



The Effect of Microgravity-Like Conditions on High-Level Cognition: A Review

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With an increasing interest in space traveling, the potential risks and benefits of microgravity on mental functioning is becoming a central research issue. Here we briefly reviewed a series of behavioral studies in order to identify what is known and not known about the effects of microgravity on higher cognitive functions. We first used a general approach to describe the interaction between microgravity and higher cognition. Subsequently, we analytically described a series of studies that focused on single high-level cognitive processes (e.g., mental imagery, working memory, etc.). Altogether, these findings point to a complex pattern of data mainly explained by the variety of methodological aspects (e.g., duration of microgravity-like conditions, low number of studies). Even so, the importance of higher-level cognitive functions for space performance remains fundamental and deserves further attention. These data are ultimately interesting in light of the potential long-term effects that microgravity may play on return to Earth.

Keywords: microgravity, cognition, higher cognitive functions, working memory, Head Down Bed Rest (HDBR)

INTRODUCTION

Microgravity effects on human cognition are not very strong. There are, in fact, many methodological concerns (e.g., low level of study replication, low number of participants, majority of male participants) that prevent us from reaching firm conclusions. According to Strangman et al. (2014) we are not yet able to state whether microgravity determines important changes in cognitive processing. However, literature on the interaction between microgravity and cognition did not adopt theoretical models of cognition that may help unravel this relation i.e., the distinction between higher vs. lower-level cognitive functions. In particular, higher-level cognitive functions refer to a set of mental processes that are involved in monitoring of behavior with controlled awareness such as working memory, attention, and decision making or more generally, the so-called executive functions. A higher cognition-focused approach may be particularly useful to help more clearly understand the interaction between microgravity and cognition. In fact, differently from low-level processing, higher cognitive functions do not occur in an automated manner and thus require a greater amount of mental resources. It is reasonable to assume that these processes may be more sensitive to contextual factors in the short- and long-term run as typically shown by the cognitive aging literature (e.g., Hitchcott et al., 2017). Our review evaluates available studies focusing on higher cognitive domains from a general to a more analytical point of view. While information on how microgravity affects some of these domains is limited or is just beginning to be studied in depth (e.g., Lipnicki et al., 2009), the available literature allows some preliminary conclusions. Sensory, motor-based functions, neurobiological, and physiological underpinnings of

cognition and stress-related studies will not be the object of our investigation as these aspects have been previously explored in numerous studies (e.g., Clément, 2007; Kanas and Manzey, 2008; De la Torre, 2014; Hilbig et al., 2017).

METHOD

The papers included in this review were selected via computer searches of the PUBMED, PSYCINFO, and Google Scholar databases. The keywords used were microgravity, cognition, and higher cognition. The majority of published studies that we reviewed here were Earth-Based simulations that adopted the technique of Head-Down Bed Rest (HDBR). This is a microgravity analog that simulates microgravity effects on human body on Earth in terms of cephalad fluid shifts. Other studies adopted the procedure of parabolic flights that repeatedly reproduce real microgravity conditions for a few seconds during flight. As suggested by Watenpaugh (2016), there are many differences between these Earth-based simulation methods and real microgravity conditions, so we decided to adopt this distinction throughout the study. Only works that investigated higher cognitive functions as defined in the introduction were selected. For example, there are many studies that used digit span tasks to tap working memory. These will not be included in our review. In fact, working memory cannot be limited to a passive repetition of digits, rather the adoption of a range of complex tasks that require active manipulation of information should be warranted.

DOES MICROGRAVITY AFFECT HIGHER COGNITION? A GENERAL POINT OF VIEW

The literature that dates back to the sixties of the last century shows a very confused pattern. In line with previous reviews (e.g., Lipnicki and Gunga, 2009, but also see Clément, 2007), studies on higher cognitive functions can be grouped in those that have highlighted an impairment, those that have not found any effect of microgravity and those that have even found improvements.

