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Neurovestibular Considerations for Sub-Orbital Space Flight: A Framework for Future Investigation

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Abstract

Commercial sub-orbital operators will soon offer the excitement of traveling to space to thousands of people. Based on previous experience in space flight and parabolic flight, sensorimotor disruptions in eye movements, postural stability, and motor coordination are likely in these travelers. Here we propose a framework for developing strategies to overcome these sensorimotor disruptions. We delineate how approaches should differ from those applied to orbital flight and between sub-orbital passengers and pilots based on differing frequency of flights and mission objectives. Sensorimotor adaptation is one strategy for overcoming disruptions; an important question is whether it occurs quickly enough to be of use during periods of reduced and enhanced gravity lasting less than five minutes. Data are presented showing that sensorimotor adaptation of the pitch vestibulo-ocular reflex during parabolic flight takes a few consecutive days of flying to overcome an initial disruption. We conclude with recommendations for operators and researchers to improve safety and comfort during sub-orbital operations. We recommend using parabolic flight as a tool for pre-adapting sub-orbital passengers, along with further research into the required quantity and timing of these pre-adaptation flights and the tasks conducted during these flights. Likewise, for sub-orbital pilots, we recommend emphasizing recency of experience.

1 Introduction

Commercial sub-orbital operators will soon offer the excitement of traveling to space to thousands of people. Sensorimotor disruptions are likely to occur in these travelers due to reduced *g* levels, based on previous experience and research in orbital space flight and parabolic flight. Previous research into physiological disruptions and the strategies that will be most effective to deal with them will need to be supplemented with new research to understand the considerations unique to sub-orbital space flight. For example, sub-orbital flights include novel trajectories and are very brief, lasting less than two hours and incorporating less than four minutes of 0 *g*. Previous research will need to be supplemented with new research to understand the unique disruptions that are likely to occur in sub-orbital flight, and the strategies that will be most effective to deal with them. This is all the more important when one considers that the passengers on such flights will not be as rigorously screened for health and fitness as have professional astronauts.

The implications of sensorimotor disruption are different for sub-orbital pilots, sub-orbital passengers, and orbital astronauts. Strategies exist for overcoming some of these disruptions, including adaptation, re-adaptation, pre-adaptation, pharmaceuticals, and cognitive preparation (section 3). The relative importance of different strategies differ for these groups, because different groups are responsible for different tasks and because different strategies are effective over different time courses (section 4). Well-defined goals, criteria and constraints can be used to guide and evaluate the success of research programs in this area. We present suggestions for the goals and criteria of a research program for sensorimotor adaptation to sub-orbital flight, with separate considerations for passengers and pilots (section 5). We then present data on the time course of some possible adaptation strategies, based on previous experience in parabolic and orbital flight (section 6). We end with recommendations for sub-orbital flight operators to minimize the impacts of sensorimotor disruptions, and for researchers to fill knowledge gaps in our understanding of disruptions and the most effective ways to overcome them (section 8).

2 Background

2.1 Sensorimotor disruption in space flight

Many studies have been performed on human sensorimotor disruption and adaptation during space flight and parabolic flight, although none yet during sub-orbital space flight. Although they are too numerous to review in detail here, it is clear that there are often serious disruptions in sensorimotor function [1], which have perhaps been most well-quantified in postflight testing [2–5]. While little or no hard evidence relates sensorimotor deficits to astronaut performance, a correlation has been noted between decrements in shuttle landing performance and impaired performance in some aspects of a qualitative postflight neurological-assessment test [6,7]. Although there is a wide range of physiological and neurological disruption, we restrict ourselves to sensorimotor issues that could be relevant to maximizing enjoyment and performance in suborbital flight. As a great many of these studies have involved the vestibular system and its most direct motor manifestation, eye movements, emphasis is placed on these aspects. They are also the ones most likely to manifest themselves in the course of a few minutes of sub-orbital flight.

Normal pitch vestibulo-ocular reflexes (VOR) may rely on otolith modulation during head motion. Decreased contribution of this otolith signal in low g levels, and increase in high g levels, might adversely affect the pitch VOR and head-eye coordination. There are reports from astronauts of hypersensitivity to pitch head movements [8,9], and pitch rotation has been reported to disrupt re-adaptation to normal gravity after eight days of space flight [2]. While one way to mimic the lack of otolith modulation on earth might be to compare pitch VOR with the head upright to that with the head/body on its side, studies based on this approach have yielded mixed results but in general have not found a large otolith contribution [10–12]. Nevertheless other results indicate that otolith modulation during upright pitch does affect the VOR [13–15], a conclusion confirmed by low-frequency eccentric rotation [16]. Results from some flight studies suggest that this contribution may be modifiable [1]. Gain during active pitching while upright is enhanced soon after return to earth, relative to in-flight and after earth re-adaptation [17]. This suggests that adaptation to 0 g may consist of adjustment in the canal and otolith contributions to the pitch VOR. In agreement with this, there are reports of at least one shuttle crew member with decreased pitch VOR gain early in flight, which recovered later in flight [18].

