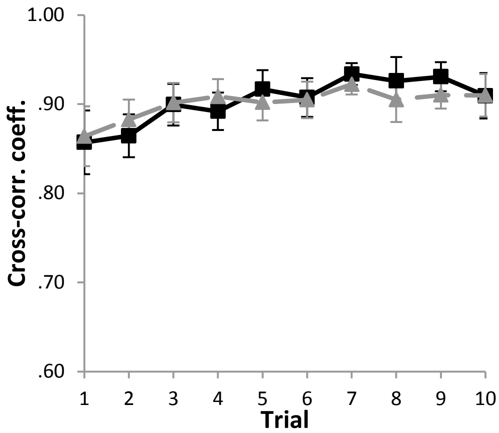


Figure 5.53: CTT Cross-correlation coefficient for the AP CoP components

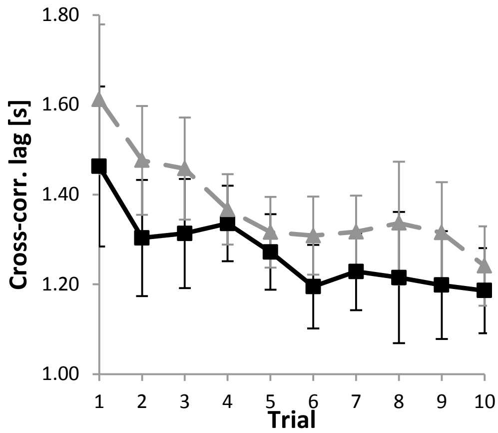


Figure 5.54: CTT Cross-correlation lag for the AP CoP components

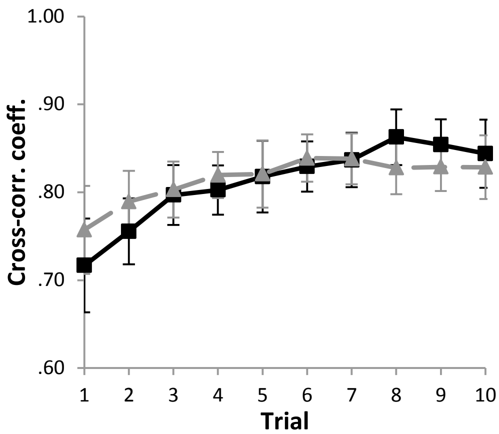


Figure 5.55: CTT Cross-correlation coefficient for the whole CoP signals

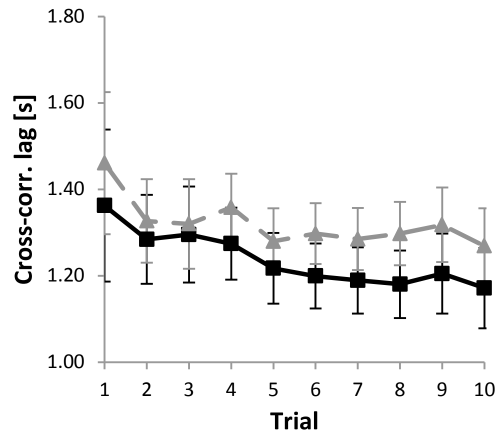


Figure 5.56: CTT Cross-correlation lag for the whole CoP signals

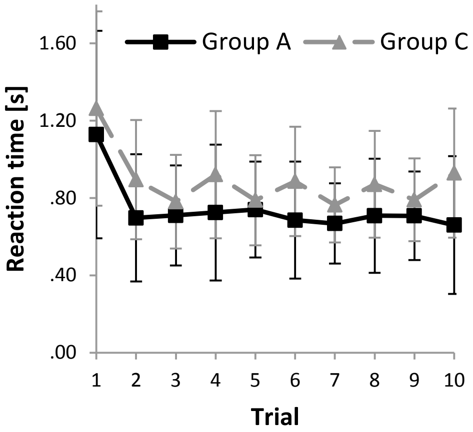


Figure 5.57: CRT reaction time (excluding subjects that did not understood the trigger functionality)

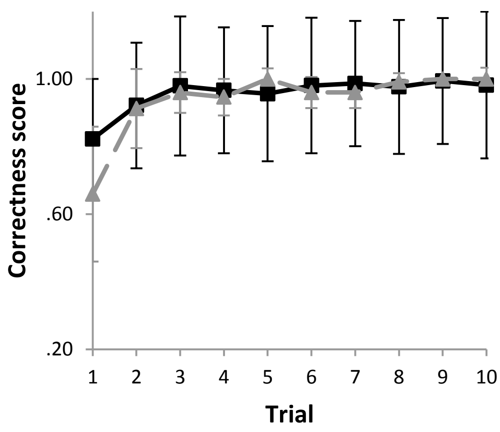


Figure 5.58: CRT correctness score (excluding subjects that did not understood the trigger functionality)

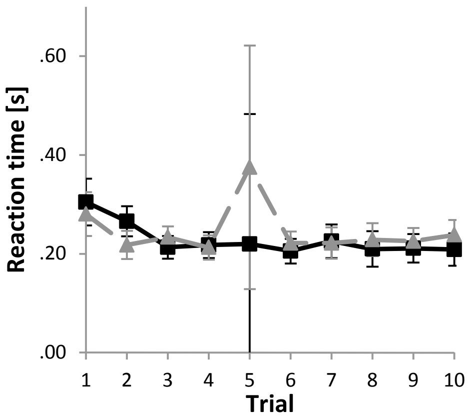


Figure 5.59: PVT Simple test reaction time [s]. There is an outliner result in trial 5 of group C

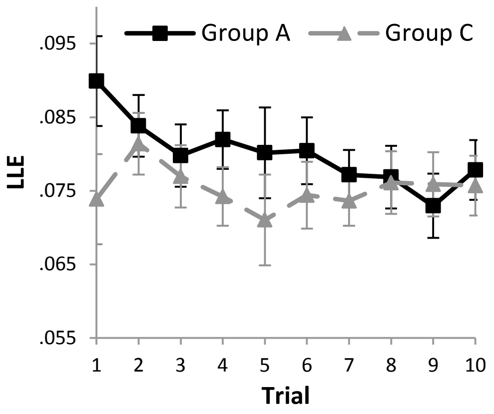


Figure 5.60: LLE for the ML CoP component

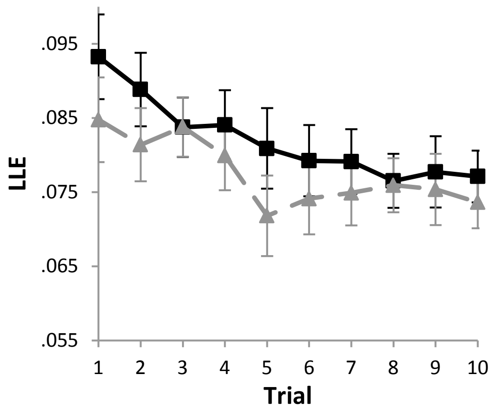


Figure 5.61: LLE for the AP CoP component

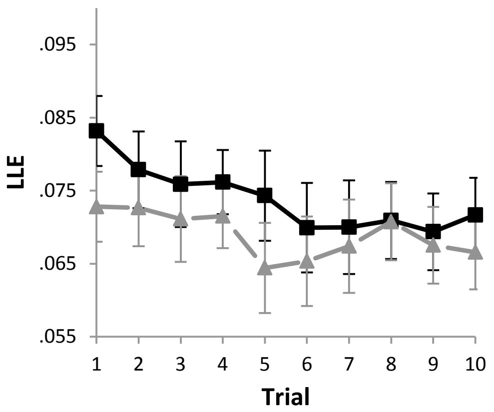


Figure 5.62: LLE for the whole CoP signal

The interviews revealed that all subjects in group C correctly identified the target signal related to the first task. However, only three subjects correctly guessed the meaning of dummy signals and the others did not. For the second task the results were as follows: three subjects did not link any meaning neither to the button nor to other symbols which appeared on the screen, three subjects associated them a different task, four subjects properly deduced the task while the remaining 6 were able to notice and correctly understand the link between the button and the symbol. Still, the entire group C expressed uncertainty about their deductions or observations.

The comparison between the absolute results of the two groups is represented by the mean of each test and the 95% confidence interval (Figure 5.51-Figure 5.62). group A and group C absolute values are respectively identified by a dot and a triangle, whereas the polynomial regression is respectively identified by a solid and dashed line. The values of the combined reaction time of the group C refer only to those who have understood correctly the second task.

The following figures and table show the results of the motor performance laws.

The comparison between the two groups for *m* coefficient of Hick's law are illustrated in Figure 5.63, which depicts also the fitting regression with power law of practice. Learning trend is illustrated through the regression coefficients calculated on the *m* normalized data. The coefficients are compared in Table 5.15.

Figure 5.64 illustrates for each target size and trial the goodness of fit of speed-accuracy trade-off (Fitts' law) calculated considering the tilt angle (IDet, Equation 5.4), while Figure 5.65 illustrates the Fitts' law results for each group whose regression coefficient of learning phase is reported in Table 5.16.

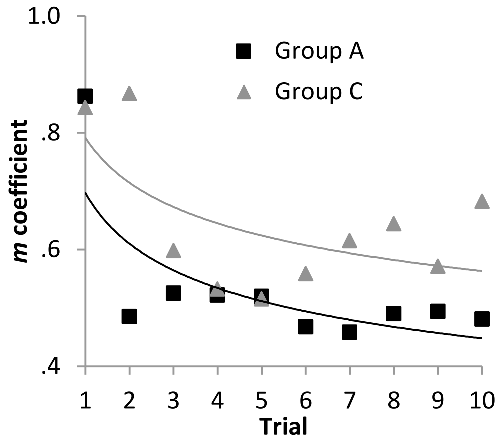


Figure 5.63: Comparison of *m* coefficient between the two groups (subjects that did not understood the trigger functionality are excluded).

Table 5.15: Regression coefficients for power law of practice calculated on Hick's results (normalized data).

Set	Regression coefficients		
	b	***m***	R^2
Group A (power)	1.445	-0.194	0.62
Group C (linear)	1.622	-0.080	0.67

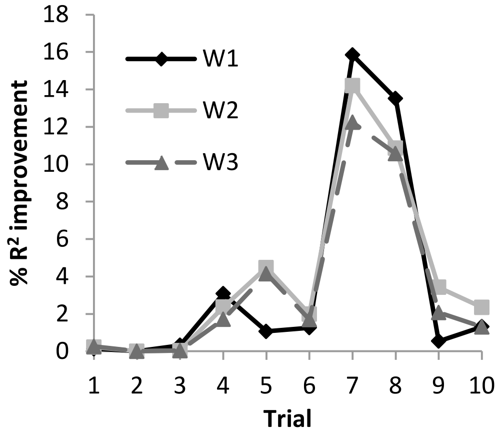


Figure 5.64: Influence of the maximum tilt angle on the modified Fitts' law for group C.

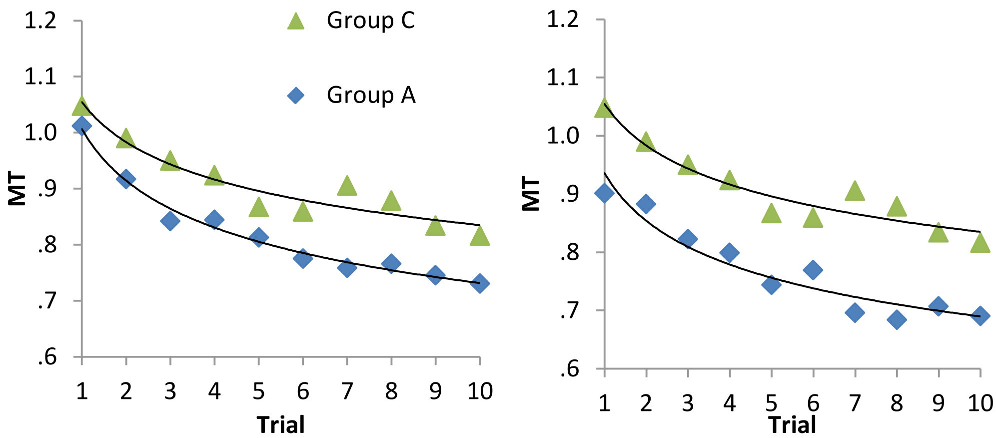


Figure 5.65.: Learning trend for Fitts' law for each group for W1 target size. Fitts' law is calculated with IDe=5 (left) and with IDet=5 (right).

Table 5.16: Regression coefficients for power law of practice calculated on Fitts' results (normalized data).

Set	Regression for IDe=5			Regression for IDet=5		
	b	*m*	R^2	*b*	*m*	R^2
Group A (power)	1.316	-0.139	0.98	1.309	-0.133	0.91
Group C (power)	1.226	-0.101	0.91	1.329	-0.139	0.91

Discussion

The majority of subject's results show trends similar to those presented in paragraph 5.2.1 (DA – Formal Learning, set 1), in fact both groups show significant differences between the first repetition and the other trials (Figure 5.39 - Figure 5.46). However, the number of repetitions required to reach a steady value as well as the overall performance varies according to the learning approach used. In group A, the CTT task shows a learning trend until the 4th -5th repetition, but from the third repetition the results become statistically similar (*p*>.05) to the remaining trials.

In the CRT task, both the correctness score and the combined reaction time reach a steady value after the first trial, while the psychomotor vigilance test (PVT), a simple reaction time follows the trend of the CTT task. Group C shows a smaller learning effect in the CTT task. The coefficient of the cross-correlation shows an effect up to 3rd – 4th repetition (Figure 5.39-Figure 5.43), while in the delay the trend reaches the 5th trial (Figure 5.40-Figure 5.44). However, from the second trial both parameters become statistically similar to the successive repetitions (*p*>.05), and only the last repetition has an AP delay significantly different from the result of the second trial (Figure 5.42). The largest Lyapunov exponent (LLE) for group C shows a learning trend only in the ML and AP plane which is respectively exhausted at the 3rd and 4th repetition whereas the group A shows learning effect also LLE calculated on the whole signal. Moreover, group C shows a slightly smaller dependency on initial conditions compared with group A.

These results are not differentiated between the subjects who have understood correctly the second task and those who did not, as no significant differences among them (*p*>.10) were found except for slight differences in CTT cross correlation lag. For the CRT task only the results of those who have understood the exercise were analyzed. The learning effect for the correctness score terminates immediately after the first trial, while for the reaction time the effect lasts until the third test (Figure 5.45-Figure 5.46); the simple reaction time presents a similar trend (Figure 5.47).

The accuracy and delay of the ML components of group C present similar results between trials whereas those of group A do not. The reason may be the fact that whereas the subjects of group A were instructed to keep their feet at shoulder width, the subjects of the group C were supposed to learn it by imitation; instead they tended to assume a wider stance, thus increasing their ML stability.

With regard to the motor performance models, the Hick's law for group C is better described by a linear law rather than the power law of learning (Table 5.15). Perhaps this is due to a slow learning rate (*m* coefficient) that does not allow to represent a full negatively accelerating curve, which is described with a power regression.

Figure 5.64 shows that considering the tilt angle IDe improves between 0% and 4% with a peak on the seventh and eighth trial. This trend is similar to group B which has retained the motor gestures of the DA task. It seems therefore that the observation of the experimenter gestures allowed to code in advance the perturbations related to the task but not the gesture coordination. In fact, the learning trend of the modified Fitts' law is similar to group A (*m* coefficient, Table 5.16). Figure 5.65 highlights that group C movement time is slower than group A, similarly to CTT cross-correlation lag.

5.2.4. Divided attention test: impaired subjects

A preliminary test on subjects that participated in a university get-together party has been carried out to investigate how degraded psychophysical conditions influence DA results. The purpose is to compare the overall performance and trend before and after the party with those of group A.

Materials and methods

Three male university students (height = 1.83 ± 0.02m) performed three trials of DA protocol before and after a university party. Informed consent was obtained before initiating the test, protocol information was verbally explained as for group A and questionnaire was also administered. The protocol instructions were not refreshed before commencing the test after the party. Subjects declared that they were healthy before initiating the first three trials, however information about their behavior during the party and their condition before initiating the last three trials was neither enquired nor recorded.

Since few subjects were measured, only the average is used to compare the results of this group (D) with group A.

Results

The means of DA and LLE are respectively illustrated in Figure 5.66 - Figure 5.74 and in Figure 5.75 - Figure 5.77. The means of the Hick's law and the Fitts' law are respectively depicted in Figure 5.78 and Figure 5.79. Since the break between the first three trials and last three trials was only a matter of few hours, they are not considered as separated sets but consequent trials except for PVT which was carried out twice (Figure 5.74).

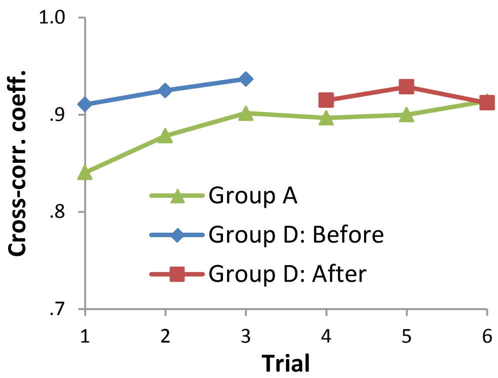


Figure 5.66: CTT Cross-correlation coefficient for the ML CoP component

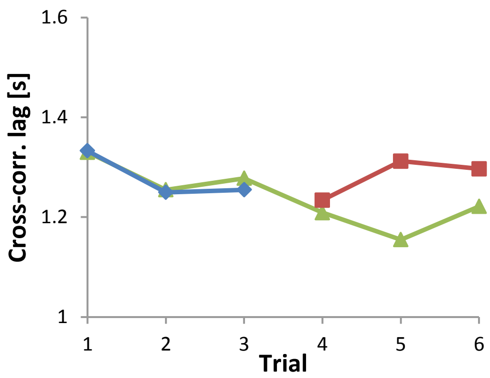


Figure 5.67: CTT Cross-correlation lag for the ML CoP component

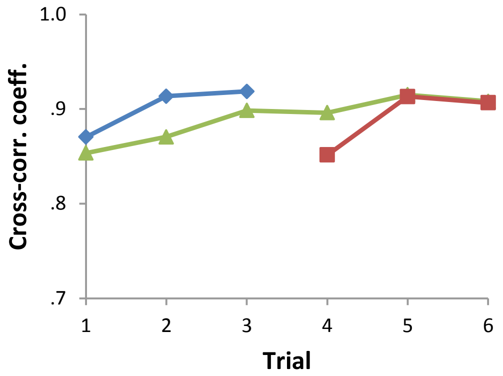


Figure 5.68: CTT Cross-correlation coefficient for the AP CoP component

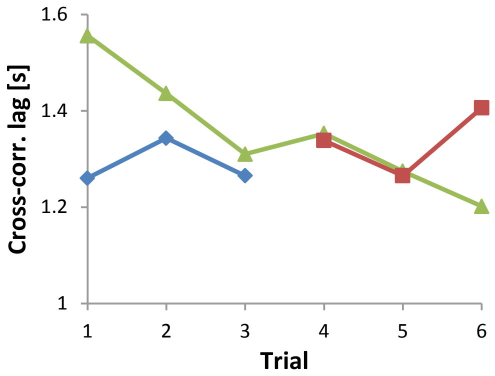


Figure 5.69: CTT Cross-correlation lag for the AP CoP component

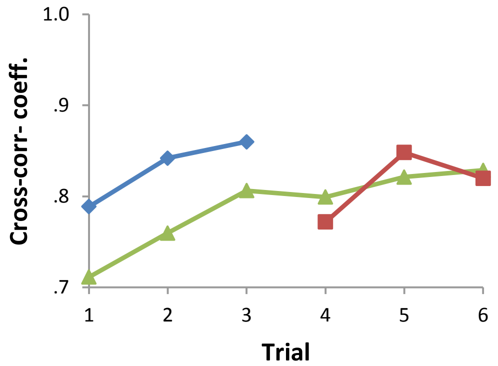


Figure 5.70: CTT Cross-correlation coefficient for the whole CoP signals

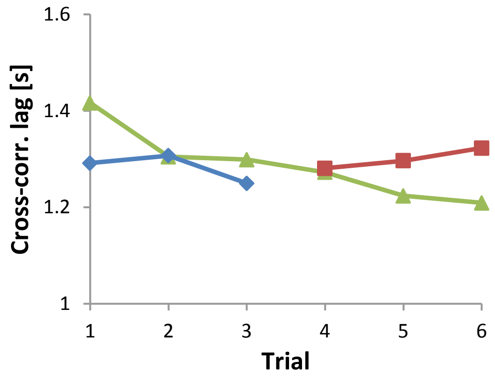


Figure 5.71: CTT Cross-correlation lag for the whole CoP signals

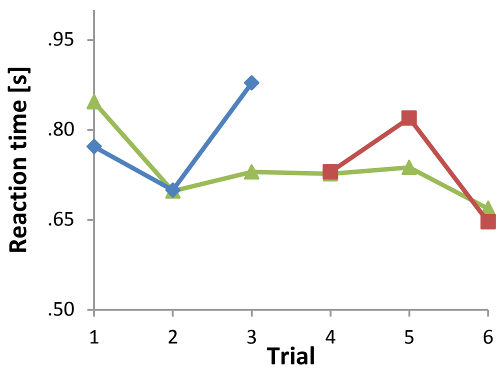


Figure 5.72: CRT reaction time

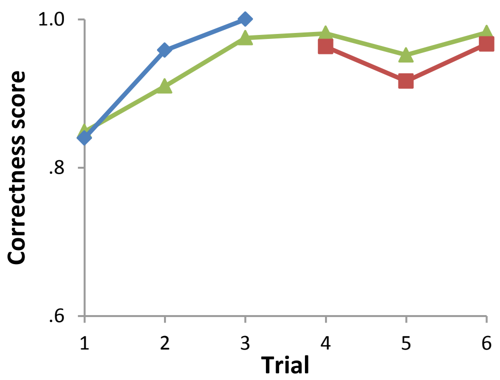


Figure 5.73: CRT correctness score

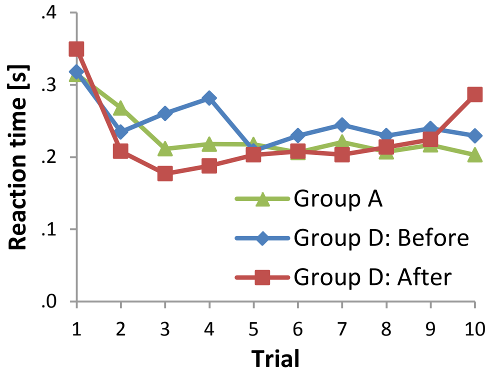


Figure 5.74: PVT simple reaction time

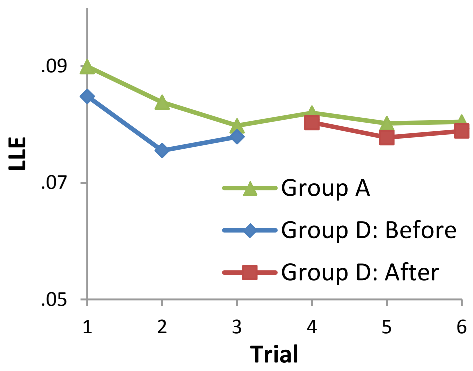


Figure 5.75: LLE for the ML CoP component

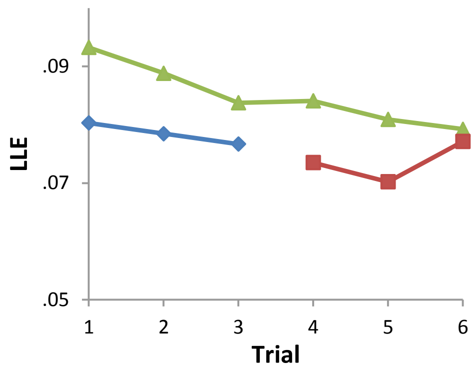


Figure 5.76: LLE for the AP CoP component

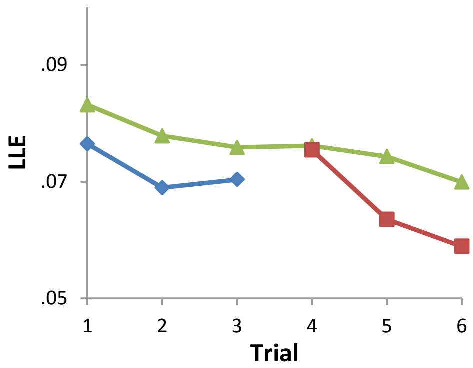


Figure 5.77: LLE for the whole CoP signal

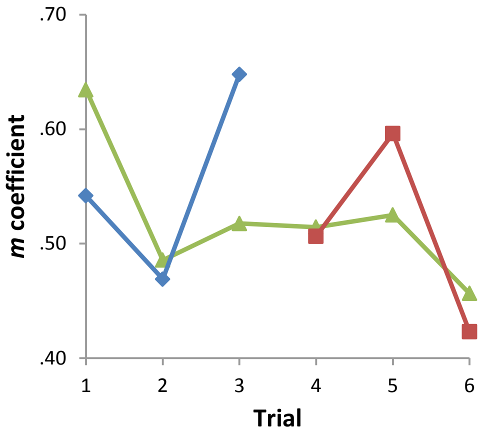


Figure 5.78: Comparison of Hick's law *m* coefficient.