Microgravity Impairs Higher Cognition With Earth-Based Simulations

Some interesting data on the negative effects of microgravity-like conditions on cognition can be found in Zubek's work (Zubek, 1969) on sensory deprivation such as darkness and white noise conditions. These studies showed general creative thinking problems especially with non-sense stimuli (e.g., non-words). In this regard, Connors et al. (1986) first highlighted how isolation and confinement could lead to an impairment of mental performance in line with the data described by Zubek. More recently, Seaton et al. (2007) found that participants under HDBR condition show an impairment in mathematical abilities (addition and subtraction) and in memory tasks (with pairs of digits and symbols) compared with the control group.

Microgravity Does Not Affect Higher Cognition With Earth-Based Simulations

Unlike the studies described above, a series of experiments found no change in higher-level cognition. One of the first study is the one by Zubek and MacNeill (1966) where no difference in critical thinking and in creative thinking was detected. Similarly, Storm and Giannetta (1974), using different cognitive tests including problem solving, showed that HDBR condition did not affect performance. At the end of the last century, Shehab et al. (1998) found no effect of HDBR condition on attention, memory and mathematical abilities. More recently, Koppelmans et al. (2015) asked a group of 10 participants during a 70 days-HDBR condition to perform a series of cognitive tasks, including a bi- and tri-dimensional mental rotation task and a digit/symbols task. No decrease in cognitive performance was observed.

Microgravity Improves Higher Cognition With Earth-Based Simulations

Behavioral data that found an improvement in cognitive performance are intriguing. In fact, the mechanisms beyond this effect are not yet clear. Marishchuk et al. (1970) were among the first to detect an improvement following a 2-months HDBR condition on a series of memory and attention tasks. The results of DeRoshia and Greenleaf (1993) are more clear: performance on 10 different cognitive tests was studied before, during and after 1-month HDBR condition and a general improvement was found. Also Pavy Le-Traon et al. (1994) a year later and with a computerized version of standardized cognitive tests, found greater accuracy in cognitive performance. More recently, Wollseiffen et al. (2016) studied mathematical abilities (e.g., arithmetic operations) during a series of parabolic flights. Participants were asked to indicate as quickly as possible which number (if the one on the right or the one on the left) was the biggest with an increasing level of complexity (e.g., 7 vs. 13 or operations). The results showed that reaction times did not slow down even in more complex trials as observed in the control group.

DOES MICROGRAVITY AFFECT HIGHER-LEVEL COGNITION? AN ANALYTICAL POINT OF VIEW

A series of studies dating back to 2009 focused on single higher cognitive functions rather than providing a general overview of the effect of microgravity on cognition. The rationale being that higher-level cognitive processes represent the essential building blocks of many complex abilities. Consequently, the analytical approach too can help us unraveling the relation between microgravity and cognition.

Mental Imagery With Earth-Based Simulations

Mental imagery is typically studied with mental rotation. This task consists of comparing two or three-dimensional objects rotated at different angles and indicating whether they represent the same object or not: to generate the "same/different" response

one must mentally rotate the object. In this case we refer to an object-based mental transformation (or allocentric), but we can also have the case in which participants are asked to imagine their body or a part of it rotating with respect to the context (egocentric mental transformation, Grabherr and Mast, 2010). In a recent study by Wang et al. (2017), no differences in mental rotation accuracy were detected before, during and after a HDBR session. Differences were instead detected in another study (Grabherr et al., 2007) which focused on the manipulation of egocentric stimuli. In particular, using the parabolic flight procedure, the participants had to compare schematic pictures of the human body parts such as an outstretched arm or hands and generate a “right/left” judgment. The data showed a slowing of reaction times in microgravity conditions and a greater number of errors. The studies therefore are in line with the hypothesis that mental manipulation of objects (allocentric) is not affected by contextual changes. Differently, mental manipulation of body and body parts is influenced by the lack of vestibular cues. In fact, microgravity does not allow the building of a representation linked to verticality, that is the typical spatial coordinates of human body on Earth. More recently, Dalecki et al. (2013) compared mental rotation of letters, hands and complex scenes (e.g., a person holding a weapon or a rose) during a series of parabolic flights in a single study. However, visual reference clues were added. In fact, the aim was to understand whether, by providing visual cues from the environment, participants could compensate for changes in the vestibular and proprioceptive system and therefore do well even in tasks based on egocentric mental manipulation (in this case hands pictures). To do so, participants could see the inside of the airplane and were hooked to a sort of rack in order to receive tactile information on the back and on the legs. The results showed that, under short periods of microgravity, mental rotation of any kind was not impaired.