The head must pitch up and down to look at targets outside the vertical oculomotor range. With each movement, a synergistic combination of eye and head motions must be made, so that the eyes reach the intended target rapidly and accurately. The effects on the VOR, combined with the tendency to restrict head movements in unusual gravito-inertial force

(gif) settings [8,19] and the likely change in head-movement dynamics in different g levels (i.e., overshooting in high g), may well combine to produce serious disruptions in eye-head control during pitching motions.

During the g-level changes of parabolic flight there are changes in torsional eye position [20] which can be markedly asymmetric [21,22]. This change in torsional alignment may be due to a loss of compensation for otolith asymmetry in unusual g environments; on earth, the nervous system presumably compensates for natural asymmetries in otolith organ properties [23], but in other than 1 g this compensation is inappropriate and produces torsional misalignment. A similar disconjugate change has been found during space flight [24]. Another consequence of this asymmetry is vertical skew which can result in diplopia. This has been demonstrated in parabolic flight and laboratory studies [25,26]. Central neural compensation for any otolith asymmetry becomes inappropriate in gravity fields other than 1 g, leading to potentially disruptive changes in ocular alignment [26].

Changes in gif, expressed predominantly through the vertical axis of the head as in space flight (and parabolic flight) while seated, might lead to vertical nystagmus and consequent changes in visual acuity. Any such nystagmus might be expected to dissipate rapidly due to adaptive mechanisms and voluntary suppression, but these compensating mechanisms are challenged during dynamic situations when gif is constantly changing. Such instability has been observed in parabolic flight as an up-beating nystagmus going into hyper-g [and vice versa: 20]. Likewise, up-beating nystagmus has been observed during 3 g centrifugation along the vertical axis, lasting throughout trials of several minutes [27,28]. Similar vertical nystagmus has been observed during long-duration space flights [29].

Saccade accuracy and spatial targeting can be critical while scanning instruments during piloting. Loss of a stable g vector may make it difficult to program accurate saccades, since gravity will not contribute to a reliable spatial frame of reference. While few if any studies have demonstrated direct effects of space flight on saccade gain, there is indirect evidence that spatial targeting of saccades may depend on the g vector. For example, saccades show systematic tilt as a function of head tilt [30–34], and directional errors of saccades to remembered targets increase in flight [35].

Manual joystick control has been shown to be affected in space flight [36], probably by an incorrect calibration of muscle force. There are also disruptions in both g phases of parabolic flight [37]. However, there are differences in the control of force and displacement: displacement is better controlled, at least in high g [38]. Pointing and limb control are also affected in altered gravity. Pointing accuracy is degraded without vision [39–41], with large errors and downward deviation in flight. Pointing movements are also slower [42], although tracking movements are unaffected. These and other results suggest a disruption in proprioception. In darkness or without precise visual information, reaching for targets tends to be too high [43] although possibly due to lack of accurate target-location information rather than faulty proprioception [44]. In parabolic flight with the eyes closed, the sizes of slow arm movements are reduced, indicating proprioceptive alteration, and overshoots are common [45]. The presence of these effects in parabolic flight suggests a rapid onset, and adaptation requires at least a few days to overcome the disruption [43], although the effects are much reduced when full vision is available. Although limb control disruption could result in errors when piloting spacecraft, such effects have not been reported by shuttle pilots, possibly because they have developed adaptations during training in high-performance jets and the limb motions required for piloting are likely to be small and aided by force feedback from the controls. Associated changes in the perception of limb position have been noted, but are likely to be of little consequence.

Long-duration flight has profound effects on posture and locomotion beyond those due to muscle atrophy and bone loss. Some of these effects are reminiscent of cerebellar ataxia. These can be especially critical immediately upon landing, especially in an emergency situation that call for rapid egress and escape from the vehicle. Postural effects revealed by moving-platform testing after shuttle flights of a week or more indicate that problems are largest when visual cues are compromised, reflecting an increased visual weighting after flight [46,47]. These effects can last for several days. There are also disruptions in the gaze-stabilizing coordination of head and body movements during walking after flight [48]. In-flight training with different amounts of optical flow during treadmill exercise has been proposed as a way to learn a class of sensorimotor interactions that includes post-flight locomotion [49], a countermeasure that is intriguing but not applicable to sub-orbital flight. Although the time course of in-flight development of these disturbances is unknown, it is unlikely that they will be problematic in the short duration of suborbital flight unless body motion in general is disrupted by severe motion sickness.

