New Paradigm for Understanding In-Flight Decision Making Errors – A Neurophysiological Model Leveraging Human Factors

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ABSTRACT

Human factors centered aviation accident analyses report that skill based errors are known to be cause of 80% of all accidents, decision making related errors 30% and perceptual errors 6%.[1]. In-flight decision making error is a long time recognized major avenue leading to incidents and accidents. Through the past three decades, tremendous and costly efforts have been developed to attempt to clarify causation, roles and responsibility as well as to elaborate various preventative and curative countermeasures blending state of the art biomedical, technological advances and psychophysiological training strategies. In-flight related statistics have not been shown significantly changed and a significant number of issues remain not yet resolved.

Fine Postural System and its corollary, Postural Deficiency Syndrome (PDS), both defined in the 1980's, are respectively neurophysiological and medical diagnostic models that reflect central neural sensory-motor and cognitive controls regulatory status. They are successfully used in complex neurotraumatology and related rehabilitation for over two decades.

Analysis of clinical data taken over a ten-year period from acute and chronic post-traumatic PDS patients shows a strong correlation between symptoms commonly exhibited before, along side, or even after error, and sensory-motor or PDS related symptoms. Examples are given on how PDS related central sensory-motor control dysfunction can be correctly identified and monitored via a neurophysiological ocular-

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[1] Wiegman DA, Shappel SA, Boquet A, Detwiler C, Holcomb K, Faaborg T, "Human Error and General Aviation Accidents: A Comprehensive, Fine-Grained Analysis using HFACS", technical report ahfd-05-08/FAA-05-03, FAA, 2005.

vestibular-postural monitoring system. The data presented provides strong evidence that a specific biomedical assessment methodology can lead to a better understanding of in-flight adaptive neurophysiological, cognitive and perceptual dysfunctional status that could induce in flight-errors. How relevant human factors can be identified and leveraged to maintain optimal performance will be addressed.

Keywords: Ocular-Visual-Postural Strategy, Fine Postural System, Postural Deficiency Syndrome, Perception, Trajectory Control, Sensory-Motor Controls, Cognitive Controls, Flight Safety, Human Factors, Prevention, Monitoring

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INTRODUCTION

Human factors centered aviation accident analyses indicate that skill based errors are the cause of 80% of all accidents, decision making related errors are 30% and perceptual errors are 6% [1]. In-flight decision making error (IFDME) is a long time recognized major avenue leading to incidents and accidents. Over the past three decades, tremendous and costly efforts have been developed, blending state of the art biomedical, technological advances and psychophysiological training strategies, in an attempt to clarify causation, roles and responsibility, as well as to elaborate various preventative and curative countermeasures. Yet, in-flight related statistics have not been shown to be significantly changed and a significant number of issues remain unresolved.

In order to address some key physiological mechanisms recognized or assumed to be possible IFDME causation, this paper focuses on introducing a new biomedical paradigm that relates to functional strategic integration of central neural sensory-motor and cognitive controls. This neurophysiological paradigm is clearly illustrated in models describing the Fine Postural System (FPS) and its corollary Postural Deficiency Syndrome (PDS). Both were defined in the mid 1980's, as neurophysiological and medical diagnostic models that reflect central neural sensory-motor and cognitive controls regulatory status.

Both models relate to fundamental concepts initially described by Charles Bell in the early 18th century (1837), and later expanded by Vierdot (1864). First and foremost, both scientists considered a functional and adaptive human postural control system as a whole relatively independent and proactive entity. The currently most well known key components of postural and perceptual controls and their relationship, which contribute to maintain and adapt human posture to postural changes in surroundings, were already foreseen and described at that time. Key controls govern subsystems such as vestibular, ocular-visual, proprioceptive in the lower limbs and the paravertebral muscles, ocular-motor as well as cognitive as it relates to the sensory-motor regulatory system. All together, they allow humans actively adapt and maintain posture, through a hierarchical multi-modal organization of a complex central neurophysiological system that works on the principles of the "sensory-motor loop".