Mental Imagery With Real Microgravity Conditions

As far as we know, Leone et al. (1995) conducted one of the first accurate studies on mental rotation during a space mission. They tested the same group of 8 cosmonauts on Earth, on the MIR space station and then again on Earth on a three-dimensional mental rotation task for objects. The pre-flight experimental training phase was particularly interesting. In fact, the authors wanted participants to be trained on cognitive skills before the mission as it is usually done during pre-flight sessions with other maintenance space-related activities. The results show that microgravity does not influence the manipulation of mental images and support the hypothesis that mental representation is independent of changes in the surrounding context.

Working Memory With Earth-Based Simulations

Working memory is crucial for performing complex cognitive tasks such as understanding, reasoning, problem solving, orientation, and many others. It is therefore a cognitive process of elective investigation when we talk about human cognition. Zhao et al. (2011) conducted one of the first studies on the

relationship between working memory and microgravity using a 15-days HDBR condition. The experimental task was the classic *n*-back which requires to indicate whether a target number is the same as seen, for example, 2 digits before (in this case the task is called 2-back). In the visual-spatial version, the numbers could appear at the top, bottom, right, or left and participants had to indicate if the position of the target number is the same to or different from that of two numbers before. The authors found no difference in either verbal or visuospatial memory performance between the HDBR condition and control one (for a similar result see also Lipnicki et al., 2009). In a subsequent study by Liu et al. (2015), instead, an interesting pattern of visual-spatial 2-back performance was found during a 45 days HDBR condition. There was an increase in accuracy coupled with a slowing in reaction times. These data were explained in terms of participants' adaptation to a longer and more stressful resting condition.

Prospective Memory With Earth-Based Simulations

Prospective memory refers to memories that will occur in the future, that is, remembering to perform a specific action at that particular moment or in response to a certain stimulus. Prospective memory may be a crucial process especially during the operations of a space mission in which the astronauts must, for example, remember to press that button at that particular moment. As far as we know the only study on the effects of microgravity in a prospective memory task is the one by Chen et al. (2013). In this experiment, participants were tested in HDBR condition that lasted 45 days. The main task was a recall of mini-lists of words, while the prospective task required to press a button at a certain time (e.g., at 2, 4, and 7 min from the beginning of the task). The number of times participants looked at the clock was also recorded. A series of analyses based on a time window of 3 s (during which the answer was considered correct i.e., participant was very close to pressing the button at the right time), revealed a decrease in prospective memory during HDBR with respect to all the other control conditions (e.g., pre- and post-rest). The number of times participants checked the clock also decreased in the HDBR condition. Thus, when participants are engaged in a double task-like condition, that is, time monitoring and task execution, microgravity may negatively impact performance.

Decision Making With Earth-Based Simulations

As in the case of prospective memory, a single study investigated the effects of microgravity on decision-making processes. Lipnicki et al. (2009) adopted a 2-month rest condition and used the Gambling Task. This task simulates the gambling and is commonly used to study decision-making processes in everyday life. Participants were presented with 4 decks of cards and told that each deck contains cards with monetary prizes or losses. They were told to make profits starting

from a given amount. Usually, after 40–50 selections, people understand which are the “good” decks and always select the cards from those. Instead, individuals with psychiatric disorders or particular injuries tend to select cards from all decks. No differences were found in this study. However, the authors detected differences in selection strategies during the last blocks of trials. In particular, the control group adapted to the task by switching from one deck to another less frequently in the last blocks, instead participants in the HDBR did not adapt their strategy at the final stages. According to the authors, this happened because executive functions are sensitive to long resting periods.

