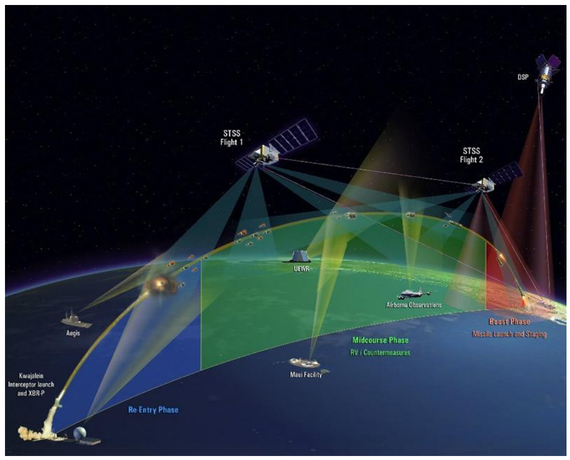
Motor control in unpredictable dynamics

- Or -

How do astronauts achieve motor tasks?

DELTA-G



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Abstract (265 words <300)

Neurological and cognitive responses to the spaceflight environment challenge the performance of crewmembers at critical times during spaceflight missions, including launch and entry. Operational performance such as controlling a vehicle or manipulating a complex system may be impaired by altered sensorimotor control, all of which are triggered by g-transitions and persist for some time after the central nervous system adapts to the new gravitational environment. **Current countermeasures have not been optimized to minimize the functional impacts of these natural adaptive responses during g-transitions or to restore appropriate sensorimotor functions after g-transitions.** Most investigations that addressed motor adaptation in new gravitational environments focused on distinct stable phases, such as the 0, 1 and 1.8g intervals in parabolic flights. However, gravity may also vary significantly and continuously over time. Multi-sensory recalibration is already time consuming in a stable new dynamical context but poses even more challenges when the underlying environment is also varying itself, bringing an additional cloud of uncertainty on motor processes. **The goal of this proposed Topical Team is to build a network of scientists with complementary expertise to advance our understanding of complex motor control tasks requiring tight inter-modal coordination when the gravitoinertial environment unpredictably varies.** Section 2 first reviews the most important results in motor adaptation in force fields. Then, critical research questions are naturally derived. Section 3 states the main objectives of this proposal in regard to recent European initiatives. Section 4 describes the timeline and the organization of the activity. Finally, Section 5 lists biographical sketches of the twelve proposed members and shows how each scientist will contribute to the goal.

Contents

1. Introduction

A spacecraft follows a specific trajectory during a mission that is unique for each flight and is broken into four phases: ascent, entry, orbit, and rendezvous. The first phase is the ascent phase which begins at lift-off and ends as the space shuttle reaches orbit. Since the space shuttle has a mass of approximately 2,000T, a very powerful propulsion system is needed to launch it into orbit. The main propulsion system, together with the Solid Rocket Boosters, supplies the thrust needed to accelerate to the speed of approximately 7.85kms^{-1} that is required to attain orbit. Within 1 minute of launch, the space shuttle breaks the sound barrier. The stress on the vehicle and the crew increases as the space shuttle accelerates. To ensure their safety, the acceleration of the space shuttle must be kept below 3g. The space shuttle continues to accelerate during approximately 8 minutes and 30 seconds along its trajectory until Main Engine Cutoff, which occurs around 104km above the surface of the Earth. Approximately 30 minutes later, the orbiter performs a final rocket engine firing to reach an orbital altitude of around 320km above Earth. Figure 1 below illustrates the g-variations experienced by astronauts during the first 10 minutes of their mission. **They experience for the first time gravitoinertial variations between zero and 3g, while they need carry on complex motor tasks.**

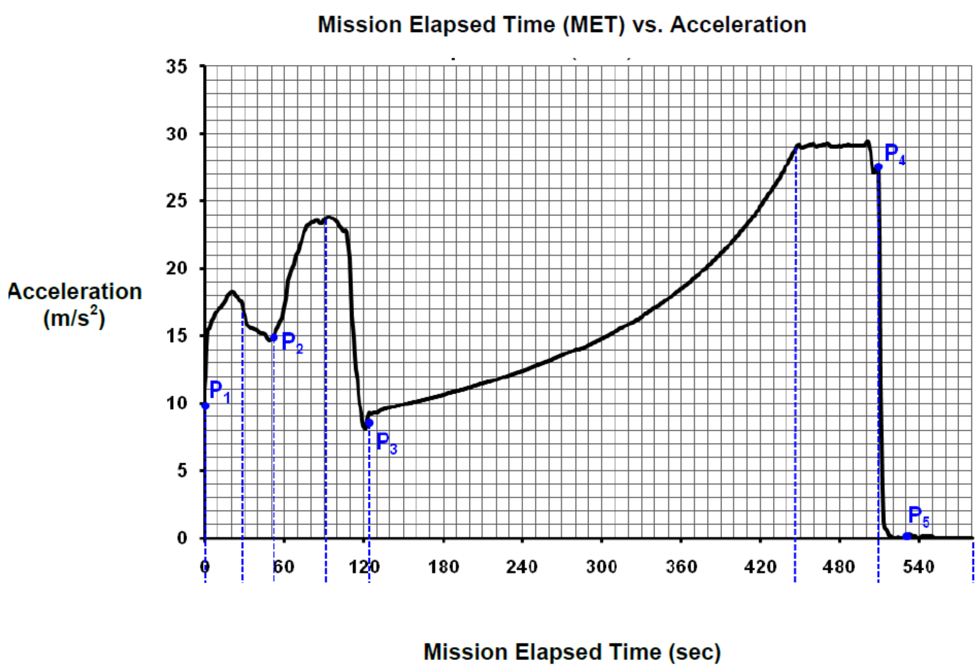

Figure 1. Typical acceleration profile of the spacecraft during the first 10 minutes of a mission. P1 to P5 correspond to key points during the initial phase of the mission.

