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Differential Role of Gravito-inertial Cues for Active and Passive Control in Degraded Visual Environments

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ABSTRACT

Future vertical lift (FVL) missions will be characterized by increased agility, degraded visual environments (DVE) and optionally piloted vehicles (OPVs). Increased agility will induce more frequent variations of linear and angular accelerations, while DVE will reduce the structure and quality of the out-the-window (OTW) scene. As rotorcrafts become faster and more agile, pilots are expected to navigate at low altitudes while traveling at high speeds. In contour terrain flight, the perception of self-position and orientation provided by visual, vestibular, and proprioceptive cues can vary from moment to moment due to visibility conditions and body alignment as a response to gravito-inertial forces and internally/externally induced perturbations. As a result, erroneous perceptions of the self and the environment can arise, leading ultimately to spatial disorientation (SD). In OPV conditions, the use of different autopilot modes transforms the pilot's role from active pilot to systems supervisor. This shift in paradigm, where pilotage is not the primary task, and where feedback from the controls is not available, has important consequences. Indeed, space perception can be strongly modulated by the nature of the displacement in space. Considering the relationships between the level of automation (LOA) and sense of agency (SoA), it is of particular interest to examine whether motor control mechanisms can modulate the level of visual-vestibular integration in tasks of movement perception vs. movement control. An experiment was conducted using the NASA AMES vertical motion simulator (VMS) to evaluate the effects of optical and gravito-inertial cues in the assessment of altitude in contour terrain flight. Seven U.S. Army pilots participated in the experiment. The aim of the proposed research was a) to establish the relative contribution of visual and gravito-inertial cues as a function of the quality of the visual cues (good vs. degraded) and the presence or absence of gravito-inertial cues; b) to determine the role of manual control vs. supervisory monitoring control on the estimation of altitude, and c) study the interactions between the nature and the quality of the sensory cues and the type of control. For the supervisory control condition, the results showed that the gravito-inertial component played a significant role in the estimation of ground height, but only in the case where the optical structure did not efficiently specify the actor-environment interaction. Meanwhile, the results for the manual control task provided evidence, at multiple levels, that the acceleration information, specified by the variations of the gravito-inertial field, has a relative character. Altogether, these results are in line with the Sensory Weighted Approach of perception, which proposes that each sensory cue is weighted depending on this reliability: gravito-inertial information is attenuated when the visual information is relevant while it enhances performance when the visual information is poor.

INTRODUCTION ¹

This study was a joint effort between the U.S. Army TDD AvMC Aviation and the Office National d' Etudes et de Recherches Aéropatiales (ONERA) in the context of a US/ French Rotorcraft Project Agreement (RPA).

The capability to govern self-motion in rich and changing environments is one of a human's most important perceptual-motor skills. Self-motion, whether walking, driving, or flying requires trajectory control while avoiding collisions with obstacles. The perception of self-motion, which includes direction perception and speed, relies on the integration of multiple sensory cues, mostly visual and vestibular. Optical

patterns specify the position and velocity of distant objects (Refs.^{1, 2, 3}), while variations in self-motion impact the gravitoinertial field (Refs.^{4, 5, 6}). Visual motion sensors are tuned to velocity rather than acceleration, and the frequency response of visual motion perception approximates a first-order low pass filter (Ref.⁷). Meanwhile, vestibular, and proprioceptive motion sensors are specifically tuned to acceleration (transient movements) and have high-pass filter characteristics (Ref.⁸). Under natural conditions, it is always the case that information from several sensory modalities is concurrently available. All the sensory modalities provide congruent spatio-temporal information, and conceptual congruency (a cat meows). In the case of self-motion, visual proprioceptive and proprioceptive-vestibular interactions are often casually related. Whereas our perception of position and orientation provided by visual, vestibular, and proprioceptive cues is relatively constant and veridical while on the ground, it can vary from moment to moment in flight due to visibility conditions, body alignment as a response to gravitoinertial forces and internally/ externally induced perturbations. As a result, erroneous perceptions of the self and the environment can arise, leading ultimately to spatial disorientation (SD). For example, erroneous visual perception of distance often occurs during poor visual conditions such as night, whiteout, or brownout. Meanwhile, erroneous perception of motion caused by extreme velocities (too fast or too slow) can result in misinterpretation of directional cues. This is exemplified in the climbing/descending illusion in which a pilot that is accelerating or decelerating can experience the illusion that the aircraft is climbing or diving due to the resultant force being perceived as the force of gravity (Ref.⁹). As a result, a novice pilot may attempt to rectify the trajectory by pitching the aircraft upward, or worse, downward toward the ground.

The effects of translational and rotational accelerations on the detection of motion and direction while resting immobile, upright, or supine, have been studied extensively in the reference literature, but little is known when motor control is involved. Most studies of perceived translation have involved the horizontal plane, however, rectilinear vertical acceleration, an inertial stimulation that remains parallel to gravity and alters only the magnitude of background force, has received little attention. In a height control task that considered visual cueing aspects as well as motion cueing, Johnson et al. (Ref.¹⁰) investigated how the displayed visual level of detail (LOD) changes as one gets closer or further away from an object. The results showed that changing the visual LOD to maintain constant global optical density (OD) as the altitude changed, like that of the real world, improved altitude awareness. Separately, adding platform motion improved speed regulation and altitude perception.

To our knowledge, the perception of altitude in low-level flight for a passive observer, i.e., when the pilot is not actively flying, was never investigated. In the context of FVL and OPVs, the use of different autopilot modes will imply a modification of the pilot's role from active pilot to systems supervisor, e.g., air mission commander (AMC). This shift in paradigm, where pilotage is not the primary task, and where

feedback from the controls is not available, has important consequences. Indeed, space perception and its geometric properties can be strongly modulated by the active or passive nature of the displacement (e.g., Refs.^{11, 12}). While the question of being an active vs. a passive operator regarding the perception of ego motion in specific gravitational and visual conditions has been largely unexplored, it can be investigated using the theoretical frame of "agency". Agency refers to one's ability to control his/her actions and, through them, events in the external world (Refs.^{13, 14}).

In the context of automation and human-computer interactions, the question of agency, i.e., the perception of the level of control that we have on these systems, is central (Ref.¹⁵). Since automation can fail, and because the AMC must maintain a holistic situation awareness (HSA), it is critical to understand how visual and gravitoinertial cues contribute to the perception of self-motion when the pilot is not an active agent, and when attention may be divided between tasks. In the case of low-level flight such as nap of the earth (NOE) missions, the perception of height is critical as flying too high can lead to aircraft detection by the enemy's radars and flying too low can lead to controlled flight into terrain (CFIT) or collision with an obstacle. Optimal perception of height relies on the synergistic contribution of multiple senses, mostly the visual and the vestibular systems, the role of each and their interactions detailed in the next sections.

Optical information and the visual system

The human visual system is composed of two complementary sub-systems, the ambient visual system which enables orientation relative to the global environment, and the focal visual system, allowing orientation relative to an object (Refs.^{1, 16, 17, 18}). Gibson (Ref.¹) has shown first that the direction of self-motion can be derived from the motion pattern of texture points in the visual field. He showed that for an observer in rectilinear motion, the "optical flow field" or "streamer" pattern seems to expand from a focal point that indicates the direction of motion.

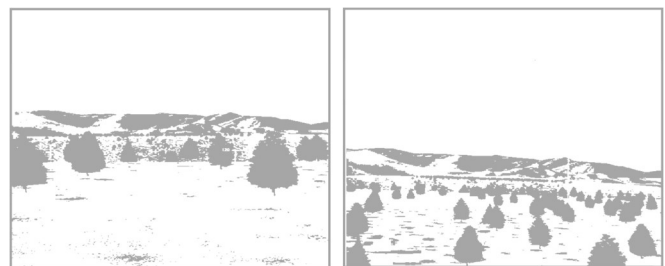


Figure 1. The same scene extracted from an experimental video trial in good visual environment (GVE) at 27 ft above ground level (AGL) on the left and 63 ft AGL on the right. Because the actual texture density is constant, the perceived texture density increases as altitude increases.