Orientation illusions come in many different forms, including illusory changes in self or vehicle orientation or motion [50]. Since they can occur rapidly and may be persistent, they may be troublesome in sub-orbital flight. The “inversion illusion” – the perception that self and vehicles are upside down – may be especially problematic in sub-orbital flight, since it is common in parabolic flight and can occur throughout the first day of orbital flight. Providing a stable visual field with strong orientation cues, and secure restraints, can be beneficial. It might also be helpful (though impractical) to have all passengers maintain upright orientations in order to avoid conflicting visual orientation cues.

Orthostatic intolerance is also common after extended flight, due at least in part to decreased vestibulo-autonomic interaction [51]. Intolerance has been noted in some subjects even after parabolic flight [52], suggesting that it might play a role in sub-orbital flight.

Taken together, these disruptions cause productivity to be reduced, performance to decrease, and the risk of mishap to increase, especially during high-workload or emergency situations, although fortunately there have not yet been any mishaps directly attributable to this cause. In aviation, fatal accidents have and do occur due to sensorimotor disruption.

2.2 Context-specific adaptation

Context-specific adaptation may allow for pre-flight training of some sensorimotor responses. By context-specific adaptation (CSA) we mean the ability of an organism to 1) maintain two different adapted states for a response, 2) have each state associated with a specific context (such as g level), and 3) switch between the adapted states immediately upon a change in context (without de-adaptation and re-adaptation). Static otolith signals can serve as a cue for switching between different vestibular responses [53,54], and vertical eye position [55,56] and vergence [57] can also serve as context cues. [Some limitations on feasible context cues were found by 58]. Welch and colleagues [59] showed dual adaptation in the case of prism displacement and a pointing task. Veteran astronauts experience fewer and less severe symptoms of adaptation to space flight on subsequent flights [1], and presumably people who wear spectacles and especially bifocals must exhibit the appropriate VOR for each lens magnification [56] – both likely manifestations of context specificity. We have been able to adapt a response (saccades to visual targets) to a particular change in gain in one gif level, and to another gain in a second gif level, and then show that the gif level itself – the context cue – can recall the previously-learned adapted responses [60,61].

3 Current strategies for dealing with sensorimotor disruptions due to space flight

Pilots, flight surgeons and life-sciences researchers have developed a multitude of strategies to deal with sensorimotor disruptions due to space flight. Here we outline five categories of strategies. In all of these cases, the particular head and body movements, visual inputs, and task type will influence the rate and success of the strategy [e.g. 8,9]. This is a research area with many open questions.

1. **Adaptation.** The brain has a remarkable ability to modify sensorimotor relationships to correct for many, but not all, disruptions. These corrections are usually very accurate (i.e., compensatory). The disadvantage is that they take time – up to 3 days in some situations. The time course of adaptation from studies by our group and others is elaborated in section 6.
2. **Re-adaptation.** The brain is able to quickly recall adapted responses from previous adaptive exposure to sensorimotor disruptions. We have found that ocular responses adapted in 0 *g* during parabolic flight can be recalled months later when subjects reenter 0 *g*. In addition, astronauts describe having fewer problems with motion sickness and navigation on repeat flights than on their first flight [4].
3. **Pre-adaptation.** Often it is too expensive to repeatedly expose subjects to the motion environments to which they need to adapt. In this case, analog environments can play an important role, although the evidence for their usefulness in sensorimotor adaptation is mixed. An obvious analog for space flight is parabolic flight. However, prior exposure to parabolic flight does not reduce the occurrence of motion sickness during space flight [1]. Parabolic flight may be more appropriate as a pre-adaptation procedure for sub-orbital flight because both have relatively short periods of 0 *g*, spaced between dynamic high *g* segments. Other pre-adaptation techniques are centrifugation (including short-radius centrifugation) [62], cross-coupled angular rotation, and high-performance aerobatic jet flight. Simulators are also used, both with combined vision and motion, and also with vision only.
4. **Pharmaceutical.** There are drugs that space flight participants can take to reduce the symptoms of sensorimotor disruption. For example, it is common for astronauts to take Dramamine, Promethazine, or Scopolamine to reduce space motion sickness symptoms. An important question is whether these pharmaceuticals also block adaptation, thus delaying the ability of the brain to overcome the sensorimotor disruption [63].
5. **Cognitive.** The final category of strategies is arguably the most important yet least understood. Higher mental function might be used to compensate for deficits that occur on a subconscious level. Training is provided about the disruptions that may be experienced, how the symptoms can be identified, and how to react. An example is the reduction of head movements during orbital flight to reduce the occurrence of space motion sickness and vomiting [19].