Neurological responses to the spaceflight environment challenge the performance of crewmembers at critical times during spaceflight missions. Operational performance may be impaired by spatial disorientation, perceptual illusions, disequilibrium, motion sickness, and altered sensorimotor control, all of which are triggered by g-transitions and persist for some time after the neurological systems adapt to the new gravitational (or gravitoinertial) loading. While crewmembers eventually adapt to new gravitational environments (e.g., microgravity), subsequent transitions back to the old environment (e.g., 1g) or to a new environment (e.g., 1/6g on the Moon or 3/8g on Mars) will cause new disruptions to these systems, impairing performance until re-adaptation (or new adaptation) has occurred. These neurological changes may have adverse effects on spatial orientation, control of vehicles and other complex systems including dexterous manipulation skills. **Current methods of pre-flight training and post-flight rehabilitation have not been optimized to minimize the functional impacts of these natural adaptive responses during g-transitions** or to restore environment-appropriate sensorimotor functions after g-transitions. There is also the question whether the new adapted state is as good as the default (1g) state, since we have learned skilled control over a lifetime and only have days/weeks/months to learn the new environment.

Most investigations that addressed motor adaptation in new gravitational environments focused on distinct stable phases, such as the 0, 1 and 1.8g in parabolic flights. However, as exemplified in the introduction, gravity may also vary significantly and continuously over time. When confronted to a radically new environment, time is needed to recalibrate causality between our actions and their consequences. This already takes time in a stable new dynamical context. However, it poses even more challenges when the underlying environment is also varying itself, bringing an additional cloud of uncertainty on motor processes.

The goal of this proposed Topical Team is to advance our understanding of complex motor control tasks requiring tight eye-hand coordination when the gravitoinertial environment unpredictably varies. A first exploratory step will be necessary to quantify the behavior in these new contexts. Section 2 first reviews the most important results in motor adaptation in force fields. Then, critical research questions are highlighted and motivated. Section 3 states the main objectives of this proposal. Section 4 briefly describes the timeline and the organization of the activity. Finally, Section 5 lists short biographical sketches of members and motivates how each scientist will contribute to the goal.

2. Motor adaptation in altered dynamics

Altered environments pose challenges to the motor system. Visuomotor transformations and force fields that deviate reaching movements are powerful paradigms to elucidate adaptive strategies of the central nervous system. Robots with various characteristics are traditionally used to implement these experiments. In the first subsection, we review important results in that field. Then, we naturally present open questions that are directly linked to the present topic, and will rest the foundations of this Topical Team.

2.1 Robot-controlled force fields

During development, the dynamic properties of the arm evolve slowly and we unconsciously adapt our movements. But humans also experience very rapid and diverse alterations of their limb's dynamics; for example, when we undergo a sharp turn in a car. To be on the safe side and generate appropriate motor commands in the end, our central nervous system predicts the consequences of our actions, given some noisy representation of the environment.

Internal models

This flexibility has been extensively addressed in visuomotor and force field paradigms (for a very nice recent review, see (Karniel, 2011). In those investigations, participants reach to targets in force fields generated by a robot or by a rotating room. On first exposures, large pointing errors are observed and then gradually decrease nearly down to baseline performance. Figure 2 illustrates this typical behavior. If the force field is unexpectedly removed in catch trials or at the end of the learning phase, deviations of the hand path (after-effects shown in green in Fig. 2) are observed in the opposite direction to the earlier errors. This shows that the participant's motor control system generates a prediction of the expected forces during a movement and produces opposing forces to compensate (Shadmehr and Mussa-Ivaldi, 1994). An internal model is build up. There is large evidence that subjects can learn elastic (Hinder and Milner, 2007), velocity-dependent (Shadmehr and Mussa-Ivaldi, 1994, Lackner and Dizio, 1994), acceleration-dependent (Wang and Sainburg, 2004) new gravitational force fields (Augurelle et al., 2003) or a composite load (Flanagan and Wing, 1997).

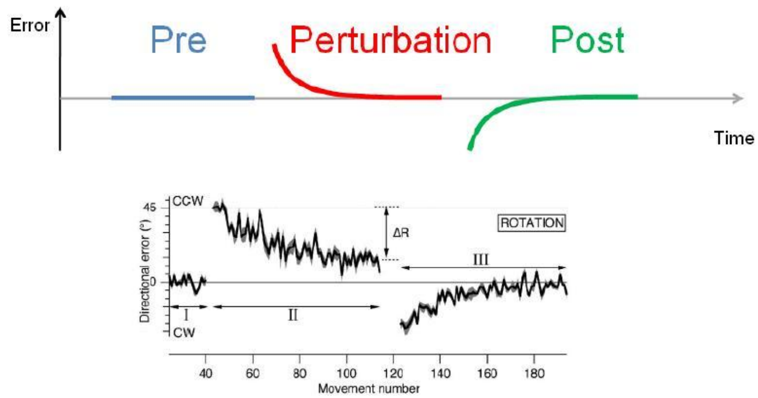

Figure 2. Sketch (above) and real data (below) illustrating typical force field adaptation protocols.

The ability to learn – or to form an internal representation of – force fields is highly context-dependent. For instance, subjects' performances are terrible when confronted to force fields that depend explicitly on time (Conditt and Mussa-Ivaldi, 1999). Instead, participants learn a sensorimotor transformation where position, velocity and acceleration input signals indicating state of the arm are mapped into a force-like output signal (Shadmehr and Mussa-Ivaldi, 1994).

Transfer, generalization and reference frames

It is worth investigating under which conditions a learned force field can be generalized, for instance to the other limb or in an unvisited part of the workspace. When generalization is beneficial, it is termed transfer, and when it is detrimental, it is termed interference. An underlying issue concerns the reference frame in which generalization occurs. In an "extrinsic" reference frame, the force field is modeled as a transformation from the hand position to the force applied at the hand. When a movement is made in a new joint configuration, this representation predicts the same forces on the hand as for the same Cartesian movement in the trained workspace. On the other hand, in an "intrinsic" reference frame, the force field is modeled as a transformation from joints angles to the torques experienced at those joints. For identical movements of the hand in external space, this model will predict different forces on the hand when the arm configuration is changed.