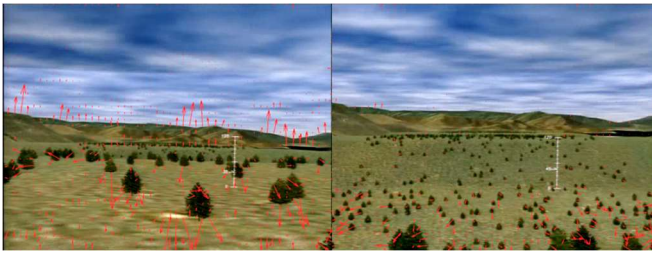


Figure 2. Example of out-the-window optical fields as a function of altitude. Left: 27ft AGL. Right: 63 ft AGL.

The optical flow generated at the pilot's observation point contains crucial information for controlling self-motion (Refs. ^{1, 19}). One of the most important components of the optical flow field structure is motion parallax, which informs about relative distance (Ref. ¹) and egocentric distance (Ref. ²⁰), and strongly depends on the ground texture.

Gravitoinertial (GI) information and the vestibular system

The vestibular system is the most influential of the non-visual senses for the detection of information about passive and active, linear, and angular self-accelerations (Ref. ²¹). The vestibular system generates information for the three axes of head translation (transverse, longitudinal and sagittal) and the rotation, and provides spatial orientation in relation to the vertical gravity. It is important to note that vestibular integration has the distinction of being intrinsically multisensory (Ref. ²²). There is no primary vestibular cortex *per se*, and vestibular system is more of a network of vestibular areas interconnected with the parieto-vestibulo-insular cortex (PVIC) (Ref. ²³). Thus, the vestibular sensory dimension is essential to a set of processes for movement perception such as vision stabilization (vestibulo-ocular reflex, VOR), balance maintenance and head orientation estimation. In addition to providing consistency with visual, proprioceptive, and auditory inputs, the vestibular system allows self-motion to be discriminated from an external movement.

Visuo-vestibular interactions

The relation between optical changes (detected by the visual system) and inertial changes (detected by the vestibular system) during self-motion has been widely investigated (Refs. ^{24, 25}) and studies have shown the importance of spatiotemporally coherent visuo-vestibular cues for successful control of self-motion (Refs. ^{5, 26}). However, discrepancies (e.g., non-coherence or noise) in the ambient arrays can lead to an erroneous sense of height, orientation, or speed, with dramatic consequences such as loss of control. Decreasing altitude in a helicopter generates both optical (e.g., variations in the flow structure) and inertial (variations in the GI structure) changes. In a nominal situation (e.g., no wind, good weather, daylight) variations in optical and GI structures are continuously congruent. But in more

challenging situations, such as when landing in a desert, the sand lifted by the rotors often creates a condition in which ground textual cues are absent and the horizon is indistinguishable (Ref. ²⁷). This sudden interruption of visual stimulation without affecting vestibular stimulation creates unnatural covariations between the two senses, and in this context, pilots are often unable to efficiently control their altitude and self-motion (Ref. ²⁸). These observations are theoretically grounded into two approaches, the sensory integration approach, and the ecological approach. According to the sensory integration approach, the various cues sampled by our senses are combined to produce an integrated percept allowing us to successfully interact with our environment. Because of the variability of sensory cue reliability (due to environmental variations, or errors in sensory detection), this theoretical framework proposes that cue integration depends on probabilistic inferences (Ref. ²⁹). One version of this approach is the sensory weighted approach, which proposes that each sensory cue is weighted based on this reliability, and that weight depends on integration patterns derived from the Bayesian probability theory (Refs. ^{6, 30, 31, 32}).

In the ecological approach, the interaction with the environment is directly specified in the covariations of the flow structures detected by the various senses. The intermodal theory of perception (Ref. ³³) proposes that variations in the optical structure reaching the eyes of the pilot and variations in the gravitoinertial structure stimulating their vestibular system are simultaneously specified in a higher-order structure called the Global Array (GA). The GA is a structure that extends across multiple forms of ambient energy. Higher-order invariants existing in the GA have been demonstrated to be responsible for the perception and control of reaching (Ref. ²⁰), but to our knowledge it remains to be discovered in the context of NOE flight. Nevertheless, and in the case of self-motion, visual information is physiologically dominant, but it is now established that the vestibular system plays a key role in the determination of this type of action (Ref. ³⁴). In 2010, Fetsch (ref. ²⁴) explored visuo-vestibular integration by introducing disparities in vestibular inputs (moving platform) and visual inputs (optical flow). They demonstrated a weighting of visuo-vestibular sensory inputs according to their reliability. More specifically, they showed that vestibular information is attenuated when the visual information is of high relevance for body movement coding summation (see also modality appropriateness hypothesis for vision and audition, Ref. ^{49, 50}).

Thus, in GVE conditions, the visual information available in the external environment can be sufficient for the pilot to characterize his own movement and attitudes with respect to the terrestrial reference. On the other hand, in DVE conditions, when visual information can be very limited (e. g., entry into a cloud layer, night or brownout), the acquisition of information about the terrestrial reference is hindered and even the most experienced pilot may be unable to properly assess (consciously or not) the attitudes of his aircraft. Furthermore, the reliability (signal-to-noise ratio) of these cues can vary rapidly and unpredictably, because of

environment changes or because of sensory encoding error. If, from an evolutionary point of view, the vestibular system is completely adapted to the earth's motion, it does not follow that it is well-adapted to the aeronautical environment and may constitute a major physiological component of the SD (Ref. ³⁵). SD is therefore due to the functional inability of the vestibular system to inform the operator about his/her own motion when visual information is deficient, given certain kinetic condition.

Automation and Sense of Agency

While automatic flight control systems can increase safety through workload reduction, empirical data also suggests that it could have negative performance and safety consequences for the pilots, a set of difficulties called the out-of-the-loop (OOTL) performance problem (Refs. ^{36, 37, 38}). OOTL performance problem is fundamentally an issue of human-automation interaction and can arise because of issues of poor performing monitoring, impaired decision-making (Ref. ³⁹), and reduced perception, i.e., lack of operator sensitivity to signal (Ref. ⁴⁰).

SoA and consciously perceived control over the immediate environment

A direct consequence of the OOTL phenomenon is a reduction of the "Sense of Agency" (SoA), i.e., the experience of being in control both of one's own actions and, through them, of events in the external world (Refs. ^{41, 42, 43}). The SoA can be subdivided into a sense of intentionality or intentional causation, a sense of initiation and a sense of control (Ref. ⁴⁴). It raises the question of how pilots perceive their agency in the context of human-machine interaction and collaborative control. Of particular interest for FVL, is how the SoA might affect the perception of self-motion (perception of egocentric distance, direction) in rapidly/ unpredictably changing environments.

In the aviation domain, Berberian et al. (Ref. ⁴⁵) investigated the participants' SoA when performing an aircraft supervision task using a flight simulator under different levels of automation (LOA). The task required the participant to monitor a flight plan. After a random time-interval, a conflict occurred due to the presence of another plane. The participant was asked to decide an appropriate action and implement it using a button-based interface. The authors found a decrease in the SoA (for both implicit and explicit measures) associated to the increase in automation. They argued that the increasing LOA tends to distract operators from action outcomes, decrease their sense of control and therefore disrupt their overall performance. Further empirical evidence comes from Coyle et al. (Ref. ⁴⁶). In a machine-assisted point-and-click task, the authors explored how the assistance given to participants could influence the user's SoA. They showed that, up to a certain point, automation could assist users while also allowing them to maintain a sense of control and ownership of their actions and the outcomes of those actions. However, their results suggested that beyond a certain level of assistance, users experienced a detectable loss in their SoA. Taken together, these studies indicate that automation

technology could disturb the mechanism underlying the SoA. This decrease in agency could generate critical concern regarding both automation acceptability and operator behavior.

The study

Rationale

The questions of 1) whether SoA influences altitude perception, 2) whether altitude perception differs as a function of the nature and the reliability of the sensory cues and 3) whether SoA interacts with 2) are fundamental for FVL. They were explored by 1) comparing altitude perception as a function of the operator's role in the flying task, active vs. passive; 2) comparing environments where gravito-inertial cues are present or absent and 3) contrasting good and degraded visual cues conditions.