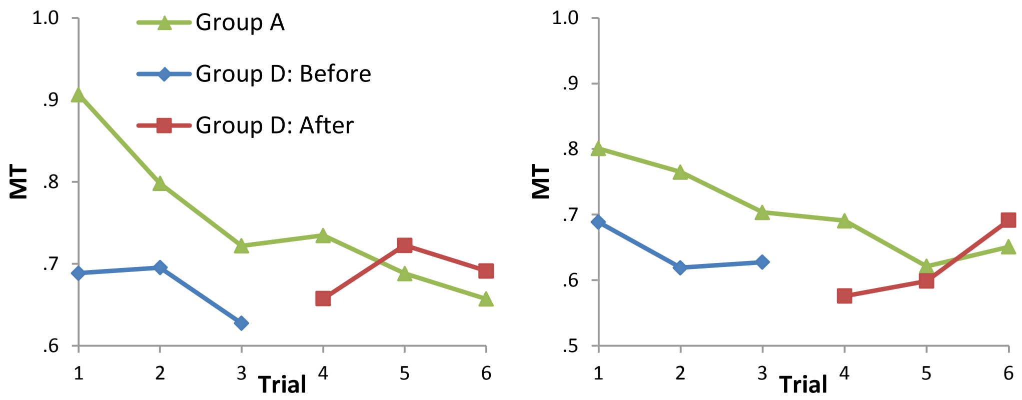


Figure 5.79: Preliminary results of Fitts' law for IDe=5 (left) and IDet=5 (right).

Discussion

This experiment provides only preliminary results since its sample size does not allow to carry out formal statistics and thus the comparison between the two groups will only regard the trend across trials.

Most of the parameters show a small difference between the third and fourth trial which is compatible with intrasession improvement. Moreover, the subjects were instructed only before the party but it seems that they have retained the task information. This means that the two sets of three trials can be treated as consequent.

Only tracking accuracy in AP plane (Figure 5.68) and whole signal (Figure 5.70) show a sharp reduction in performance in the fourth trial, while CRT reaction time (Figure 5.72) and the related Hick's *m* coefficient (Figure 5.78) show a spike in the third trial that originates from the results of two subjects.

Only PVT reaction time trials have been considered separately because DA – Formal Learning, set 2 results do not show motor retention for this task. This is confirmed also in this results where the learning trend of the first repetitions are similar to the other two slopes (Figure 5.74). It should be reminded that PVT task is too short to measure sustained vigilance and thus, here it is considered as a reference learning trend for CRT reaction time and Hick's law.

It should be noted that since the first three trials were performed around 9 p.m., the subject might have been measured already in fatigue conditions. Still, the data trend does not show clear differences between the two groups that allow the reliable inference.

Experiments on subjects exposed to alcohol reported impairment in spatial learning (Beatty et al., 1997) and memory deficiency (Solowij et al., 2011). Even though the subjects' activity between those two sets is unknown, it may be presumed that their psychophysical condition was worst after the party. This is supported by interesting trends that appear in the results regarding the movement time related to the target pursuit, that is the DA tracking delay (Figure 5.67, Figure 5.69 and Figure 5.71) and the related Fitts' law (Figure 5.79). Both parameters show that performance has an increasing trend when the subjects were measured after the party. It seems that after the party, rather than learning, subjects forget and performance deteriorates with practice. On the contrary, LLE shows a noticeable reduction in sensitivity to initial conditions when the whole CoP is analyzed. LLE is found to be smaller for subjects with degraded conditions which indicates that sway patterns are more periodic. Perhaps this is because their motor control is less reactive in correcting perturbations related with the target tracking movements or it is less able to handle the instability.

Only movement time and LLE seems to be influenced by psychophysical conditions as no difference in data trend is found for CTT tracking accuracy (Figure 5.66, Figure 5.68 and Figure 5.70), PVT reaction time (Figure 5.74) and correctness score of CRT task (Figure 5.73); while reaction time of CRT task (Figure 5.72) and Hick's law (Figure 5.78) show an unclear trend.

5.2.5. Perturbed stability test: first set

In this experiment subjects performed a perturbed stability test to verify if there is a learning effect and how long it last. This data are also used to compare subjects that performed the divided attention test with different learning approaches. The recorded data of this set are also used in Pagnacco et al. (2012).

Materials and methods

In this experiment participated 25 healthy subjects (13 females and 12 males, age = 26.3±7.9 years; height = 1.71±0.08m; weight = 70.19±10.10kg). They self-declared that they had never undergone posturographic testing before and they were free from any known pathology, injury or disease that would affect equilibrium.

After obtaining their informed consent, the subjects were tested four times with the perturbed condition of the mCTSIB protocol, in either the perturbed stability eyes open (PSEO - 14 subjects) or perturbed stability eyes closed (PSEC - 11 subjects) conditions. That is, there were a total of 25 perturbed stability (PS) tests.

The data analysis was performed using the Matlab statistical package (MathWorks – Natick MA, U.S.A.). Each subject results was normalized by their average across the last trials (3 and 4 when considering 60s trial, 3a to 4c when considering 20s block) in order to allow to compare learning phase across subjects and across test types.

The one-way analysis of variance (ANOVA) was calculated using the Matlab *anova1* function, then these results were used in the function *multcompare* (alpha level 0.05 and Tukey's honestly significant difference criterion) to identify the results that are significantly different from the others. Output of the function *multcompare* allows also on graphic analysis as means and confidence intervals are plotted. In this case, two means are significantly different when confidence intervals do not overlap each other ($p<.05$).

Results

Table 5.17 shows the subject's overall average performance (mean and standard deviation) for two test conditions (eyes open and eyes closed) considering the last eight trials in which the learning effect is exhausted. Additionally, in this table the results of the one-way ANOVA (*p* values) on the normalized data are reported.

Table 5.17: Mean values (average and standard deviation) for the two test conditions calculated across all subjects on the last 2 trials or 6 blocks to exclude any learning effect and the *p* values obtained from the normalized data.

Test type		Stability score [%]	Normalized average velocity moment [mm²/s]	Normalized average velocity [mm/s]	Largest Lyapunov Exponent
PSEO	Trial (60s)	87.3±3.9, p=.681	36.8 ± 16.1, p=.138	9.7±2.3, p~.05	0.074±0.02, p=.854
	Block (20s)	89.2±2.9, p=.408	36.6 ± 17.3, p=.101	9.7±2.0, p<.01	0.092±0.02, p=.528
PSEC	Trial (60s)	75.1±4.6, p=.886	103.3 ± 26.6, p=.054	23.3±4.6, p<.01	0.095±0.03, p=.265
	Block (20s)	77.7±5.9, p<.01	103.2 ± 36.3, p<.05	23.3±5.3, p<.01	0.111±0.02, p=.262

From Figure 5.81 to Figure 5.86 is shown the graphical output of the function *multcompare* for each parameter (with prior data normalization by the last six tests average). Comparison results are differentiate by using three colors. The blue color represents the test taken as a reference to which all other samples are compared. Red colored columns indicate data which are significantly different from the reference sample while grey columns mark data not significantly different.

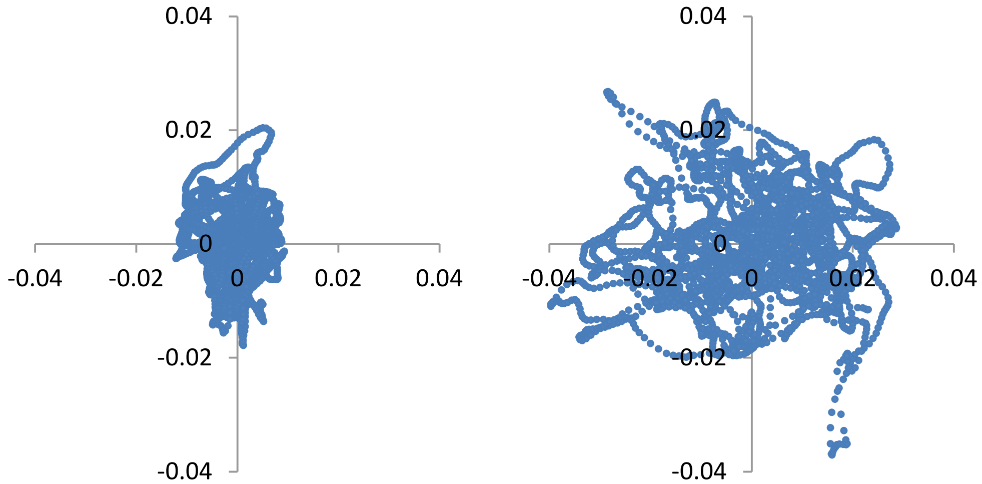


Figure 5.80: Example of CoP for eyes open condition (left) and for eyes closed condition (right). Axis units are in meters.

Discussion

Results show that there is a learning effect across the stability score (SS) and normalized average velocity moment (NAVM) for eyes open condition (Figure 5.81 and Figure 5.83) and the normalized average velocity (NAV) for both conditions.

Considering the stability score and the NAVM, there is a learning effect only in the eyes closed condition, in which the learning phase is exhausted from the second block of 20s of the first trial (1b, Figure 5.82 and Figure 5.84). Moreover, there is only a slight improvement in the stability score and the NAVM for the eyes open condition in the first block of 20s (1a, Figure 5.81 and Figure 5.83), however, the difference is not statistically significant.

Eyes open condition	Eyes closed condition

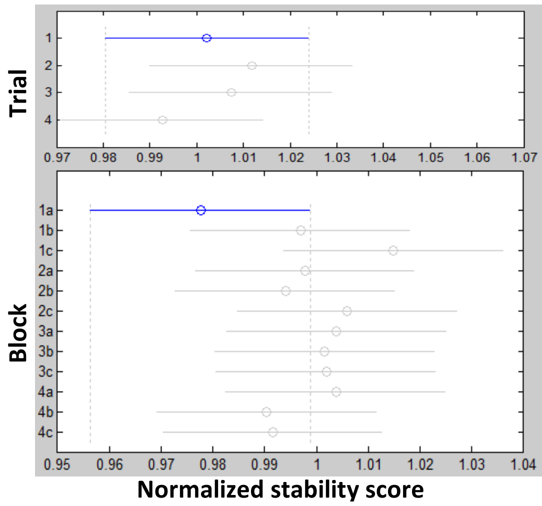


Figure 5.81: PSEO stability score

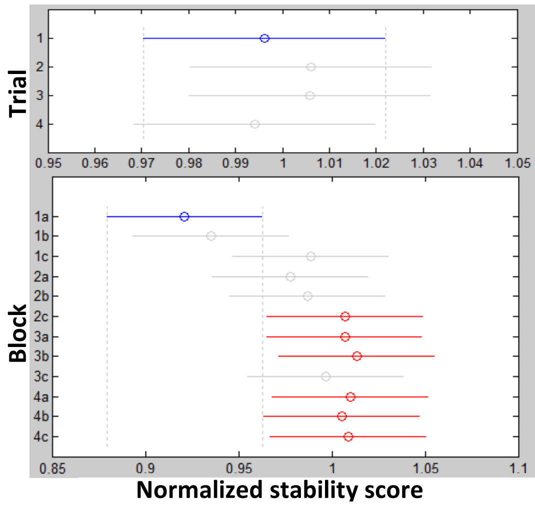


Figure 5.82: PSEC stability score

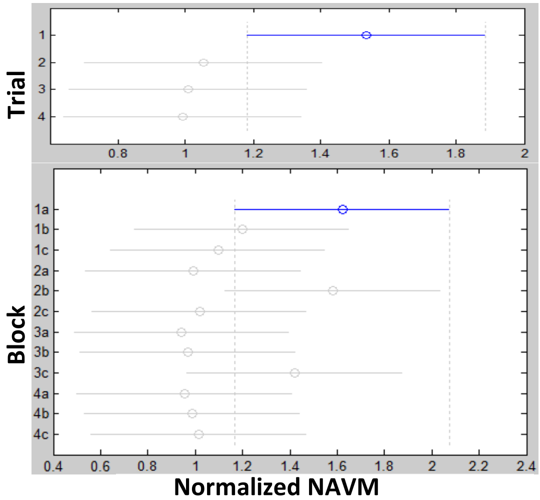


Figure 5.83: PSEO normalized average velocity moment

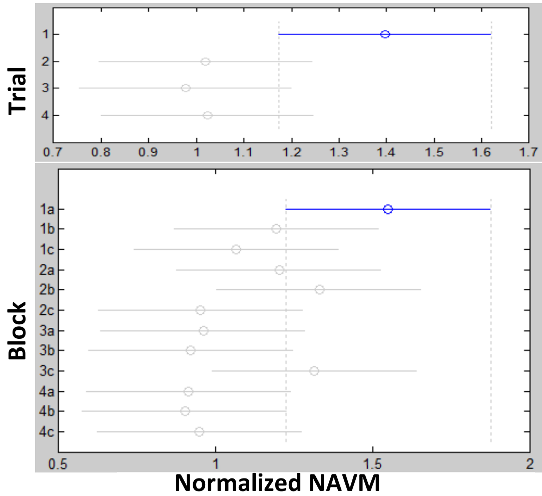


Figure 5.84: PSEC normalized average velocity moment

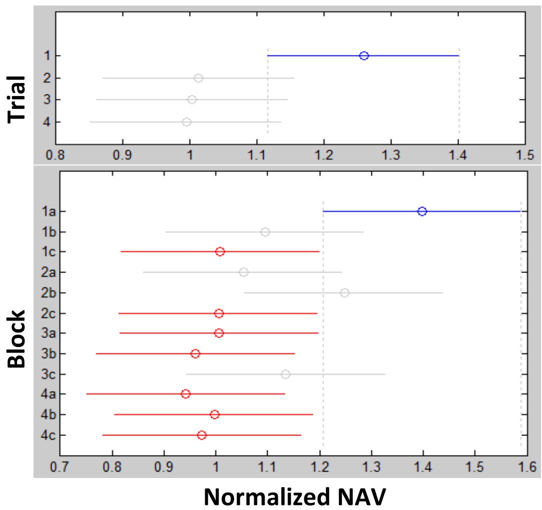


Figure 5.85: PSEO normalized average velocity

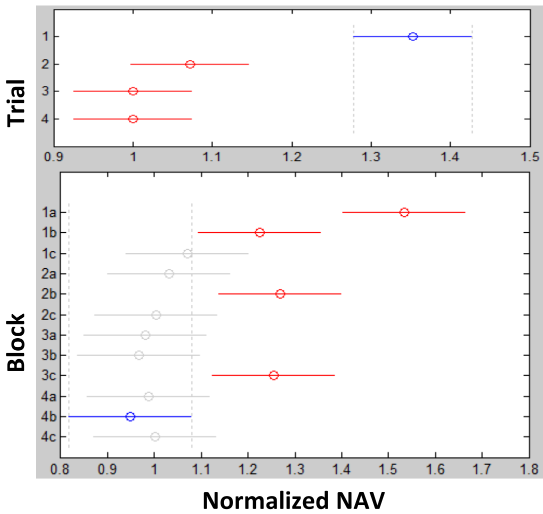


Figure 5.86: PSEC normalized average velocity

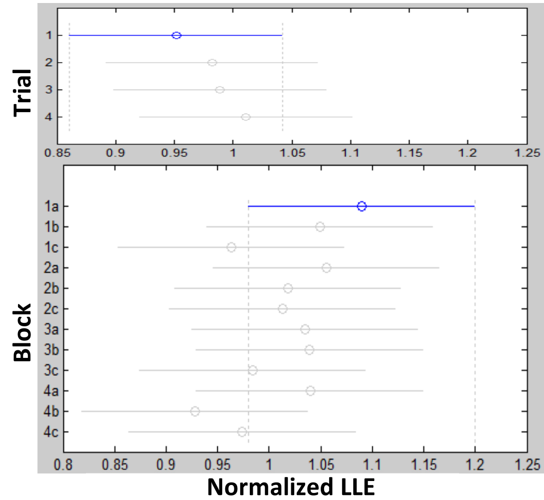


Figure 5.87: PSEO largest Lyapunov exponent

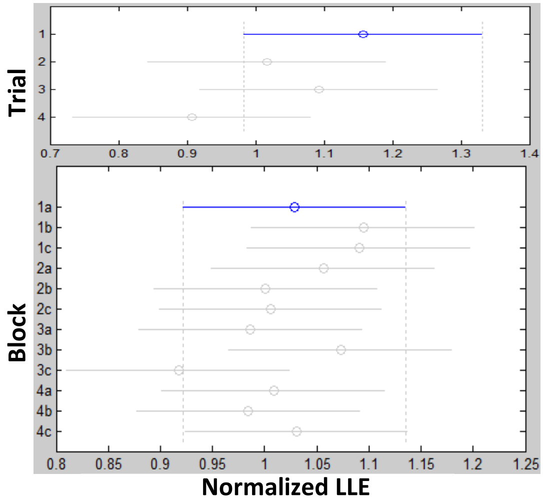


Figure 5.88: PSEC largest Lyapunov exponent

Considering the normalized average velocity (NAV) both conditions show a learning effect. In the eyes open test, the learning effect is exhausted from the second block of 20s of the first trial (1b, Figure 5.85) while in the eyes closed test, the learning effect is exhausted from the second trial (2a, Figure 5.86) and the second block of 20s of the second trial (2b, Figure 5.86).

It should be noted that although sometimes being not significantly different, all the first bocks of 20s show slightly higher means in the eyes closed condition (1a, 2a, 3a, and 4a, in Figure 5.82, Figure 5.84 and Figure 5.86). Probably this is due to another adaptation phase caused by the fact that the subject closes his/her eyes and consequently has to get used to the new condition. In fact, this is not a case of open eyes test, in which the test conditions does not change from the time the subject steps onto the foam cushion. However, LLE does not show any learning in both conditions (Figure 5.87-Figure 5.88), meaning that the sway movement pattern (i.e. perturbation reactions) remains unchanged across the trials.

As expected, the eyes closed condition show worst general performance when compared to the eyes open condition (Figure 5.80). It is so, as the subject cannot rely on his/her vision system, but just on the vestibular and proprioception information, while adapting to the perturbations.

Generally, the learning phase can be considered as exhausted from the second block of the second trial (2b) that is after ninety seconds of test. In this case should be considered also the fact that the subject stepped onto the platform 20s before initiating the test. Therefore the total time in which both adaptation and learning phase duration are exhausted, is about 2 minutes (considering that subject constantly stays on the platform without stepping out of it). Further repetitions are not necessary as the subsequent trials are not significantly different.

However, if considering only the full trials comparison (1, 2, 3 and 4), there is not possible to appreciate any learning effect in the stability score (Figure 5.81) and the NAVM (Figure 5.83) because it is mitigated by the subsequent blocks. In reality, however, the first trial of 60s still comprises some learning effect which must be excluded from analyzed data. It becomes quite an issue especially when comparing subject's performance over different sessions.

5.2.6. Perturbed stability test: second set

In this experiment, some of the subjects that had undergone the first set were reassessed (paragraph 5.2.4). The purpose of this experiment was to verify if the learning effect appears also when repeating the test after about six months and if the overall performance is different from the previous set.

Materials and methods

Seventeen healthy subjects participated in this study (8 females and 9 males, age=26.5±9.6 years, height=1.61±0.09m, weight=65.0±8.1kg), 10 of them performed with open eyes condition and 7 with closed eyes condition. All subjects denied pathologies or being under the influence of psychotropic substances before one set on trial and declared that they did not use or trained on any stabilometric platform between the two sets. Participants were voluntary and were not paid.

The protocol, materials, methods and analysis used here in this work are presented in paragraph 5.1.2, except for what is reported below.

The subjects firstly went through the protocol test (first set) and then after about six months (180 days) they repeated it again (second set). Before starting the second set the informed consent was obtained and the experiment was re-explained.

The IBM SPSS statistics software (IBM – Armonk NY, U.S.A.) was used for all statistical analysis.

The learning effect of the singular set was analyzed using univariate GLM repeated-measures (interaction model, type-3 sum of squares, alpha level 0.05, Helmert's contrast, Holm-Bonferroni's correction) with normalized data. If Mauchly's test indicated a violated sphericity, the conservative Greenhouse-Geisser's correction was chosen. To compare the results of the two set of trials multivariate GLM repeated-measures analysis (interaction model, type-3 sum of squares, alpha level 0.05) was performed. Partial η^2 is listed for effect size.