We present original clinical data on patients admitted and successfully treated in neurophysiology-based trauma recovery programs using these models. Findings also include significant common symptomatic, dynamic and mechanistic denominators between post trauma Postural Deficiency Syndrome (PDS) and biomedical neurophysiological conditions frequently displayed along IFDME occurrence. Both models are precise tools as they reflect CNS sensory-motor and cognitive controls interaction and dysfunction patterns. Some of these dysfunction patterns may lead, whether independently or combined, to IFDME onset due to particular circumstances frequently encountered in aviation.

IN FLIGHT ADAPTATION OF THE SENSORY-MOTOR CONTROLS SYSTEM

The sensory-motor controls system can be explored in respect to the physical, mental and perceptual adaptation of aviation crewmembers in comparison to patients suffering from post-traumatic conditions.

Correct transduction and integration of signals from all areas of the sensory-motor system is essential for maintenance of stable vision; spatial orientation; eye-head and eye-hand coordination, as well as postural and locomotion control. Perception of spatial location and body positions results from the brain's ability to integrate visual, auditory, and vestibular inputs (from gravity and motion detecting organs in the inner ear) as well as proprioceptive input (motion, pressure and temperature sensors in the tendons, muscles, joints and skin). When subject to significant environmental change, this sensory multi modal input prompts the CNS functional hierarchy to develop a new interpretation, hence initiate and sustain a different (compensatory) adjustment strategy.

Central neural plasticity allows individuals to adapt and compensate under fast changing and altered sensory stimuli conditions such as those experienced during flight. For instance, adversely fast or random paced stimulus changes (whether gravity or any other physical, cognitive, emotional or intellectual stimulus) applied on sensory receptors or systems may rearrange transduction and combinatory processing of signals from vestibular, visual, skin, muscle and joint receptors. If this new interpretation does not match current operating built in or acquired specific calibrated functional patterns in the brain, dysfunction leading to IFDME is likely to incur, significantly reducing a pilot's operational efficiency [2]. All flying personnel may be subject to IFDME as they both experience similar high variability in related physical, cognitive or mental symptomatology.

The Vestibular System

The peripheral vestibular apparatus located in the inner ear consists of two sensory receptors, the semi-circular canals and the otolith organs. The semicircular canals detect head rotations. Liquid filled tubular loops act as angular accelerometers arranged in three orthogonal planes. The otolith organs sense linear forces such as gravity acting on the head. Calcium carbonate concretions embedded in gelatinous material act as linear accelerometers. Neural signals produced under acceleration are centrally integrated with signals from proprioceptors which report relationships of the limbs, trunk and neck. Signals from skin pressure receptors, vision and stored cognitive perceptual memory data, are integrated to coordinate movements of the limbs, head, and eyes.

Postural reflexes under otolithic control may appear be either exacerbated or depressed during stressful flight conditions such as strong turbulences or heavy traffic density in poor visibility conditions. They may return to their normal pattern within minutes or hours after landing. A comparison must be made here with observation in astronauts of such symptoms which occur even after missions of relatively short duration [3]. One possible reason for such reactions to relatively fast physical change overload is described in the Otolith Tilt Translation Reinterpretation (OTTR) hypothesis [4]. It states that the brain learns to reinterpret signals coming from the vestibular system to represent only linear acceleration rather than pitch or roll of the head [5]. It is reasonable to think that this hypothesis could be extended to fighter and aerobatics pilots who experience large and sudden changes in g-forces (from micro-g to hyper-g), and perhaps should be investigated further in this context. Altered signals and processing patterns may play an important role in triggering and contributing to IFDME.

The Fine Postural System

An important function in postural control is the coordination of various muscular activities to maintain proper orientation of the body with respect to flight performance. This is provided by a complex regulatory system, the Fine Postural System (FPS) defined by Gagey in 1987 [6]. The FPS models the core neurophysiological system that provides balance control to the human body during static and dynamic performance. Known components of the FPS include ocular motricity and vision, vestibular system, proprioception of the lower limbs as well as of the paravertebral muscles.

The structure of the FPS consists of exosensors and endosensors [5]. These components only control small postural disturbances that move the body's axis up to four degrees from the balance reference in a given position, hence the name the Fine Postural System. Research has shown that postural balance control utilize differing adaptive strategies that depend on the amplitude of spontaneous movements to and from the equilibrium position (not necessarily vertical) varying within four degrees [7].