For the SoA, two conditions were tested. In the first condition, referred to as Passive Control condition, simulating supervisory control, pilots were asked to report their perceived altitude above the ground level (AGL) while moving in a simulated NOE flight in a pseudo auto pilot (AP) mode. In the second condition, referred to as Active Control condition, the pilots actively had to regulate their altitude, speed and heading as if they were in a real NOE situation. These two conditions require different perception mechanisms. In the Passive Control Task, the representation of the self in the environment relies on the integration of relative cues during visual *perception decoupled from action*, where the pilot is expected to experience a reduced SoA. Conversely, in the Active Control Task, the representation of the self in the environment is mediated by *control-oriented action-perception* mechanisms, where the pilot has a strong sense of control.

For the effect of the nature and reliability of the sensory cues on height perception, two sensory conditions were tested, one where only visual information was available, and one where spatially and temporally visual and gravito-inertial information were present. Two environmental conditions were evaluated, manipulating the reliability of the visual cues: GVE and DVE, with a ¼ mile visibility.

In GVE, where the visual cues are highly reliable, one may expect no or a very low level of contribution of the gravito-inertial cues to altitude perception. Conversely, in DVE, the reliability of the visual cues decreases, and the contribution of the gravito-inertial cues is expected to increase and should give rise to some level of multisensory enhancement. The reliability of the visual cues was further investigated by introducing a vertical perturbation in the passive condition and a fly over maneuver in the active condition. When pilots are flying higher, the quality of the visual cues decreases and therefore, one may expect a greater contribution of the gravito-inertial cues in these conditions.

Assuming transitivity between passive and active observer perceptual mechanisms, the hypothesis was that pilots would produce a better performance in the presence of congruent

visual and gravito-inertial stimulation rather than during visual stimulation alone. It was also posited that when the visual information was compromised in DVE or when flying higher, the contribution of the gravito-inertial cues would be more heavily weighted.

The results for the passive and active conditions have been extensively separately discussed in two papers (Ref. 47, 48). The results for the Passive Control task showed that the gravito-inertial component played a significant role in the estimation of ground height, but only in the case where the optical structure did not specify efficiently the actor-environment interaction, i.e., when the reliability of the visual cues was low. Similarly, the results for the Active Control task provided evidence, at multiple levels, that the acceleration information, specified by the variations of the gravito-inertial field, has a relative character.

The aim of the present paper is to determine if the observed perceptual mechanisms show some form of transitivity between control modes, and whether the SoA modifies the rules for multisensory integration. Due to the differences in the two conditions in the manipulation of height perception, the comparisons are strictly qualitative.

Methods

Participants

A total of seven male pilots from the U.S. Army (one research instructor pilot, three experimental test pilots, two research pilots and one instructor pilot) aged 27 to 57 (mean 37.5 years) participated in the experiment. Flight hours varied between 560 hours and 7300 hours (mean 2736 hours) and simulator experience between 100 hours and 1000 hours (mean 365 hours). All had flown NVG / DVE conditions (40 to 1500 hours, mean 765 hours).

The Simulator

The experiment was carried out on the NASA Ames Research Center VMS, an uncoupled six-degree-of-freedom (three translational and three rotational) motion simulator (Figures 3, 4, 5). The distinctive feature of the VMS is its unequalled large amplitude, high fidelity motion capability. It was equipped with a R-cabin emulating a utility class UH-60 sized helicopter, with an out the window (OTW) field of view representative of that class of vehicle. Two gravito-inertial conditions were tested, one with cabin motion (the gravito-inertial profile is the double derivative of the terrain profile) and one without cabin motion (the visual environment only is optically in motion).

The Visual Display

The OTW visual scene was generated by a Rockwell-Collins EPX-5000 image generation system providing a high-resolution visual environment at update rates $\geq 60\text{Hz}$. The visual scene was presented on the cockpit top three windows (the chin window was not used to prevent the ground from being viewed and used to assess the altitude). The horizontal field of view spans ± 78 degrees and the vertical field of view spans -16 to $+12$ degrees, as shown in Figure 4.

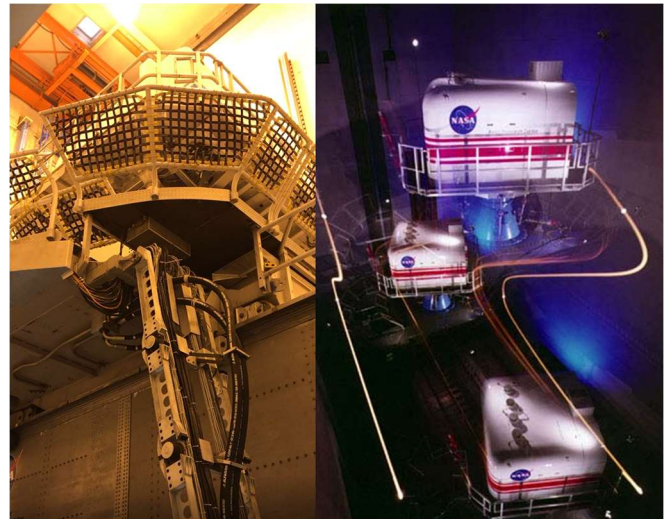


Figure 3. NASA Ames Vertical Motion Simulator.

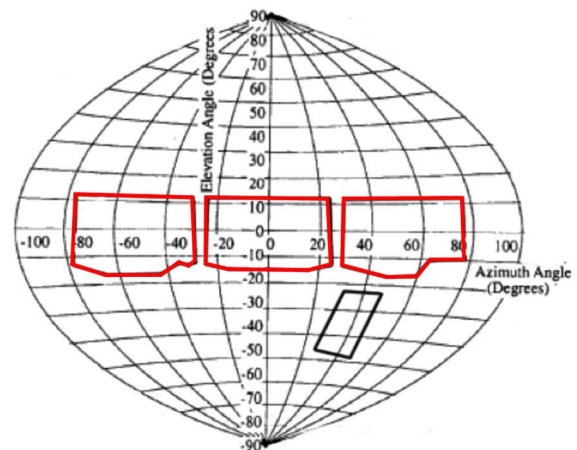


Figure 4. R Cab cockpit Field of view.



Figure 5. R Cab cockpit emulating a utility class UH-60 sized helicopter.

The Virtual Environment

The virtual visual environment characteristics, terrain profile, flight and perturbation/obstacle parameters are summarized in Figures 6 and 7 and Table 1.

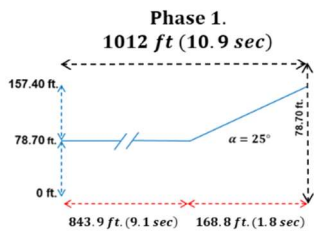


Figure 6: Terrain profile for phase 1 (distance travelled at 55 knots).

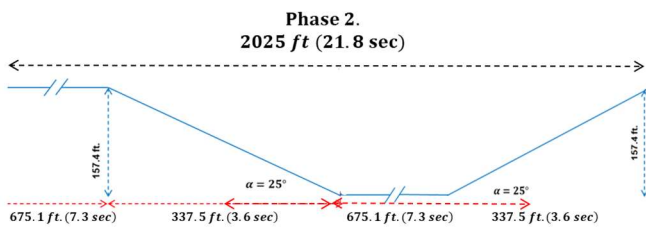


Figure 7: Terrain profile for phase 2, 1 block, repeated 3 times (distance travelled at 55 knots).

Phase 1 initiated the flight level (45ft +/- 10%) and speed (35 or 55 kts). The virtual environment started as a flat ground surface followed by a short ascent that ended Phase 1. This phase was followed by a succession of high plateau (PH) Descent (DOWN), low plateau (PL) and Ascent (UP) over 2025 ft (phase 2), forming a cycle repeated three times in the passive condition and approximately three times in the active condition, given the speed variations. Trials lasted on average 90 sec.

Visual cues

GVE vs. DVE

In the good visual environment (GVE) condition, all the visual cues are available to the pilot. In the degraded visual environment condition (DVE), the visibility level is degraded with fog and set at ¼ mile, which reduces the structure and the quality of the out of the window (OTW) cues (optically relevant primitives). Because heading was maintained relatively constant (rectilinear motion), and no pitch was involved, the optical flow field was generated by a strictly forward translation. Therefore, variations in the optical flow field were only induced by the terrain variations (plateau, ascent, descent), the meteorological conditions (GVE vs. DVE), and the flight level (see Figure 8). Previous research has shown that performance in simulated NOE tasks (altitude maintenance) is related to variations in global object density, object height an object radius (Refs. ^{28, 32}).