When selecting strategies for overcoming disruptions, it is important to consider the time course of each disruption and each strategy, as well as the effectiveness of each strategy.

The strategies need to be matched with the length and repetition of exposure to the motion environment, and thus some strategies that are important in orbital space flight will not apply to suborbital space flight (Table I). For example, motion sickness usually takes tens of minutes to manifest, and adaptation to overcome it takes days. Prophylactic pharmaceuticals can be taken beforehand and will offer protection for hours, although they

are not as effective as adaptation in preventing motion sickness in the longer term. Another example is inappropriate nystagmus, which manifests almost immediately upon a g level change, but lasts only seconds.

4 Sub-orbital flight presents unique challenges in dealing with sensorimotor disruptions

Although exposure to $0\ g$ is the most unusual aspect of sub-orbital space flight, it is important to consider the disruptive effects of the entire flight. There are variations in flight profiles because each sub-orbital flight company plans to use a different vehicle. However, we can isolate a few key phases of flight. While some vehicles will be ground-launched, others will be launched from an aircraft, with a gentle one-hour climb followed by rocket-powered climb where the g level will reach $3\ g$ for 1–3 minutes, and the aircraft will pitch up 90° to a vertical attitude. The $0\ g$ cruise phase will last between 2 and 4 minutes. During descent, the g level will reach $5\ g$ [64]. Some landings will involve parachute descent to the ground while others will entail conventional landing on a runway.

Sub-orbital flight will present researchers with different challenges compared to orbital flight. Both the types of sensorimotor disruption and their implications are different. Firstly, sub-orbital flight is shorter than orbital flight, and thus there is less time for symptoms to manifest. This also means that there is less time for occupants to adapt, particularly to $0\ g$, which will last less than five minutes. Another difference is that in orbital flight, the main implications of disruptions are safety and productivity, since schedules are demanding. In sub-orbital flight, the implications can be delineated by separately considering passengers and pilots (Table I).

For most sub-orbital passengers, flying as space tourists, the main concern is to maximize enjoyment, which directly relates to corporate revenue via customer referrals. Although in-flight schedules may seem more demanding for orbital astronauts, they have more flexibility due to the longer missions, while some sub-orbital passengers (especially those carrying out experiments) may have many goals to accomplish during a very short flight. For example, during approximately four minutes of $0\ g$, they will likely want to experience weightlessness and the way it changes spatial orientation and navigation ability, spend time at a window observing space and Earth, and interact with other passengers. Some passengers may also volunteer to be subjects for scientific experiments, either self-administered or administered by an investigator, which will require part of their limited $0\ g$ time. Still others may be operating experimental apparatus, for example, for atmospheric sampling or Earth observation. Since each phase of flight is short, being prepared to take advantage of (fully enjoy) each experience will likely be more important to passengers than any delayed negative effects such as motion sickness. Although unlikely, sensorimotor disruption might become a safety issue for passengers during incidents such as an egress after off-nominal landing. For sub-orbital passengers, pre-adaptation, cognitive training and pharmaceuticals will likely be important strategies. In-flight adaptation is not applicable because of the short amount of time spent in each phase of flight. Re-adaptation is applicable only to a small number of passengers who plan on multiple sub-orbital flights. An important research consideration is how activities in one phase of flight will impact the next – for example, learning how avoiding certain head movements during the high- g climb phase will reduce disorientation during the $0\ g$ phase.

Sub-orbital pilots should be treated differently than passengers when considering the implications of sensorimotor disruption. Pilots will be exposed to the same flight profile daily or at least weekly, and possibly multiple times per day. This contrasts with orbital flight where repetition occurs less than once every few years. Repetition will enable the

brain to overcome many sensorimotor disruptions. Adaptation and re-adaptation, as well as cognitive training, will likely be important strategies. Pre-adaptation and pharmaceuticals will be less important, partly because these will be experienced pilots who have likely reached the limit of pre-adaptation. Also, the use of medication to prevent symptoms including motion sickness may inhibit adaptation, which will be important in the long run for pilots [63]. One research question is how complete adaptation will be to rapid variations in phase of flight (e.g., experiencing 3 *g* during climb, 0 *g*, then 5 *g* during reentry within 10 minutes). Our evidence shows that the brain can simultaneously adapt to two conditions even though exposure to each is short (discussed in detail in section 2.2). Some companies plan to use fully automated flight, which introduces risks related to automation failure, but eliminates risks due to sensorimotor disruption.