Results

Table 5.18 first set results show learning effect similar to the results of set 1 (PS, set 1), except for normalized average velocity moment (NAVM) with closed eyes condition, in which in this case there is not significant learning effect. The second set of trials shows a learning effect which is quite different from the first set of trials, except for two cases: with open eyes condition in NAVM and with closed eyes condition in normalized average velocity (NAV). However, apart from NAVM, the first trial or blocks for both stability and NAV are not statistically different between the two sets.

Results reported in Table 5.19 show no significance difference in performance between the last two trials and the last six blocks of each set, except for NAVM which is significantly different in all conditions.

Table 5.18: Comparison of the learning effect. For each parameter and set it is indicated the trial at which there is no more statistical difference (Helmert's contrast) and the set within-subjects results (*F*, *p* and partial η^2).

Parameter	First set		Second set	
	Open Eyes	**Closed Eyes**	**Open Eyes**	**Closed Eyes**
Stability score	None, $F(3,27)=0.496$, $p=.688$, partial $\eta^2=.052$	Block 1b, $F(3,18)=0.485$, $p=.697$, partial $\eta^2=.075$	2nd trial, block 1b, $F(1.57,14.1)=2.39$, $p=.135$, partial $\eta^2=.210$	2nd trial, block 2b, $F(3,18)=1.90$, $p=.166$, partial $\eta^2=.241$
NAVM	None, $F(1.41,12.7)=1.18$, $p=.320$, partial $\eta^2=.116$	None, $F(1.41,6.84)=1.42$, $p=.280$, partial $\eta^2=.192$	None, $F(3,27)=0.217$, $p=.884$, partial $\eta^2=.024$	Block 1b, $F(3,18)=0.051$, $p=.984$, partial $\eta^2=.008$
NAV	Block 1b, $F(3,27)=3.90$, $p<.05$, partial $\eta^2=.303$	Block 2b, $F(3,18)=10.6$, $p<.001$, partial $\eta^2=.639$	Block 2b, $F(3,27)=1.76$, $p=.178$, partial $\eta^2=.164$	Block 2b, $F(3,18)=3.13$, $p=.051$, partial $\eta^2=.343$
LLE	None, $F(1.91,24.8)=0.234$, $p=.783$, partial $\eta^2=.018$	None, $F(3.24,42.2)=1.11$, $p=.359$, partial $\eta^2=.079$	None, $F(1.56,16.0)=1.49$, $p=.252$, partial $\eta^2=.130$	None, $F(4.04,40.4)=1.32$, $p=.278$, partial $\eta^2=.117$

Table 5.19: Multivariate repeated measures comparison between the last two trials of the first set and the last two trials of the second set.

Parameter	Open eyes condition		Closed eyes condition	
	60s trial	**20s block**	**60s trial**	**20s block**
Stability score	$F(1,9)=0.543$, $p=.480$, partial $\eta^2=.057$	$F(1,9)=0.505$, $p=.495$, partial $\eta^2=.053$	$F(1,6)=1.43$, $p=.277$, partial $\eta^2=.192$	$F(1,6)=1.91$, $p=.217$, partial $\eta^2=.241$
NAVM	$F(1,9)=40.8$, $p<.001$, partial $\eta^2=.819$	$F(1,9)=40.1$, $p<.001$, partial $\eta^2=.817$	$F(1,6)=10.98$, $p<.05$, partial $\eta^2=.647$	$F(1,6)=25.50$, $p<.01$, partial $\eta^2=.810$
NAV	$F(1,9)=0.234$, $p=.640$, partial $\eta^2=.025$	$F(1,9)=0.234$, $p=.640$, partial $\eta^2=.025$	$F(1,6)=1.43$, $p=..277$, partial $\eta^2=.192$	$F(1,6)=1.43$, $p=.277$, partial $\eta^2=.192$
LLE	$F(1,9)=0.013$, $p=.913$, partial $\eta^2=.001$	$F(1,9)=0.151$, $p=.707$, partial $\eta^2=.016$	$F(1,6)=1.17$, $p=.321$, partial $\eta^2=.163$	$F(1,6)=1.18$, $p=.319$, partial $\eta^2=.164$

The absolute results of the two sets (average and their confidence interval) are shown in Figure 5.89-Figure 5.92. The data are grouped by trial (x-axis), set and condition. The first set is identified by black solid line while the second set of trials are identified by grey dashed line. Closed eyes and open eyes conditions are respectively identified by squares and triangles. Better performance is generally obtained in the open eyes condition.

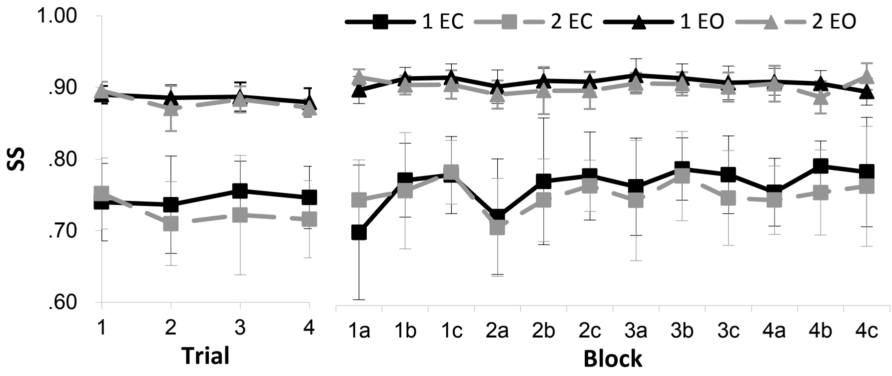


Figure 5.89: Stability score (SS) comparison. Left panel shows trial results (60s), right panel shows block results (20s). Values closer to 1 mean higher stability.

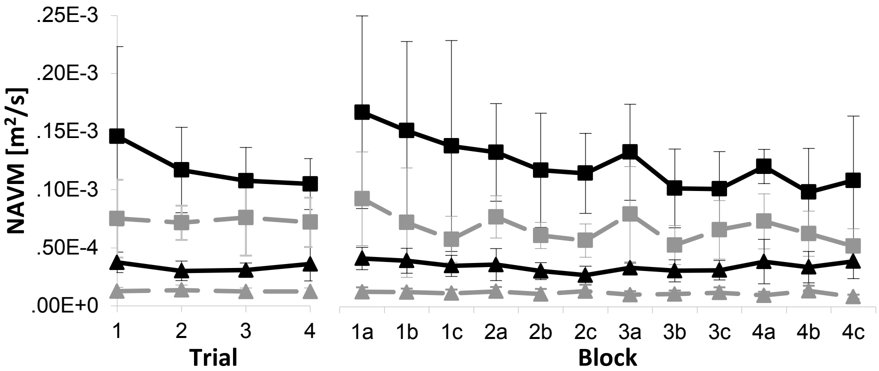


Figure 5.90: Normalized average velocity moment (NAVM) comparison. Left panel shows trial results (60s), right panel shows block results (20s). Smaller results mean better performance.

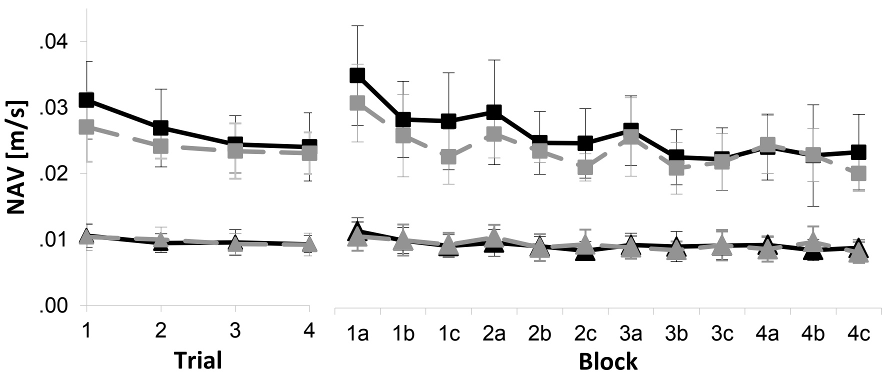


Figure 5.91: Normalized average velocity (NAV) comparison. Left panel shows trial results (60s), right panel shows block results (20s). Smaller results mean better performance.

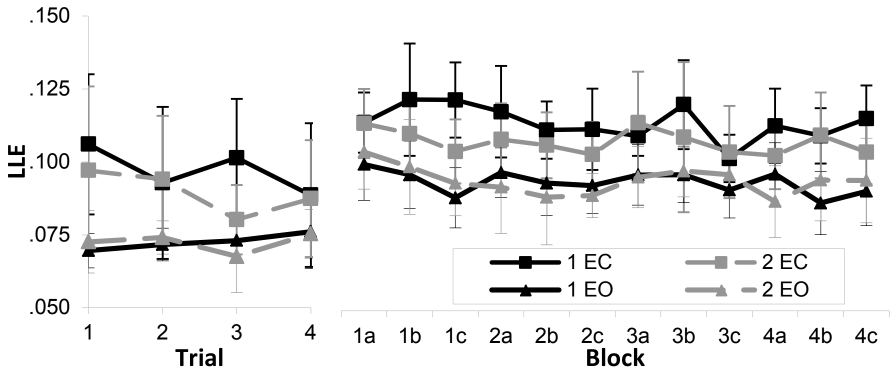


Figure 5.92: Largest Lyapunov exponent (LLE) comparison. Left panel shows trial results (60s), right panel shows block results (20s).

Discussion

Comparing the learning phase of the two sets of trials, it arises that there is a variability in the learning phase among the parameters considered. The stability score learning phase is shifted to one full trial in the eyes closed condition while in the second set it arise a new learning effect also for the open eyes condition. NAVM shows a new learning effect for the eyes closed condition. NAV learning phase is increased of one full trial only in the eyes open condition.

The general learning curve is similar to the first set but it seems that there is a need for more trials in order to exhaust the learning effect. Perhaps the variability of the perturbations causes the subject to be like he/she never underwent the test. However, there is a significant performance progress in the NAVM ($p<.001$ for eyes open and $p<.01$ for eyes closed condition, Table 5.19). On the contrary, LLE does not show any learning phase nor it permits to discriminate between the test conditions (Figure 5.92).

Considering that the stability score (which represents the size of the 95% confidence ellipse) and average velocity (which represents the velocity of the CoP path) do not statistically differ between the two sets, a smaller NAVM can be only obtained if the subject reacts on perturbations with movements that are more directed to the stable position instead of swaying around. That is, being not able to reduce the magnitude of the perturbations, the subject's motor strategy learnt in the previous set to counter-act the perturbations. This learning result was not only retained after 6 months but also the time between the two sets has even enhanced it. This finding becomes quite an issue especially when comparing subject's performance over different sessions.

5.2.7. Perturbed stability test: imitation group

In this experiment, the subjects that had undergone the divided attention test – Imitation learning (paragraph 5.2.3) were assessed with the perturbed stability test. The purpose of this experiment was to verify that the equilibrium ability of the group was not different from the control group (DA – formal learning, set 1). Subjects performed only eyes closed condition as it is more demanding than eyes open condition.

Materials and methods

Fourteen healthy students participated in this study (9 males and 7 females, age = 22.3 ± 3.2 years, height = 1.74 ± 0.09m, weight = 68.7 ± 15.6kg). The participants declared that they had never undergone posturographic tests before and were free from any disease or pathology that could affect their equilibrium. Before initiating the test informed consent was obtained from the subject.

The protocol and the analysis were similar to the one presented in paragraph 5.2.4, except for the fact that the subjects performed only PS with eyes closed condition.

The IBM SPSS statistics software (IBM – Armonk NY, U.S.A.) was used for all statistical analysis. The learning effect of the singular set was analyzed using Univariate GLM repeated-measures (interaction model, type-3 sum of squares, alpha level 0.05, Helmert's contrast, Holm-Bonferroni's correction) with normalized data. If Mauchly's test indicated a violated sphericity, the conservative Greenhouse-Geisser's correction was chosen.

The control group, that is group A from perturbed stability, set 1 experiment, did not comprise subjects over 30 years old in order to have comparable age range. Control group was therefore composed of 10 subjects (5 males and 5 females, age = 23.4 ± 2.8 years, height = 1.69 ± 0.10m, weight = 69.6 ± 11.3kg). Univariate GLM repeated-measures analysis (interaction model, type-3 sum of squares, alpha level 0.05, between subjects factor: group) was performed between the data sets of the two groups. Partial η^2 is listed for effect size.

Results

In Table 5.20 and Figure 5.93 - Figure 5.96 the learning trend of the group C perturbed stability with eyes closed is shown. The data were first normalized by considering the average of the last two trials (3 and 4) or the last six blocks (3a to 4c).

In Table 5.21 it is shown the univariate comparison between the two groups (A and C). In this case the data have not been normalized.

60s trials	20s blocks

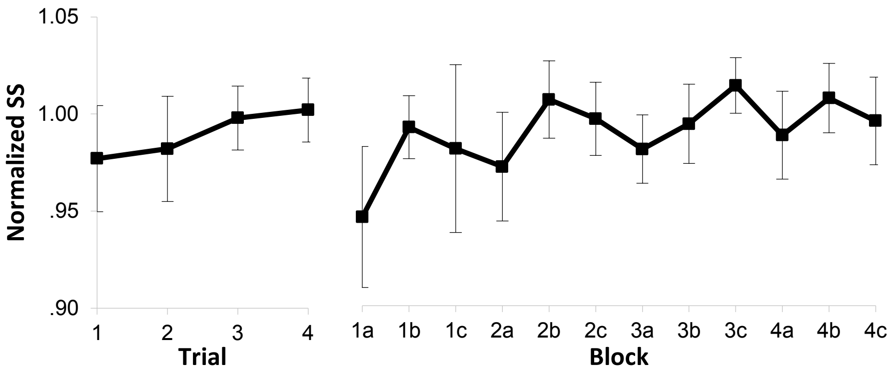


Figure 5.93: Group C stability score (SS).

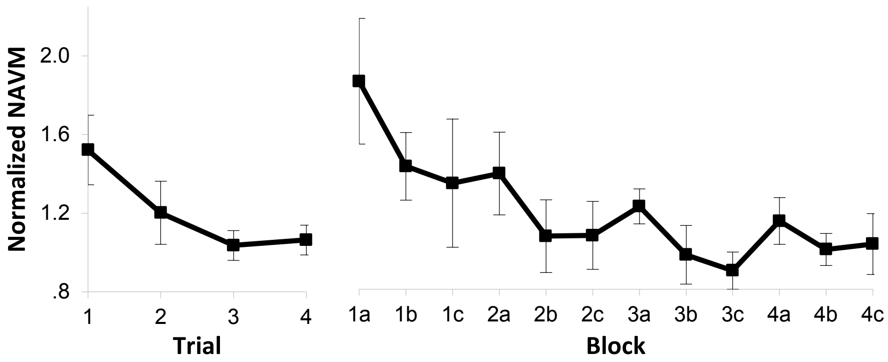


Figure 5.94: Group C normalized average velocity moment (NAVM).

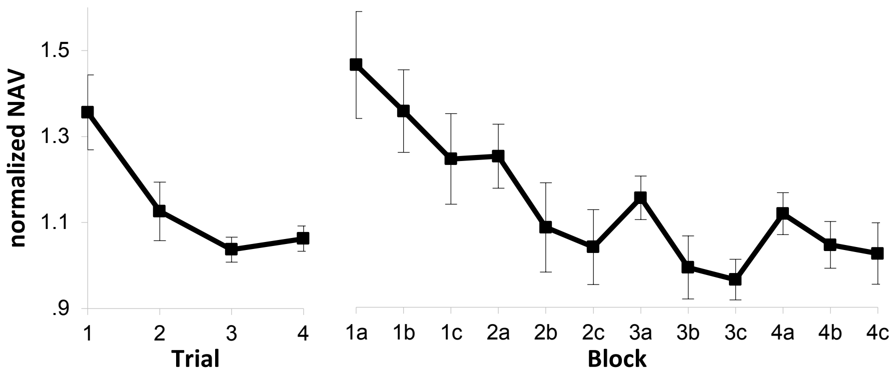


Figure 5.95: Group C normalized average velocity (NAV).

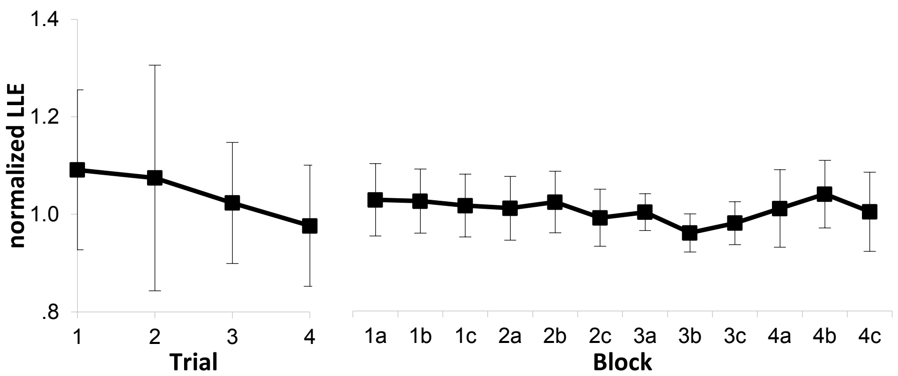


Figure 5.96: Group C normalized largest Lyapunov exponent (LLE).

Table 5.20: Trial or part of trial (block of 20s) at which the learning effect is exhausted. Data were normalized by dividing the results with the mean of the trial 3 and 4 or the blocks 3a to 4c.

Parameter	Within subjects contrast – GLM repeated measures (Helmert's comparison) 60s trial comparison	 20s block comparison
Stability score	No differences between the first trial and the later ones. Therefore only Within subject effects is reported: $F(3,45)=1.27$, $p=.298$, partial $\eta^2=.078$	Block 1b (intermediate 20s of trial 1) $F(1,15)=0.016$, $p=.900$, partial $\eta^2<.001$
NAVM	Trial learning end: 2nd trial $F(1,15)=3.95$, $p=.065$, partial $\eta^2=.209$	Block 1c (last 20s of trial 1) $F(1,15)=2.56$, $p=.146$, partial $\eta^2<.001$
NAV	Trial learning end: 3rd trial $F(1,15)=1.14$ $p=.302$, partial $\eta^2=.071$	Block 2b (intermediate 20s of trial 2) $F(1,15)=0.65$ $p=.431$, partial $\eta^2<.05$
LLE	No learning effect $F(3,48)=0.461$, $p=.711$, partial $\eta^2=.028$	No learning effect $F(4.25,68.0)=0.614$, $p=.664$, partial $\eta^2=.037$

Table 5.21: Comparison between group A and group C. Reported results regard Within Subject Effects of GLM Repeated Measures.

Parameter	Univariate statistics comparison 60s trial comparison	 20s block comparison
Stability score	$F(3,72)=1.29$, $p=.285$, partial $\eta^2=.051$	$F(6.48,155.62)=0.705$, $p=.657$, partial $\eta^2=.029$
NAVM	$F(1.36,32.56)=1.16$, $p=.307$, partial $\eta^2=.046$	$F(2.69,64,44)=1.01$, $p=.389$, partial $\eta^2=.040$
NAV	$F(3,72)=0.935$, $p=.429$, partial $\eta^2=.037$	$F(5.79,138.88)=0.849$, $p=.531$, partial $\eta^2=.034$
LLE	$F(3,78)=0.332$, $p=.802$, partial $\eta^2=.013$	$F(5.62,146)=1.159$ $p=.332$, partial $\eta^2=.043$

Discussion

Figure 5.93 - Figure 5.96 and Table 5.20 show the learning trend of the group C of subjects that participated in the DA imitation learning experiment. Considering the Stability parameter, the results show no difference between the four trials (Table 5.20).

However, the first trial comprise also a learning effect, as analyzing the subsets of 20s it emerges that the first block (1a) is significantly different from all the subsequent blocks (Helmert's comparison). Also the other parameters show a difference in learning effect according to which trials or blocks are analyzed. Normalized average velocity moment (NAVM) needs one full trial of 60s in order to exhaust learning effect, however the last block of the first trial (1c) can be already considered as valid for subject's assessment. Some more trials are needed for the normalized average velocity (NAV) in order not to show statistically significant difference: the third trial or the second block of the second trial (2b). Again, LLE does not show any learning phase (Table 5.21), neither in the 60s trials nor in the 20s blocks.

Furthermore, observing Figure 5.93 - Figure 5.95 it is noticeable that also the first 20s block of the second and third trial are different than the subsequent block, except for the Stability parameter where there is difference only in the second trial 2a-2b $p<.05$ ($F(1,15)=9.06$, partial $\eta^2=.291$).

For NAVM Within Subject contrast between blocks 2a-2b gives $p<.05$ ($F(1,15)=6.03$, partial $\eta^2=.287$), an between 3a-3b gives $p<.05$ ($F(1,15)=7.29$, partial $\eta^2=.327$). For NAV Within Subject contrast between blocks 2a-2b gives $p<.01$ ($F(1,15)=11.77$, partial $\eta^2=.440$), and between 3a-3b $p<.01$ ($F(1,15)=16.44$, partial $\eta^2=.523$). Only Within Subject contrast between blocks 4a-4b shows no difference for all considered parameters. This indicates that each trial contains some learning effect, hence the first 20s should not be considered for analysis.

Comparing the two groups, it is found that there are no statistical differences ($p>.2$, Table 5.21). Learning trends are in fact similar for Stability and NAV in which the learning effect is exhausted respectively from block 1b and 2b. Only the NAVM shows that learning effect of group A is exhausted little earlier than in group C, respectively block 1b and block 1c.

Chapter 6:

DISCUSSION

Two tests were administered to 42 healthy adults that self-declared they had never undergone a posturographic test, they were free from any condition that would influence their equilibrium ability such as vestibular, proprioceptive and somatosensory pathologies, psychoactive substances, medicines such as antihistaminic, antibiotics or ototoxic substances, and without injuries to body parts or joints such as lower limbs, spine and head. Moreover, three further subjects were measured before and after a university get-together party for preliminary DA test investigations on degraded conditions.

The divided attention test required the subjects to perform simultaneously two tasks: follow the target on the screen by moving his/her body (critical tracking test, CTT) and react to the trigger target (choice reaction test, CRT).

The perturbed stability test required the subjects to stand onto a foam surface that causes perturbations and somatosensory disruption either with eyes open or eyes closed.

In the following paragraphs the results of the tests are thoroughly discussed in relation to the objectives of this work.

6.1. IMITATION BY OBSERVATION

By using transcranial direct current recording technique it has been found that some neurons of area F5 were activated either when the monkey was grasping a nut or when the monkey was looking at someone else doing the same action (Rizzolatti et al., 1996), thus 'mirroring' the action. Such response, however, was not found when non-goal oriented actions were performed by the experimenter, such as mimicking grasping when there was no food on the tray. Moreover, some neurons were discharged only for few or one specific action (either seen or performed), while for other actions no activation was found.