Table 1. Visual Environment, Terrain, and Flight Characteristics.

Parameters	
Tree height (all same color)	18 ft. (+/- 1 ft.)
Tree canopy diameter	15 ft. (+/- 1ft.)
Tree density	193/square mile
Height (altitude) initialization (Pilot eye-level)	45ft. (2.5 trees) AGL ± random * 4.5 with 0 ≤ random ≤ 1
Height (altitude) above tree	27ft.
Phase 1: Plateau altitude	78.7ft
Phase 1: Plateau length	843.9 ft. (9.1 sec)
Phase 1: Ascent length/ angle of attack	168.78 ft. (sec), 25°
Phase 2: Plateau low	0 ft.
Phase 2: Plateau high	157.4 ft.
Phase 2: Plateau length	675.12 ft. (10 sec)
Phase 2: Ascent/ Descent length/ angle of attack	168.78 ft. (sec), 25°
Passive Control Task: perturbation magnitude and direction (Upward vs. Downward), randomly presented 10 to 55 sec after the beginning of Phase 2)	±18 ft. (+/- 1 ft.), randomly occurring within a descent (DOWN), low plateau (PL) or ascent (UP) segment
Active Control Task: obstacle powerline locus	50ft high powerline obstacle, randomly positioned within a high plateau (PH), descent (DOWN), low plateau (PL) or ascent (UP) segment
Initial speed	55 kts
Block trial length	6413.67 ft., ≈ 90 sec at ≈ 55 kts

To control for these effects, the terrain was populated with 193 identical trees per square mile randomly distributed (Figure 8) to maintain the same density gradient (number of trees per degree of visual angle) throughout the entire trial. The trees height and canopy diameter were maintained constant to prevent differences in the magnitude of visual occlusion (refer to Table 1 for details). A patched texture was layered over the profile. A mountainous background surrounded the experimental environment.

Global Level of Detail (LOD)

In the Passive Control condition, the global LOD was manipulated by the introduction of +/- 18ft vertical perturbation. Upward perturbations resulted in altitude change from 45 ft to 63ft, while Downward perturbations resulted in altitude change from 45 ft to 27 ft. The resultant altitude was maintained until the end of the trial. Therefore, the level of detail would decrease in the Upward perturbation condition, while it would increase in the Downward perturbation conditions.

In the Active Control condition, pilots actively increased their altitude momentarily to fly over a 55 ft powerline, before resuming the initial altitude. So, in the vicinity of the obstacle, the global LOD was poorer. A consequence of the hilly structure of the terrain was that the line of sight, i.e., how far ahead a pilot can see, would vary as a function the different terrain segments, as seen in Figure 8.

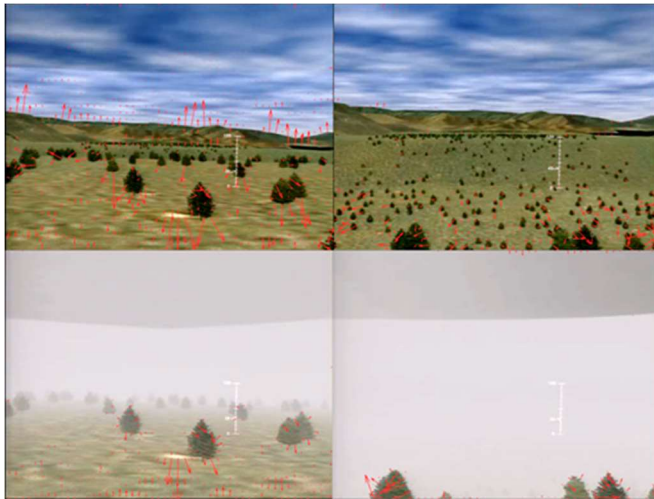


Figure 8. Example of out-the-window (OTW) optical fields as a function of altitude. Top to Bottom: GVE and DVE. Left to Right: 27ft AGL and 63 ft AGL. Optical vector fields (red arrows) are superimposed on the simulation image to represent the differences in visual cues available in the different configurations.

Table 2. Experimental Design: two experimental conditions (Passive vs. Active Control), two levels of visual environment (GVE vs. DVE), two levels of gravito inertial environment (Cabin Motion ON, Cabin Motion OFF). The results presented here are for the 55 kts condition. Five repetitions were performed randomly between conditions for each configuration.

	Passive Control Task				Active Control Task			
	GVE		DVE		GVE		DVE	
	35	55	35	55	35	55	35	55
GI OFF	5	5	5	5	5	5	5	5
GI ON	5	5	5	5	5	5	5	5

Gravito inertial cues

Two gravito inertial conditions were tested, one with cabin motion (the gravito inertial profile is the double derivative of the terrain profile) and one without cabin motion (the visual environment only is optically in motion).

In the Passive Control condition, an unknown (to the pilot) forcing function (sum of sines, SOS) is introduced after a random delay, giving rise to an upward or downward 18ft/vertical perturbation.

Experimental Test Matrix

The experiment followed a full-factorial repeated-measures design (all the pilots experienced all the conditions) with two within subject factors, Visibility (GVE, DVE) and Cabin Motion (ON, OFF), giving rise to 4 experimental blocks: Visual [GVE, DVE] * Gravito inertial [Cabin motion ON, Cabin motion OFF] (see Table 2). Each block contained 10 trials (5 at 35 kts, 5 at 55 kts). The experiment consisted of 20 trials per participant, each block (Visibility * Gravito inertial) counterbalanced between participants. Each trial lasted on average 2 minutes (90 seconds trial + reconfiguration). Pilots were encouraged to take five minutes breaks between blocks (10 trials).

For each trial and each pilot, the initial flight level (pilot’s eye level) was set to a randomized value of 45 ft AGL +/- (4.5 ft * random), with $0 \leq \text{random} \leq 1$; min=40.51, max=49.44. Initial speed was set at 57 kts.

The tasks

The two tasks required different perceptive-motor mechanisms. The Passive Control task relied on the integration of relative cues during visual perception decoupled from action, while the Manual Control task involved a continuous control-oriented action-perception loop.

In the Passive Control task, the pilots were observers of a pseudo automated NOE flight. They had no control over the simulated motion. Instruments were not providing any information of speed or altitude. They were instructed that they were observing a pre-recorded flight with inherent small variations in height, and that an 18ft vertical perturbation, upward or downward simulating a vertical wind shift would be introduced during the Phase 2 of the flight (Figure 9, top). The pilots’ task was to report their perceived height above the ground using a cursor on a vertical tape, from 0ft to 120 ft, displayed on the HMD window, controlled by the collective position.

Table 3: Visual information reliability as a function of the experimental conditions.

Very High	High	Low	Very Low
GVE, Downward	GVE, Upward	DVE, Downward	DVE, Upward

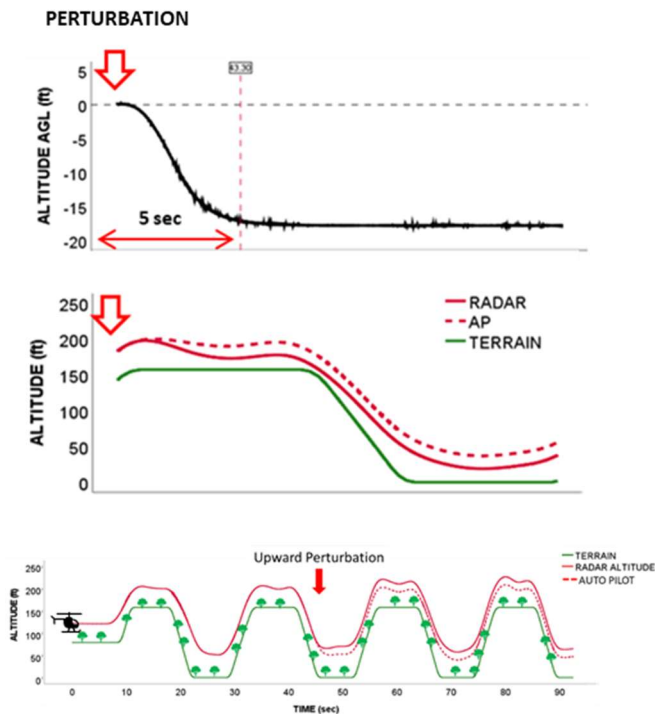


Figure 9: Passive Control Condition. Top: Time series for the perturbation profile for a downward condition. Bottom: Experimental terrain and flight profile.