5 A research framework for sensorimotor disruption in sub-orbital flight

There are numerous avenues for research to improve sensorimotor performance in sub-orbital space flight. Defining research goals, criteria and constraints can help to prioritize these efforts. In addition, it is important to be mindful of the differences between passengers and pilots in suborbital flight. Table II and III present research frameworks for sub-orbital passengers and pilots, respectively. These frameworks try to link sensorimotor disruptions with the goals of passengers and pilots so that they can be prioritized. Each table lists research goals in the top-right corner. To work toward these goals, important disruptions are also listed, along with suggested functional criteria for judging whether these disruptions have been mitigated, and constraints for acceptable rate of disruption. Working toward these constraints will lead to satisfying the research goals.

The numerical constraints given in Table II and III are examples, although they are inspired by rates of disruption in domains such as parabolic flight passengers, military pilots and boat passengers. These are suggestions for a starting point, because full resolution of all issues will take significant data collection. Ultimately, they relate to a cost-benefit analysis – for passengers, the additional revenue for improvement in the experience – and for pilots, the reduction in errors and mishaps.

6 The time course of strategies for dealing with sensorimotor disruption

It is important to consider the time course of strategies for dealing with sensorimotor disruption, because it affects their utility in different situations. This section presents results from studies we have performed on the ability of humans to adapt sensorimotor reflexes during parabolic flight, including adaptation, re-adaptation, and pre-adaptation.

6.1 Methods

We studied sensorimotor adaptation to parabolic flight by measuring changes in VOR gain during pitch head movements. We chose the pitch VOR because it may be dependent on the otolith organs, which detect the direction and magnitude of gravity, and thus changing the *g* level may cause inappropriate changes in the pitch VOR response. With ideal sensorimotor adaptation, there should be no difference in VOR gain between the responses in 0 *g* and 1.8 *g*.

We conducted experiments aboard NASA KC-135A and C-9B aircraft, which fly parabolic trajectories to provide between 40 and 50 parabolic arcs per flight, producing 1.8 *g* for approximately 40 sec followed by 0 *g* for approximately 25 sec [65]. Measurements were made in experienced parabolic flyers (*n*=3), subjects with previous pilot experience but not parabolic flight experience (*n*=2), and naïve subjects (*n*=4). Naïve subjects were tested over three consecutive days both early (first 10 parabolas) and late (final 10 parabolas) in each

flight. Eye movements were measured using a binocular video system with an accuracy of approximately 0.1° and sampling rate of 50 Hz, using methods that we have described previously [25,66]. Head angular velocity and net g level were also recorded and synchronized to the video stream. Subjects were trained to make sine-like active head movements ($0.3\text{--}1.6$ Hz, $20\text{--}30^\circ$, $40\text{--}90^\circ/\text{s}$) while gazing at a point in front of the head. Pitch VOR gain was calculated by least-squares fitting of eye angular velocity to head angular velocity. We then found the gain-difference, the average difference in pitch VOR gain between $0\text{ }g$ and $1.8\text{ }g$. We restricted analysis to head movements between 0.6 and 1.3 Hz.

6.2 Results regarding the time course of adaptation

Figure 1 shows the difference in pitch VOR gain between $0\text{ }g$ and $1.8\text{ }g$ for three categories of subjects. Larger values of this gain-difference indicate greater sensorimotor disruption. Experienced parabolic flyers (blue) had an average gain-difference of 0.01, which is not significantly different from zero, meaning that there is no evidence of a sensorimotor disruption. In contrast, naïve subjects on their first day of parabolic flight (black) had an average gain-difference of 0.15, which is significantly different from the experienced group ($p < 0.07$; Wilcoxon rank sum test), suggesting that they do have a sensorimotor disruption. By their third day of flight, there has been 76% decrease in gain-difference, suggesting a reduction in sensorimotor disruption. Importantly, this decrease was present early on day 3, which means the adaptation was preserved from the previous day, rather than being relearned during the course of the third flight. Although there is a decrease in gain-difference on day 1 late, this result was not statistically significant. These results suggest that adaptation to overcome this sensorimotor disruption takes between one and three days of exposure to parabolic flight.

These data support our claim that adaptation will be useful only for overcoming sensorimotor disruption for individuals flying on multiple sub-orbital flights, such as pilots and researchers. However, these data do suggest that multiple parabolic flights will be required if parabolic flight is being used as an environment to prepare for sub-orbital flight. If these data are extrapolated to answer questions about the rate of adaptation to sub-orbital flight, there are several considerations. Since our data are gathered in parabolic flight where the g level is varying twice per minute, adaptation may occur faster in sub-orbital flight because of the continuous periods of $0\text{ }g$. On the other hand, the total time in $0\text{ }g$ in one flight is less in sub-orbital flight ($\sim 3\text{--}4$ minutes) than in one parabolic flight (16 min).