The sensory-motor controls system underlies the FPS. Located in the brain, it handles through the CNS hierarchy multivariate sensory input and directs integrated motor adjustment and movement throughout the body. It governs adjustments of postural neuromuscular tonus, visual-ocular motor controls, and vestibular controls. Hence, the FPS regulates postural tone and precisely adjusts posture and gait to match the given circumstances, whether static or dynamic. Its functional core structure includes synergistic and antagonistic sensory motor and cognitive structures that are part of a network diffusely located in various areas of the brain [8].

FPS Related Primary Factors Involved in Leveraging Human Factors

The human factors listed below are presented as key contributors to in-flight decision-making errors (IFDME).

1. Factors Involved in Spatial Orientation

In the free-fall phase of parabolic flight, feelings of inversion of self and the aircraft are often experienced. The absence of falling sensations during periods of weightlessness points to the importance of visual and cognitive factors in eliciting such sensations[9]. Human spatial orientation and ocular-motor control are under multimodal influence. Many patterns of behaviour and response that have been attributed solely to vestibular function are actually dependent wholly or in part on touch, kinesthetic, and proprioceptive stimulation [10].

2. Factors Involved in Spatial Representation and Localization

Gabriel Gauthier, et al demonstrated the capacity of the vestibular apparatus for coding spatial information through a better use of vestibular signal for further motor purposes than for cognitive matching [11]. Posture dependent performance relates to position in a given spatial environment (cockpit etc.), and space perception, to complex motor skills and gait [12].

3. Factors Involved in Perceptual Abilities

The perceptual localization of sound often is thought to depend solely on the pattern of auditory cues at the ears. Evidence has been presented to show that computation of auditory direction also involves non-auditory information from visual, vestibular, tactile, and proprioceptive sources concerning the spatial configuration of the entire body [13]. The biasing of auditory localization indicates that identical patterns of arrival time and intensity cues at the ears can give rise to the perception of sounds in widely disparate spatial positions in relation to the head and body, depending on the proprioceptive representation of the direction of the sound source [14].

4. Factors Involved in Detection of Relative Motions

Detection of relative motions between the subject and the objects relies on the perception of peripheral visual field stability. It results from the integration of the four signals: visual, ocular-muscular proprioceptive, vestibular and ocular-cephalic movement (efferent copy). Incoherence in activation patterns of these various signals results in illusory motion perception such as that experienced during two to three days of exposure to magnifying lenses. Previous experiments have demonstrated the involvement of the cerebellum in the mechanisms responsible for the adaptive changes resulting from the alteration of the normal visual-vestibular relationship [9].

RELATING TRAUMA TO IFDME – A PATHOPHYSIOGENIC MODEL

Postural Deficiency Syndrome (PDS) – Definition and Diagnosis

Postural Deficiency Syndrome (PDS) is conventionally described as a medical condition that includes a composite of symptoms in relationship with variations of the upright position [15]. PDS labeled patients acknowledge, among other signs, balance disorders, postural instability, sensory and cognitive overloads, hypersensitivity, dizziness, pains radiating from or to their body axis, circulatory disorders. As defined, PDS does not correspond to any macroscopic lesion of an anatomically defined system. The severity of PDS symptoms has no relationship to that of the cause [16,17].

Table 2 shows the “cardinal” neuromuscular and neurovascular functional signs and other characteristics of symptoms of patients suffering from PDS as defined by Da Cunha in 1987 and more recently by Quercia et al in 2005 [18]. Such signs are conventionally used in medical traumatology to diagnose PDS.

Table 2: PDS

Signs	**Clinical manifestations**
Pain	Headache, retro-ocular, thoracic or abdominal , joints, and paraspinal and back
Imbalance	Sickness, nausea, dizziness, inexplicable falls
Ophthalmological	Asthenopia, dim vision, diplopia, directional scotoma, metatopsia
Proprioceptive	Dysmetria, somatoagnosia, errors of appreciation of the body image
Articular	TMJ Syndrome, stiff neck, lumbago, periarthrities, sprains
Neuromuscular	Paresia, defect of driving control of the extremities
Neurovascular	Paresthesia of the extremities, Raynaud's phenomenon
Cardio-circulatory	Tachycardia, lipothymia
Respiratory	Dyspnoea, fatigue
Otorhinolaryngological	Hummings, tinnitus, deafness
Cognitive	Dyslexia, dysgraphia, agoraphobia, defect of orientation, defect of spatial localization right and left, defect of concentration, loss of memory, asthenia, anxiety, and depression

NEUROPHYSIOLOGICAL BASIS OF THE FINE POSTURAL SYSTEM

The fine postural system regulates the overall postural tone under all circumstances, whether static or dynamic. The whole central neural hierarchical processing works in line with a classical neurophysiological concept: *the sensory-motor regulatory loop*, as shown below in Figure 1.