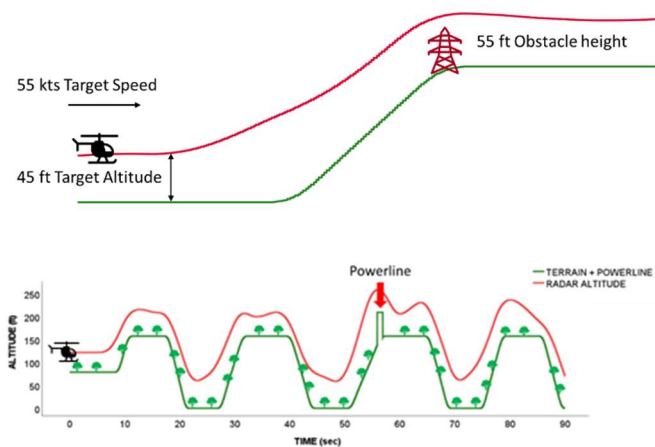


Figure 10: Active Control condition. Top: Powerline obstacle located on top of the ascent (UP segment). Bottom: Experimental terrain and flight profile.

At the beginning of the trial, the aircraft position was set at a random height (45 ft +/- 4.5 ft) unknown to the pilot. The cursor's initial position was also set at a random position (45 ft +/- 4.5 ft), uncorrelated to the aircraft's initial altitude. Pilots had no access to instruments. Upward perturbations resulted in altitude change from 45 ft to 63ft, while Downward perturbations resulted in altitude change from 45 ft to 27 ft. Therefore, the level of detail would decrease in the Upward perturbation condition, while it would increase in the Downward perturbation conditions. As a result of this

manipulation, four levels of visual reliability were defined, from very high to very low (see Table 3). The contribution of the GI cues is expected to be inversely proportional to the reliability of the visual information, as specified by the visibility level and the global LOD.

In the Active Control task, pilots were instructed to fly above the terrain at a constant 45 ft altitude and constant speed of 55 knots while keeping the heading constant. After a random delay, pilots had to climb over a 55 ft powerline (Figure 10), before returning to their initial flight level, speed and heading as soon as possible. The Powerline obstacle was located either on a DOWN, PL or UP terrain segment. Pilots had no access to instruments (no information relative to altitude or speed).

Independent Variables

The independent variables for the comparison of performance between Active and Passive Control Tasks were Visibility (GVE, DVE) and Motion (GI OFF, GI ON). To ensure a relative comparison between the active and passive conditions, the analyses in the passive conditions will be strictly limited to the cases where the perturbation was upward.

Dependent Variables: Quantitative Measures of Performance

Comparisons were made between:

- Mean biased tracking error (MBE) for the passive condition and clearance magnitude for the active condition. MBE expresses the quality of the tracking error, i.e., overshoot or undershoot
- Perturbation detection for the passive condition and pull-up initiation time for the active condition. The methodology used to compute these metrics is detailed in (Ref. ^{45,46}).

Data analysis

Univariate and repeated-measures analyses of variance (ANOVAs) computed with SPSS were used to test for effects of Cycle (within-subject-factor), Visibility and Motion (between-subjects variables). Means (μ) Standard Errors (SE) and/or Standard Deviations (SD) were computed for the pre-(C0) and the two post-perturbation cycles (C1 and C2), described previously in section "Profile segmentation and Pre- and Post-Perturbation Cycles". Post-hoc Bonferroni test were performed for multiple comparisons. All the effects described here were statistically significant at $p < 0.05$ or better. Outliers (7.9 % of the data in the passive condition, 2.8% for the active condition) were removed using Mahalanobis distance procedure for multivariate data (3 variables). The threshold value of .001 was suggested by Tabachnick & Fidell (2007, Ref. ⁴⁹), who state that a very conservative probability estimate for outlier identification is appropriate for the Mahalanobis Distance.

RESULTS

In the passive condition, the pilots' task was to report the perceived altitude AGL. The tracking response was compared between identical terrain segments to control for the effects of terrain profile. A pre-perturbation region (referred to as Cycle 0, C0) and two post-perturbation regions (Cycle 1, C1 and Cycle 2, C2) were determined based on the time of the perturbation, and the period of the terrain. For example, as illustrated in Figure 11, if the perturbation occurred during a descent, it would end at the same descending terrain location one terrain period later. The second cycle starting $\cong 21.8$ sec after the perturbation (see Figure 11) would follow the same rules. Similarly, the pre-cycle would start at the exact same locus, $\cong 21.8$ sec before the perturbation.

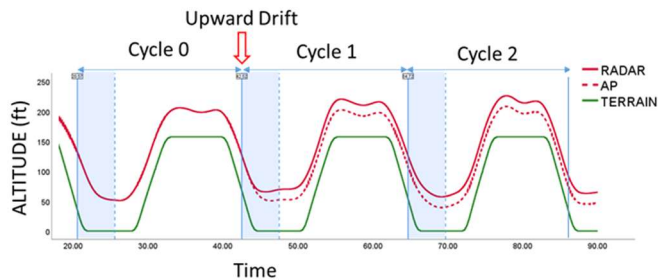


Figure 11. Pre-Perturbation (C0) and Post-perturbation Cycles (C1, C2). To minimize the effects of terrain, the time window analysis was set to 5 sec after the beginning of a cycle. Here, an Upward Perturbation was introduced 42.5 sec after the beginning of the trial. The dashed line indicates the autopilot (AP) altitude above ground level (AGL) without the perturbation for reference.

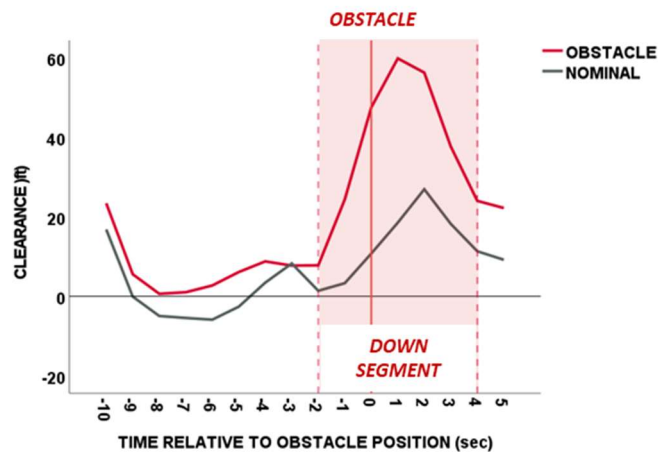


Figure 12. Clearance magnitude for a Down segment (from powerline maximum height) at the locus of the powerline, and at the exact same position for the preceding identical segment. The overall clearance profiles covary strongly, suggesting an effect of terrain and that the effect of the obstacle is essentially that of an increase in clearance magnitude in the vicinity of the obstacle.

To further minimize the effects of terrain, the time window analysis was set to 5 sec after the beginning of a cycle.

In the active condition, pilots' task was to maintain the initial altitude AGL. Following the same logic than for than passive condition, the altitude clearance above the powerline maximum height was compared between identical terrain segments, at the exact same locus for the segment preceding that where the powerline obstacle was located (Nominal condition, C0) and the segment where the obstacle was present (obstacle condition, C1) (see Figure 12). In addition, a comparison of altitude clearance was performed within the terrain profile segment where the obstacle was located, at the beginning of the segment (SEG START), at the exact locus of the powerline (LOCUS) and at the end of the segment (SEG STOP).

Altitude tracking and clearance

At a first glance, one can see the effect of the perturbation on altitude perception in the passive condition (see Figure 13) and the effect of the presence of the powerline on altitude AGL in the Active condition (Figures 14, 15).