6.3 Re-adaptation

A few studies have shown that sensorimotor changes are preserved for days or longer. Alahyane and Pelisson adapted the gain of saccadic eye movements during a single session, then tested for recall of that adaptation for a few days after [67]. They found a statistically significant difference in responses for the first 5 days, but not after 5 days. Our group adapted saccade gain during parabolic flight using the g level as a context to recall different adaptations [60,68]. In a single subject who was tested after eight months, a statistically significant response was recalled. The longer period of recall compared to the Alahyane study is likely due to the unusual context of parabolic flight – this subject did not experience any parabolic flights between the two test sessions.

6.4 Pre-adaptation

Figure 1 shows that pilots (red) were better adapted to parabolic flight than naïve subjects (black; day 1) even though neither had previous exposure to the parabolic flight environment ($p < 0.05$; Wilcoxon rank sum test). In addition, pilots were not significantly different from experienced parabolic flyers. These data show that sensorimotor adaptation acquired by

pilots in non-parabolic flight transferred to parabolic flight. This shows that pre-adaptation for sub-orbital spaceflight may be feasible using a different motion environment, such as parabolic flight. An important question is the amount of pre-adaptation required for sufficient adaptation, both in the length and number of flights.

7 A wider sensorimotor research agenda for sub-orbital flight

Commercial sub-orbital flight presents a unique and valuable opportunity for sensorimotor research in areas that are relevant to human health in general, beyond the operational concerns described previously. Passengers might agree to serve as test subjects for some portion of the flight, or for pre-flight and post-flight testing. This would dramatically increase the size and diversity of the pool of subjects flying in space, with commensurate advantages for researchers. Research results obtained from these subjects could be more directly relevant to the general population than is the case with studies in professional astronauts, which are constrained by smaller subject pools which are by their very nature not representative of the general population in physical fitness and health.

As but one example, basic questions of canal-otolith interaction are corrupted by the unavoidable presence of a terrestrial g vector on earth. Short-duration studies of the response to combinations of head translation and rotation could be performed in sub-orbital flight, with the appropriate portable equipment, to improve our understanding of this processing. The role of the otolith organs in the pitch and roll AVORs is another example; conflicting findings from several earth-bound studies with the head in different orientations with respect to gravity might be reconciled if the gravity vector were to be removed altogether. Enhanced understanding of the transduction mechanism that leads to VEMPS can also result from such studies carried out in the $0\ g$ condition.

Non-vestibular behaviors can also benefit from exploration in a reduced-gravity environment. Oculomotor examples include study of asymmetries between upward and downward reflexes found on earth in vertical pursuit [69], saccades [70] and OKN [71–73]. Even more intriguing is determining if and how organisms take advantage of gravity in performing desired limb movements [74]. Finally, the general role that gravity might play in establishing a frame of reference for sensorimotor behaviors is almost completely unknown and unexplored; research in this area could involve visual scan paths and eye or limb movements to remembered targets (with absolute or relative target locations).

8 Recommendations

Based on the research and analysis presented here, we make the following recommendations to sub-orbital flight operators:

1. **Use pre-adaptation in parabolic flight for sub-orbital passengers.** Our results show that 3–4 minutes of $0\ g$ is insufficient for adaptation to occur. Thus, passengers will not achieve any reasonable degree of sensorimotor adaptation during a single sub-orbital flight, and so pre-adaptation becomes the most important strategy for reducing sensorimotor disruption in passengers. The closest analog to sub-orbital flight is parabolic flight. Although previous studies suggest limitations in the transfer of adaptation between parabolic flight and orbital space flight, there might be beneficial transfer to the essentially “magnified” parabolic flight that is sub-orbital flight. At least one sub-orbital operator is planning to allow passengers to experience parabolic flight beforehand, and the cost of parabolic flight (~US\$3000) is small compared to sub-orbital flight (~US\$200000) which makes this a reasonable approach.