General Model – The Sensory-Motor Loop
Inbound Information Processing

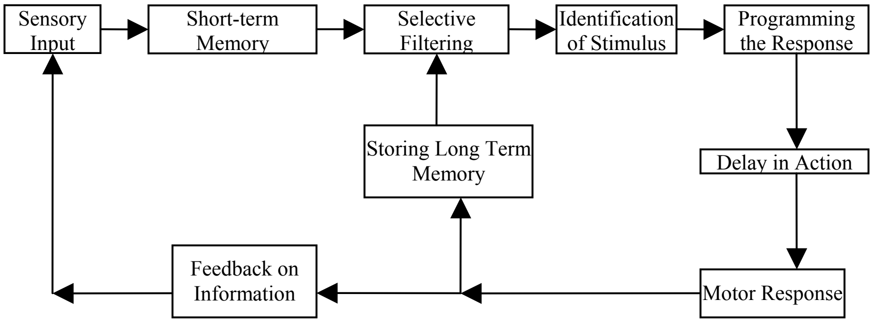

Figure 1

Perception occurs through two types of sensors, the exosensors and endosensors, which are described below in Figure 2:

1. **Exosensors** provide information about the relation between the body and the surroundings. They are:
   - The eye, which shows the body's position with respect to its surroundings;
   - The vestibular system, which shows not only the current position of the body, but also its movements in space;
   - The mechanoreceptors in the sole of the foot, which note pressure of the foot on the ground, especially when standing.
2. **Endosensors** give information about the respective and reciprocal positions of each of the exosensors at any one time. The most characteristic examples are seen in functional synergies involving oculomotor and paravertebral muscles.

Anatomical and Physiological Basis of the Fine Postural System

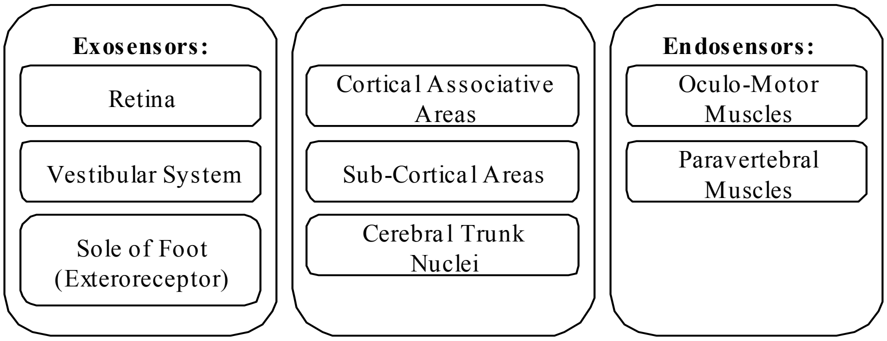

Figure 2

Figure 3 below displays the pattern of how transmission of this information occurs along the neuro-sensory pathways to the cortical sensory and associative areas specific to the site and type of sensor that was activated, this occurring after passing through the sensory and/or sensory-motor nuclei in the brain stem. After the differentiated information received has been integrated in the associative and sensory areas, the motor response is worked out by the motor cortex and subcortical structures and, along its efferent pathway, is tuned up by complementary information received from the subcortical and cerebellar areas.