The reference frame in which force fields are learned and transferred is highly dependent of the context. On the one hand, transfer of learning of the same limb across different configurations in the workspace is encoded in an intrinsic joint (muscle-based) system of coordinates (Shadmehr and Moussavi, 2000, Shadmehr and Mussa-Ivaldi, 1994). On the other hand, Criscimagna-Hemminger (found that training with the dominant arm transferred to the non-dominant arm in an extrinsic reference frame (Criscimagna-Hemminger et al., 2003). To shed light on these apparent conflicting results for the transfer of learning within and between limbs, Malfait and Ostry tested the hypothesis that generalization could be dependent on how the force field is presented (Malfait and Ostry, 2004). Namely, they expected that an abrupt introduction of load would induce large kinematic errors in the first exposures, hence providing multiple sources of information that are likely to involve different systems of representation. Indeed, they found that when the field was gradually presented as opposed to suddenly applied by the robot, the internal model of the force field was not transferred to the other limb. However, they confirmed that when the same limb was tested gradually in different joint configurations, forces transferred in an intrinsic representation. Furthermore, under some circumstances, the transfer of learning a force field across limbs was best described within an intrinsic coordinate system (Dizio and Lackner 1995; Wang and Sainburg 2004) or even based on a reference centered on a complex object being manipulated (Ahmed et al., 2008). These divergent conclusions in the patterns of interlimb generalization are likely due to a combined effect of the nature of force field and the availability of sensory information.

Learning in variable – but cued – dynamics

In contrast to the flexibility of switching control policies, the ability of the nervous system to learn different task dynamics in different contexts is often limited (Gandolfo et al., 1996, Karniel and Mussa-Ivaldi, 2002). Many studies investigated this phenomenon using robotic devices to apply velocity dependent forces perpendicular to the direction of an arm movement. Learning is prevented if the force field changes direction on a trial-by-trial basis. Surprisingly, this is even the case when the change of direction is made fully predictable through the use of an alternating sequence (Conditt et al., 1997) or a predictive visual cue (Osu et al., 2004, Krakauer et al., 1999). In other contexts, however, the motor system is quite capable of learning different force field dynamics if these are associated with different tools, objects, or effectors (Cothros et al., 2006, Nozaki et al., 2006).

In sum, the above results demonstrate the flexibility and highlight the limits of our central nervous system to create and maintain accurate representations (internal models) of external dynamics to perform successful reaching movements. But still, **these experimental contexts are far from a natural situation in which a human subject is immerged into a structurally new and variable environment and is asked to operate an instrument requiring tight coordination between, e.g., eyes, head, arm and finger movements. Despite intensive training on the ground prior to mission departure, an astronaut exactly faces these challenges.**

2.2 Open questions

To approach the natural situation described above, at least three additional steps are required. First, **many robotic-based studies employed perturbations with fixed and repeatable structures**. For example, Shadmehr and Mussa-Ivaldi used a robotic device to apply mechanical forces to the hand (Shadmehr and Mussa-Ivaldi, 1994). These forces had a fixed linear dependence on the speed of the subject's hand. Second, in most cases, only the end effector (and sometimes the upper limb) was perturbed by the robot. In these cases, the sensory system remains calibrated and most likely attributes the error to the effector that it sensed perturbed by an uncontrollable phenomenon. In other words, in a Bayesian framework, the feedback gains will be larger for unperturbed effectors, because they will be deemed more reliable. **However, parabolic flight and rotating-room experiments allow circumventing these concerns.** Third, although some studies addressed eye-hand coordination in natural tasks (e.g. (Land et al., 1999), to the best of our knowledge, we currently don't know anything about learning strategies involving eye and hand movements in varying dynamics and we know very little about eye-hand coordination in constant altered gravity (White et al. submitted). These three points are detailed hereafter.

Learning in unknown and unpredictable dynamics

The perturbations that people encounter in everyday life do not always have a repeatable and consistent structure. Consider, for example, a worker whose job might be to sort packages of varying size and weight into bins, bags, or slots. Each of these packages will have different inertial properties and will impose different loads on the arm as it moves toward the desired target position. If the worker carries out this task for a prolonged time, some adaptation will take place (Kawato, 1999). In this case, the perturbations are not fixed but vary from object to object and follow a given statistical distribution depending both on the object properties and on the sequence of movements in the task. **Despite the fact variability occurs trial by trial, this is still a predictable environment in the sense that the worker can estimate the upcoming mechanical properties based on visual cues. Now the question arises as to what strategy is adopted when no clue about the environment is available?** To take another analogy, consider a mother holding her child's hand on a footpath. The attention of the children may suddenly be turned to the rolling red ball that her parent didn't see around the corner and she may start pulling on her hand. It was shown for instance, that in unpredictable or unstable dynamics, subjects do not build up an internal representation of the force field but instead increase stiffness by co-contracting muscles (Burdet et al. 2001). **This strategy is however rather sub-optimal because it requires an increment of force that may be repeated over and over and fatigue may accumulate.** In other words, the cautious parent may end the walk with pain in the hand…

Can the motor system adapt to a variable environment? And if so, how is this adaptation accomplished? Does the motor system use information it acquires on a trial-by-trial basis, or does it attempt to extract some definable statistical property about the perturbations it encounters, such as the mean or the most likely perturbation? A very interesting study addressed these questions by submitting a subject to a sequence of perpendicular viscous force fields with stochastically varying gains (Scheidt et al., 2001). They found that **an adaptive process compensated for the approximate mean field gain** from that sequence. Furthermore the force-field gain that subjects adapted to was not the most frequently experienced gain nor was adaptation dependent on the particular distribution of perturbations. Although adaptation to the mean field gain would be optimal in the sense that squared movement error would be minimized in the steady state, this strategy is computationally costly and does not allow sufficient flexibility to accommodate efficient learning of non-stationary environments. A simple model of motor performance that depended only on movement error and perturbation gain from the previous trial achieved substantial reduction in movement error, while allowing a rapid and appropriate response to long-term changes in the distribution of perturbations. **These findings suggest that the nervous system uses a nonspecific strategy when it has high uncertainty about the nature of perturbations during trial-by-trial learning, and do not explicitly retain memories of performances or perturbations beyond one or two trials in the past** (Scheidt et al., 2001, Wei et al., 2010).