Further research on these MN has hypothesized that the MNs manage the sensorimotor components involved in complex behaviors imitation (Arbib et al., 2000). In order to do so the brain must generate internal representations of sensory and motor behavior. In other words, the internal models are constructed with a bottom-up approach in order to imitate and make internal simulations. However, since only goal oriented actions seem to involve the MNS, imitation should not be possible if the subject does not know or recognize the goal of the action. On the contrary, Kosonogov (2012) points out that other brain structures are involved in understand the action before the motor areas where MNs are located.

Practitioners commonly describe and demonstrate the motor gestures that the learner has later to reproduce. To investigate the effectiveness of a single type of information acquisition, it is compared the performance of two groups provided with either mere verbal description (group A, DA – Formal Learning, set 1) or demonstration (group C, DA – imitation) of the DA test information. The latter group of subjects had just the chance to learn the gestures through a delayed imitation by observation schema because they first observed and only later they performed (about 2 minutes).

To exclude that the DA results are biased by subject's postural control, both groups underwent also a perturbed stability (PS) test. PS results in paragraph 5.2.7 show that there is no difference in equilibrium ability between the two groups as their trend and performance are similar.

Delayed imitation is performed when there is some time delay between the observation of the gestures and its replication. Several research have proposed that the mirror neuron (MN) system underlies the imitation process because when an action is observed, the MNs that code the goal of that action 'resonate' with it. Therefore, since the MNs are involved in the action goal understanding and movement production, 'resonation' allows to start up the MNs that later replicate the gesture.

The results illustrated in paragraph 5.2.3 shows that the delayed imitation alone is less effective than verbal explanation. Some issues that affect the imitation process are discussed below.

6.1.1. Goal comprehension

The results of this work enlighten important issues in goal understanding. The comparison results of DA shows that the two groups performed differently depending upon the information received. While group A correctly understood the tasks, in the imitation approach (group C) the comprehension differed according to the task.

The actions required in the critical tracking test (CTT) cause large, slow and visible movements that the subject can well recognize and observe while watching what is happening on the screen. On the contrary, the choice reaction test (CRT) makes more difficult to simultaneously observe the trigger and the screen outcome. However, auditory MNs should have been able to link the sound of pressing the trigger to the visual stimuli appearing on the screen. In other words, they should allow to associate a noticeable click with what the subject is looking at. These auditory MNs are a subset of the MN system that activates when a typical sound of an act is heard (Rozzi et al., 2013), therefore they code the motor representation from the sound of the motor action.

However, even though auditory MNs are also goal-specific some subjects of group C did not associate correctly the visual stimulus with the sound of the trigger action. Still, even the subjects that understood the aim related to the trigger, were unsure about the inference they made.

Probably, the subjects did not notice triggering or did not associate any goal with it because their working memory and their attention were devoted to understand the goal of the experimenter's movements. Therefore, the goal understanding of CTT interfered with the understanding of the CRT task even though a different neural circuitry of MN was involved. Hence, if the same neuronal circuitry is involved in the action understanding and action performing, the immediate reaction is not possible, which, in turn, can be dangerous especially in critical situations (Pascolo et al., 2010). This means that another neural circuitry is involved in the information chain before the MN system, which can also saturate when multiple inferences have to be made. Though, this does not exclude that MN are not necessary for goal understanding. Perhaps, another circuit just maps the inputs and outputs and later involves the group of MNs which are deputed to code that action (motor, auditory).

Furthermore, these results show that the quality of feedback information is also important in goal understanding, and thus in imitation. The identification of the CTT task is easier, because its feedback information is simple. In fact, the subject can check its position on the screen and thus can easily discriminate the target signal from the dummy ones. This information is categorized as intrinsic knowledge of results (KR), which is sufficient for goal understanding of CTT.

Conversely, although the visual cue reaction signal, either correct or dummy, disappears once the trigger is pressed, it often goes unnoticed or it is only seen as an unrelated effect. In fact, when it comes to replicate the trials, the subjects try to guess the purpose of the trigger within the task, assuming the most plausible and sensible function. Though, sometimes it happens that they get wrong. In this task extrinsic KR information is therefore a necessary input for the goal understanding and thus for the entire imitation process.

6.1.2. Resonation

Highly congruent MN are a class of neurons that activate only to specific actions (tearing, grasping, manipulating) and goals (grasping an object for eating, grasping for placing), while broad congruent MN are a class of neurons that activate to a wider variety of actions and goals (Rozzi et al., 2013). However, in both cases the actions to which they activate must be pre-constituted. In fact, MNs have been mainly related to repetition of known motor gestures, and in this work the subjects perform novel gestures which do not allow to make the MN 'resonate'. Nevertheless, the subjects in this test were able to imitate the observed gestures.

The role of MN in motor learning is still controversial. Ferrari et al. (2006) tried to demonstrate that MN support also imitation learning with experiments on newborn macaques, which have shown to imitate tongue protrusion, sucking and gaze direction of an experimenter. However, it is more the case of an automatic replication rather than imitation (Heyes, 2010). To the knowledge of the author there is only one study with experiments that recorded the MN activity of subjects that observed and replicated a novel motor gesture (Buccino et al., 2004). The fMRI results of that study have shown activation of the brain areas that overlapped the MN locations both when observing and when performing the action. However, this does not necessarily mean that the MN were active since the areas activated are large, these cerebral areas comprise several circuitries and since the limitation in spatial accuracy of the fMRI technique.

Buccino et al. (2004) point out that the imitation of a new gesture pattern composed of already coded actions involve a recombination of the related ‘resonating’ MNs. However, since some groups of MNs only ‘resonate’ with specific actions, acquiring a brand new action might require a new group of MNs that code the specific action or goal and its observation. This is consistent with the fact that practice is needed to acquire a new gesture, still this is not an ecological perspective because in this way brain resources are not optimized in terms of memory and neuronal circuitry, unless only the existing broaden MNs are in charge of coding new actions or congruent MNs became broaden MNs.

Further, since MN theory use the same class of neurons to code the action and understand the action goal it shares the same limitations of the perceptual and memory trace of Adams’ theory. Sharing the feedforward controller (action coding) and feedback controller (action observation) generates interferences which reduces the movement performance. Conversely, Schmidt’s schema theory predicts that the two mechanisms, respectively the *recall* and *recognition* sub-schema, are separate in terms of behavior and underlying neural network substrate. Furthermore, even though MNs regard well coded actions, they often activate after a well-known action has been completed (Pascolo et al., 2010).

6.1.3. Action coding

Assumed that the action goal is understood, either through verbal explanation or action-outcome mapping, the absolute results of group C show that observing the movements improves the CTT movement accuracy and coordination. In fact, subjects in the first and second repetition tended to have more precise movements in CTT than group A. On the contrary, the movement time delay and CRT reaction time is worst in the imitation group. Once the learning terminated, the results of group C present higher average delay and higher average visual cue reaction time (Figure 5.55 - Figure 5.57). However, it should be noted that the time delay of group C is biased by the feet position. Indeed, the subjects were supposed to imitate any posture included the feet position on the platform; instead they tended to assume a wider stance than shoulder width, thus increasing their ML stability.

The observation of gestures improves the understanding of the movements compared to the mere oral explanation but it requires a greater cognitive load that involves working memory due to the deductive processes necessary for the task understanding. In fact, the subjects of group C have to verify their deductions while performing the trial, which results in an increased slowness of their movements. This is confirmed by the interviews, in which all subjects of group C reported their uncertainty about the second task, also those who deduced correctly its purpose. Even though, the verbal explanation requires less inferences on understanding the tasks, it occurs at the expense of mobility, so more time is needed to acquire the required motor skills.

These findings suggest that a top-down process (verbal explanation) allows to properly constrain the cognitive processes related to the task understanding, whereas the bottom-up process (imitation) is less constrained and the subject deducts the task goal by using his/her own perception and experience which also increases the cognitive load. In fact, the mere observation does not necessarily lead to a correct perception. As just mentioned, such inferences involve cognitive processes and neural networks prior to the motor sequence planning. Thus, these inferences happen without the support of the mirror neuron system, confirming the fact that the imitation process is complex and involves many neural networks.

Moreover, subjects of the group A remember the gestures when repeating the test after six months (DA – Formal Learning, set 2). This confirms that they created an internal model of the tasks without the need of gesture observation, indeed without involving the mirror neuron mechanism. In fact, motor retention is not only associated with motor and primary somatosensory cortex (M1, S1), but also with areas where the MNs have not been located, such as basal ganglia (Boyd and Winstein, 2004) and cerebellum (Herzfeld et al., 2014).

Summarizing, while formal learning in this protocol is sufficient to provide fair results, imitation approach alone lets the subject to interpret and simulate goals by his/her own, and even in case of correct deduction, to remain uncertain about the task and results.

Hence, pure imitation bears substantial risk that some important fine gestures go unnoticed. Therefore, it seems better to setup the motor system with high level information. Probably, the best performance of this test can be achieved by using the pros of each learning approach; namely by verbally explaining the test and showing the related gestures. In fact, motor coordination of gross motor gestures is better performed with imitation learning whereas smaller reaction time and full understanding of the fine motor tasks are achieved through formal learning.

6.2. MOTOR LEARNING

In this section the results of the DA and PS test are analyzed in terms of motor program and motor learning.

First, the tests that regarded naïve subjects, then the motor retention when the subjects repeat the test after six months are discussed. The last section discusses the postural models and compares them with the behavioral motor schema model.

6.2.1. Motor learning of novel gestures

What emerges from the first set of trials of both the divided attention (DA) test and the perturbed stability (PS) test is that subjects performing for the first time the balance test need some practice trials before initiating the test. That is consistent with experiments where subjects underwent other posturographic tests (Leitner et al., 2009; Pagnacco et al., 2008). Learning phase is generally found when performing a novel task. For instance, when subjects were required to grasp an object with distorted vision or move a robotic arm to which force perturbations were applied, some attempts were necessary before reaching a stable performance (Wei et al., 2009).

DA protocol

One first consideration on the learning of the DA protocol regards the interaction between its related tasks. Since this test requires to perform concurrently two tasks, the critical tracking test (CTT) and the choice reaction test (CRT), they are affected by two kinds of interference: capacity and structural (Schmidt and Wrisberg, 2004). This interference is used in the DA protocol to highlight the difficulty in performing the first task, because even in increased task difficultness, the subject might not show decreased performance if only one task is executed. In fact, with regard to the capacity interference, it is unknown how many cognitive resources, such as working memory and attention capacity, are necessary to accomplish a task.

Therefore, the subject can still perform well by using more of those resources that are still available. On the contrary, the cognitive resources available for the first task are reduced when a second task is executed, thus making more evident the difficulty of the first task. However, the second task must also split the cognitive resources which is not possible if they are related to the first task. In fact, similar tasks would allow to optimize resources by sharing them instead of allocating new ones (Brown and Poulton, 1961). In this protocol, the two tasks are unrelated because the two stimuli have different meaning and their motor schemas involve either continuous movements (CTT) or discrete movements (CRT). However, this latter is not highly unrelated since the task is controlled by very different motor areas. Higher unrelation would be achieved with a task that involves similar body limbs, e.g. the famous childhood game of ‘pat your head and rub your stomach simultaneously’.

There is also a slight intrinsic capacity interference inside of each test. The outer shape and color of both correct and dummy cues are quite similar, they are differentiated only because the correct symbol is a full shape and the dummy is hollow. The latter has an inner shape similar to the outer. In this case there is no interference between the two tasks because the shapes are different.

Moreover, this protocol involves also structural interference, which is related to the limitation of a physical structure to handle two tasks. In this protocol, the two movements, target tracking and triggering, are achieved with different body parts, but the eyes must follow up to five visual cues that appear on the screen at random locations and random time: four cues for the CTT task (subject’s CoP, one correct target, two target dummies), and sometimes one cue related to the CRT trigger signal, either correct or dummy. Since focal vision can follow only one signal at a time, the subject has to continuously scan the screen to keep track of the succession of the visual cues. The interference is only reduced when all the cues are located near to each other, which rarely occurs due to the random nature of the signals.

As a result the two tasks mutually interfere at different levels, which makes the test more difficult to practice and susceptible to learning disruptions.

Analyzing the learning trend of the subjects that first underwent to the tests, the results of this work show that the trend is well fitted by the power law of learning for all the tests and their measures: CTT, CRT, and the psychomotor vigilance test (PVT).

The CRT is measured by means of reaction time and correctness of the response but it is not a complete double choice test. In fact, the task does not require to select between two movement patterns; in this case the choice is either to react with the planned motor gesture or not to react. This means that the response selection is suppressed when the dummy cue appears. However, capacity interference caused by the concurrent performing of another task reduces the suppression ability, therefore more attention is needed to avoid errors.

In this task, the response can be preprogrammed because it does not change during the execution of the protocol. This means that once the input is recognized (first step of executive stage of motor schema) and the response is selected (second step), the response programming (third step) and motor programming (first step of effector stage) are straightforward. Since the gesture related to the task is simplistic action and well coded, the motor programming of this gesture only requires to retrieve the action program. Therefore, right after the first execution, learning should only involve the improvement of the executive stage, in particular the response selection, and the improvement in estimating the noise of the neuronal signals. Results show that both, the reaction time (RT) and correctness score (CS) greatly improve in the first few trials.

Feedback of this task only regards the correctness of the response as an intrinsic KR because the related visual cue disappears once the trigger is pressed. Subjects do not focus on RT because they are more focused on the accuracy and also because it is difficult to appreciate the extent of RT.

The PVT is also a reaction test but it is carried out after the DA protocol in order to have a reference value that is free from interferences of other tasks, has a lower cognitive elaboration and easier gestures to perform. The RT of this task shows faster reaction than CRT because the response does not have to be selected. Therefore, the entire reaction is pre-programmed after the input recognition.

PVT also comprises an intrinsic KR in terms of correctness of response. Among all the subjects and trials, there was only one reaction to absent cue, which is the outcome of an anticipated reaction. For this reason, the scoring criteria for PVT are not shown nor analyzed.

Comparing the reaction time of PVT, CRT and CTT delay, results show that with reference to the PVT reaction time, the CRT and CTT respectively are almost 3.2 and 5.5 times greater for the subjects of group A (DA – Formal Learning, set 1) and respectively 3.6 and 6 times greater for the subjects of group C (DA – Imitation Learning).

As expected, the performance increases according to the neuronal mechanism involved and according to the length of neural signal travel path. In fact, the CRT and even more the CCT require additional cognitive elaboration and attentional working memory and additionally, the neural signals in the CCT have almost twice longer path to travel (till the ankle) than the CRT and PVT (till the finger). Moreover, additional time is required for CCT and CRT tasks due to their mutual influence because they are being performed at the same time, because the finger has much less inertia than the entire body, and because the subject is continuously scanning the screen in order to follow the appearance of the symbols. However, as the triggering action should be well coded by the subject, the improvement is mainly due to the time necessary to pre-activate the moto-neuronal path.

Furthermore, subjects that acquired the test information through observation show higher RT. This is the result of capacity interference due to the inferences necessary to guess the meaning since imitation is not properly constrained for the fine gestures of the second task.

In this test, the reaction time of CRT is about 700ms but the typical RT of a double choice test is about 300-350ms. Therefore, it can be presumed that the interference of the concurrent tasks causes about 350-400ms delay.

In consideration of the CTT test, postural balance is affected by several sources of noise, which cause substantial variability in the measured quantities. However, results show that the ability of the subject in controlling the intrinsic noise is improved with performance. This is shown in all the measured variables: the cross-correlation coefficient and lag, the motor performance model of speed-accuracy trade-off (Fitts' law), and in the largest Lyapunov exponent (LLE). LLE results show that subjects reduce their variability of movement patterns which finds confirmation in the cross-correlation results. However, cross-correlation provides more usable parameters (tracking accuracy and delay) and requires much less computational resources.

In this task, learning involves all the parts of the Schmidt's schema theory, from the input recognition to the muscles and back with the feedback, because each target always requires to produce different movements. However, similarly to the CRT, few trials are sufficient to tune the internal models. Moreover, showing once the test allows some pre-programming of the *recall* sub-schema. In fact, the results of the imitation group demonstrate that the accuracy is improved, however, at the expense of RT, which is slightly higher as above mentioned.

Further considerations on the CTT task are reported in the next paragraph.

Motor performance models

With regard to the speed-accuracy trade-off, Duarte and Freitas extended the Fitts' law also to postural balance tasks, but targets were fixed and subjects were required to sway continuously back and forth only in the AP plane (Duarte and Freitas, 2005). The lateral movements of the CoP (ML component) were discarded from the analysis, therefore it was considered the actual value of the target distance, not the effective one. However, the calculation of the ID considered the effective target size. Moreover, its data were low-pass filtered (<10Hz), which further reduced the noise influence on the analysis.

In that experiment, learning phase was considered as a biasing factor but it was generically excluded by leaving the subjects practicing until they were comfortable with the task. Therefore, it was not well-defined the extent of the learning phase and for how long subjects practiced before commencing the test.

Instead, in the experiment of the present work, subjects were moving in any direction and to random positions while carrying out concurrently the second task. The movements were not repetitive but it is demonstrated that Fitts' law holds also in single attempt pointing tasks (Schmidt and Lee, 1999).

Contrary to experiments with fixed targets, following random target locations in any direction produces higher variability which does not allow to achieve same improvement ratio in motor control.

The results reported in this work show that the Fitts' law for speed-accuracy trade-off pointing tasks can be extended also to postural tasks in any direction only if the index of difficulty (ID) is calculated with the effective movements of the subjects, not the ones displayed on the screen. In this way IDe considers also the perturbations which are negligible in the original Fitts' experiments, where the pointing task was achieved with hand movements, but not in postural movements. In fact, the results of DA test show that the original ID poorly correlates with the movement time (MT), while with the effective ID (IDe) there is a huge correlation improvement.

The reason is that the CoP path to reach the target is not straight but it is highly influenced by the perturbations. Similarly, also the target size is influenced by the perturbations since the subject is not able to stay still on the target once it is reached, but he/she sways around it. Moreover, the perturbations more affect the targets that are more distant, in particular, up to 25mm the correlation of the Fitts' law is high. Results show that the correlation between ID and MT depends on the measuring criteria and on the maximum tilt angle of the subject (about +5%).

In this test, the performance of the Fitts' law can be modeled as in Equation 6.1, where the MT of the P-th trial is calculated from the results of the first trial. $MT_{IDet=0}$ refers to the coefficient b of the law, m_1 to the sensitivity to the difficulty of the task, P to the amount of practice and m_2 to the learning ratio.

Equation 6.1: Modified Fitts' law to consider the amount of practice (P).

$$MT = \left(MT_{ID_{et}=0} + m_1 \cdot \log_2 ID_{et}\right)_{\mathrm{P}=1} \cdot P^{m_2}$$

Three criteria were used to investigate how the trend and the performance change. Three different target sizes were considered to measure the movement time. First, MT and IDe slightly increase with the target size reduction. Second, comparing the learning trend across the trials, results show that the correlation of the law is slightly reduced, the learning ratio m is markedly reduced, the maximum performance is slightly worst and reached earlier (floor effect).

The selection of the correct criteria is important because according to it the measure will show different trend and performance. For instance, naïve subjects can show the same learning trend of experienced subjects, if the first are measured with a large target size (e.g. W1) and the latter with a smaller target size (e.g. W3).

Factors that could influence the pointing performance have also been investigated with regard to the Fitts' law fitting, such as the direction of the movement, the location of the target (in front, lateral, back) and the tilt angle of the subject. Only the latter one has shown improvement in fitting the data. This regards the theoretical angle at the ankle of the subject calculated through its CoP position, which is related to the action of the calf muscle.

It is included in the IDe term hypothesizing that the difficulty of the task increases when the subject moves near his/her limit of stability. Results show that the correlation of the Fitts' law that includes this angle does not cause a decrease but only improvements. However, the results are not constant across trials and groups. Considering group A of paragraph 5.2.1 (DA – Formal Learning, set 1), two improving phases can be distinguished: a first phase on the 1^{st} trial, with the highest influence of the tilt angle (+10%), and a second smaller phase (+4%) on the 7^{th}-8^{th} trial. Conversely, group C of paragraph 5.2.3 (DA – Imitation Learning) shows only the second phase that occurs at the last trials. The first phase is absent because the subjects of group C had the chance to pre-construct their motor program and therefore to pre-consider the action of the calf muscle. Therefore, the first phase regards the coordination and control of the gross movements, where performance improvement is high, while the second phase (small performance improvements) regards the improvement of fine movements, the possible adaptation to fatigue conditions, and the search for different motor solutions.

However, it should be considered that the tilt angle used in the calculation is theoretical since it is based on a single link inverted pendulum. This is really true when only the ankle strategy is used. Therefore, this assumption is less valid for movements in the ML plane and for targets near the limit of stability as subjects use also a bit of hip strategy.

The results of the sensitivity to the number of choices (m coefficient) of Hick's law show, that the power law of learning can be also extended to describe this performance law across the trials, at least for a double choice test.

Following the above example, Hick's law can be modified to model the performance improvement as in Equation 6.2, where the RT of the P-th trial is calculated from the results of the first trial. $RT_{NC=1}$ is the coefficient *b* of the law, which refers to the PVT reaction time (which has NC=1) calculated with the average of the last six trials to avoid including learning effect. Moreover, m_1 refers to the sensitivity to the number of choices (NC), P to the amount of practice and m_2 to the learning ratio of the test.

Equation 6.2: Modified Hick's law to consider the amount of practice (P).

$$RT = (RT_{NC=1} + m_1 \cdot \log_2 NC)_{\mathrm{P=1}} \cdot P^{m_2}$$

PS protocol

The perturbed stability (PS) test regards the execution of the mCTSIB protocol, however, to avoid possible bias and interference between the eyes closed (EC) condition and eyes open (EO) condition, subjects performed only in one condition. Moreover, the full mCTSIB balance test does not encompass stepping off the platform between the EO and EC condition, because the single tests are performed in sequence. Therefore, in that case it should be expected a reduced learning effect for the EC condition as it is carried out after the EO condition.

The trend of the PS test across the trials is similar to DA test and is well fitted by the power law of practice. Conversely, in the PS test the subjects experience unnatural and random perturbations which are caused by the foam cushion, the disruption of the feedback signal and the correcting actions itself. Since the cushion is not a firm surface, the tactile sensory system of sole feet is disrupted, therefore the postural control must rely only on the proprioception (body displacement, vestibular) and on the vision for the EO condition, and only on the proprioception for the EC condition.