In both Passive and Active conditions, there was a significant effect of interaction between Visibility and Gravitoinertial factors (Passive: Visibility * Motion: $F_{1,60} = 4.38, p = .04$; Active: Visibility * Motion: $F_{1,132} = 5.47, p = .02$), and the effect of cabin motion was only observed in DVE conditions. In GVE, pilot flew at the same altitude, with or without cabin motion (Passive: Motion: $F_{1,32} = .67, p = .41$; Active: $F_{1,66} = .09, p = .75$).

In DVE, conversely, there was a significant effect of cabin motion (Passive: Motion: $F_{1,28} = 4.27, p = .04$; Active: $F_{1,66} = 10.06, p = .002$).

In the Passive condition, the mean biased tracking error (MBE) was lower when gravito inertial cues are present (cabin motion ON), regardless of the cycle.

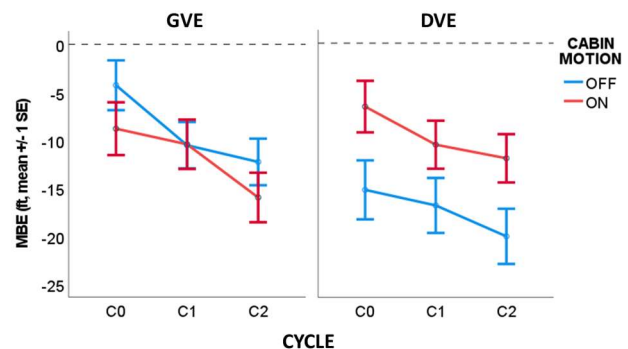


Figure 13. Passive Condition. Mean Biased tracking Error (MBE, ft) for identical terrain profile segments before the perturbation (C0), during the perturbation (C1) and after the perturbation (C2), in GVE (left) and in DVE (right) as a function of the gravito inertial condition (cabin motion OFF, cabin motion ON).

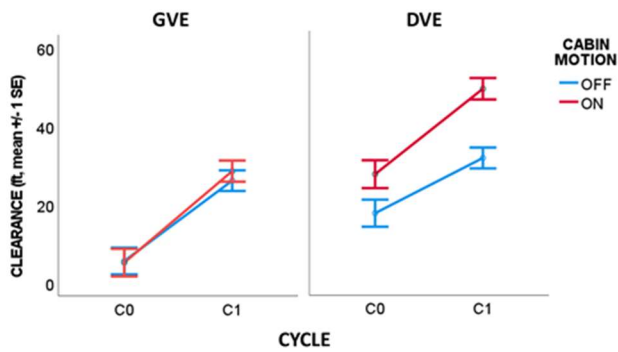


Figure 14. Active Condition. Clearance magnitude (ft) above obstacle powerline maximum height for identical terrain profile segments at the exact same locus before the perturbation (C0), and during the perturbation (C1), in GVE (left) and in DVE (right) as a function of the gravito inertial condition (cabin motion OFF, cabin motion ON).

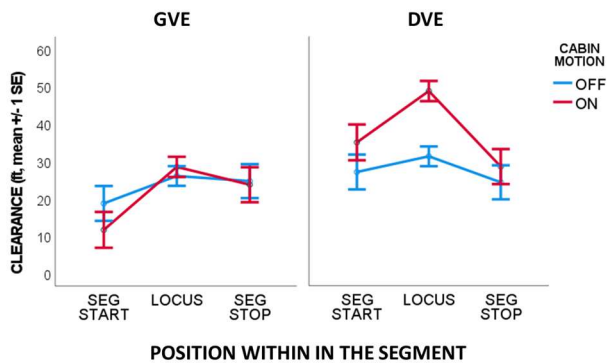


Figure 15. Active Condition. Clearance magnitude (ft) above obstacle powerline maximum height at the start of the segment containing the powerline (SEG START), at the locus of the powerline (LOCUS) and at the end of the segment (SEG STOP), in GVE (left) and in DVE (right) as a function of the gravito inertial condition (cabin motion OFF, cabin motion ON).

In the Active condition, the clearance magnitude was higher when gravito inertial cues were present, again, regardless of whether an obstacle was present or not. In both cases, the magnitude of the differences between motion conditions remained relatively constant.

If higher clearance magnitude equates safer flight, one can conclude that in both Passive and Active conditions, gravito inertial cues contributed to performance enhancement only when the visual cues are less reliable, i.e., in DVE. Thus, cabin motion totally mitigated the effects of visibility in the passive condition, leading to a tracking error comparable to that in GVE (Cabin Motion ON: GVE: $\mu = -11.73, SD = 2.55$; DVE: $\mu = -9.68, SD = 2.50$; GVE, DVE: $t = 2.04, p = .57$). In the Active condition, an extra $\cong 10$ ft clearance was observed for C0 and an additional $\cong 17$ ft for C1 when GI cues were present.

Reaction time

Passive condition: Response time (RT) to the perturbation

Because pilots were not asked to report when they first perceived the perturbation, a methodology was designed to infer the perception/reaction time (RT) based on the differences between the pseudo autopilot (AP) altitude (without perturbation), RADAR altitude (with perturbation) and tracking height. One way to assess whether the participant detected the perturbation is to compare the error between the tracking height and both the RADAR altitude and the AP altitude (RADAR altitude minus 18ft perturbation). One can see in Figure 16 an illustration of the method. After the beginning of the perturbation, AP and RADAR curves start to separate to reach a maximum of $\cong 18$ ft after 5 sec (Figure 15, Top). The tracking error relative to RADAR altitude and AP altitude was computed and is plotted in Figure x, Center. Figure x, Bottom, shows the mean absolute tracking error in reference to AP altitude and RADAR altitude. One can clearly see the crossover between the two curves: before the crossover, tracking error is lower in relation to AP than to RADALT, indicating that the pilot did not detect/ or react to the perturbation. After the crossover, the tracking error is lower in relation to RADALT than in relation with AP, indicating a detection of the perturbation. It is likely that the RTs were identified a few seconds after the actual detection, at the maxima of the curve before the crossover. In some instances, for Upward perturbations, the tracking height varied little after the introduction of the perturbation, while the tracking height curve remained largely superimposed over the AP curve. In these cases, a way to determine the RTs was to look at the direction of the error locally, i.e., the sign of the error around the reference curve (RADALT or AP). A change preceded and followed by a sustained constant sign was interpreted as a perturbation detection.

Active condition: Pull-up maneuver initiation time

Altitude reversals were used to determine the *time of maneuver initiation* (pull-up). Sustained, monotonous increase in altitude all the way to the obstacles were identified, and their starting point determining the time of maneuver onset. This is illustrated in Figure 17 with a fly over clearance trajectory in a DOWN segment. In this example, the Minimum Clearance occurred 5 sec prior to the beginning of the segment, which also corresponds to the position of the obstacle.

The time of pull-up initiation in the nominal condition occurred 2 sec after the beginning of the segment.

Table 4 summarizes the results as a function of the visibility level (GVE vs. DVE) and the gravito inertial condition (cabin motion OFF vs. cabin motion ON) for the Active and the Passive conditions.

In the Passive condition, RTs were in general shorter when gravito inertial cues were present (cabin motion ON) (Motion: $F_{1,60} = 6.37, p = .01$) and shorter in GVE than in DVE (Visibility: $F_{1,60} = 4.09, p = .04$).