Learning in altered gravity

Gravity has multiple implications for motor control. It influences reference frames for body orientation in the environment and for interaction with moving objects (McIntyre et al., 1998, Pozzo et al., 1998, McIntyre et al., 2001, Senot et al., 2012). Adaptation in motor responses following changes in gravity were observed from various contexts such as the synchronization of grasping forces and isometric force production (Augurelle et al., 2003, Crevecoeur et al., 2009a, Mierau et al., 2008, White et al., 2005). Similar conclusions were reported in gravitoinertial environments (Goebel et al., 2006). In the context of vertical pointing movements, the characteristics of arm kinematics in Earth's gravity led to the hypothesis that the gravitational constraint is internally represented in the planning process of motor actions (Papaxanthis et al., 1998). Vertical pointing movements typically exhibit skewness in the velocity profile, with the peak velocity occurring before the middle of the movement. This is in contrast to the horizontal pointing movements, which demonstrate symmetric velocity profiles (Gentili et al., 2007). In addition, simulations of arm trajectories with minimal absolute mechanical work reproduce the skewness in the velocity profiles (Berret et al., 2009), suggesting that the central nervous system accounts for the action of the gravitation al torque on the limb to optimize the motor commands. A recent investigation in hypergravity further confirmed that arm motor commands are optimized with respect to the action of gravity on the limb (Crevecoeur et al., 2009b) and that adaptation can be seen as a re-optimization process (Izawa et al., 2008).

Most of these studies investigated motor adaptation in sustained altered gravity (hypergravity or microgravity). In other words, they concentrated on stable phases of parabolic flights maneuvers without considering the sequence of alternating episodes of gravitational changes (1g – 1.8g – 0g – [1.8g; 1.5g] – 1g). However, these different force fields to be learnt concurrently may interact with independent learning processes. **Only a few experiments focused on sharp transitions between gravitational phases**. In a first study, grip forces exerted against a stationary held object were scaled to the object's weight under normal and hypergravity conditions, and the grip force changed in parallel with the weight during the transitions between hyper- and microgravity (Hermsdorfer et al., 1999). More recently, we demonstrated that the frequency of a rhythmic movement of the upper limb is systematically influenced by the different gravitational conditions created in parabolic flight, including during transition phases (White et al., 2008a). It is worth noting that, in these two studies, participants learned the time course of the transition after a few parabolas, which improved predictability of the g-profiles.

Learning to coordinate eye and hand movements

Humans move their eyes to locations containing salient information to achieve the current task. It is well established that eyes and hand are not independently controlled by the central nervous system in experimental contexts like pointing to targets (Abrams et al., 1990, Binsted et al., 2001) or catching a real object (McIntyre et al., 2001, Senot et al., 2012). This collaborative control also holds in more natural situations like driving (Land, 1992), tea making (Land et al., 1999), or playing table tennis (Bootsma and Oudejans, 1993, Rodrigues et al., 2002). An invariant relationship between the spatiotemporal characteristics of eye movements and limb kinematics emerges in goal-directed movements that are optimal for the pickup of visual feedback. Specifically, the end of a saccade toward a target corresponds temporally to the peak acceleration of the hand. Thus, during the decelerating portion of the hand movement, the eye is already on the target and well placed to provide visual information regarding their relative position for closed-loop control (Binsted and Elliott, 1999, Helsen et al., 2000).

For the first time, we analyzed the coordination between gaze, hand and grip force when naïve participants performed up and down collisions while they were exposed to parabolic flights (White et al, Submitted). We found that durations of fixation increased after impact in micro- and hyper-gravity. Surprisingly however, this dwell did not decrease with practice. Finally, despite dramatic changes in arm movement dynamics and kinematics in the different conditions, we found that the central nervous system invariably triggered a saccade 130ms before the hand acceleration peaked.

To sum up, **these three steps have somewhat been touched by recent investigations but never considered together**. It is unlikely that computational approaches such as optimal feedback control would be able to model subject’s behavior when gravity is unpredictably changing such as in the first minutes of a mission; how could re-optimization occur in an uncertain dynamics? New simulation can be performed to tackle this issue. Furthermore, what become learning rates when the environment changes? Because of its relative biomechanical insensitivity to gravity (compared to the second order upper arm system), has the visual strategy a fundamental role in achieving successful actions?

3. High level goals of the proposal

The objective of this topical team is to build a network of scientists with complementary expertise in the topics highlighted above to investigate motor control in unpredictable dynamics. During this activity, the following high level steps will be followed:

(1) Brainstorming sessions around motor adaptation in unpredictable dynamics, altered gravity and eye-hand coordination will be organized to further refine important issues. Participants will be invited to give focused presentations in relation to the discussed topics.

(2) Propose a set of preparatory ‘conventional’ robotic experiments to explore these new lines of research. Modeling will be at the heart of the investigations. Here, it is unlikely that optimal feedback control would be able to explain subject’s behaviors as accurately as in stable (new) dynamics. Rather, we expect to find simpler, more cost effective strategies relying on recent history that may however depend on the structure of the covariance matrix of measurement and/or state noise.

(3) Discuss setting up of more complex experiments to be performed in centrifuges and ground based analogues in order to explore and understand motor strategies used by human subjects in those environments. Beside variability in the environment, one important aspect of the question is to further understand adaptive processes in sustained hypogravity. Indeed, there are reasons to believe that x-g ($x \geq 1$) can be generalized from 1-g by applying a gain factor whereas this reasoning doesn’t hold true for hypogravity ($0<x<1g$). Furthermore, nothing has been done to test whether these mechanisms are also applicable the other side of the mirror ($x<0$)... Figure 3 below illustrates the state of our knowledge in motor control in altered gravity.

(4) Apply for research funding in the framework of relevant R&D programs, in particular EU, to implement a series of relevant experiments identified in step 3.

A final report summarizing scientific findings and recommendations of countermeasures will be provided to ESA. A wikipedia-like website will be set up to promote discussion among team members and provide continuous update about the activity.