Reaction to perturbations is much more difficult in this test, for this reason learning is harder in any part of the Schmidt's motor schema: at the executive stage to recognize inputs and select response, at the effector stage that constructs the motor program which coordinates and selects the actuators, and at the *recognition* stage that compares the desired output with the feedback signals. However, in this case, the motor schema cannot completely describe the correction movements because also the long-latency reflex (LLR) operates in the control process. Moreover, when the subject is near the limit of stability, the spinal reflex (SLR) imposes its control.

For this reasons, it is unlikely that the controller works on the sole feedforward control since perturbations are not predictable. However, subject still shows an improvement performance across the trials. In particular, both EO and EC conditions show a decreasing trend in sway velocity, while only the EC condition shows improvement in the stability score and areal velocity. The reason is because the EC condition is less constrained and thus it is more difficult to counteract the perturbations. On the contrary, the largest Lyapunov exponent (LLE) does not show any learning trend, which means that the variability in movement patterns is similar across the trials. Moreover, all the measures show higher performance in the EO rather than in the EC condition.

Comparing the LLE of DA and PS test, the results show that PS values are about three folds the DA values. This confirms that the LLE accounts for the dependency on the initial conditions and the repetition of the movement pattern. Moreover, DA results shows also LLE improvement across the trials, which means that the subject is able to predict the perturbations. On the contrary, in the PS test LLE is steady across the trials, therefore the learning only involves the improvement in correcting the perturbations, not in their prediction.

6.2.2. Motor retention

Motor retention is the only way to confirm, whether learning effectively occurred or the intrasession performance improvement was only due to an adaptation phase. The results of this work show, that while for DA test there was retention, for PS test there was only a slight retention.

The following discussion regards the paragraph 5.2.2 (DA – Formal Learning, set 2) and paragraph 5.2.6 (PS – set 2) in which the tests were repeated after about six months.

DA protocol

Considering the repetition of the DA test after six months, results show no learning effect just for the test related gestures, which encompasses the CTT, in which the subject by moving his/her CoP has to follow a target displayed on the screen, and the CRT, in which the subject has to react appropriately to symbols appearing on the screen. On the contrary, the PVT shows that there is no learning retention. In fact, results and trend of the second experiment are similar to the previous set (DA – Formal Learning, set 1). Hence, only adaptation to the test conditions occurred for the PVT.

The results show therefore, that in this set, the subject does not restart with the cognitive stage but already with the associative stage, which is characterized by small performance gains. In this stage, improvement regards interpretation of sensory information, optimization of the muscles modulation and their recruiting, as well as prediction of the perturbations. Working memory is still necessary, but in a lesser extent than in the previous stage. In fact, results show that the capacity interference is slightly reduced between the two concurrent tasks. The ratio between the CRT and PVT reaction time changes from 3.2 of the first set to 2.8 of this set. However, a similar trend is not found for the ratio between CTT lag and PVT since it remains unchanged from the first set.

This retention is possible only if the subject was able to generate a novel motor schema in the previous session, which refers the CTT and CRT task. It is supposed that the retention of these tasks does not depend on how the motor schema was constituted, therefore this considerations can be extended also to the subjects of the imitation learning group. On the contrary, the PVT shows again a steep improvement in the first trials because it is performed without the need to constitute a new motor schema.

Several other factors may have influenced the learning retention diversity between the gestures related to DA and to PVT. Willingham and Dumas (1997) suggest that as the target following actions are made of non-discrete movements, they are retained for a longer time, unlike in pushing button action which is a discrete gesture. In fact, in the PVT the trend of the two sets is similar, which indicates the absence of learning retention, while the CRT shows motor learning retention. The level of training achieved for the two tasks is not the same: while the PVT is practiced in few trials and in a rapid succession, the CRT is being repeated many times during the DA test. Also in the CRT the subject is not required to respond automatically to the stimulus but to discern between right and dummy target.

Furthermore, the work of Wulf et al. (1998) has shown that also the type of instruction given to the subject influences the retention of motor gestures. Instructions that focus on the movements to be performed (internal focus) reduce the ability of the subject and are soon forgotten. On the contrary, the instructions that focus on the purpose of the movement (external focus) lead to better movements and memory retention. Besides, instructions with an external focus are more effective as they are related to top-down processes, opposed to instructions with an internal focus linked to bottom-down processes (Sun and Zhang, 2004).

In this protocol, the instructions given to the subject are top-down as they regard the functioning of the equipment and the meaning of the symbols which appear on the screen. Even in the initial phase of adaptation, the subject performed actions with external focus as he/she was confronting his/her movements with the general CoP displayed on the screen.

Another factor that may have led to the retention of learning, regards the movements' feedback. In fact, the protocol provides visual feedback to the tracking action (CTT task), where the subject watches on the screen the location of his/her CoP and the position of the symbol target to reach. However, for the action related to the cue vision (CRT task), either the correct symbol or the dummy one disappears when pressing the button and so, it does not allow the subject to discriminate with certainty the symbols meaning (in particular for group C). Still, the subject can deduce the correct symbol by comparing it with the symbols of the first task, in which, similarly, there are dummy symbols consisting of hollow figures, and a correct symbol represented by a full figure.

Other studies show that the memory span of an action coding depends also on whether the task is associated with a reward or punishment (Nakatani et al., 2009). The protocol used does not contain any form of reward or punishment, so a reduction in the retention should be expected as also suggested by Abe et al. (2011). However, the results do not show any reduction, perhaps because subjects that voluntary participate in these laboratory conditions have self-motivation induced by curiosity or by considering the test as a challenge.

In this second set, the learning trend of the CTT and CRT is better fitted with a linear law, not with the power law of learning. However, since the learning ratio *m* is much smaller than in the previous set, the number of performed trials might not be sufficient to show the real learning curve. That is, these data might only display a small window of a power curve. Instead, the power law of practice well fits the PVT, which confirms that no learning occurs for this task but just an adaptation.

The measured parameters do not show an improvement in the overall performance, except for a slight improvement in the CRT reaction time. In particular, the cross-correlation coefficient and the correctness score are more difficult to show improvement due to their ceiling effect. In fact, their maximum value is 1 and the results of the first set are already close to it. Though, it does not mean that learning has stopped. Perhaps further improvements might regard a reduction in cognitive resources necessary to perform the test, which will reduce the capacity interference between the two tasks.

Analogous trend is found also for the Fitts' model of the speed-accuracy trade-off, which is better fitted with a linear law. Also in this set, the MT increases with the reduction of the target size with an average of about 3.5% for W2 and 5% for W3.

In this second set the results show that the influence of the tilt angle has a small first phase that last till the 4^{th} trial and a high second phase on the 8^{th}-9^{th} trial. This trend is very similar to group C, perhaps because they both had their motor schema already pre-constituted. This confirms that the observation of the gestures allows to setup at least a part of the response programming.

Contrary to the parameters used to assess the CTT tracking (cross-correlation) and the CRT, there is a substantial improvement in the movement time (MT) of a given index of difficulty (ID_{et}). This is possible because ID_{et} and MT show a smaller floor effect, which allows to highlight the improvement in the postural control. Indeed, about 20% fewer targets are not reached by the subject in set 2 (group B), with comparison with set 1 (group A) (Table 5.8).

Similarly, also the *m* coefficient of the Hick's law is better fitted with a linear law. Moreover, the reduction of its RT highlights an improvement in the coordination of the two tasks.

PS protocol

Considering the repetition of PS test, results show that there is a motor gesture retention as there is an improvement in counteracting perturbations between the two sets. Yet, the first trial cannot be taken as a reference result because there is still a learning factor. Figure 5.90 shows that the areal velocity (velocity moment, NAVM) improves markedly between the two sessions, while Figure 5.89, Figure 5.91 and Figure 5.92 respectively show that stability score (SS), the sway velocity (NAV) and the largest Lyapunov exponent (LLE) did not improve. These three latter parameters are associated with the perturbations caused by standing onto the cushion, while the first is linked with the ability to respond to the perturbations. In particular, since the sway velocity is unchanged but its moment is reduced, the improvement regards the lever-arm of the velocity. This means that the subject does not sway around but the corrections of the perturbation are directed towards the center of the CoP.

Moreover, the power law of learning is still valid for the EC condition but not for the EO condition, which is better fitted with a linear law. Perhaps the knowledge of results (KR) provided by the vision has an influence on the allowable improvement, which is higher for EC condition. Considering that SS, NAV and LLE do not show retention, they can be well used in the assessment without including intersession improvement. However, except for the LLE, they are still biased by the learning phase.

The results of this test (SS, NAV and LLE) show that the subject is not able to avoid perturbations but only to retain the strategy to compensate them (NAVM). Therefore, the learning involved only the response selection of the *recall* sub-schema, while chaotic perturbations do not allow to generate a *reference* sub-schema.

The limited motor retention is probably due to the chaotic nature of the perturbations, which impedes the subject in identifying an optimal motor strategy. Moreover, the control strategy is further constrained by the fact that the subject already has a consolidated postural control. This is also confirmed in the case of the PVT in the second set of tests, where results show that there is no retention of the gesture in the case of an action that requires only to press a button when an evident stimulus appears. Probably the learning phase is superimposed to an adaptation phase, in which the subject get used to the conditions of the test. In fact, in the case of PVT the triggering is an action that should already be coded by the subject, for which an improvement can be achieved only through specific trainings (Uimonen et al., 1994).

Moreover, there is evidence that the inter-session break allowed the subject to retain and improve the postural adjustment strategies used to counteract perturbations. The subject got used to the perturbations and does not overreact anymore while responding to them. This is consistent with an inter-session learning retention, even though results do not show performance decay as it would be expected after such a long break between the two sessions.

In a shooting task, in which the subject has to move a robotic arm to reach a target without the possibility to see his/her own limb, Huang and Shadmehr (2009) demonstrated that a slow decay in performance is observed when the perturbations to the robotic arm are gradually introduced before practicing the trials with full perturbation. This happened also when the subjects did not have the chance to do some practice trials once they reach the full level of perturbation. On the contrary, when the perturbations were suddenly applied to the robotic arm, the study shows that there is a faster performance decay.

In the case of this PS test, even though the subject could practice just for a total of 7 minutes in the first session and that the perturbations were generated right when stepping onto the cushion, results show that there is just a slight performance decay in the areal velocity only in the first block of 20s and for eyes closed condition. In fact, generally there is a great improvement (Figure 5.90).

Learning effect exhaustion

Analyzing motor retention, an important question emerges: at which point measurement parameters are free from learning effect?

Probably at no point. Crossman (1959) demonstrates that practice continually improves gestures even after they are repeated 10 million of times. However, after some practice, the difference between one trial and the subsequent one fades out.

In this DA protocol from the third trial on it is possible to consider measures free from learning effect. Thus subsequent results can be averaged without biasing the data. However, in this test the subjects performed only up to ten trials with enough break time to rest between each repetition. In case of longer tests, after a certain number of repetitions it should be expected a performance reduction due to a fatigue. Hence, this will also bias the averaged data.

Results of DA – Formal Learning, set 1 show that at least two trials are needed to exhaust the learning phase in all of the measured parameters, both CTT and CRT. Only from the third trial there is no statistical difference between the subsequent repetitions (Figure 5.6-Figure 5.20). Similar learning phase is also found in PVT. DA test shows limited learning effect in the second session of trials but it is not always possible to know how many times the subject performed the test. Thus, for this protocol, although the parameters used to assess the overall performance do not change, one should anyway repeat three times the test. This phase can be reduced just to one trial by showing once the test to the subject.

Results of PS test, both first set and imitation group, show that there is a learning effect that varies according to the test conditions. For eyes open condition, results show a small learning phase, thus it is required only 20 seconds of practice before the results can be considered reliable. On the contrary, the eyes closed condition is more demanding as the subject is deprived of the visual information. Therefore, the learning effect lasts longer than in the previous condition. Hence, before the results can be considered free from learning effect at least two trials of 60s or four trials of 20 seconds must be practiced. Further tests are useless as they are statistically similar to each other.

Nevertheless, if the subject steps off the platform after one practice and before another, each first 20s of standing on the cushion should be discarded. This is so called an adaptation phase and both conditions require it. Besides, a second minor adaptation phase is found when the subject closes his/her eyes, therefore an additional 20s from the moment of closing eyes are needed to exhaust it.

PS test shows, that in the second session of trials, the subjects still need to accustom themselves to the test conditions, although the adaptation mechanism to the perturbations is much improved. Moreover, as expected, subjects carrying out the PS test with EO condition perform better compared to the subjects with EC condition. Furthermore, there is a minor adaptation phase when the subjects, already on the cushion, close their eyes to initiate the test. This should be excluded by making the subject stepping into the platform 20 seconds before initiating the test.

What emerges from the experiments of PS is that the subjects need basically to get familiar with the test condition and that long lasting tests or multiple repetitions are not necessary. On the contrary, extended or numerous assessments can just cause fatigue. Nevertheless, results show that if only the LLE is measured, one trial is enough to provide a value unbiased by the learning phase.

In conclusion, the learning phase of a task is often underestimated or not even taken into consideration when measurements are carried out on human beings. Before proceeding with any measuring, it is suggested to investigate the learning curve of the parameter in use and be prudent in selecting variables and in averaging the results. Moreover, besides analyzing the overall performance, a closer look should be taken at the learning trend, as it might carry useful and valuable information. Indeed, from the preliminary results of paragraph 5.2.4, it seems that learning is disrupted in degraded psychophysical conditions.

6.2.3. Postural controls

Most of the postural controls are coupled with 2-D models because they provide an understandable system, thus allowing to study the posture kinematics and control with a certain simplicity. In particular, the single inverted pendulum, the simplest albeit already with complicated stability issues, is the most popular among researchers. Comparisons with the experimental CoP show that already the 2-D multilink model can provide good biofidelity in terms of magnitude and frequency of sway.

However, the main limits of the 2-D models regard their kinematics and dynamics. In fact, they can move just in one plane, either sagittal (anterior-posterior) or coronal (medio-lateral), while in reality the body sways in both plane. Therefore, excluding the coronal plane brings the model far from being true reflection of real system. Hence, the kinematics and dynamics of 2-D models does not provide a sufficient base to study efficient control mechanisms. Another limitation is that they do not allow to build the whole SKG but only one of its component. By implementing coupled 2-D models some of these limits may be overcome. Through provided plane interactions a SKG can be plotted, however, at the expense of a more complicated control.

The 3-D model gives the closes resemblance of numerical data with the experimental group comparing to the 2-D models. Thus it has the higher biofidelity results of all previously mentioned models even though some elements are still simplified or even neglected. Table 6.1 summarizes and compares the mathematical models here described.

Table 6.1: General model family characteristics

Model	Main advantages	Main disadvantages	Allowable biofidelity of postural control
Single link 2-D	Simple to work with	Weak kinematics and dynamics simulation, simple postural control	Very low
Multi-link 2-D	Still simple to work with	Just one plane	Low to medium
Multi-plane 2-D	Consider both AP and ML plane	Complexity in coupling, adjustments to make it work, axial rotation neglected	Medium
3-D	Closest replication	Require complex postural control, numerical instability	High

The most sophisticated postural controls are conceived for intrinsically stable systems such as the hand-arm system with movements on the horizontal plane. As a result, these controllers efficiently implement mixed controllers with forward predictors, which can be used for pointing or grasping tasks. However, since the human posture is intrinsically unstable, it is more difficult to implement such features in a controller.

In fact, while postural controls are mainly implemented to maintain the erect stance of the model, in reality their aim is to maintain the optimal position of each segment of the model, rather than the overall equilibrium.

For this reason, most of the postural controls are feedback based and are coupled with the single-link inverted pendulum (Chagdes et al., 2013; Elias and Forner-Cordero, 2011; Toppila and Pyykkö, 2000; Winter, 1995), while the most challenging controls are applied on multi-link models (Suzuki et al., 2011; Xinjilefu et al., 2009). Moreover, the feedback controller is often based on a proportional-derivative system (Suzuki et al., 2011). Only recently more sophisticated controllers comprise learning capabilities (Ruan et al., 2007), neural networks (Yu et al., 2006), chaos theory (Toppila and Pyykkö, 2000), or stochastic programming (Xinjilefu et al., 2009).

However, the biologic postural control is very complex and yet not well understood. Some of the progress in postural controllers come from behavioral models, which resemble closer the human capabilities.

Figure 6.1 depicts a postural control derived from the Schmidt's motor schema. The input is fed to high cognitive centers which according to the system state elaborate the appropriate response to achieve the goal. Then the signal is fed to the motor areas that, according to the MN theory, include an internal model of the system and elaborate a motor plan according to a cost function. The torque values plus a certain amount of noise are then forwarded to the muscles. This is already complex to manage for a feedforward controller because it has to take into account the signal time delays and noise. Moreover, the linearized torque controls of Equation 2.2 are valid only for small tilt angles. In the case where the postural control has to pursuit the CTT targets this assumption is not valid anymore.

Additionally, the feedforward controller is fed with a learning signal from the comparator (forward model). Therefore, this is similar to the feedback-error-learning (FEL) described in paragraph 2.2.4, which allows to reduce the error at each repetition of the program. Precisely, it is a structural learning because the controller should not have to setup its internal model from scratch. For instance, in the CTT the controller learns and improves the control of the tilt angle. However, one drawback of the FEL is that it mostly depends on the last feedback data received, which restricts the application of the controller to one single type of duty.

Furthermore, the input of the muscular system is also feedback controlled with two different systems, the SLR and LLR, which makes the entire system a mixed-model controller. SLR and LLR are respectively mediated by the spinal and the cerebellum, however, the SLR only activates when the muscle spindles exceed a certain threshold value. Conversely, the LLR controller is always active and corrects the perturbations that occur during the movement.

Some parts of the schema of Figure 6.1 can be neglected according to the purpose of the postural control. For instance, in the case of the CTT balance pointing task, it is possible to exclude the SLR since the subject will not make fast movements and stays on a stable surface. On the contrary, SLR might not be ignored in the PS test.

Concurrent SLR and LLR controller were successfully implemented in a two-link inverted pendulum robot through the disturbance estimation and compensation (DEC) model, a Kalman based filter, which estimates the disturbances of gravity, contact force and support surface with the inputs of vestibular, joint torque and angle signals (Mergner, 2013). The DEC controller is able to counteract both sudden impulses and slow tilting movements of the platform.

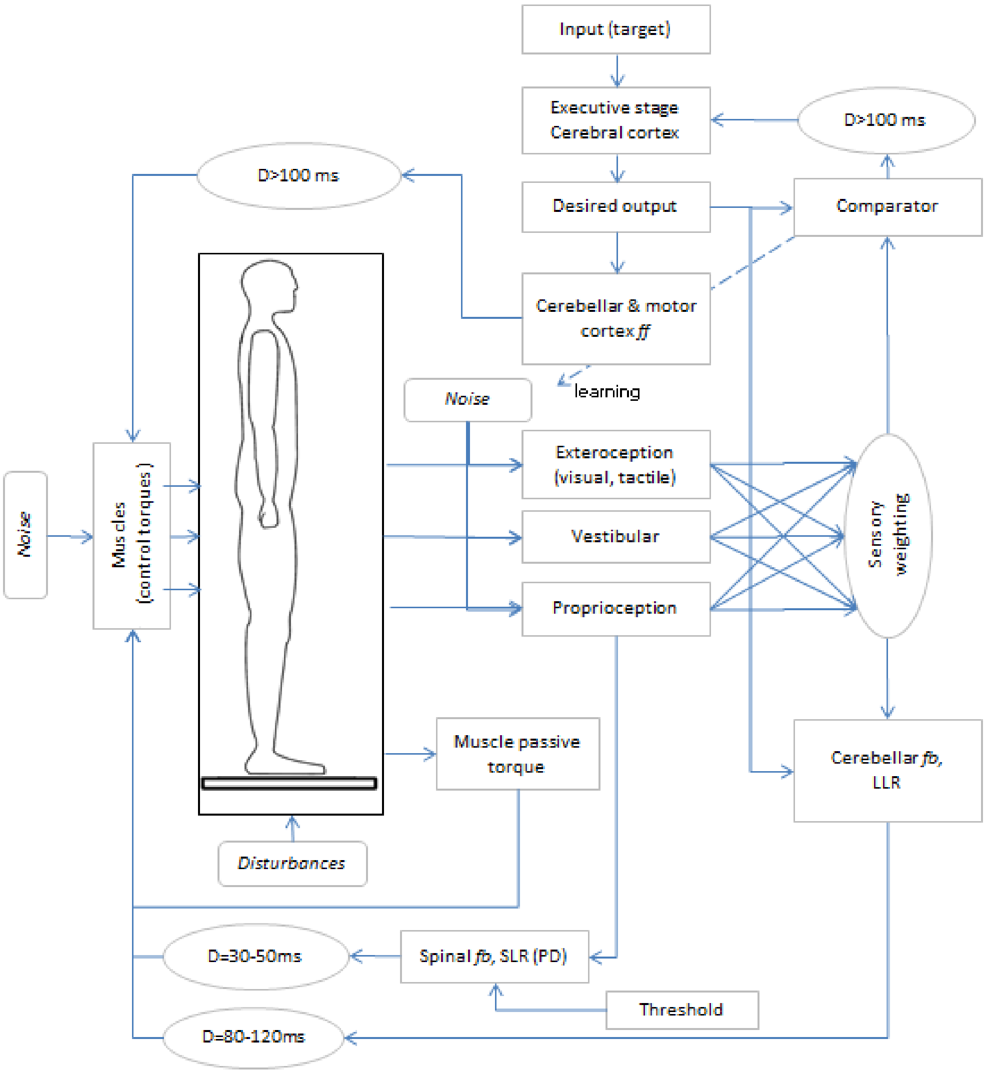


Figure 6.1: Example of postural control according to the motor schema. *fb* refers to feedback, *ff* to feedforward, D to delay, and PD to proportional-derivative.

The delays and noise of this system require to perform slow movements until the feedforward control has adapted its parameters through the learning signal. The learning performance of the feedforward control can be measured with the power law of practice (Equation 3.5) or in the case of CTT task, with the m_2 coefficient of the modified Fitts' law presented in Equation 6.1.

With regard to the feedback signal, the sensory inputs are weighted according to the controller involved and according to the available information. For instance, when vision is not available, vestibular and proprioception increase their weight.

To achieve better biofidelity, these biological signals should be implemented into the controls:

- Force feedback (muscle spindles, Golgi tendon sensors);
- Muscle involuntary contractions, muscle fatigue;
- Passive torques at joints, to consider passive muscle visco-elasticiy;

- Consider the agonist and antagonist muscles (two torques for each joint);
- Actuators described with Hill model muscle;
- Actuators control such as torque, time to peak torque (Corbeil et al., 2001)
- Time delay for actuators activation (Y. Li et al., 2012);
- Internal perturbations such as breathing and cardiac contraction;
- Anticipated postural adjustments.