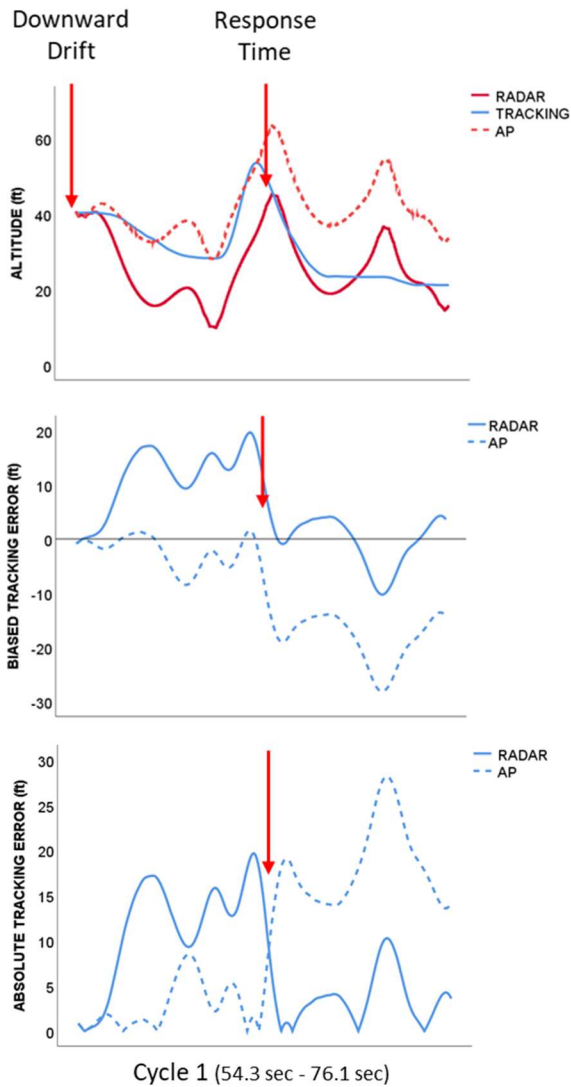


Figure 16. Passive condition. Illustration of the methodology used to determine indirectly the detection of the perturbations. In this example, a Downward perturbation is introduced 54.3 sec after the beginning of the trial. Top: RADAR altitude, tracking altitude and AP altitude (RADAR minus Perturbation). Center: Biased (signed) tracking error in relation to RADAR altitude and AP altitude. Bottom: Absolute tracking error in relation to RADAR altitude and AP altitude. Response Time (here 11.5 sec after the beginning of the perturbation) is determined by the crossover between the RADAR and AP curves.

Note that time of maneuver initiation could be situated within or outside the segment, as the powerline could be located anywhere between the beginning and the end of a segment. Segment duration is speed dependent, on average 4 sec. Response time to the perturbation in the Passive condition and pull-up maneuver initiation time in the Active condition showed similar trends.

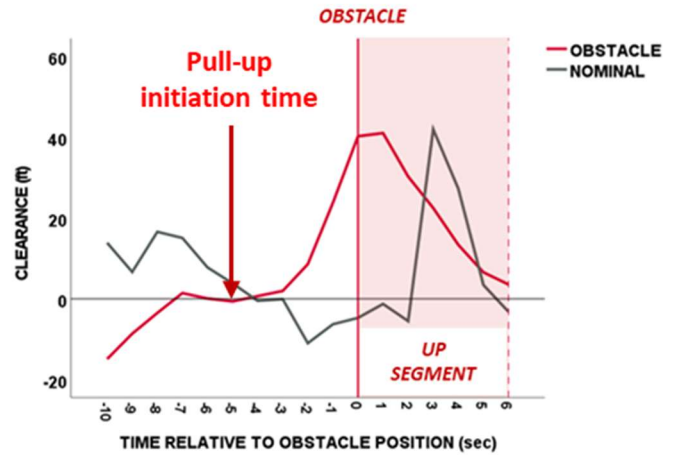


Figure 17. Active condition. Illustration of the methodology used to determine the response time to the obstacle. Clearance reversals followed by a sustained increase in altitude all the way to the obstacle.

Table 4. Perturbation detection time in the Passive condition and pull-up initiation time in the Active condition as a function of Visibility (GVE vs. DVE) and Cabin Motion (OFF vs. ON)

	Passive condition (reaction time, sec) *		Active Condition (pull-up initiation time, sec) **	
	Cabin Motion OFF	Cabin Motion ON	Cabin Motion OFF	Cabin Motion ON
GVE	8.13 (5.78)	6.75 (4.07)	-5.50 (2.18)	-6.11 (2.40)
DVE	13.95 (9.30)	7.34 (5.65)	-4.76 (2.34)	-5.85 (2.03)

* Reaction time to the perturbation: a shorter RT indicates a greater performance

** Pull-up initiation time (time of clearance reversal) in relation to the powerline obstacle: longer initiation time indicate greater anticipation, hence a greater performance.

Therefore, RTs to the perturbation were statistically equivalent in GVE and DVE when motion cues were available to the pilot (Visibility: $F_{1,31} = .11, p = .73$).

Another supportive element for the differential contribution of the GI cues as a function of the reliability of the visual cues comes from the comparison of the data between the different terrain profile segments (plateau high, PH; downhill, DOWN; plateau low, PL and uphill, UP). Indeed, the line of sight (LOS) defined as the maximum distance at which visual cues are accessible to the pilot, is directly influenced by the nature of the terrain, and is the shortest for UP segments, and maximum for DOWN segments. Thus, one might expect that the contribution of the GI component would be at its highest

when the LOS is minimum, for UP segments, and minimum when LOS is the longest, i.e., for the DOWN segments (see Figure 18).

The predictions of some form of relationship between LOS and RT were supported and are illustrated in Figure 19. Overall, in GVE, the RTs were the shortest when the LOS was maximum, i.e., for DOWN segments and the longest for PL segments. The second important result relates again to the global visibility level. In GVE, there is no significant performance enhancement when GI cues were present, and no real effect of segment type. Conversely, in DVE, RTs were significantly shorter when motion cues were present, and there was a significant effect of interaction between Motion and Segment type. Without GI information, RTs increased significantly as the LOS decreases, as seen in Figure 19, right. When GI cues were available, RTs were significantly shorter when LOS was at its minimum, for UP segments (Motion OFF, Motion ON: $t = 25.56, p = .005$). Note also that the magnitude of the differences between GI cues present vs. absent was the greatest when the LOS was the shortest, i.e., for the UP terrain profile segment.

This result reinforces the relationship between sensory reliability and weighted approach of perception, which postulates that the contribution of sensory modality is proportional to its reliability.

In the Active condition, the results also support the positive role of GI cues, more particularly when the visual cues are degraded. Pull-up maneuvers were initiated overall earlier with motion than without motion (Motion OFF: $\mu = -5.13, SD=2.27$; Motion ON: $\mu = -5.98, SD=2.21$; $F_{1,132} = 4.84, p = .02$).

When vision was optimal, in GVE, the gain associated to the presence of GI cues was on average of .61 sec, a difference that was not significant (Motion OFF, Motion ON: $t = .61, p = .26$).

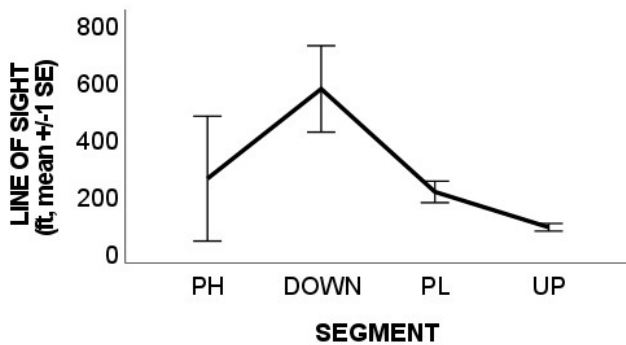


Figure 18. Line of sight (LOS) as a function of the nature of the terrain profile segment (plateau high, PH; downhill, DOWN; plateau low, PL and uphill, UP). LOS was maximum ($\cong 600$ ft) for DOWN segments and minimum for UP segments ($\cong < 200$ ft).

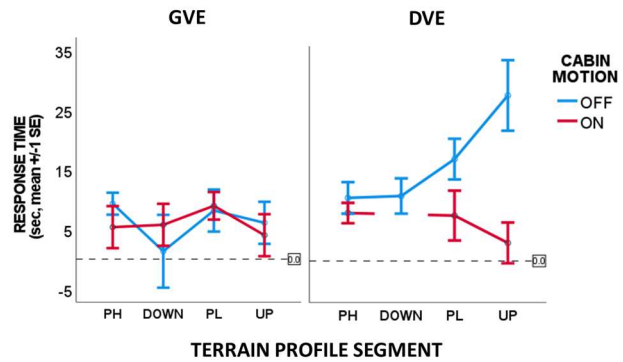


Figure 19. Passive condition. Perturbation detection time as a function of terrain profile segment (plateau high, PH; downhill, DOWN; plateau low, PL and uphill, UP), visibility level (GVE, DVE) and gravito-inertial condition (cabin motion ON, cabin motion OFF).