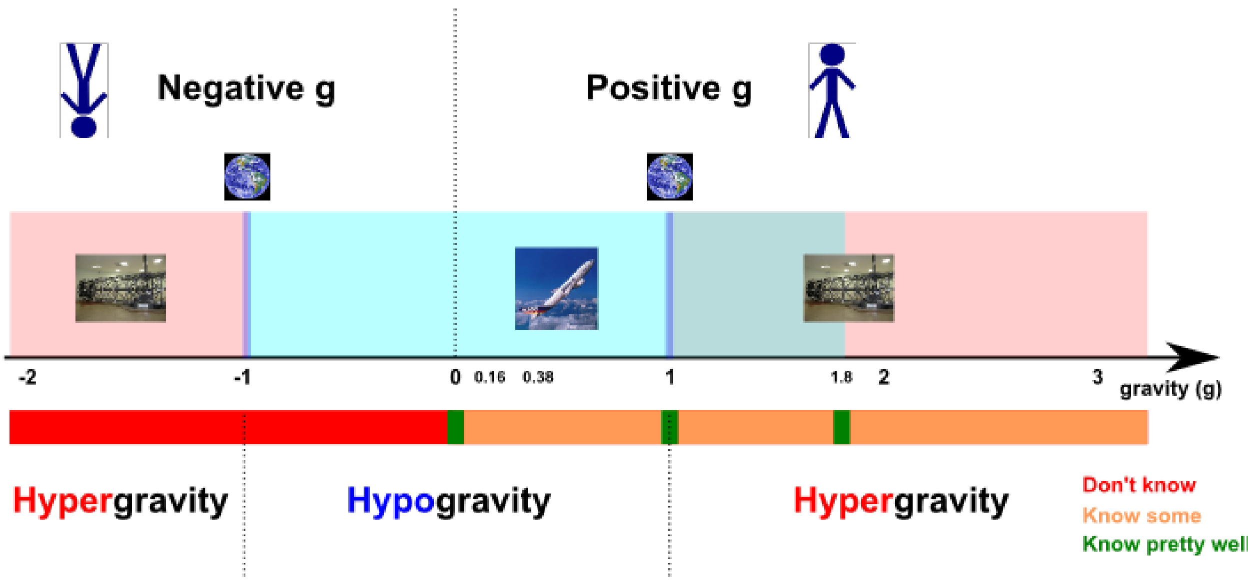

Figure 3. Gravity spectrum currently explored in motor control. Gravity is represented on the horizontal axis. Centrifuges can be used to explore the red zone above the axis and parabolic flights can be used to explore the blue zone. The special conditions at +1g and -1g can be tested on the ground. Interestingly, the interval 1-1.8g can be studied both in centrifuges and parabolic flights. Below the axis, the rectangle quantifies the knowledge we have about motor control across gravitational environment (see legend).

It is important to emphasize that this topical team proposal is timely. Indeed, a recent activity funded by the EC aimed at identifying key research issues in life sciences that challenge long term exploration missions. This activity (THESEUS[1]) drew particular attention to consider these important topics from a holistic, trans-disciplinary approach. Furthermore, identification of infrastructure and technology requirements to advance knowledge, potential Earth based benefits and applications and strengthening of European competitiveness were among the points put forward by the activity. **This Topical Team will address a subset of key issues identified by experts of THESEUS** (mainly in the clusters Integrated Systems Physiology and Psychology) **whilst keeping in mind the high level objectives of THESEUS**. The next paragraph summarizes the main recommendations put forward by THESEUS in its final report.

Specific key issues identified by THESEUS

While humans have sensory organs that specifically detect changes in the accelerations and forces acting on our bodies, there are no specific gravity receptors. Instead, the direction and strength of the gravity (or gravitoinertial) vector are deduced from the central integration of information from many types of sensory receptors distributed throughout our bodies, including visual, proprioceptive, haptic,

[1] Towards Human Exploration of Space – a European Strategy (www.theseus-eu.org)

and vestibular receptors. Crewmembers are called upon to perform some of the riskiest tasks associated with spaceflight missions during and after g transitions, which also happen to be the times of greatest environmental effects on the neurological system during a mission. One means of understanding how these control mechanisms function is to investigate their routine accommodations of daily function when the gravitational environment has changed.

- While the effects of sustained 0g on some sensory and perceptual functions have been well studied (Lackner and DiZio, 1996), little is known about the effects of sustained hypo-g ($0<g<1$) on these functions. Similarly, while the transient (adaptive) effects on some sensory and perceptual functions have been well studied following shifts from 0g to 1g (and, to a lesser extent, 1g to 0g), little is known about the transient effects on these functions following shifts from 1g to hypo-g (and vice versa). The time courses associated with adaptive responses of the sensory and perceptual systems following launch into space (transition from 1g to 0g) and following transition between 0g and hypo-g (or vice versa) should be quantified.

- Furthermore, little is known about what happens to sensory and perceptual functions during g-transitions (e.g., during launch or entry, where gravito-inertial forces can vary over by 2-3g or more during periods of 10-30 minutes) from any starting g-level to any finishing g-level. The time courses associated with adaptive responses of the sensory and perceptual systems in rapidly changing gravitational environments should be investigated (e.g. in rooms rotating at variable rates).

- Another essential research topic that must be considered to enable future planetary exploration is human adaptation not only to weightlessness, but also reduced gravity. The biological effects of long-duration exposure to reduced gravity levels that will be experienced during stays on the Moon (0.16g) and Mars (0.38g) are completely unknown. It seems unlikely that the countermeasures developed on-board the International Space Station will adequately protect crews on a journey to Mars and back over a 30-month period, or prevent the effects of a long-duration exposure to reduced gravity on the Moon or Mars. There is therefore a need to obtain basic knowledge on physiological adaptations to reduced gravity levels. Also, new insights could then be used in designing an "integrated countermeasure" for preventing the detrimental effects of weightlessness and/or reduced gravity on the physiological systems of the human body.

- Sustained hypo-g fields cannot be created on Earth, but sustained hyper-g ($g>1$) fields can be created easily using rotating habitats. Can transitions between hyper-g and 1g be used as a valid experimental model for examining neurophysiological responses to transitions between 1g and hypo-g? Test subjects in prolonged hyper-gravity induced by aircraft or long-radius centrifuges.

- Few mathematical models exist to describe sensory motor adaptive responses, especially to altered gravity. Mathematical models should be further developed to simulate sensorimotor responses to changed gravity.

- How do changes in sensorimotor control associated with altered gravitoinertial force fields affect crew performance of operational tasks? What training methods, physical aids, medications, or countermeasures could be used to minimise these effects?
- Only limited research data has been collected during g-transitions to and from space platforms.