DISCUSSION

The findings reviewed here show that a higher cognition-focused approach can help contribute to the understanding of cognitive changes under microgravity conditions. Previous studies concluded that microgravity does not lead to any change in cognition. However, this conclusion was mainly derived by studies interested in showing whether microgravity may impact cognition in general. The pattern on higher-level cognitive processes seem to partially support this view. Nevertheless, we believe that these data represent important steps toward unraveling the differential facets of the interaction between microgravity and cognition. It should also be noted that even in the absence of effects, these data are interesting in light of the changes that had been observed on the central nervous system (De la Torre, 2014; Yuan et al., 2016) and for the potential long-term effects that microgravity may play on cognitive functioning. A recent study points to this direction. The so-called NASA Twins Study by Garrett-Bakelman et al. (2019) highlighted a different cognitive profile between the twin astronaut (TW) who took part in a 1-year space mission on the International Space Station and the other twin (HR) served as control participant on Earth. In particular, an interesting aspect is that mean accuracy (including performance on a fractal 2-back task) decreased significantly after the mission compared to HR and this deficit lasted up to about 6 months from the end of the mission. This study is thus informative also with regards to long-term effects of microgravity on higher cognitive functions.

With regards to the focus on single cognitive processes, we found the following cognitive profile. Mental imagery suffered with egocentric requests compared to allocentric ones and prospective memory decreased. Working memory and decision making were less affected by microgravity-like conditions although qualitative changes were observed.

We believe that a fundamental aspect that may allow to identify changes in higher-level cognition remains the duration of the microgravity condition. Usually HDBR conditions that lasted up to 2 weeks did not detect relevant changes. However, extended periods like those faced by astronauts during a space mission may affect higher cognitive functions. It remains to be clarified whether cognitive changes that may show during

long-term duration flights are associated to microgravity effects *per sé*, to a higher level of stress or both. This is an important issue as emotional stress may stem from multiple environmental factors during a space mission. For example, social and environmental confinement, enforced interaction between crewmembers, noise, to cite only few. Neurobiological correlates of stress may help us disentangle the role of specific stress-related effects on higher cognitive performance (e.g., Gemignani et al., 2014).

The more recent focus on single cognitive processes shows a research interest toward the study of executive functions (working memory, decision processes, those of shifting attention from one task to another as in the case of prospective memory). We can assume that these tasks, by recruiting the prefrontal cortex, may be more sensitive to contextual factors such as journey duration and, generally speaking, more demanding conditions. In this regard, Bock et al. (2010) advanced an interesting hypothesis that can be extended to higher cognitive functions as well. More specifically, fluctuations in higher-level cognition may be observed when double-task-like conditions occur in microgravity. That is, when cognitive resources are directed toward the execution of multiple tasks (e.g., both in the cognitive and emotional domain), the effect of microgravity may show either in the short- or long-term run. So far, with a small range of higher-level cognitive tasks being restricted mostly to mental imagery, the available data suggest a mixed pattern of results. Further studies will have to be done to clarify whether such influence of microgravity on higher cognitive functions is transient or relevant. Useful information about how microgravity may impact on cognition may also stem from investigations of cognitive status in divers and pilots who may show similar pattern of performance (e.g., Steinberg and Doppelmayer, 2017; Causse et al., 2019). These works may add to the issue of compensatory mechanisms that individuals develop to cope with extreme environmental conditions. This review suggests that this may be a fruitful area for investigation. Finally, recent progress in genetics is introducing a more complete view of interpreting behavioral data (e.g., Mammarella et al., 2016). Converging perspectives across behavioral approaches and neuroscience will surely contribute to the explanation of microgravity effects on higher cognition.

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The author confirms being the sole contributor of this work and has approved it for publication.

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