Perhaps more bio-fidelity posture controls will be available with the implementation of multi-level neuronal networks that resemble the cerebral control. Nevertheless, it is still not possible to model every aspect of the human postural control as it is still unclear how exactly the central nervous system controls balance or why a pleasing sound makes the subject sway towards it and vice-versa why the subject sways away from an unpleasant noise (Agaeva et al., 2006).

6.3. NOVEL METHODOLOGY TO ASSESS IMPAIRMENT

Traffic accidents are now ranked as the 9th (2.2%) cause of death, right after diseases like heart ischemia, cancer and infections; but in 2030 traffic accidents are projected to become the 5th (3.6%) cause of death (*GLOBAL STATUS REPORT ON ROAD SAFETY*, 2009).

Although such rank varies with age, it remains one of the first three causes of death for 5-44 years olds (Angermann et al., 2005; *GLOBAL STATUS REPORT ON ROAD SAFETY*, 2009). In EU23 (EU27 except Bulgaria, Cyprus, Lithuania, Malta) in 2010, 10% of people aged between 14-30 died in road accidents with a peak of 17% for 17-22 years olds (Brandstaetter et al., 2010). U.K. seems to have either better road safety policies or their better enforcement than any other EU country. Comparing indicators with Italy, it is found that accidents occurred for the same traveling distance (per vehicle billion kilometer travelled), in 2012 fatalities ratio were 4.5 (UK) and 5.4 (IT). Comparing accident severity (deaths every 100 accidents) again Italy has a higher severity rate: 1.96 (IT) against 1.24 (U.K.).

In the latter years high income countries have approved policies that drastically reduce road collisions. In fact, fatality rate in EU28 has been almost halved from 2001 to 2012, that means an average of 13500 less deaths every year (10000 in EU15), while injuries in EU15 in the same time span were reduced by 40%. However, in some countries, e.g. Australia, fatalities are decreasing but with a steady or an increasing number of collisions. Probably there is just a reduction in the accident severity (*Road Safety Annual Report 2014*, 2014). Indeed most of the public attention on driving safety is on alcohol restrictions, which is only one of the vehicle accidents most causes (about 30%). Actually, there are other 60% of fatalities that are not connected to DUI.

Many studies report that lowering blood alcohol content (BAC) limits provides a reduction in alcohol related crashes, but some research cast doubts whether alcohol limit reduction has influence on decreasing fatalities. Wagenaar et al. has analyzed the effect of reducing BAC in U.S., from 1976 to 2002. Reducing BAC from 1g/L to 0.8g/L provided a 360 life save per year and a further reduction to 0.5g/L is estimated to save 538 more lives (Wagenaar et al., 2007). However, such fatalities reduction is not much when compared with an average of minus 10000 deaths each year from 2001 to 1012 in EU15. Moreover, the amount of fatalities provided by NHTSA (NHTSA, 2013a) shows steady figures between 1995 and 2007 (about 42000), even though the BAC limit was lowered from 1 to 0.8 g/L in all states in 2000. Before 2000 only 19 states had a limit of 0.8 g/L whereas other states used 1g/L (*Traffic Safety Facts 2000*, 2001; Wagenaar et al., 2007).

On the contrary, a study conducted in Norway shows that the reduced BAC limit in 2001 (from 0.5 g/L to 0.2 g/L) did not provide a fatality reduction. Alcohol related accident statistics were terminated in 1996, therefore the authors used single-vehicle night crashes as surrogate alcohol-related fatality measure. Looking at those fatalities six years before the law amend and six years after, no fatality reduction can be found.

The same study provides the results of an interview survey conducted in 1998 (before the limit lowering) and in 2001 (after the amendment) in which 3001 drivers were interviewed. Results show that the drivers were more aware of the alcohol dangerousness but they would not drink because of fines, rather because of increasing crash risk.

Alcohol or drug-related fatalities are about 20-40% of total fatalities. Even though there is another 60-80% not related to DUI, their intake certainly leads to higher chances of serious injuries or death, which generate the most part of economic loss.

The other 60-80% of fatalities are mainly due to driver or pedestrian responsibility. In particular, Figure 4.14 and Figure 4.15 show that the main human/anthropic factor is distraction, driving error, disobedience of road rules and speeding. Moreover, most of the road accidents occur during working hours with a peak right after working shifts. Although from 9 p.m. until 6 a.m. fewer accidents occur, they have higher severity.

Road safety policies are also moving towards the reduction of distraction. Calling with mobile phones is permitted only using hands-free in U.K. and Italy but not for non-professional drivers in 19 U.S. states. Though, any conversation causes distraction or mental workload. A mobile phone usage increases the risk of collision by at least 1.7 times (*Car telephone use and road safety*, 2009).There are also discussions towards the complete ban on calling. In U.K. it is even prohibited to smoke while driving.

“Drink and Drive” campaigns and other restrictions might have helped in reducing collisions. Also the implementation of oral fluid drug test might have discouraged the motorists to drive under psycho-physical degraded conditions. However, as pointed out in paragraph 4.2, a comprehensive and reliable test that assesses driving impairment and that overcomes the present roadside test limitations has not been implemented yet.

Nevertheless, some other factors that diminished the road accidents include driver education and safer vehicles. About the first factor, in 2006 driving license rules have changed in EU and in 2013 were fully implemented (Directive 2006/126/EC). For instance, moped drivers now may be required to follow a training course and a skill test in order to get driving license, thus acting to increase safety on the most vulnerable users. In order to allow a progressive access to motorbikes, a limit on power to weight ratio was imposed for young riders and for non-experienced users. Driving license renewal, required every 10-15 years, is just for security issues in order to avoid fraud and to keep up-to-date information. No skill or medical test is required, even though some countries may require medical test, e.g. Italy.

In 2006 new EU rules were issued also for professional drivers. Driving working hours were made shorter, license have to be renewed every 5 years with medical checks and a refresher course. Moreover, the professional drivers training was enforced and like for mopeds, progress access to powerful heavy good vehicles (HGV) has been made. Recommendations to driver examiners were also issued: setting a compulsory, periodic training and hold a driving license for the category examined, therefore they have to go under renewal (Directive 2006/126/EC).

To sum up, in the EU road accidents have decreased significantly but not as much as it was targeted. Many policies have been implemented with good results but far can still be done, especially in driver error or injudicious action avoidance. By 2020 the EU challenge is to halve another time the road accident fatalities. Table 4.7 shows that reducing accidents does not only have moral motivations but also economic implications since each euro spent on safety generates high savings. An important role might be played by the assessments techniques of driver's psychophysical conditions.

In this work a novel test for driving while impaired evaluation is proposed (DA), but in order to be used some requirements must be satisfied. The proposed methodology will be assessed for its content such as evaluation of driving abilities and psycho-physical conditions as well as overall protocol comprehension and feasibility. Eventually, the methodology limitations are presented.

6.3.1. Driving abilities evaluation

According to Kay and Logan (2011) and Walsh et al. (2008), roadside tests must evaluate essential driving abilities and subject's behavior.

Essential driving abilities can be categorized into five domains that depend on motor, perceptual and cognitive abilities (Kay and Logan, 2011), such as: alertness, attention and processing speed, reaction time, sensory perceptual, executive functions.

The executive function regards the ability of the subject to plan, coordinate and monitor cognitive processes. Sensory perceptual abilities concern sensorimotor, proprioception, visual and auditory-vestibular systems. Postural control relies on all of such systems even though at least only two of them are necessary. Both, executive functions and sensory systems can be impaired or desensitized by diseases and drugs, either medical or illegal. On the other hand, alertness plays a primary role in perceiving the stimuli: without being vigilant is not possible to activate the subsequent processes (inattention) that will focus the attention on the new stimuli and then elaborate them. Impairment of vigilance might be caused by drowsiness, hallucinogen and depressants drugs.

With regard to attentional abilities, psychologist have categorized various types of attention abilities, but there is not a neat distinction and often categories concurrently overlap each other to some extent. Selective attention is the ability to focus the attention on the objective. This is achieved by suppressing stimulus that are not important for the task or external noises. Divided attention is the ability to pay attention to multiple stimulus at once; this is requested during driving as one has to observe the road environment and contemporary manage the vehicle. Attention shift is the ability to change the focus of attention to different stimulus; in particular shifting delay plays an important role. Sustained attention is the ability to maintain attention to a certain level over time; attention level changes during a performance or during concentration. For instance, fatigue reduces the sustained attention ability which consequently makes more difficult to suppress external stimulus (distraction) and shifting delay is increased.

Alertness and working memory are essential for attentional abilities. If the subject is not vigilant, he/she would not perceive any stimulus, thus the attentional mechanism will not even be involved. Working memory allows to temporary store information necessary to elaborate the stimulus as well as to hold attention of different stimulus. Usually working memory has a storage capacity of up to about seven-nine elements at a time.

Behavior skills related with driving can be categorized into the subsequent three core levels (Walsh et al., 2008). The first, automatic behavior, regards motor and cognitive skills that are well-coded by the subject, such as vehicle handling and road tracking. The second, control behavior regards skills that the subject compares his/her internal parameters with the external environment. That is, keeping safety distance from the vehicles, speed regulation, overtaking etc. and it is related to perception, divided attention and motor performance. Third, executive planning behavior regards the functions that are connected with the information processing, decisions and judgment. It is related to risk taking, impulsivity, choice reaction time and selective attention.

This protocol test requires the subject to have all of the Driving Essential Abilities and most of the behavior abilities. For instance, it is known that executive function is associated with balance ability (van Iersel et al., 2008), and by doing a second task the executive functions must be shared thus conditioning equilibrium stability (Kosonogov, 2011). Moreover, this protocol requires the subject to plan the movement in order to reach the new target position, to coordinate and control gestures. Still, the tasks cannot be made more complicated as it would be more difficult to learn them and because the excessive cognitive load might reduce the threshold of fall risk, in particular for elderlies. In this test, vigilance is required to follow the stimuli that appear on the screen.

By doing the CTT together with the CRT, both attention and reaction time domains are included in the evaluation, as well as the automatic and control behavior. The first requires to discard dummy symbols and to focus on the target following with the smallest delay, the second requires to constantly scan the screen to find visual cue symbols, to discern between right or wrong reaction stimuli and to respond with the smallest delay.

Considering that the test should be repeated three times in order to obtain results free from learning effect, and that each test of 60s is carried out every 3 minutes, the total duration (7 minutes) allows to evaluate the ability of the subject to sustain attention over time, and still without causing fatigue. Both tasks are also influenced by impulsivity and executive planning behavior, as a subject can overreact to the visual cue stimuli or move his/her body with reduced control.

On the contrary, attentional shift is not a part of the assessment as the subject does not have to shift attention to other stimulus than the ones required in the test. Also the attentional working memory is used in little extent as few stimuli appear contemporary on the screen.

6.3.2. Psycho-physical conditions evaluation

Impaired motorists show decreased attentiveness, slower movements and reaction times as well as reduced ability to judge distance and time. A test has to be designed to assess this psycho-physical conditions.

In this work only healthy subjects participated in the controlled experiments. However, as already mentioned in the above paragraphs, this test evaluates skills such as executive functions and attentional functions, which can be impaired by fatigue, drowsiness, psychoactive drugs or toxic substances. The reduced attentional control might cause a higher sway velocity, a wider CoP area or even a balance loss (Patel et al., 2008).

Moreover, it is proved that drug abuse (Liguori et al., 1998; Moreira et al., 2012) or alcohol (Kubo et al., 1989; Liguori et al., 2002) reduce balance control. In fact, alcohol reduces general abilities with particular extent of multitasking ability (Harrison and Fillmore, 2011; Wester et al., 2010), as it increases attentional switch delay, mainly when cognitive tasks are involved rather than visual tasks (Rudin-Brown et al., 2013). Notably, a study on psychomotor tests was conducted. It was shown that mere alcohol increases a choice reaction time, brakes latency and postural sway and the caffeine administration does not counteract those alcohol effects (Liguori and Robinson, 2001).

Balance capability can be affected also by fatigue and tiredness (Paillard, 2012; Pline et al., 2006), sleep deprivation (Bougard and Davenne, 2012; Patel et al., 2008; Schlesinger et al., 1998; Uimonen et al., 1994), environmental conditions, such as a high volume music or noise and stroboscopic lights (Pascolo et al., 2009). Such factors can impair balance in a similar extent as alcohol does. In particular, it was shown that listening to a very loud music for a long time can cause dizziness and increase of a postural sway comparable to alcohol (Pascolo et al., 2009).

However, these research did not consider the learning or adaptation phase in order to become accustomed with the tasks or test conditions. Although, in adulthood there is generally limited motor learning as the optimum of postural control was already reached (Uimonen et al., 1994), the execution of novel or unfamiliar sensorimotor task involves the motor learning. Thus, subject must find new different motor strategies when a steady standing test becomes less stable, i.e. with closed eyes and feet together (Tarantola et al., 1997), on a cushion foam (Pagnacco et al., 2008) or with a new gestures coordination like here proposed.

Moreover, research carried on habitual drug addicts show that prolonged usage of alcohol or drugs (e.g. marijuana) in short-term reduces the spatial and non-spatial learning (Beatty et al., 1997) and memory capacities (Solowij et al., 2011). Similar experiments on rats with administered alcohol and drugs, confirm these results (Cha et al., 2006; Fehr et al., 1976).

Therefore, analysis of the learning phase might be the first clue to differentiate unimpaired subjects from the impaired ones. This appears to be supported also by the preliminary data presented in paragraph 5.2.4, which shows that it seems possible to discriminate subjects in degraded conditions by means of learning trend rather than overall performance. Jongen et al. (2014) confirm that postural balance test, psychomotor vigilance test and divided attention test are highly correlated with alcohol dose and already doses of alcohol over 0.2 g/L can be detected by using those three tests together (PBT, PVT, DA).

While stimulants drugs are thought to improve reaction time, they also reduce impulse control and thus cause mistakes or overreaction. On the contrary, sedatives drugs, such as marijuana and opioids, increase reaction time, condition automatic behaviors and complex task handling (M.-C. Li et al., 2012). Moreover, balance tests seem not to be sensitive to caffeine or caffeine-based drinks even when used to counteract alcohol impairment (Liguori and Robinson, 2001).

6.3.3. Protocol comprehension

In order to be useful, a test must be easy to understand and must allow to be learnt within few practice trials.

The proposed divided attention test is made by two tasks which objectives are simple enough to be easily recognized. One must find the movements that are more productive for the critical tracking test and find good coordination to perform the second task (choice reaction test).

Experiments, in which the DA test was administrated to subjects, show that the neuro-muscular activities related to the protocol tasks are tuned-up with just two repetitions (DA – Formal Learning, set 1) and the third repetition being the effective one.

In the second set of trials (DA – Formal Learning, set 2) the subjects show motor persistence and one trial is enough to adapt again to the test conditions and recall both gestures and motor coordination. Nevertheless, this retention was possible even after a quite short but intensive training, which is a ten times repeated test six months earlier (DA – Formal Learning, set 1), sustaining that subjects did not execute any posturographic test in the meantime, as they declared. This is in line with another study conducted by Sawers and Hahn (2013), showing that the same retention is obtained either by a short intensive training or by a gradual one. Thus, the first test session was sufficient for motor gestures to be encoded and generalized (Boutin et al., 2013). This can be only possible with an understandable protocol and easiness to perform its objectives by the associated gestures (Boutin et al., 2013). Furthermore, looking at the overall performance, subjects perform similarly in both set of trials (DA – Formal Learning, set 1 and 2), therefore the test is also found to be repeatable over time.

The results of the DA protocol in which the test information was conveyed by means of imitation by observation (DA – Imitation Learning) show that this method is effective only to reduce the learning phase of gross motor tasks, which are related just to the critical tracking test. Conversely, less obvious objectives and fine motor gestures still need formal learning in order to be apprehend by the subject. Nevertheless, the overall performance is similar in both approaches. Perhaps, by using formal learning and showing one trial it would be possible to take the pros of each method without conditioning overall performance.

6.3.4. Protocol feasibility

The protocol feasibility to be implemented as a roadside test is below discussed.

Motor learning is of course continuous and performance improves with practice. However, the DA test experiments show that the cross-correlation and reaction time measures are good variables to assess DA test performance because they exhibit either ceiling or floor effect, which means that they rapidly reach an asymptotic value. In fact, the asymptotic value is reached at most with just two repetitions (DA – Formal Learning, set 1) since further trials are not statistically different from the third one. The motor gestures related to the trigger pressing, that are used in the choice reaction test and the psychomotor vigilance test, do not need to be learnt as they are simple gestures already well-coded by the subject. Therefore, for this task, the increased performance is related to an adaptation phase rather than learning phase.

Assuming that just three test repetitions are necessary to collect enough data, the break between the test repetitions can be reduced to only one minute without the risk of including fatigue effects in the results. This makes in total five minutes of the effective testing time, plus the additional time needed for the test explanation, which is comparable with the SFST execution that lasts about 10mins. Moreover, the test result is immediately made available by the software, uncommon to some other tests currently in use, i.e. a simple oral fluid analysis for drug screening takes about 15mins to get the result.

The setup time of necessary equipment is also relatively short. The setup of the conducted experiments took 5mins by using general equipment, and the ready-to-use kit should allow to further time reduction. In particular, the platform needs to be placed, a screen must be positioned at a certain height and distance and everything plus a trigger must be plugged into a PC or laptop.

The test administration is as well quite simple. Practically the test can start right after the instructions are read out and the subject holds the finger trigger and is standing on the platform. The protocol instructions and procedure were clear to all subjects since the gestures and coordination was long-term retained (DA – Formal Learning, set 2).

The personnel training time should be also limited as the results are not evaluated by the test conductor, instead just read from a PC. This makes the training at reasonable duration about the same as BrAC test – that is, about 4 hours (Substance Abuse Program Administrators Association, 2015). To give just one example, SFST necessitate about 24 hours training (NHTSA, 2001), mainly because the test personnel provides also the evaluation.

Furthermore, the proposed protocol overcomes some of the limitations of fluid analysis and SFST. Indeed, the aim is to objectively assess only the amount of impairment, regardless of its cause, the amount of an impairment factor or multi-factor proportion and the combination. No necessity to collect body fluids makes it safer, as sometimes fluids are handled inappropriately or are difficult to obtain, i.e. smoking marijuana makes the dry mouth. Still, in countries with the legislation based only on drug thresholds, body fluid analysis is mandatory for legal punishment and fines. Hence, it would be useful to provide an alcohol equivalent impairment parameter. The performance score presented in (DA – Formal Learning, set 1) seems to be a valid candidate since it resemble the characteristics of learning trend and performance of the analyzed variables.

The main protocol limitation concerns the test instruments. In fact, the platform must be placed on a flat, plain and firm surface like a regular road, pavement or footpath, which might be a problem in areas with a very poor infrastructure or in rural areas. Conversely, traditional DUI detectors can be used in any place. Nevertheless, this limitation might be compensated by the potentials of this test, which have been developed to provide a more comprehensive and unbiased tool for impairment evaluation.

The proposed protocol still requires further tests and analysis. The environmental influence like noise and individual characteristics like age, stress and anxiety need to be examined on a wider population as well as in roadside conditions. Moreover, the driving tests on impaired subjects must be carried out (i.e. DUI, medicines, sleep-deprivation) to research on the correlation between the protocol outcomes and the driving abilities, since currently seems to be just indirect proofs. Indeed, it has been demonstrated that impairing conditions correlate with driving abilities (Ogden and Moskowitz, 2004) and correlate with postural sway (Liguori et al., 2002; Pascolo et al., 2009).

To sum up, the proposed novel divided attention test, based on balance and trigger tasks, seems suitable for further validation of road side test to assess motorist's impairment as it is composed of understandable tasks; it evaluates brain functions related to behavior and driving abilities; it assesses balance which posture control is sensitive to impaired conditions, either caused by internal factors (i.e. fatigue, drowsiness) or external factors (i.e. drugs, medicines); and it is feasibly to be carried out.

Chapter 7:

CONCLUSIONS

In this work two posture assessment tests were used to study the learning abilities of healthy subjects: a novel protocol conceived to assess subject's psychophysical conditions and a clinical protocol used to assess subject's neurological disorders and fall risk.

The psycho-physical conditions test protocol is based on a divided attention (DA) test by combining a critical tracking test (CTT), choice reaction test (CRT) and psychomotor vigilance test (PVT) where subjects, while standing on a posturographic platform, had to simultaneously perform two tasks: move their center of gravity (CoG) in order to follow a target displayed on a screen (first task) and react to other visual stimuli by pressing a handheld button (second task). This protocol requires the subject to use executive functions to identify tasks and visual cues and to control the body shift movements.

The clinical protocol regards the perturbed condition of the modified clinical test for sensory interaction in balance (mCTSIB), where subjects were assessed while standing on a foam cushion either with eyes open or with eyes closed (perturbed stability test, PS). The purpose of the thick foam is to perturb the proprioceptive and somatosensory information by providing a soft contact surface with the feet and chaotic perturbations. In this way, in order to maintain balance, the subject has to rely mostly on his/her vestibular system. Additionally, this test stresses the subject's postural control because it is forced to react to unpredictable perturbations and it has to discard erroneous sensory information.

Currently available mathematical models of erect stance do not sufficiently describe the posture control and they lack in biofidelity. For instance, most of postural controls are applied to single link inverted pendulum in the sagittal plane, thus neglecting body segments relative movements, coronal and axial movements. Hence, as mathematical models have limited usefulness when it comes to study the central neuronal system, experimental studies with subjects are still needed.

In this work a total of 42 subjects were assessed, both tests required to perform repeated trials in order to estimate their learning curve and some subjects were assessed over two separated sessions of tests.

The first aim of this work was to investigate whether the gesture recognition mechanism provided by the mirror neurons has useful applications in trainings. The protocol explanation of the DA test was therefore conveyed to the subjects either through verbal explanations (top-down approach) or through imitation by observation, that is by only demonstrating it (bottom-up approach).

The second aim of this work was to investigate whether balance tests provide reliable results straight from the first trial or their outcome are influenced by adaptation and learning phases. In order to verify how many of practice trials, if any, are needed before they are capable of providing valid results, both DA and PS tests were repeated several times in two distinct sessions with six months break. Having reliable results, that is without any transient effect such as learning or adaptation, is particularly important in clinical trials when subjects' performance is tested and compared over time, as well as in in research experiments to conceive models and draw conclusions.

The last aim of this work was to study the feasibility of the proposed novel psycho-physical condition test for further research in order to be used as roadside or at-risk activities impairment test. The subject results of the DA test were investigated in the light of easiness to understand the protocol tasks and test repeatability. Vehicle accidents related to degraded psycho-physical conditions, either caused by fatigue or by psycho-active drugs, are rising but a comprehensive test that objectively evaluates all sources of impairment is still missing.

In the following paragraphs the conclusions for each thesis objective are drawn.