A word on technological needs

From the figure shown above, **it is clear that we don't need further fundamental methodological developments to explore the complete spectrum of gravity**. On the one hand, hypergravity (either below -1g or above +1g) can be simulated with nearly arbitrary profile in a centrifuge. Time is also much less constrained in those experiments. Parabolic flight can be used to explore hypogravity between 0 and ca 2g, with however more constraints on gravitational profiles and times. The negative part of hypogravity could easily be explored as well but ethical considerations must be considered because it involves flipping the participant upside down. **We can even exploit redundancy**… centrifuge-based experiments and parabolic flights could both be used to explore the 1-2g interval!

A word on Earth relevance

Spatial disorientation and situational awareness issues are responsible for up to a quarter of all civil aviation accidents. Better understanding of the mechanisms underlying disorientation as well as development of physical aids (e.g., tactile situational awareness system) and countermeasures developed to aid space travelers might also be useful for commercial and military aviation. The altered gravity environments available during spaceflight offer platforms to study the basic neurophysiology of dexterous manipulation (eye hand coordination), balance and locomotion, and vehicle control, providing knowledge that serves to help patients with vestibular, neurological, and motor control problems as well as the elderly. Knowledge gained from studying the training and rehabilitation protocols developed for use with astronauts can be transferred directly to patients with specific lesions or disorders requiring retraining or rehabilitation. Finally, mathematical models developed in the context of a space environment could shed light on mechanisms that can't be observed on Earth (0g is a model of hypo-activity, which is common in elderly populations).

A word on European competitiveness

A quote from the THESEUS' final report says: *"Besides direct research funding, another efficient way to address the challenges raised by THESEUS would be to foster and catalyze networking and exchange of knowledge around these challenges, such an approach would definitely better structure the European scientific community and create synergies by addressing common complementary research topics"*. **This approach is precisely what we want to achieve in this topical team.**

4. Organization and timeline of the project

High level scientists from different countries and backgrounds are involved in this proposal. The coordination effort will be under the responsibility of the project's coordinator. Olivier White has relevant experience in coordinating international multi-year projects (experience gained during his work at the European Science Foundation) and he was a member of a previous Topical Team in a similar domain (PI: Prof. JL. Thonnard). Furthermore, the coordinator has already personally worked/collaborated with most participants, which means that the "learning curve" is very steep.

This project is intended to last (at least) two years. Three physical meetings involving all or some of the team members will be scheduled: (1) kick-off, (2) mid-term and (3) final meeting. The first meeting mainly aims at refining the ideas concerning concepts. Focused and short presentations done by participants will provide a comprehensive context for discussions. Furthermore, exploratory robotic experiments will be proposed. Dijon is equipped with a Phantom robotic device and the coordinator has already worked with the same system in the UK (White and Diedrichsen, 2010, White et al., 2008b). Kinarm robots are available at Queens (CA) or at Université catholique de Louvain (BE). The second meeting will present preliminary results obtained from the robotic experiment and use that valuable information to incept discussions toward specific experiments using ground-based facilities (centrifuge). In parallel, the team could already apply to CNES funding using centrifuges. Other scientists (also suggested by ESA) may be invited to present their work related to the topic of interest. ESA representatives will be informed about exact dates and locations of the meetings and are most welcome to attend. Depending on the exact number of participants, by experience a fixed cost of 800€ per travel is budgeted. **We expect ten external participants for the three meetings, which amount to: 3 meetings x 10 x 800€ = 24,000€.** Video-conferences may also be set up.

In order to inform everybody about the progress of the Topical Team and the fulfillments of the objectives, a Wikipedia website will be developed. This doesn't represent an important extra work and will be part of the coordination task performed by Olivier. We think that spending some time in proper communication would be highly beneficial for the activity and its promotion beyond its scope. **For the first time, international scientific strengths will be coordinated toward the achievement of this common goal.**

5. Biographical sketches of proposed team members

Dr. Gunnar Blohm	**CA**	**1**

Gunnar Blohm (DE, 1976) attended the European School of Luxembourg before entering a double-diploma program between University of Stuttgart (DE) and the Ecole Centrale Paris. After graduating in Physics and General Engineering, he did a PhD in Applied Mathematics/Neuroscience at the Universite catholique de Louvain (BE). During his PhD, he worked on models and behavioral experimentation investigating how the two main voluntary eye movement systems (saccades and pursuit) interact. He then extended his expertise on eye movement toward eye-hand coordination during a post-doctoral fellowship (Marie Curie Outgoing International Fellowship, EU) at York University (Toronto, CA). There, and during a second postdoctoral fellowship back in Belgium, he investigated mathematically and experimentally how sensory signals are transformed into geometrically accurate motor commands towards static and moving targets. Since 2008, he is an Assistant Professor in Computational Neuroscience at Queen's University (Kingston, CA). His lab works at uncovering fundamental principles underlying brain function by means of a multi-disciplinary approach bridging computational modeling, behavioral experiments, clinical investigations and neuroimaging. His main research interests involve sensory-motor transformations, multi-sensory integration, eye-head-hand coordination and 3D vision. He has published numerous influential papers introducing conceptually novel ideas that have had a broad impact within the field of sensory-motor neuroscience. He is also the founder and main organizer of the annual summer school in computational sensory-motor neuroscience (CoSMo).

Role: eye-head-hand coordination, multi-sensory integration, modeling.

Dr. Frédéric Crevecoeur	**CA**	**2**

Frédéric Crevecoeur was born in Belgium in 1982. After his studies with orientation in mathematics and Latin, he entered the Louvain School of Engineering (EPL, BE) in 2000 and obtained his master degree in Applied Mathematics in 2005. Then, he entered the graduate school at EPL to investigate the effect of changes in gravity on sensorimotor coordination in collaboration with the Institute of Neuroscience of the Université catholique de Louvain (IoNS, BE). During his PhD, he had the opportunity to participate in 6 ESA parabolic flight campaigns as experimenter responsible for experimental design and data collection in flight. His research interests focus on object manipulation, motor control of the upper limb as well as advanced analysis of physiological rhythmic patterns such as gait. He is now a post-doctoral fellow in the Centre for Neuroscience Studies (Queen's University, Kingston, CA) where he investigates the neural processes engaged in feedback control. His post-doctoral research is conducted under the supervision of Prof. S. H. Scott and is funded by Fellowship Award of the Canadian Institute of Health Research (CIHR).

