Abstract

In aeronautics, Spatial Disorientation (SD) includes situations in which the aviator fails to correctly perceive aircraft attitude, position or motion. SD is often quantified in terms of task and accident use-case, making it difficult to develop a generalized and fundamental understanding of the occurrence of SD and viable solutions. In order to investigate SD in a generalized manner, a comprehensive ergonomics study on SD in aviation was performed, including both experimentation and model prediction of SD. Motion detection experimental methods were used to measure perceptual joystick response in different vestibular stimulation contexts, thus creating a generalized SD perception dataset. Joystick response derived features, from the generalized SD perception dataset, were used to investigate Machine Learning (ML) parameter tuning selection for SD prediction. Specifically, the motion detection experiments consisted of a vestibular whole-body rotational and translational compensatory tracking task, performed in a KUKA motion simulator under a naturalistic flight context. Using the generalized SD experimental dataset, five combinations of key ML modeling parameters were evaluated using averaged 5-fold prediction accuracy and Receiver Operating Characteristic Area Under the Curve (ROC-AUC); modeling parameters included number of features, eight model types, dataset conditions, feature type, and semi-supervised label type. Additional measures of SD were investigated, for future ML feature usage, such as questionnaire based physical disorientation measured by the SSQ disorientation sub-scale questionnaire. The perceptual SD dataset was statistically proven to be representative of human motion detection behavior, demonstrating that the simulation environment was sufficient to generate realistic piloting responses. ML modeling comparison analysis demonstrated that SD can be accurately predicted regardless of the feature quantity used, however model type, specialized dataset models, feature type, and label type significantly influence prediction accuracy. Finally, no significant relationship between physical disorientation and motion detection was found, indicating that two-sample before and after questionnaire based methods are insufficient to uncover correlations with perceptual disorientation; a more frequent physical disorientation measure is needed. This research demonstrates that SD can be studied and predicted in a generalized manner, and not necessarily by use-case, using general flight and human-related measures (e.g.; physical discomfort report) to monitor performance with respect to the task; successful ML modeling parameter tuning are reported.

Simulation and Classification of Spatial Disorientation in a Flight use-case using Vestibular Stimulation

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1 Introduction

Spatial Disorientation (SD), in aviation, is the failure to perceive orientation, position, or movement. It is caused by multiple factors including environmental references and conditions, experience, and stress.There are diverse types of SD symptoms, ranging from confusion to physical sickness, and currently there is no proven method or solution to prevent it [?], [?], [?], [?], [?]. International studies on the frequency and severity of SD accidents show that the cause of 6-32% of major accidents are due to SD, similarly 15-26% of fatal accidents are a result of SD [?]. Recovery from SD is strongly connected to the pilot's awareness of the situation, and his/her ability to perform corrective control, despite the disorientation, to maintain aerodynamic stability; 80% and 20% of SD incidents are caused by unrecognized and recognized situations respectively [?]. Currently, SD is treated by educating pilots of the signs and symptoms of SD, and instructing them to fly below the physiological thresholds of the human vestibular system [?]. Treating SD has been challenging because SD is often defined with respect to a specific aeronautical context [?], [?]. SD definitions focus on flight performance errors but seldom include context independent behavior, perceptual, or physiological trends. Due to the fact that SD is studied case-by-case in an aeronautical context, there is little general understanding of the onset of SD and orientation, position, or movement perception with respect to environmental references. It would be of interest to study SD using a motion detection experimental paradigm, measuring SD in a general context with respect to whole-body orientation, position, speed, and perceptual feedback. And, ultimately outlining a general framework for modeling and predicting the occurrence of SD based on perceptual feedback.