Neurophysiological Mechanisms Of Deterioration of the Postural System

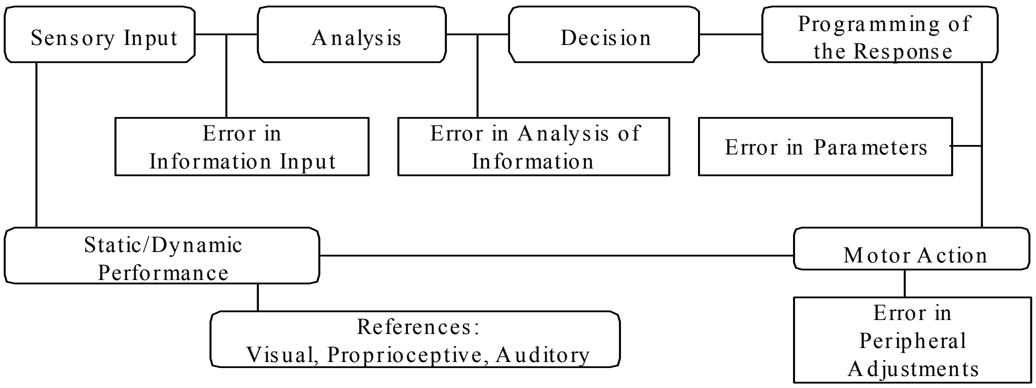

Figure 3

As noted previously the, fine postural controls system is therefore a complicated system, which input and output of information at various levels, which enables the individual to be balanced automatically in his surroundings and regulates itself through ongoing information received from various central controls.

A particular characteristic of this mechanism is that it only operates for small postural disturbances that only move the body's axis by 3 or 4 degrees from the postural vertical reference axis. Experimental data show us that an individual's balance control relies on at least two very different mechanisms, depending on whether the amplitude of spontaneous movements to or from the balance position, which is not necessarily vertical, is greater or less than 4 degrees. Within this cone, an automatic mechanism is used. Outside the cone the regulatory mechanisms become very different. In given circumstances, the postural system may deteriorate more or less quickly and severely because of a dysfunction at a given stage quickly because of a dysfunction at any of the stages of this loop, as shown schematically in Figure 3.

We will now illustrate this general model with examples.

Static Situation: Steady Level Flight

Here we consider steady-level flight, prior to any major perturbations occurring. In such sustained conditions, prolonged static postural positions, seated in most cases, may have to be strictly maintained over long hours. As a result, position may increasingly become discomforting, stiffer and painful, particularly due to lack of muscle and membranous stretch and prolonged abnormal isometric overuse of tendons and ligament as well as ocular-visual sensors. This manifests clinically by rising postural stiffness and pain, which can include various types of headaches and backache, and more rarely, thoracic pain and cervical-brachial neuralgia. Other important factors to also consider are sensory visual and cognitive workload from sustained screen and text reading, constant multivariate fast changing three dimensional context visualization processing and understanding, and complying to multiple requirements and requests at the same time, as well as the workplace setting. As a result, gradual overuse of the retinal visual loop causes endosensors' overuse, most particularly the oculomotor and occipital cervical neural muscular system. Common symptoms may include diplopia, asthenopia, heterophoria scotoma, and routine objective examination will often find only a painful red eye.

At any given time, visual signals may become altered by related compensatory and regulatory systems and subsequently the new information, which has therefore become incorrect, then induces a specific motor and/or cognitive response unsuited to the on going situation.

In our experience, we have seen that depending upon the nature and the level of the area of dysfunction in the previously described flowchart, consequences may or may not be compensated for, or corrected spontaneously.

Dynamic Situation: Piloting High Performance Aircraft or Spacecraft

In addition to what has been described in static situations, many other exteroceptive and interoceptive stimuli can be superimposed, by the act of steering, moving, or being moved in a vehicle or a machine, whether in the air/space, along the ground, or in the water.

In this configuration, other inherent environmental physical factors should also be noted:

- The effect of vibrations, shaking, acceleration and deceleration combined with positional changes
- The effects of the various sensory stimuli, such as a blast, chronic high-intensity noise, or abrupt changes in lighting

Other important facts well explained with this neurophysiological model include the effect of the retinal ocular visual system involved in motion or movement, even at low speed. It is well known since Helmholtz introduced the concepts of action-perception theory [19] that the visual system not only relies on the precise synchronized movement of the eyes themselves, but also on constant postural changes (e.g. head and spinal movements) to help provide information about changing surrounding environments. Besides this, even during steady-level flight, often the pilot is constrained by seat belts and cumbersome helmets or heads-up displays, preventing normal movement of the head and body. These baseline constraints also contribute to compound adverse effects during large and abrupt changes of the lighting of the surrounding and the cockpit controls display as well as during exposure to fast changing peripheral visual images and will provoke or accrue fatigue in the systems involved in the regulation of postural, sensory-motor, and cognitive accommodation. Secondly, certain vibration frequencies may cause rhythmical shaking of the eyeballs through resonance (as demonstrated in Kauerman's model). Consequently, the synergies between the right and left oculomotor systems become more and more difficult to maintain locally and regionally.