2. **Emphasize recency of experience for sub-orbital pilots.** Adaptation and re-adaptation will be the most important strategies for sub-orbital pilots to maintain sensorimotor adaptations appropriate to the flight environment. Our limited results show that some sensorimotor adaptation can be retained for months or years. However, before further research is performed to measure recall of adaptation at various times, the gap between exposures to the sub-orbital environment should be considered. We recommend that pilots who have not flown more than a few weeks should fly for a few consecutive days with another pilot with more recent experience.
3. **Develop and conduct a neurological examination for sub-orbital pilots.** Quantifying sensorimotor disruption will aid both in detecting deficits that could affect safety, and in creating a database for future research. Shuttle astronaut piloting performance correlates with simple measures of sensorimotor disruption [6]. We recommend adopting and extending existing assessment tools to evaluate pilot neurological function before and after each flight, in order to develop a database of function-performance correlations. This can then be used to help judge pilot proficiency and level of adaptation to the flight setting.
4. **Consider screening of passengers for latent and undiagnosed neurovestibular problems before sub-orbital flight.** While it is generally desirable to allow as many people as possible to participate in these flights, it is possible that the dynamics of the flights – especially the *g* transitions – will exacerbate minor vestibular problems and cause others to become manifest. Clearly a passenger with benign paroxysmal positional vertigo (BPPV), even if treated, could be at increased risk for relapse. Other conditions, such as vestibular migraine and mal de débarquement, could be induced by the flights and have long-lasting consequences. Given the high prevalence of vestibular problems (Agrawal et al. 2009) and the likely dynamics of the flights, such pre-screening might well become an issue. Early passenger experience should be monitored closely for any such effects, and the possibility of a simple neurovestibular assessment before and after flight, for all passengers, should be aggressively pursued.

Based on questions raised by the analysis presented here, we make the following recommendations to the research community about important issues facing sub-orbital research:

5. **Study the effectiveness of parabolic flight as a tool to pre-adapt sub-orbital passengers.** Important questions include the number of parabolic flights required to improve outcomes in sub-orbital flight, and the optimal amount of time between parabolic flight and sub-orbital flight so that pre-adaptation is conserved. Outcomes that can be measured are inappropriate eye movements and severity of motion sickness. Also important are the head and body movements and specific activities – both type and timing – that result in maximum pre-adaptation.
6. **Find sensorimotor symptoms caused by the unique sub-orbital flight trajectory, and ways to mitigate them.** Simple instrumentation to measure basic vestibular and oculomotor effects during flight (as well as immediately before and after), and associated questionnaires, can provide important initial information on those sensorimotor functions that are adversely affected.
7. **Study the correlation between sensorimotor disruption and pilot performance and appropriate countermeasures.** The database described above, based initially on standard qualitative measures of neurologic function, can form the basis of a research endeavor to correlation sensorimotor function with piloting performance.

Those performance measures that are most commonly affected, or have the most serious consequences, can then be linked to specific sensorimotor deficits. In this way, countermeasures to these sensorimotor deficits can be designed and prescribed (for each pilot as needed) in order to alleviate the underlying sensorimotor causes of the performance deficits. The same data can be used to study the effect of gaps in exposure to sub-orbital flight on pilot sensorimotor disruption.

10 Conclusion

Commercial sub-orbital flight will present many exciting opportunities for scientific investigation. These studies can range from operational (improving the flight experience and its safety) to basic (using brief 0 *g* as a tool to examine human physiological processes). The ability to test dozens or even hundreds of subjects, with short lead times and rapid turnaround, make these flights appealing as a complement to more logistically challenging orbital flights.

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Figure 1.

Differences in pitch VOR gain between 0 *g* and 1.8 *g* (mean $\pm$ s.e.m.). Results are shown for experienced parabolic flyers (*n*=4; red), naive parabolic flyers with previous pilot experience (*n*=2; blue) and naive parabolic flyers (*n*=3; black). Results for naive parabolic flyers are shown for their first day in flight at the beginning of their exposure to the parabolic flight environment, the end of the first day, and the end of the third day.

Table I

The importance of various strategies for overcoming sensorimotor disruption for different types of space flight. Because of differences in both duration and repetition of exposure to altered g levels, strategies that are important in orbital flight may not be useful in sub-orbital flight. The number of stars indicates our suggestion about the importance of each strategy.

Strategy	Orbital flight	Sub-orbital passengers	Sub-orbital pilots
Adaptation	*****	*	*****
Re-adaptation	**	*	*****
Pre-adaptation	***	*****	**
Pharmaceutical	***	***	**
Cognitive training	*****	*****	***

Table II

Goals and constraints on disruptions for sub-orbital passengers. Each disruptions has a suggested functional criteria for judging whether it has been mitigated, and constraints for acceptable rate of disruption. The numerical constraints given are examples, although they are inspired by rates of disruption in domains such as parabolic flight and boat passengers. Ultimately, they relate to a cost-benefit analysis – for passengers, the additional revenue for improvement in the experience.