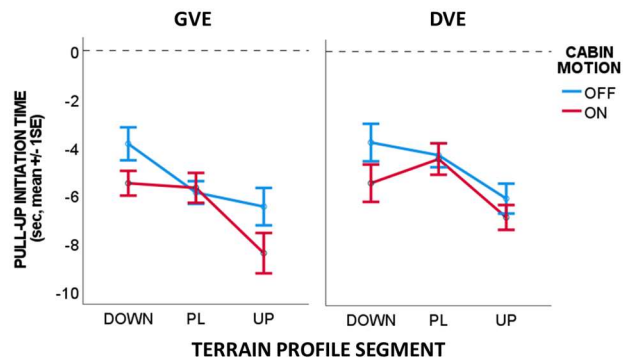
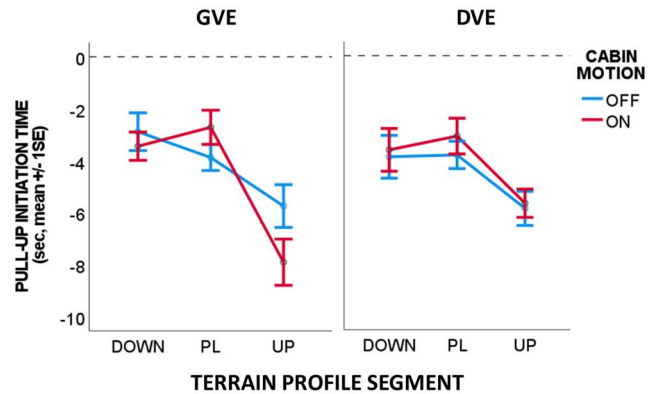


Figure 20. Active condition. Top: Pull-up initiation time in the Nominal condition (no obstacle) and Bottom: when the powerline was present, at as a function of terrain profile segment* (downhill, DOWN; plateau low, PL and uphill, UP), visibility level (GVE, DVE) and gravito-inertial condition (cabin motion ON, cabin motion OFF).

* Powerline obstacle was never presented on the high plateau (PH).

Conversely, when vision was suboptimal, in DVE, the presence of GI cues led to an advantage of 1.08 sec, a difference that was statistically significant (Motion OFF, Motion ON: $t = 1.08, p = .04$).

The question of differences in reaction time to the powerline obstacle as a function of terrain segment type and LOS was addressed. Figure 20 shows the pull-up initiation time when no obstacle was present (Figure 20, Top) and when the powerline was present (Figure 20 Bottom). As expected, the pull-up initiation maneuver occurred earlier when an obstacle was present ($\mu = -1.33 \text{ sec}, SD = 2.72$), and earlier when cabin motion was ON (ON: $\mu = -1.74 \text{ sec}, SD = 2.60$, OFF: $\mu = -.94 \text{ sec}, SD = 2.79$). In both cases, the results showed that the pull-up maneuvers were significantly related to the terrain characteristics (Nominal: Segment: $F_{2,124} = 21.88, p < .0001$; Powerline: $F_{2,124} = 12.81, p < .0001$). Indeed, earlier maneuvers were observed for climbing terrain (UP segments) and later maneuvers for descending terrain (DOWN segments). There was no effect of interaction with Motion and Visibility.

CONCLUSIONS

The aim of this experiment was to assess the contributions of gravito-inertial and visual cues in two conditions, to evaluate: 1) the relative contribution of Visual and Gravito-inertial cues in the perception of altitude in low-level forward flight and 2) how the Sense of Agency (SoA) may interact with the perception and integration mechanisms.

In the first condition, referred to as Passive Control condition, pilots were asked to report their perceived altitude above the ground level (AGL) while moving in a simulated NOE flight in AP mode.

In the second condition, referred to as Active Control condition, the pilots actively had to regulate their altitude, speed and heading as if they were in a real NOE situation. The two conditions require different perception mechanisms. In the Passive Control Task, the representation of the self in the environment relies on the integration of relative cues during visual *perception decoupled from action*, where the pilot is experiencing a reduced SoA. Conversely, in the Active Control Task, the representation of the self in the environment is mediated by *control-oriented action-perception* mechanisms, where the pilot has a strong sense of control.

The results for the Passive Control task showed that the gravito-inertial component played a significant role in the estimation of ground height, but only in the case where the optical structure did not specify efficiently the actor-environment interaction, i.e., in DVE. The detection of the 18ft upward perturbation occurred also significantly sooner when motion cues were available but with a magnitude inversely proportional to the visibility level. Indeed, the magnitude of the gain in detection time (on average 6 sec) was the highest in DVE conditions, and in the conditions where global optical density (OD) was poor, i.e., in particular for the UP terrain profile segments. This advantage in detection time that can be critical in conditions where automation fails, in particular in NOE high speed flights.

Similarly, the results for the Active Control task provided evidence, at multiple levels, that the acceleration information, specified by the variations of the gravito-inertial field, has a relative character.

Firstly, the clearance magnitude was higher in DVE than in GVE, an effect that was expected because the pilot wants to increase their safety margin. More importantly, there was a differential effect of the gravito-inertial cues as a function of the global visibility level. In DVE, there was no effect of motion on the magnitude of the clearance. In DVE conversely, pilots flew on average more than 10 ft higher in the presence of GI cues.

Secondly, the analysis of the response times, also revealed that motion cues mitigated the effects of DVE, with pull-up initiation time elicited on average 1 sec earlier.

The improvement of the performance in the visuo-vestibular setting as compared to a visual only setting when the visual cues were degraded indicated some level of multisensory integration. The results showed that multisensory integration is a transitive phenomenon between conditions, Passive vs. Active. However, the contribution of the gravito-inertial cues appeared to be stronger when the pilot was a passive observer than when he was actively piloting the aircraft.

Altogether, these results are in line with the Sensory Weighted Approach of perception, which proposes that each sensory cue is weighted depending on this reliability. Typically, gravito-inertial information is attenuated when the visual information is of high relevance while it enhances performance when the visual information is less appropriate to perform the task (Modality Appropriateness Hypothesis, see Refs. ^{50, 51}). According to the Bayesian probability theory (Refs. ^{6, 29, 52, 53}), the relative unisensory weights depend on specific integration patterns. The experimental conditions tested in this simulation prevented the testing of the Maximum Likelihood Estimate model, because the purely gravito-inertial condition (no visual cues) was not tested.

Of course, there are some limitations to the analyses. The two tasks were not identical, and the data comparison between Active and Passive conditions could apply only to upward perturbations. Furthermore, the detection times and pull-up initiation times were not directly measured and had to be inferred from the pilot's activity. However, the methodology used to determine the response times showed to be useful and to produce significant consistent results.

From an applied standpoint, the results have consequences in terms of the conditions in which pilots interact with their environment. They question the transfer of expertise between platforms for supervisory control tasks. In the context of UAV monitoring, for example, one can expect that the perception of altitude would be affected by the nature of the platform, grounded or airborne. For example, in case of automation failure, it might be more difficult for the pilot on the ground to detect a change in altitude, whether its own, or that of monitored UAVs. Optionally Piloted Vehicles' control on the ground may be less effective than on aerial platforms, and may benefit from supplementation, for example, improving situation awareness via spatial auditory cueing (Refs. ^{54, 55}).

Our results also relevant to flight simulation and motion simulation fidelity. Typical motion-based simulators have physical motion limitations (Ref. ⁵⁶), a reason why most experimental and training simulators are composed of motionless platforms. These allow the creation of high-fidelity visual environments but are limited regarding coherent visuo-vestibular interactions (Ref. ⁵⁷). However, these simulators would not be adequate to simulate a realistic NOE scenario. Indeed, as shown, the NOE flight involves rich GI variations which are needed to reach proficient level of flight performance and task monitoring. Our experiment has demonstrated that these vestibular stimuli must be considered. Thus, motion-based simulators are needed to investigate task performance in realistic ecological environments. Given natural low-level flight situations typically involve coherent visual and vestibular stimulation, pilot training in flight simulators obviously benefits from coherent visuo-vestibular stimulation.

Further research will investigate the effects of speed on the degree of multisensory enhancement, as well as the effects of noise (seat vibrations), alone and combined to gravito-inertial cues. More attention will be given to pull-up control strategy (cyclic and collective) and how the tau theory could be used to account for the performance data in both the Passive and Active Task.

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