Role: parabolic flights, object manipulation, reaching movements, modeling.

Prof. Joachim Hermsdörfer	**DE**	**3**

Joachim Hermsdörfer is Full Professor at the Department of Sports and Health Science at the Technische Universität München (TUM). He finished his study of engineering at TUM in 1985 and received his PhD at the Medical Faculty of the Ludwig-Maximilians-University in Munich 1993 where he also received the habilitation degree in 2004. From 1990 he worked at the "Clinical Neuropsychology Research Group" in the "Hospital München-Bogenhausen" between and chaired the research group "Sensorimotor disturbances" until he obtain the Chair of Human Movement Science at TUM in 2010. His main interest is sensorimotor-control in healthy individuals and in patients with neurological diseases. He is studying a variety of motor skills ranging from elementary acts such as reaching and grasping to complex tool use actions. He uses behavioral as well as neuroimaging methods to investigate motor learning, high performance in sports, effects of perturbations in healthy subjects as well as consequences of brain damage. He and his group have studied fine motor control during parabolic flights.

Role: parabolic flights, object manipulation, reaching movements, learning, performance, neuroimaging.

Prof. Amir Karniel	**IL**	**4**

Amir Karniel received a B.Sc. degree (Cum Laude) in 1993, a M.Sc. degree in 1996, and a Ph.D. degree in 2000, all in Electrical Engineering from the Technion-Israel Institute of Technology, Haifa, Israel. He received the E. I. Jury award for excellent students in the area of systems theory, and the Wolf Scholarship award for excellent research students. He had been a post doctoral fellow at the department of physiology, Northwestern University Medical School and the Robotics Lab of the Rehabilitation Institute of Chicago. He is currently an associate professor since 2003, he is within the Department of Biomedical Engineering at Ben-Gurion University of the Negev where he serves as the head of the Computational Motor Control Laboratory and the organizer of the annual International Computational Motor Control Workshop. In the last few years his studies are funded by awards from the Israel Science Foundation, The Binational United-States Israel Science Foundation, and the US-AID Middle East Research Collaboration. Prof. Karniel is on the Editorial board of the IEEE Transactions on System Man and Cybernetics Part A, and the Frontiers in Neuroscience. His research interests include Human Machine interfaces, Haptics, Brain Theory, Neural Networks, Motor Control and Motor Learning.

Role: human-machine interfaces, motor learning, computational motor control.

Prof. Thomas Lang	**US**	**5**

Thom's primary research interests are the application of non-invasive imaging, in particular CT and PET, to study the morphological and functional alterations of the musculoskeletal system related to osteoporosis and sarcopenia. Over the last 15 years, his laboratory has developed widely used methods to analyze musculoskeletal images, and he has accumulated considerable experience in applying these methods to solve important biomedical problems, including the recent implementation of a method to study skeletal muscle protein synthesis in vivo with PET. In addition his laboratory has been carrying out exercise studies in the context of their National Space Biomedical Research Institute (NSBRI) grant, and his laboratory has built up expertise in exercise, muscle physiology and performance measurements. As part of their NSBRI project, his group has developed a compact multifunctional exercise platform that integrates lower-body strength training and cardiovascular exercise with a dynamic balance protocol that combines an unstable surface with six degrees of freedom with projection of changing visual scenes on a screen facing the subject. Recently, Thom as also been appointed as an expert in the Bones and Muscles group in THESEUS.

Role: exercise and performance measurements, countermeasures, imaging, balance control, alterations of the musculoskeletal system.

Prof. Philippe Lefèvre	**BE**	**6**

Philippe Lefèvre is Full Professor of biomedical engineering at the Université catholique de Louvain (ICTEAM and Institute of Neuroscience). He is chair of the Biomedical Engineering program committee and Head of the Department of Applied Mathematics (School of Engineering). He obtained his electrical engineering degree and his PhD in applied sciences both from UCLouvain in 1988 and 1992 respectively. He has been investigating the neural control of movement for more than 20 years, by combining both experimental and modeling approaches. He has a broad experience on the interaction between vision and eye movements, including eye-head coordination. He also has expertise in the field of dexterous manipulation in micro-gravity.

Role: eye-head coordination, dexterous manipulation in altered gravity, modeling.

Dr. Joe McIntyre	**FR**	**7**

Joe has 20 years experience designing, implementing and exploiting the results from experiments on human physiology carried out in weightlessness. His experience includes the French-Russian missions to the Mir station (Andromède, Altair, Cassiopée, …), an experiment aboard the space shuttle during the STS-90 Neurolab mission and numerous ISS experiments, including COGNI, NeuroCog, NeuroSpat, Passages and Dexterous Manipulation (in progress). Dr. McIntyre has a proven track record of publication of these studies in high-ranking journals (J. Neuroscience, Nature Neuroscience).

Role: space experiments, co-PI of GRIP, reference frames, motor control in altered gravity.

Prof. Charalambos Papaxanthis	**FR**	**8**

Prof. C Papaxanthis has defended his PhD thesis on the topic of ‘central integration of gravity force during arm movements’. Since 20 years, he has been involved in several experiments carried out during parabolic flights and during long spatial flight missions. He has supervised three PhD students and published more than 20 peer-review papers on the topic of motor control in a gravitoinertial environment. The main goal of his research is to understand in which level of the elaboration of the motor commands the brain encodes gravity force. He records and analyses kinematics, dynamics, electromyographic patterns of arm or whole body movements in normal gravity and microgravity conditions.

<u>Role</u>: representation of gravity, space experiments, EMG.

Prof. Thierry Pozzo	**FR**	**9**

Thierry is head of the INSERM U1093 Laboratory and member of the Institut Universitaire de France. In his project, Thierry explores the organizational principles subserving the control of natural goal oriented action and how this control is implemented physiologically. The research is based on recent advances in neuroscience showing a strong coupling between action and perception through psychophysics, TMS and fMRI. I contributed to several studies conducted both in 1g and 0g demonstrating that gravity is not only a load acting locally and continuously on the body limbs, but is also used by higher levels of the nervous system as a dynamic orienting reference for the elaboration of motor commands.