Sub-orbital passengers	Goals: <ul style="list-style-type: none"> • Allow passengers to fully focus on the flight experience without distraction of sensorimotor disruption • Allow passengers to complete a set of personal tasks within a short period of time, such as movement in 0 <i>g</i>, flips, looking out the window, and interacting with other passengers • Allow scientist-passengers to complete scientific tasks quickly and accurately • Consider any interactions between flight phases specific to sub-orbital flight 	
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Disruption	Criteria	Constraint
Loss of spatial awareness	Time required for subject able to locate important landmarks in spacecraft	Subject can locate and travel to seat in 10 seconds 99% of the time
Motion sickness	Onset and severity of motion sickness	Before 0 <i>g</i> : 99% no vomiting; 95% no symptoms Immediately after 0 <i>g</i> : 90% no vomiting; 70% no symptoms At landing: 80% no vomiting; 50% no symptoms
Loss of visual acuity	Amount of lost visual acuity	Able to read 12 point text at a rate at least 60% of that on the ground
Manual control accuracy, including incorrect limb motion forces for 0 <i>g</i>	Rate of mishaps / collisions	A collision with no injury occurs a maximum of once/ flight A collision with minor injury occurs a maximum of once every 100 flights
Changes in posture, limb control and gait	Performance in post-landing egress situation	Able to exit vehicle within 30 seconds
Orientation illusions	Interference of illusions with ability to return to seat	Subject can locate and travel to seat in 10 seconds 99% of the time
Orthostatic intolerance	Number of passengers experiencing temporary blackout and loss of consciousness	Blackout: less than 1 passenger every 5 flights Loss of consciousness: less than 1 passenger every 20 flights
Pitch vestibuloocular reflex gain	Amount of visual blur caused by gain errors	See functional criteria under “loss of visual acuity”
	Contribution to sensorimotor conflict leading to motion sickness	See functional criteria under “motion sickness”
Eye misalignments in gravity fields other than 1 <i>g</i>	Amount of lost visual acuity due to misalignment	See functional criteria under “loss of visual acuity”
	Contribution to sensorimotor conflict leading to motion sickness	See functional criteria under “motion sickness”
Vertical nystagmus	Amount of visual blur	See functional criteria under “loss of visual acuity”
Saccade accuracy	Decrement in scanning performance due to inaccurate eye movements	See functional criteria under “loss of visual acuity”

Table III

Goals and constraints on disruptions for sub-orbital pilots. Each disruptions has a suggested functional criteria for judging whether it has been mitigated, and constraints for acceptable rate of disruption. The numerical constraints given are examples, although they are inspired by rates of disruption in domains such as military pilots. Ultimately, they relate to a cost-benefit analysis – the reduction in errors and mishaps.

Sub-orbital pilots	Goals: <ul style="list-style-type: none"> • Ensure that sensorimotor disruption does not interfere with the ability to pilot the aircraft during both nominal and emergency situations • Quantify re-adaptation capability by study the effect of gaps in sub-orbital exposure on functional neurological tests and actual flight performance metrics 	
Disruption	Criteria	Constraint
Inaccuracy in spatial orientation	Error in following glide slope	Within 0.2° vertically 99% of the time Within quarter-scale deflection 99% of the time
Loss of spatial awareness	Ability to orient to landing field and emergency sites	Able to locate within 5 sec 99% of the time
Loss of visual acuity	Amount of lost visual acuity	Able to read checklists during slow head movements at a rate at least 90% of that on the ground
Gaze disruption	Speed of locating and reading error messages	Within 25% of ground time 99% of the time
Errors in sensory integration	Correct timing and angle of landing flare	Airspeed within 5 knots of target Forces on landing gear within target margin 95% of time; within safety margins 99.99% of time
Motion sickness	Onset and severity of motion sickness	No vomiting on 95% of flights Able to continue tasks after vomiting on 99% of flights One of two crewmembers able to continue tasks on 99.99% of flights
Errors in manual control, including limb control	Yoke and pushbutton manipulation	Greater than 99.5% accuracy at selecting switches and buttons No more than 5% overshoot in yoke manipulation
Changes in posture and limb control	Performance in post-landing egress situation	Able to exit vehicle and carry one passenger 10 meters
Orthostatic intolerance	Number of passengers experiencing temporary blackout and loss of consciousness	Blackout: less than 1 passenger every 5 flights Loss of consciousness: less than 1 passenger every 20 flights
Orientation illusions	Interference of illusions with ability to pilot vehicle	See functional criteria under "Inaccuracy in spatial orientation"
Pitch vestibuloocular reflex gain	Amount of visual blur caused by gain errors	See functional criteria under "loss of visual acuity"
	Contribution to sensorimotor conflict leading to motion sickness	See functional criteria under "motion sickness"
Eye misalignments in gravity fields other than 1 <i>g</i>	Lost visual acuity due to misalignment	See functional criteria under "loss of visual acuity"
	Contribution to sensorimotor conflict leading to motion sickness	See functional criteria under "motion sickness"
Vertical nystagmus	Amount of visual blur	See functional criteria under "loss of visual acuity"
Saccade accuracy	Decrement in scanning performance due to inaccurate eye movements	Able to perform scan of instrument panel at a speed at least 80% of that in the simulator