7.1. IMITATION TRAINING BASED ON MIRROR NEURONS MECHANISM

The performance of two groups of subjects performing the DA protocol are compared, to whom the instructions on how to execute the tasks were given either through verbal communication or through an imitative process. In the case of imitation, the protocol was introduced to the subject by some verbal information only regarding the equipment, thus conditioning the identification and observation of the exercise. Moreover, it was necessary to perform a delayed imitation since it is not possible to show the experiment while contemporary the subject was trying to replicate it. The subject would have to look at the same time the instructor gesture, the screen of the instructor and its screen. Indeed, the mirror neuron (MN) theory allow for delayed imitation mechanism.

This work demonstrates that acquiring the test instructions through imitation by observation is effective in generating the internal model of the understood actions and goals. However, results show that the performance of the imitation process in the CRT task is less effective compared to the first one (CTT) when fine gestures have to be imitated. In a relevant proportion of subjects the imitation process cannot be triggered because the goal associated with it, and to a lesser extent the action as such, are not perceived appropriately by the subjects. The results are consistent with the fact that imitation is guided by the goal (Bekkering et al., 2000; Bird et al., 2007) and that the feedback helps in understanding the goal (Rucci and Tomporowski, 2010) and in the task performance (Engelhorn, 1997). Therefore, the mere observation is not sufficient to capture with certainty all task aspects.

The results reveal that the DA test is more repeatable when it is described by means of verbal explanation. In fact, even though the imitation approach leads to a shorter learning phase, it does not allow to correctly perceive the fine motor gestures and non-evident goals. Fine motor gestures are in fact harder to capture and perceive without verbal instructions that would either explain or direct attention. For this reason, individual exploration through ‘trial and error’ is generally used to bridge imitation gaps (Byrne and Russon, 1998). Moreover, objective recognition is fundamental to correctly imitate the gestures, otherwise it would just be a mimicry action.

Hence, if MNs are proved, in this case they are not necessary to understand someone else actions because an upstream circuitry is involved in mapping actions with observations. This is consistent with other research where it is pointed out that other brain structures are involved in goal understanding before the MNS (Csibra, 2005; Kosonogov, 2012).

Additionally, the verbal explanation proved to require lower cognitive load compared to the imitation and thus, led to a better reaction time and tracking delay performance.

Therefore, the motor theory of MN is not sufficient to support imitation learning and generally, bottom-up process alone proves to be inadequate to learn fine motor gestures. Imitation approach alone is therefore suitable only when goals are easily recognized and the motor sequences to be repeated are short (Agam et al., 2005). Even the mere ‘trial and error’ approach would not be sufficient unless the goals are correctly perceived (Hayes et al., 2008). Indeed, the learning process requires many observations as well as many trials, verbal explanations, corrections (feedback) and rest periods (Kerr and Booth, 1978). Based on these findings, the protocol therapies which use the MNS theory should be carefully adopted.

Future developments can involve investigations on learning the DA protocol with combined bottom-up and top-down approach in order to take advantages of both methods and their features (Luft and Buitrago, 2005; Sun and Zhang, 2004).

7.2. LEARNING PHASE IN BALANCE TESTS

Practice is needed to allow the subject to construct or adapt his/her internal models related with the task. However, once it is set, it is retained for long time. Learning adaptation in quiet standing test is boundless in toddlers and continues till the adolescence. Later there is a limited learning adaptation as adults have already a full developed postural control which cannot improve anymore without specific training (Uimonen et al., 1994).

Nevertheless, in cases when performing novel or unusual sensorimotor tasks subjects still show motor learning. For instance, there is motor learning when quiet standing test is performed either with feet together and eyes closed (Tarantola et al., 1997) or feet positioned toe to heel like in “sharpened Romberg test” (Lee, 1998). Instability increases and subject must find new motor strategies, for which three to four trials are needed. Moreover, subjects that underwent tests where they had to grasp an object while a force field was applied or the visual was distorted, they adapt to the new situation with 2 to 4 attempts (Wei et al., 2009).

Both the DA and PS test show a negatively acceleration learning curve, which is typical in motor learning. Thus, some practice is needed in order to become familiar with the required actions and the coordination of various gestures.

In the case of DA, the CTT and the CRT require spatial-cognitive abilities (Barra et al., 2006), such as assimilating received instructions, organizing motor gestures and coordinating the two tasks, which need time to be consolidated. However, the initial body movement inaccuracy in target tracking needs just few practice trials also because the subject can directly see his/her feedback on the screen (Wei et al., 2009). In fact, results show that there is the need to practice the test only two times when the subject is exposed for the first time to the protocol. This is also consistent with the fact that verbal explanations can be acquired in just one exposure or trial (Luft and Buitrago, 2005).

The second session of DA test results do not show any learning phase nor reduction in performance. Therefore, subjects in the past session have created an internal model of the test thus allowing long term motor retention. This is due to several factors, such as the presence of feedback and possible self-reward (Nakatani et al., 2009) and the fact that the tasks were made of non-discrete or non-automatic movements (Willingham and Dumas, 1997).

On the contrary, in the case of PVT and PS, results show that there is the need to some practice trials not only if the subject have never underwent this test before, but also when tests are repeated after six months. The PVT test is a simple reaction test and the subject has already well coded the required action, therefore no learning occurs and the improved performance shown in the results is due to an adaptation phase to the test conditions. In the PS test, however, only the strategy to counteract the chaotic perturbations was retained, which were new to the subject, but not the ability to predict the perturbations. Therefore, the subjects should be provided with 120s of practice as adaptation or learning phase every time they undergo to a PS test session. Moreover, an additional 20s of practice are necessary from the time the subject close his/her eyes.

Comparing the overall performance between the two sessions, DA test shows no improvement while PS shows marked improvement in counteracting the perturbations caused by the thick foam. Probably the chaotic perturbations are strong stimuli that allow for off-line neuronal adaptation (Mozzachiodi and Byrne, 2010).

The results show no interference learning between the two tests (DA and PS) as they regard similar gestures (Luft and Buitrago, 2005). In fact, both DA set 1&2 and PS set1&2 show gesture retention (DA movements connected with the tracking, PS postural adjustments).

These results imply important consequences on posturographic protocols that are in use. Currently clinical posturographic tests are usually performed just once and common test duration is 20 to 30s. What emerges from these experiments is that, it is important to let the subject “get used” to the test conditions to avoid comprising any learning or adaptation effect in the results, which in consequence can bias the comparison over sessions. Moreover, excessive repetitions or longer tests are not needed, as whenever the learning and adaptation phase are exhausted, there is no further improvement. Furthermore, marked improvement in tests with perturbed stability might be due to intersession adaptation rather than physical improvement.

However, it must be taken into account that in these experiments, the DA test was repeated 10 times (600 seconds in a 30 minute session) and PS test was repeated 4 times or 12 times considering that usual balance test duration is 20s (240 seconds in a 7 minute session). In real cases, the DA test would be performed only thrice (180 seconds) while the PS test is performed just once or twice (20-40 seconds). Therefore, probably the learning effect here illustrated will not be found immediately unless the subjects undergo the test many times or in many sessions.

Future experiments are needed to verify if groups different than those experimental samples such as children, elderly, and subjects affected by different pathologies show any learning or adaptation phase and at which extent.

Learning in models

With regards to the models of motor performance, the results of this work demonstrate that the Fitts' law can be extended also when the pointing task is achieved by means of postural balance. However, it is found that the goodness of this law depends on several factors, such as noise and target size. By considering the effective movements the subject makes (path and sway on the target), it is possible to improve the goodness of fitting of the law at least 5 times. On the contrary, the law poorly correlates if the actual target distance and size are considered. Moreover, when the target size diminishes, more time is required to reach the target and the law is more influenced by the perturbations.

Interestingly, the tilt angle has a variable trend which can be related to the learning process. In fact, if the subject has never underwent the test, there is a great improvement at the first repetition. Conversely, if the subject has already acquired the internal model, it shows a noticeable improvement only after 6-7 trials. This seems not to depend on how the internal model was obtained, either with formal learning or imitation learning. Therefore, this means that the mere observation is effective to acquire gross motor gestures. However, this is not extendable to fine motor gestures which can be obtained with certainty only with verbal instructions.

On the contrary, the tasks here proposed are not sufficient to fully demonstrate the Hick's law because only a single choice (PVT) and a double choice test (CRT) were performed. Still, the difference between the two tests provides useful information on the amount of interference between the two tasks concurrently performed (CTT and CRT). Moreover, it is found that this interference is reduced in the second set of trials, which confirms that there is an intersession improvement.

The results of CTT and CRT show that practice influences the coefficients of both laws, that there is an intersession improvement, and that the performance across trials is well described by the power law of practice.

Moreover, results show that the performance and improvement rate depends on the chosen measurement criteria. Therefore, if the measurement criteria is wrongly chosen, some aspects of the experiment might not even be noticeable.

With regards to the postural control models, it is illustrated that learning is still a challenge. Even though the postural controls are becoming more sophisticated, they are mainly able to control up to a 2-D two-link inverted pendulum which limits their application in studying the learning process. Some advances have been recently made with the use of learning features, but the still remaining main limitation is the ability to work with unstable, delayed and noisy system. In fact, when such factors are excluded, i.e. in arm-hand movements on horizontal plane, the controllers appear to provide a good response to perturbations and to delayed signals.

Moreover, there are still some factors that has not been included in the postural controls yet, such as multiple cost functions, the prediction of the required force to make the desired movement at the time the signal reaches the muscle, and the anticipatory postural adjustments. Moreover, controller optimization usually regards energy minimization, while in reality human might use different criterions (i.e. maximum efficacy in life risk situations).

While 3-D kinematic models provide already good biofidelity, only when the implementation of multi-level neuronal networks will be available it might be possible to resemble the cerebral postural control.

7.3. NOVEL METHODOLOGY TO ASSESS IMPAIRMENT

Vehicle accidents are one of the world top-ten causes of death (Mathers et al., 2009) and just in Europe every year over one million persons are injured and over thirty thousand die in a crash generating large social and economic consequences (Elvik, 2000; *EU transport in figures 2013*, 2013). Driving a vehicle requires to pay attention to multiple stimulus at once (Kay and Logan, 2011) and thus excellent psycho-physical conditions are needed. Psychotropic substances, fatigue and mental workload may produce attention impairment and/or longer reaction times (Ogden and Moskowitz, 2004).

Although about one third of the accidents can be addressed to the driver conditions (NHTSA, 2013b), also known as driving under the influence (DUI) or driving while impaired (DWI), current roadside fitness tests, like BrAC, field sobriety test or biological liquid sample tests, suffer various limitations. For instance field sobriety test suffer from confounding subjective variables (Booker, 2004; Rubenzer, 2008), while some drugs have short-window detection (Kidwell et al., 1998) and drug-drug or drug-alcohol interaction is not well assessed yet (Schroeder, 2012). Therefore, these tests cannot be considered as reliable and sufficient impairment indicators.

The divided attention test here proposed is made of tasks that are congruent with the Driving Essential Abilities Domain (Kay and Logan, 2011) and with the Driving Behavior Skills (Walsh et al., 2008). In fact, the test allows to evaluate in real-time the subject ability to perform, coordinate and control multiple tasks at a time, as it requires the subject to simultaneously activate motor control to follow the target (critical tracking test, CTT) and to press a hand-held trigger. Moreover, this DA test provides objective assessment, while the standardized field sobriety test is subjective, and does not require to perform long battery tests.

The DA test results show that it easy to understand as when a subject approaches the protocol for the first time, only two practice trials are required to learn the protocol. While in the subsequent session the performance does not improve and it is possible to consider the very first trial as the effective one.

However, in a case of a real roadside test is not always possible to know whether the subject has already undergone once the test; therefore it is preferable to repeat all instructions and only consider the results of the third test repetition. Furthermore, particular care must be taken when instructing subjects. Indeed, the test information should be conveyed by means of verbal explanations that focus on the objectives of the tasks and not on the movements. In particular, imitation by observation approach should be avoided unless combined with verbal explanations that direct attention and explain the task objectives. Moreover, this is a non-invasive test as it does not collect body sample liquids. Therefore, the test protects subject’s privacy as it would only provide an impairment level or go/no-go results, regardless the cause of impairment.

The proposed methodology appears promising in overcoming current roadside test limitations and deficiencies. In fact, preliminary results show that degraded conditions disrupt the learning abilities and reduce the task performance. This is also found in other experimental results which show differences between healthy and DUI subjects in balance assessment or divided attention tasks. Moreover, it is known that attentional abilities are influenced by both physical and mental fatigue (Boksem et al., 2005; Lorist et al., 2002), cognitive load (Brookhuis and de Waard, 2010; Kantowitz, 2000) and emotional conditions (Lansdown and Stephens, 2013; Pecher et al., 2011).

Further, the setup time of the equipment and administration of the test is comparable with the existent tests. Additionally, the test results are immediately available and since they are not biased by subjective assessment, test conductors need limited training, comparable with the simple BrAC test. As a result, the test seems feasible for random test campaigns. The main drawback of this test is the need to place the force platform onto a firm and plain surface, which might be unavailable in rural areas.

This work provides evidence that the proposed novel divided attention test is suitable for further validation tests in order to be used as a roadside Driving While Impairment assessment test.

Future developments involve verifying if this test discriminates between healthy and impaired subjects and detecting thresholds values for impairment following the Recommendation B19 in Walsh et al. (2008) which suggests that impairment test should be validated with drugs alone or in combination with alcohol. Unfortunately, it is not possible to use existing data from other research as test conditions, methods used and analysis are not standardized in this field and pharmacokinetic data are not always available or recorded.

Validation will also concern running the protocol either with driving simulators, real world conditions, or with randomly stopped drivers, in order to take into account factors such as anxiety and environment noise. Nonetheless this protocol can also be extended to more general cases, i.e. subjects operating at-risk activities and medical control for workers (e.g. exposure to toluene).

APPENDIX

8.1. ROAD ACCIDENT FIGURES

Table 8.1: Total fatalities per year

Country	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Italy (ISTAT)	7096	6980	6563	6122	5818	5669	5131	4725	4237	4114	3860	3653
U.K. (STAT19)	3598	3581	3658	3368	3336	3298	3059	2645	2337	1905	1960	1802
EU15 (CARE)	38914	37529	35131	32020	30646	28833	27642	24868	22975	20966	20784	17984
EU28 (CARE)	59875	59000	55866	53412	51013	48260	48017	44648	39970	35527	30700	28100
US (NHTSA)	42196	43005	42884	42836	43510	42708	41259	37261	33883	32999	32479	33561

Table 8.2: Total injuries per year

Country	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Italy (CARE)	373286	378491	356475	343179	334858	332955	325850	310745	307258	304720	292019	264716
U.K. (CARE)	310000	299000	287099	277619	267816	255232	275554	228367	219924	206798	202049	193969
EU15 (UNECE)	1792348	1738099	1664225	1586941	1547743	1525240	1433020	1505653	1341978	1130358	1128503	1078370
US (NHTSA)	3033000	2926000	2889000	2788000	2699000	2575000	2491000	2346000	2217000	2239000	2217000	2362000

Table 8.3: Driving under the influence analyzed studies, ordered by year of investigation

Study	Year	Where	Cases	Who	How	Free of drugs	Alcohol and/or drugs	Alcohol only	Legal limit [g/L]	Illegal drugs	Legal drugs	Other
(Cusack et al., 2012)	2007-2011	Ireland	7776	drivers suspected of DUI	blood and urine samples	23.5%	76.5%					
(Gjerde et al., 2011)	2003-2007	Norway - south east	204	killed drivers	blood samples	64.80%	35.20%		0.2	11.80%	13.20%	
(Alan Wayne Jones et al., 2009)	2003-2007	Sweden	1403	killed drivers	blood and urine samples	60%	40%	17%	0.2	2.80%	13.30%	7.20%
(Gjerde et al., 2008)	2005-2006	Norway - south east	10835	random highway drivers	oral fluid	95.50%	4.50%	0.40%	0.2	1%	3.40%	
(Ingsathit et al., 2009)	Dec05-May06	Thailand	1635	random drivers stopped at checkpoints, bus-truck stations and petrol stations	Breath test, urine samples	88.50%	11.50%	5.50%	0.5	4.00%	2.80%	
(Augsburger et al., 2005)	2002-2003	Swiss - Canton of Vaud, Valais, Jura and Fribourg	440	drivers suspected of DUI	blood and urine samples	11%	89%		0.5		13%	
(Appenzeller et al., 2005)	Fall2001-Spring2002	Luxembourg	210	drivers with BAC request	blood samples	7.60%	92.40%	61.90%	0.5	10.50%	22.80%	
(Mura et al., 2003)	Jun2000-Sept2001	France	900	drivers involved in non-fatal accidents, admitted to hospital emergency unit	blood samples		26%	17.00%	0.5			
(Mura et al., 2003)	Jun2000-Sept2001	France	900	Control group: non-traumatic patients in emergency units	blood samples		9.00%	5.00%	0.5			
(Drummer et al., 2003)	1990-1999	Australia states: VCT, NWS, WA.	3398	killed drivers	blood samples	50.10%	49%	29.10%	0.5	23.50%	4.10%	

Table 8.4: Detailed contributing factors in reported accidents in the U.K. in 2012 (Graves et al., 2014)

Contributory factors	Fatal accidents	All accidents
Driver error or reaction	1023	78460
Driver failed to look properly	386	45503
Failed to judge other's path or speed	201	23768
Poor turn or maneuver	213	15998
Loss of control	501	15148
Road environment or external factors	286	26349
Road layout	79	4039
Slippery road	77	9565
Reduced visibility (sun, rain, fog, lights)	77	7040
Poor or defective road surface	10	793
Vehicle defects	42	2000
Tires illegal, defective or underinflated	17	656
Brakes defective	10	742
Impairment or distraction	346	13690
Impaired by alcohol	128	4679
Impaired by drugs	31	594
Fatigue	68	1751
Distraction by mobile phone	22	422
Distraction in vehicle	84	2995
Distraction outside vehicle	27	1627
Injudicious action	416	24842
Exceeding speed limit	216	4753
Disobeyed to signals	58	6163
Travelling too fast for conditions	191	7477
Behavior or inexperience	422	25897
Careless, reckless or in a hurry	294	18167
Aggressive driving	127	3375
Nervous, uncertain or panic	17	1775
Lerner or inexperienced	61	4610

Table 8.5: Detailed contributing factors in reported accidents in Italy in 2012. Modified from (*Incidenti stradali in Italia 2012*, 2013)

Contributory factors	Urban roads		Non-urban roads		Total	
	Value	%	Value	%	Value	%
Driver or pedestrian responsibility	140119	80.7	42476	73.9	182595	79.0
Distracted or hesitant	27381	15.8	11051	19.2	38432	16.6
Disobeyed to road rules or signs	32896	19	4505	7.8	37401	16.2
Disobeyed "Stop" sign or mark	11025	6.4	1887	3.3	12912	5.6
Did not give the right of way to cars on the right hand side	9158	5.3	1055	1.8	10213	4.4
Disobeyed "Give way" sign or mark	10752	6.2	1434	2.5	12186	5.3
Disobeyed traffic lights or officer's instructions	1961	1.1	129	0.2	2090	0.9
Speeding	16340	9.4	9567	16.6	25907	11.2
Travelling too fast for conditions	15705	9	9218	16	24923	10.8
Exceeding speed limit	635	0.4	349	0.6	984	0.4
Driver error	49409	28.5	14838	25.8	64247	27.8
Following too close	15781	9.1	7674	13.4	23455	10.2
Poor maneuver	14608	8.4	3194	5.6	17802	7.7
Illegal turning	5712	3.3	897	1.6	6609	2.9
Driving on the wrong way	3651	2.1	1702	3	5353	2.3
Illegal overtaking	3323	1.9	1254	2.2	4577	2
Disobeyed pedestrian crossing facility	6334	3.6	117	0.2	6451	2.8
Other causes of driving behavior	6593	3.8	1987	3.5	8580	3.7
Pedestrian behavior	7500	4.3	528	0.9	8028	3.5
Road environment	26445	15.2	9777	17.0	36222	15.7
Accidental obstacle on road	3573	2.1	2262	3.9	5835	2.5
Irregular vehicle stopping	2358	1.4	392	0.7	2750	1.2
Avoiding stopped vehicle	1569	0.9	1928	3.4	3497	1.5
Road layout	893	0.5	635	1.1	1528	0.7
Unknown reason	18052	10.4	4560	7.9	22612	9.8
Other causes	7028	4	5228	9.1	12256	5.3
Total causes	173592	100	57481	100	231073	100

Table 8.6: Casualties figures in the United Kingdom while working or commuting (Graves et al., 2014)

U.K.	2005	2006	2007	2008	2009	2010	2011	2012	2013
Driving as part of work									
Killed	850	858	890	748	592	540	559	539	515
Seriously injured	6012	6622	6673	6150	5456	5281	5197	5231	5052
Slightly injured	56540	59879	58165	53525	50080	48868	47052	44819	42035
All casualties	63402	67359	65728	60423	56128	54689	52808	50589	47602
Commuting from / to work									
Killed	348	327	352	275	241	204	225	169	219
Seriously injured	3402	3435	3354	3178	2958	2818	2855	2936	2937
Slightly injured	30001	29246	27951	25883	24115	23922	22837	23098	21935
All casualties	33751	33008	31657	29336	27314	26944	25917	26203	25091
Total (part of work and commuting)									
Killed	1198	1185	1242	1023	833	744	784	708	734
% of total vehicle fatalities	35.9	35.9	40.6	38.7	35.6	39.1	40.0	39.3	42.8
Injured	95955	99182	96143	88736	82609	80889	77941	76084	71959
% of total vehicle injuries	35.8	38.9	34.9	38.9	37.6	39.1	38.6	39.2	39.2

Table 8.7: Casualties figures in Italy while working or commuting (Ciriello et al., 2013)

Italy (INAIL)	2007	2008	2009	2010	2011
Driving as part of work					
Killed	452	435	393	395	294
Injured	53536	52669	52547	56110	51243
% of work injuries	5.35	5.46	5.99	6.44	6.27
Commuting from / to work					
Killed	364	347	331	273	263
Injured	83641	83375	74949	70336	66212
Total (part of work and commuting)					
Killed	816	782	724	668	557
% of total vehicle fatalities	15.9	16.6	17.1	16.2	14.4
Injured	137177	136044	127496	126446	117455
% of total vehicle injuries	42.1	43.8	41.5	41.5	40.2

8.2. PROTOCOL ADMINISTRATION

8.2.1. Operator instructions: divided attention protocol

Test setup:

- Position the CAPS™ Professional force platform straight in front of the computer monitor;
- Start the **VTImpair** software and make sure the CAPS™ Professional force platform is connected to the computer and in working order, as is the clicking device;
- Position a standard chair in front of the CAPS™ Professional force platform, leaving enough room so the subject's feet can rest on the floor in front of the CAPS™ Professional force platform without touching it.