Furthermore, this heavily dysfunctional state may become more complicated and "locked in" with additional disorders such as, among others, proprioceptive generated by paravertebral endosensors as well as perceptive from the exosensors in the feet. Subsequently, SMC related cognitive processing might become gradually overloaded and become a secondary factor to IFDME conditions. Here observations of mild to intense intellectual and emotional symptoms and defects describe a range of various mental executive dysfunctions, such as misinterpretation of perceived traffic or aircraft control information coming from perceived truncated data, ”blank mind”, mental “freeze”, short memory loss, inappropriate word pattern reiteration, as well as emotional turmoil and panic attacks perceived by pilots as not being directly tied to the flight conditions themselves, and later explained as “strangely coming from within and nowhere, out of the blue”.

How to Better Monitor IFDME Proneness and After Occurrence?

Whether in the military or civilian Aerospace industries, aircrew biomedical management should always keep IFDME risk in mind and constantly watches out to detect possible leading markers and risk factors at the time of mandatory routine assessments. Systematic and thorough review of the FPS status and research of a possible PDS can be accomplished by using a relatively simple but comprehensive assessment methodology which discretely will provide key neurophysiological cues, leading to various therapeutic avenues. Description and discussion of both assessment and therapeutic methodologies are not included in the scope of this paper.

After ruling out a possible illness or degenerative disease, a possible deterioration of the postural system should be thought of, as well as the possibility of an evolving PDS. If there is confirmation of a PDS, specific treatment should be recommended. Medical and clinical management in aerospace settings should stay simple, effective and keep the above pointers in mind when there is complaint or evidence of:

- Alteration in the usual performance,
- Difficulty in adaptation to a new job,
- Poor adaptation to a regular job,
- Patient with trivial complaints, which are variable, but chronic and without obvious cause.

In this case, a few tests need to be performed by a physician well trained in medical neurophysiology and include, among others:

- Stabilometric/posturographic studies, which reflects overall performance of the postural system,
- Clinical postural examination combined with a comprehensive neurophysiological assessment which analyses the various spontaneous regulatory systems.

PDS variations may be the result of either acute injury or chronic overuse. Recognition and identification of whether the site and type of conflicting sensory-sensory, sensory-motor, and/or sensory-cognitive stimuli or dissociation between synergic systems are of primary importance to the setup of specific treatment protocols that directly address the syndrome’s root cause.

Flying personnel we have assessed often discover that their IFDME proneness may actually be tied with neurophysiological dysfunctional mechanisms underlying recognized objective clinical physical, cognitive, emotional or intellectual disorders. These can be measured and compared through time using a specific neurophysiological ocular-vestibular-postural monitoring methodology.

Besides addressing directly biomedical human factor, ergonomic review and further correction of the work environment if required is also essential, but it may not be enough to make the symptoms disappear.

CONCLUSION

Any personnel exposed to long hours or strenuous workload can develop PDS, especially if exposed to certain particularly demanding factors with respect to their compensatory capabilities.

PDS is capable of explaining long-term symptoms and complaints without any objective basis and denied by occupational/medical examiners, as well as unexplained in-flight errors (i.e. accident proneness) due to: fine tuned dexterity and complex skills, perception of body, space and surroundings, attention span and focus.

Analysis of clinical data from acute and chronic post-traumatic PDS patients has shown a strong correlation between symptoms commonly exhibited before, along side, or even after error, and sensory-motor or PDS related symptoms. Examples can be seen in how PDS related central sensory-motor control dysfunction can be correctly identified and monitored via a neurophysiological ocular-vestibular-postural monitoring system. The data presented provides strong evidence that incorporation of PDS clinical methodology can lead to a better understanding of in-flight adaptive neurophysiological, cognitive and perceptual dysfunctional status that could induce in flight-errors. Such approach is expected to significantly assist in decreasing flight accidents rate as it relates to IFDME.

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