<u>Role</u>: motor control, action and perception coupling, TMS, representation of gravity.

Dr. Jonathan Scott	**UK**	**10**

Jon was born in the UK in 1978. After gaining his A' Levels in physics, mathematics and design, he attended The University of Bath and obtained a 1st Class BSc. in Sports and Exercise Science in 2002. In the following two years he worked briefly as a Teaching Fellow at The University of Bath and travelled in Australia and the South Pacific. He joined QinetiQ Ltd. in 2004 and worked on occupational physiology-based research, mainly for the UK Ministry of Defence, across a range of areas including epidemiology, metabolic physiology, and biomechanics. Between 2006 and 2010, whilst continuing to work at QinetiQ, he completed his PhD examining the biochemical response of bone to acute, weight-bearing exercise. Since 2010, he has been a Senior Scientist at QinetiQ's UK human, long-arm centrifuge facility where he is responsible for delivering the sustained acceleration research programme. He also works as an advisor to QinetiQ's Flight Physiological Centre in Linköping, Sweden, which includes QinetiQ's second human-rated long-arm centrifuge facility. He is currently Development Manager for the UK Space Biomedicine Association, Acting Secretary to the UK Space Biomedicine Consortium, and a member of the UK Space Environments Working Group, responsible for the development of the business case for the UK's participation in the European Space Agency's ELIPS programme from 2012.

<u>Role</u>: experience in performing experiments with humans using a long-arm centrifuge, human responses to sustained acceleration, exercise, inactivity and bone metabolism.

Prof. Jean-Louis Thonnard	**BE**	**11**

Jean-Louis Thonnard is Full Professor at the Université catholique de Louvain (Institute of Neuroscience and Faculty of Motor Science). Since 2010, he is the head of the "System and Cognition" division in the Institute of Neuroscience. He has 75-refereed scientific papers on motor control and touch, including many studies in Parabolic Flights. His group participated to the NanoBioTact (FP6) and is currently involved in the NanoBioTouch (FP7) projects. He was the coordinator of a previous ESA Topical Team entitled "Eye-hand coordination: dexterous object manipulation in new gravity fields" (ESA publication

SP-1281, pp148-163 (ISBN 92-9092-974-X)). He is also the Co-PI with J. McIntyre of the ISS experiment "GRIP".

<u>Role</u>: space experiments, object manipulation in altered gravity, co-PI of GRIP, physiology, haptic and touch.

Dr. Olivier White	**FR**	**12**

Olivier White (Belgium, born 1977) obtained his master degree in Computer Engineering in 2000. Between 2000 and 2002, he worked in the Rehabilitation Unit (medicine faculty, Université catholique de Louvain, BE) as a software and hardware engineer to create an experimental platform for parabolic flight experiments. Between 2002 and 2007, he completed a PhD in systems and control at the Center for Systems Engineering and Applied Mechanics (UCL). He was an active member of a Topical Team funded by ESA and he contributed to the writing of an ILSRA proposal (Dexterous is now scheduled to fly). His main interests were focused on the role of gravity in the control of dexterous manipulation. Between 2007 and 2009, he was a postdoctoral fellow at Bangor University (UK) and investigated motor control in redundant systems (advisor: Jörn Diedrichsen's). Then he worked during 1.5 years as a Science Officer at the European Science Foundation (ESF) to support peer review activities and participate to the elaboration of THESEUS. He is now associate professor in Computational Neuroscience at Université de Bourgogne (Dijon, FR). His current research addresses computational motor control, object manipulation, redundant systems, role of noise in planning and execution, adaptation to force field and altered gravity. He is also responsible for the setting up of a new fMRI platform in Dijon. Olivier is member of the ELGRA association.

<u>Role</u>: coordinator, experience in working in a Topical Team, performed parabolic flights, force field adaptation, object manipulation, altered gravity and modeling.

Prof. Alan M. Wing	**UK**	**13**

Alan Wing studied Physics and Psychology as an undergraduate at Edinburgh University. After completing a PhD (with AB. Kristofferson) on timing of movement at McMaster University in Ontario, he continued this research as a postdoctoral research fellow (with S. Sternberg) at Bell Labs in New Jersey. He then joined Medical Research Council staff at the Cambridge Applied Psychology Unit (with AD. Baddeley) where he commenced studies of anticipatory control of posture in whole body balance and precision grip. Alan is presently Professor of Human Movement in the School of Psychology at The University of Birmingham where he leads the Sensory Motor Neuroscience group. Current funding includes MRC (Motor relearning in upper limb rehabilitation after stroke), BBSRC (Light touch for balance in the elderly), EPSRC (Multiperson synchronisation), Stroke Association (Retraining hemiparetic gait), EU FP7 (Nano-resolved multi-scale investigations of human tactile sensations and tissue engineered nanobiosensors, Apraxia rehabilitation, Human robot interaction).

<u>Role</u>: object manipulation, postural control, haptic feedback and sense of touch.

Completeness of the team regarding the topic of investigation

The table below illustrates how the skills of the team as a whole contribute to investigating the topic of interest on a holistic manner. Each row corresponds to one participant and each column defines a principal component of the research questions. **The cell [i,j] is green when participant i is an expert to deal with subtopic j.**

	Main axes of expertise required												
	Learning, adaptation	Parabolic flights	Centrifuges	Modeling	Dextrous manipulation	eye-hand coordination	Perception of gravity	Multisensory integration	Human-machine interface	Coutermeasures	Performance and exercise measurements	ISS/MIR Experiments	Haptics, sense of touch
Dr. Gunnar Blohm				X		X		X					
Dr. Frédéric Crevecoeur	X	X		X	X								
Prof. Joachim Hermsdörfer	X	X			X			X			X		X
Prof. Amir Karniel	X			X					X				
Prof. Thomas Lang										X	X	X	
Prof. Philippe Lefèvre		X		X		X						X	
Dr. Joe McIntyre		X		X		X	X	X				X	
Prof. Harris Papaxanthis		X					X				X		
Prof. Thierry Pozzo							X	X			X		
Dr. Jon Scott			X							X	X		
Prof. Jean-Louis Thonnard		X			X							X	X
Dr. Olivier White	X	X		X	X	X							
Prof. Alan M Wing					X						X		X

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