For each subject:

- Give the subject the instructions to read and answer any questions the subject might have;

- Once the subject confirms to have understood the instructions and to be willing to participate (informed consent), officially enroll the subject in the research protocol with a unique **Subject's ID**;
- Have the subject seat on the chair;
- Have the subject fill in the questionnaire;
- Enter the **Subject's Height** in the software.

For each test:
(**t** indicates the beginning of the pretest – one test every three minutes)

- **t-30s** Start the zero acquisition;
- **t-15s** The subject picks up the clicking device and stands on the CAPS™ Professional force platform, with feet shoulder width, looking straight to the monitor, and with the arms to the side;
- **t=0s** Start the test acquisition (with 5 seconds pretest during which the subject should try and stay as still as possible);
- **t+5s** The actual acquisition starts and the subject should follow the CoP target, and react appropriately at the visual cues;
- **t+65s** The acquisition is done. Save the subject's file using the name: GxxSyyTzzPkk.csv
  Where G is the group of subjects, S the subject ID, T type of test, P number of trial.
  Have the subject step off the CAPS™ Professional force platform, put down the clicking device, sit on the chair as before the test and rest for 85 seconds;
- **t+150s** Restart the cycle from **t-30s.**

8.2.2. Operator instructions: Perturbed stability protocol

Test setup:

- Position the CAPS™ Professional force platform straight in front of the computer monitor;
- Start the VTCAPSEQ software and make sure the CAPS™ Professional force platform is connected to the computer and in working order, as is the clicking device;
- Position a standard chair in front of the CAPS™ Professional force platform, leaving enough room so the subject's feet can rest on the floor in front of the CAPS™ Professional force platform without touching it;

For each subject:

- Give the subject the instructions to read and answer any questions the subject might have;
- Once the subject confirms to have understood the instructions and to be willing to participate (informed consent), officially enroll the subject in the research protocol with a unique **Subject's ID**;
- Have the subject seat on the chair;

- Select the type of test (PSOA for odd subjects, PSOC for even subjects);
- Insert "Subject ID", "Sex", "Date of birth" and "Height" of subject;

For each test:
(**t** indicates the beginning of the pretest – one test every two minutes)

- **t-30s** Start the zero acquisition;
- **t-15s** The subject stands on the CAPS™ Professional force platform with feet shoulder width;
- **t=0s** Start the test acquisition (with 5 seconds pretest during which the subject should try and stay as still as possible);
- **t+65s** The acquisition is done automatic, the subject steps off the CAPS™ Professional force platform and sits for **40s** waiting for a new cycle;
- **t+105s** Restart the cycle from **t-15s.**

8.2.3. Informed consent form

1 General Purpose of the study

You are invited to participate in a research study to evaluate the feasibility of using computerized dynamic posturography (CDP, based on measurements obtained with a force platform) to assess in real time the psycho-physical conditions of a subject.

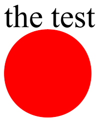
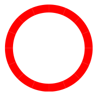
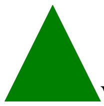
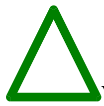
Your participation in this study is entirely voluntary.

You will be at most actively involved for approximately one hour, during which all the testing will be done.

2 Procedure

If you choose to participate, you will undergo two types of CDP testing:

- a standard CPD testing namely perturbed stability with eyes open (PSEO) or eyes closed (PSEC):
  - You stand barefooted on a compliant surface (a 100mm/4" tall foam cushion of known mechanical properties), with either your eyes open or closed;
  - The test will last 60 seconds;
  - The test will be repeated 4 times.
- the proposed new testing protocol, evaluating your ability to move your weight while standing barefooted on the force platform, following a target appearing on the computer screen in front of you, your reaction time to visual cues and your ability to discern between valid and invalid cues:
  - You will be given time to practice shifting your weight to familiarize yourself with the response of the force platform represented in the screen in front of you by the marker with cross-hair ;

- When the test start you'll have to follow the movement of the correct target . The target can jump from one position to the next, or could move smoothly across the screen: you should try and reproduce the movement of the target, matching the position of the marker representing you on the screen with that of the target;
- Up to two more incorrect targets  will appear on the screen at the same time of the correct target, to "distract you". You should try to ignore them.
- Sometimes during the test, another target of different shape and color  will appear: when you see it, press the button on the clicking device you'll be holding in your hand to make the target disappear;
- At other times during the test, a similar target  will appear to "confuse you": when you see it, DO NOT PRESS THE BUTTON;
- See the test quick reference for samples of what you'll see on the computer screen and how you should react each time;
- The actual test will last 60 seconds;
- The test will be repeated 10 times, one test every three minutes.

The testing procedure is completely noninvasive and no biological samples will be taken from you for this research project.

The CDP testing will be performed using an FDA registered, portable, three-component force platform (CAPS ™ Professional, Vestibular Technologies, LLC, Cheyenne WY).

You may also be asked to fill in some questionnaires pertaining to your physical health and your daily habits.

3 Disclosure of risks

CDP testing is commonly utilized in a variety of diagnostic and therapeutic applications. There are no known risks to CDP testing.

4 Benefits

The investigators do not envision any benefit, direct or indirect, for you if you choose to participate in this project.

It is hoped that this research will help verify the feasibility of using the proposed protocol to assess in real time the psycho-physical conditions of a subject.

No incentive, monetary or other, will be given to you, nor your participation in the research project will have any effect on you.

5 Confidentiality

Standard procedures will be utilized in preserving confidentiality and record storage. You will be assigned an alphanumerical ID that will identify your CDP testing results and questionnaires throughout the entire research project. The only document linking your name with your ID will be this signed consent form. No names or other identifiers will be utilized to maintain anonymity. The only other personal information required from you is your date of birth and your height and this information will be stored inside the software and protected together with the data.

The information collected using the questionnaires will be stored in a digital format and any paper copies will be shredded and destroyed. The CDP testing results will be stored in the proprietary format of the software application used to acquire the data. The computers used to collect and store the data will be password protected and only the investigators will have access to it. The investigators may not be required by law to protect it and may share your information with others without your permission, if permitted by laws governing them.

At the end of the study, all reporting will be generated in a format that will guarantee anonymity and no publication or public presentation about the research described above will reveal your identity.

Please note that you do not have to sign this Consent.

6 Freedom of consent

My participation is voluntary and my refusal to participate will not involve penalty or loss of benefits to which I am otherwise entitled, and I may discontinue participation at any time without penalty or loss of benefits to which I am otherwise entitled.

7 Consent

YOUR SIGNATURE INDICATES THAT YOU HAVE READ AND UNDERSTAND THE ABOVE INFORMATION, THAT YOU HAVE DISCUSSED THIS STUDY WITH THE PERSON OBTAINING CONSENT, THAT YOU HAVE DECIDED TO PARTICIPATE BASED ON THE INFORMATION PROVIDED, AND THAT A COPY OF THIS FORM HAS BEEN GIVEN TO YOU.

________________________ ____________________ ___________

Printed Name Signature Date

8.2.4. Questionnaire

Subject ID ____________ Group ID__________

Personal characteristics		
Gender	M ☐	F ☐
Date of birth		
Job type and main duties (manual, office, etc.)		
Level of education		

Psycho-physical conditions	Yes	No
Have you taken enough rest in the last 2 days?	☐	☐
Do you feel tired now?	☐	☐
Have you regularly taken over last week medicines such as aspirin, antihistamines, barbiturates, sleeping pills, antibiotics?	☐	☐
Do you have diseases that can reduce your balance abilities? (Labyrinthitis, Parkinson's, multiple sclerosis)?	☐	☐
Do you suffer from anxiety?	☐	☐
Do you regularly drink coffee? How many times a day?	☐	☐
Do you smoke? How many cigarettes a day?	☐	☐
Do you usually drink alcohol? How often? Which beverages? In which occasions?	☐	☐
Do you practice sport? Which? Level? How often per week?	☐	☐

Stabilometry or posturology tests	Yes	No
Have you already undergone such tests?	☐	☐
If yes, when was it?		
If yes, how many times?		
If yes, which kind of test?		

In the last 3 hours prior to testing have you taken	Yes	No
Caffeine (coffee or other beverages with caffeine)	☐	☐
Nicotine (cigarettes, patches)	☐	☐
Food (specify if ☐ heavy or ☐ light)	☐	☐

Anthropometric characteristics	
Body mass (from platform)	kg
Height (instructor must measure it)	m
Body mass index (from platform)	

Date	Instructor signature

8.3. SUBJECTS DEMOGRAPHICS

Table 8.8: Subjects demographics.

ID	Gender	Age	Height [m]	Actual Mass [kg]	Body Mass Index
1	M	21	1.79	73.6	23.0
2	F	25	1.59	66.1	26.2
3	M	22	1.71	62.2	21.3
4	F	23	1.58	60.4	24.2
5	M	21	1.83	81.6	24.4
6	M	22	1.82	82.6	24.9
7	M	18	1.75	68.8	22.5
8	M	22	1.81	72.7	22.2
9	F	20	1.65	56.6	20.8
10	F	22	1.73	70.2	23.5
11	M	53	1.73	81.4	27.2
12	F	27	1.62	49.9	19.0
13	F	47	1.65	60.4	22.2
14	F	24	1.57	57.6	23.4
15	M	27	1.73	73.0	24.4
16	M	23	1.75	62.4	20.4
17	M	24	1.82	80.7	24.4
18	M	34	1.72	72.2	24.4
19	F	23	1.64	60.1	22.4
20	F	25	1.58	61.8	24.7
21	F	25	1.75	63.2	20.6
22	F	28	1.67	65.9	23.6
23	F	28	1.67	59.9	21.5
24	M	26	1.78	88.9	28.1
25	F	28	1.69	52.6	18.4
26	F	25	1.69	56.7	19.9
27	M	25	1.81	75.5	23
28	M	21	1.83	82.8	24.8
29	F	24	1.69	48.1	17.1
30	F	20	1.67	55.1	19.8
31	M	26	1.87	104.8	30
32	M	21	1.72	66.1	22.4

33	F	22	1.55	55.7	23.2
34	F	20	1.62	55.6	21.2
35	M	20	1.78	64.7	20.4
36	M	20	1.84	79.0	23.3
37	M	20	1.84	69.3	20.5
38	F	20	1.64	57.9	21.6
39	M	30	1.84	94.0	27.8
40	M	20	1.74	60.0	19.9
41	F	20	1.79	73.0	22.8
42	M	27	1.8	76.8	23.7
43	M	-	1.81	-	-
44	M	-	1.85	-	-
45	M	-	1.82	-	-

Table 8.9: Subjects demographics for subjects that underwent the second set of trials (divided attention test and perturbed stability).

ID	Gender	Age	Height [m]	Actual Mass [kg]	Body Mass Index	Days between set 1 and set 2
1	M	22	1.79	72.8	22.7	205
2	F	26	1.59	65.7	26	167
5	M	22	1.83	77.9	23.3	160
6	M	22	1.82	84.3	25.5	189
8	M	22	1.81	72.8	22.2	186
10	F	23	1.73	71.1	23.8	226
11	M	53	1.73	81.5	27.2	221
13	F	48	1.65	60.4	22.2	221
14	F	25	1.57	61.3	24.9	163
16	M	24	1.75	64.4	21	141
17	M	25	1.82	77.4	23.4	215
18	M	34	1.72	67.1	22.7	208
19	F	23	1.64	62	23.1	159
20	F	26	1.58	62.1	24.9	161
23	F	29	1.67	59.6	21.4	206

Table 8.10: Subjects related to experiments.

ID	PS – set 1	PS - set 2	PS imitation group	PS Condition	DA- Formal Learning, set 1	DA- Formal Learning, set 2	DA - imitation learning
1	x	x		Eyes open	sw changed		
2	x	x		Eyes closed	sw changed		
3	x			Eyes open	sw changed		
4	x			Eyes closed	technical problem		
5	x	x		Eyes open	x	technical prob-lem	
6	x	x		Eyes closed	x	x	
7	x	x		Eyes closed			
8	x	x		Eyes open	x	x	
9	x			Eyes closed	x		
10	x	x		Eyes open	familiar with Nintendo-Wii		
11	x	x		Eyes closed	x	x	
12	x	x		Eyes open	x		
13	x	x		Eyes open	x	x	
14	x	x		Eyes closed	x	x	
15	x			Eyes closed	x		
16	x	x		Eyes open	x	x	
17	x	x		Eyes closed	technical problem		
18	x	x		Eyes open	x	x	
19	x	x		Eyes open	x	x	
20	x	x		Eyes closed	x	x	
21	x			Eyes open			
22	x			Eyes open			
23	x	x		Eyes open	x	x	
24	x			Eyes closed	x		
25	x			Eyes open	x		
26			x	Eyes closed			x
~~27~~			antibiotics	Eyes closed			antibiotics
28			x	Eyes closed			x
29			x	Eyes closed			x
30			x	Eyes closed			x

31	x	Eyes closed	x
32	x	Eyes closed	x
33	x	Eyes closed	x
34	x	Eyes closed	x
35	x	Eyes closed	x
36	x	Eyes closed	x
37	x	Eyes closed	x
38	x	Eyes closed	x
39	x	Eyes closed	x
40	x	Eyes closed	x
41	x	Eyes closed	x
42	x	Eyes closed	x

8.4. EXAMPLE OF RECORDED AND ANALYZED DATA

In the following tables an example of raw recorded data of one trial is presented for both divided attention and perturbed stability test. The subsequent figures illustrate how the trial results are organized for the statistical analysis.

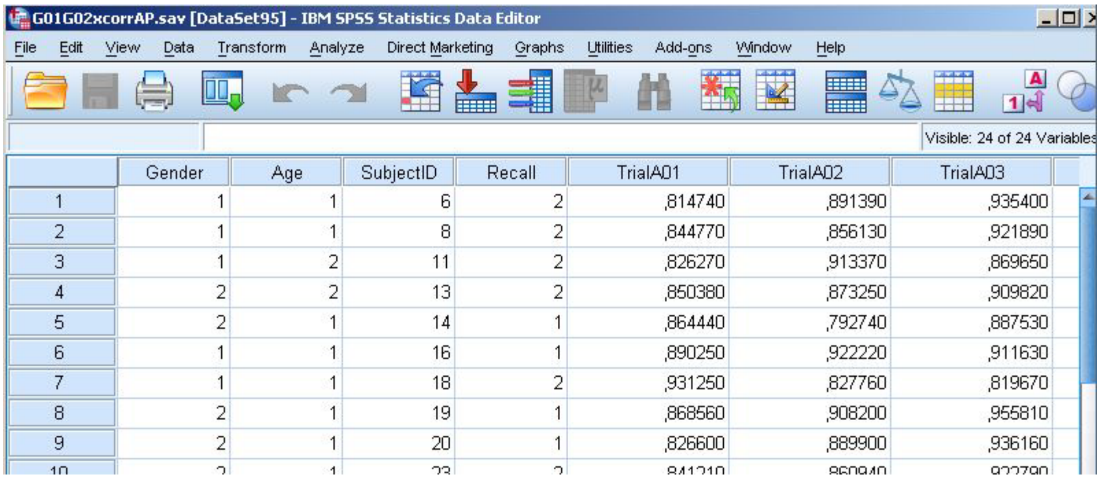
Table 8.11: Example of recorded data of the divided attention test. For each sample the CoP and target coordinates are recorded as well as the trigger and the CRT visual cue status.

Sample	CoPx [m]	CoPy [m]	Tgx [m]	Tgy [m]	Trigger Status	CRT visualCue	*Comments*
1	-0.01667	-1.37E-02	-2.09E-02	-6.64E-02	0		Empty CRT visual cue field: no visual cue is presented.
2	-1.66E-02	-1.35E-02	-2.09E-02	-6.64E-02	0		
3	-1.66E-02	-1.33E-02	-2.09E-02	-6.64E-02	0		
4	-1.66E-02	-0.01317	-2.09E-02	-6.64E-02	0		
5	-1.66E-02	-1.30E-02	-2.09E-02	-6.64E-02	0	#FALSE#	#false#: dummy visual cue.
…							
100	-1.65E-02	-2.47E-02	-2.09E-02	-6.64E-02	0	#FALSE#	
101	-1.61E-02	-0.02591	-2.09E-02	-6.64E-02	0	#FALSE#	
102	-1.59E-02	-0.02725	-2.09E-02	-6.64E-02	0	#TRUE#	#TRUE#: correct visual cue. Start counting reaction time.
103	-1.56E-02	-2.87E-02	-2.09E-02	-6.64E-02	0	#TRUE#	

104	-1.51E-02	-3.01E-02	-2.09E-02	-6.64E-02	0	#TRUE#	
…							
156	-1.45E-02	-5.12E-02	-2.09E-02	-6.64E-02	0	#TRUE#	
157	-1.45E-02	-5.20E-02	-2.09E-02	-6.64E-02	0	#TRUE#	
158	-1.45E-02	-5.29E-02	-2.09E-02	-6.64E-02	0	#TRUE#	
159	-1.45E-02	-5.38E-02	-2.09E-02	-6.64E-02	0	#TRUE#	
160	-1.48E-02	-5.45E-02	-2.09E-02	-6.64E-02	0	#TRUE#	
161	-1.52E-02	-5.50E-02	-2.09E-02	-6.64E-02	1		1: trigger activation. Finish counting reaction time. CRT visual cue disappears.
162	-1.54E-02	-5.54E-02	-2.09E-02	-6.64E-02	0		
…							

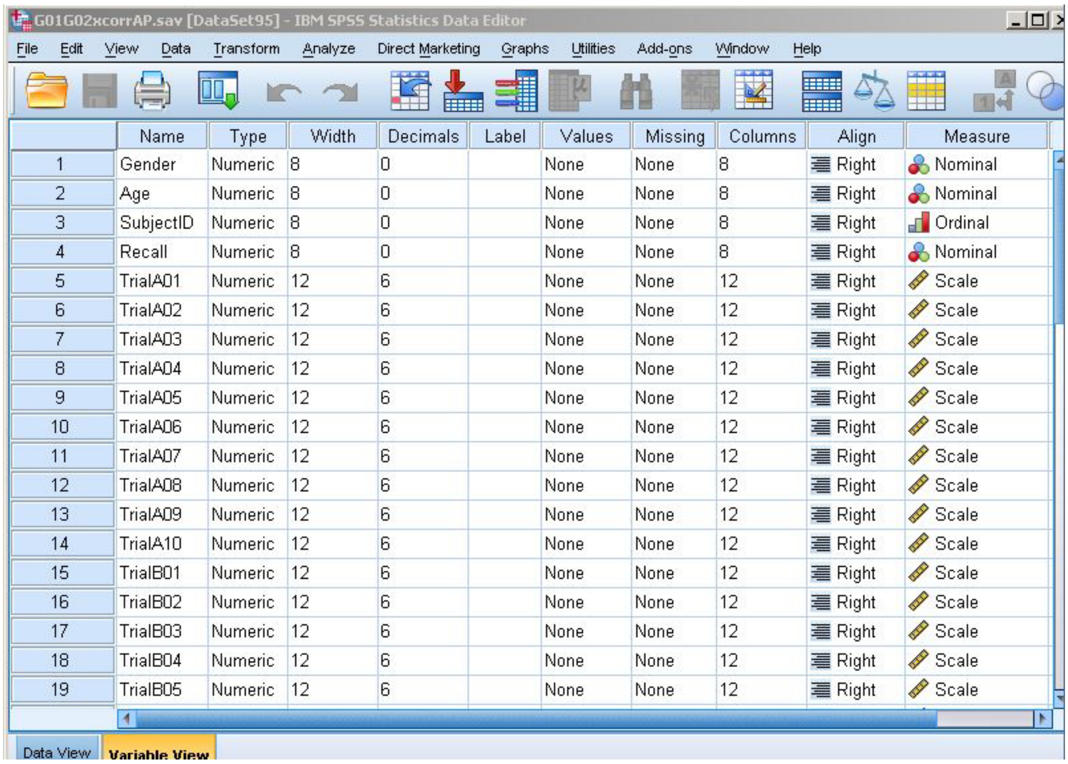
Table 8.12: Example of recorded data of the perturbed stability test. For each sample the coordinates of the CoP are recorded.

Sample	CoPx [m]	CoPy [m]
1	0.007813	0.018928
2	0.00749	0.019176
3	0.007187	0.01966
4	0.007096	0.020306
5	0.007269	0.020986
6	0.0075	0.021721
7	0.007606	0.022367
8	0.007618	0.022735
9	0.007576	0.022828
10	0.007478	0.022851
11	0.00731	0.022927
12	0.007076	0.023015
…		



	Gender	Age	SubjectID	Recall	TrialA01	TrialA02	TrialA03
1	1	1	6	2	,814740	,891390	,935400
2	1	1	8	2	,844770	,856130	,921890
3	1	2	11	2	,826270	,913370	,869650
4	2	2	13	2	,850380	,873250	,909820
5	2	1	14	1	,864440	,792740	,887530
6	1	1	16	1	,890250	,922220	,911630
7	1	1	18	2	,931250	,827760	,819670
8	2	1	19	1	,868560	,908200	,955810
9	2	1	20	1	,826600	,889900	,936160
10	2	1	23	2	,841210	,860940	,922790

Figure 8.1: Example of data analysis organization in SPSS. Rows represent the subject while columns the measured variables.



	Name	Type	Width	Decimals	Label	Values	Missing	Columns	Align	Measure
1	Gender	Numeric	8	0		None	None	8	Right	Nominal
2	Age	Numeric	8	0		None	None	8	Right	Nominal
3	SubjectID	Numeric	8	0		None	None	8	Right	Ordinal
4	Recall	Numeric	8	0		None	None	8	Right	Nominal
5	TrialA01	Numeric	12	6		None	None	12	Right	Scale
6	TrialA02	Numeric	12	6		None	None	12	Right	Scale
7	TrialA03	Numeric	12	6		None	None	12	Right	Scale
8	TrialA04	Numeric	12	6		None	None	12	Right	Scale
9	TrialA05	Numeric	12	6		None	None	12	Right	Scale
10	TrialA06	Numeric	12	6		None	None	12	Right	Scale
11	TrialA07	Numeric	12	6		None	None	12	Right	Scale
12	TrialA08	Numeric	12	6		None	None	12	Right	Scale
13	TrialA09	Numeric	12	6		None	None	12	Right	Scale
14	TrialA10	Numeric	12	6		None	None	12	Right	Scale
15	TrialB01	Numeric	12	6		None	None	12	Right	Scale
16	TrialB02	Numeric	12	6		None	None	12	Right	Scale
17	TrialB03	Numeric	12	6		None	None	12	Right	Scale
18	TrialB04	Numeric	12	6		None	None	12	Right	Scale
19	TrialB05	Numeric	12	6		None	None	12	Right	Scale

Figure 8.2: Example of variables characteristics in SPSS.

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