Vibrations or motion, measured by the human vestibular system, contain important information about the environment and our orientation and position with respect to the environment. Motion detection is the act of discerning self-motion with respect to a reference in the environment [?]. Human motion detection and perception is quantified, by stimulating the vestibular system systematically, via different vibrational and motion experimental paradigms [?]. Initially, motion detection was quantified by observing at which directions and speeds, angular or linear, humans could perceive self-motion. Experimental paradigms included the usage of different experimental conditions such as, acceleration amplitude, trajectory of stimuli, sequence and exposure time of movement and non-movement events, movement direction with respect to the orientation of the head, whole-body stimulation [?]. Recent motion perception research has adopted robotic simulation tools and standardized experimental paradigms, including a greater range of motion test frequencies, allowing for more precise and consistent motion detection boundaries for a large variety of perceptual situations. Additionally, vestibular motion perception studies investigate context-driven parameters, such as: 1) stimuli direction, rate, and acceleration, 2) vestibular dysfunction vs control detection, 3) orientation and/or movement of the user's body during exposure to stimuli, 4) expertise vs novice detection, 5) user age. Depending on the context parameters and the stimuli trajectory, the vestibular-proprioceptive system detects motion differently and thus behavioral responses are different [?], [?], [?], [?], [?]. For SD applications, the observed values where humans could not perceive correct self-motion, called vestibular thresholds, were used as an indicator to be aware of SD [?], [?]. However, it remains uncertain how to reliably use thresholds to assist with SD in a functional aviation context.

In an online flight context, it is more accurate to predict states of disorientation from modeled physiological or movement signatures than using vestibular thresholds. Thus, instead of applying perceptual threshold values from motion detection research to SD research, as was done in the past within aviation, SD researchers are beginning to conduct motion detection experiments using realistic flight scenarios. For instance, directional perception was investigated in a realistic helicopter task where participants were asked to point towards the sky to demonstrate a non-SD state [?]. Similarly, continuous heading detection was investigated using a compensatory task such that perceived heading was measured with respect to a remembered target [?]. Most recently, the individual and interactive influence of optical and gravito-inertial stimuli during simulated Low-Altitude Flight demonstrated the importance of sensory integration effects of on height perception [?]. These applied studies are useful and give insightful information about motion perception in realistic contexts. There is a need for more psychophysical SD motion perception studies using an ergonomics approach, where the results can be generalized and directly used in the field of aviation.

In this study, we investigate SD by using : 1) motion perception experimental methods to create a generalized SD occurrence dataset containing a perceptual feedback measure, 2) statistical and Machine Learning (ML) methods to identify optimal modeling parameters for predicting SD. During the dataset creation phase, we used existing motion detection experimental design methodologies, and designed a generalized motion detection experiment. A vestibular whole-body compensatory task in darkness was used to produce realistic motion cues that a pilot might experience, where motion detection behavior was recorded via joystick movements. Two experiments were conducted, a rotational and translational motion detection task. The rotational and translational experiments administered angular and linear whole-body stimulation, around and along the 3 Cartesian coordinate frame axes, respectively. Participants were given randomized combinations of three parameters that created the angular or linear motion stimuli: axis, direction along the axis, and speed. A motion simulation system was used to administer whole-body stimulation. The goal of phase 1 was to create a realistic and diverse dataset of perceptual joystick motion with respect to the occurrence of SD. The motivation of the dataset creation phase was not to identify vestibular thresholds and report corresponding behavior, but to recreate realistic flight response data in a controlled manner such that states of disorientation could be modeled. It was necessary to first recreate a motion detection experiment based on previous research before SD could be investigated and modeled, because there were no public datasets of a naturalistic piloting task that denoted the occurrence of SD while containing a perceptual feedback measure. Despite the advent of public datasets, such as Google Cloud and Kaggle, psychophysical experimental data for a specific context are rare or unavailable. Next, using the generalized SD dataset, machine learning methods were chosen for SD modeling because their reliable and effective predictive capabilities [?]. During the comprehensive modeling parameter search phase, we 1) categorized participant response into 4 profiles, 2) created 3 semi-supervised labels from the profiles for identifying SD-state, 3) created six unique features from the perceptual joystick feedback measure, 4) compared test set prediction accuracy and Receiver Operating Characteristic Area Under the Curve (ROC-AUC) for five key modeling parameters: number of features, 8 model types, dataset conditions, feature type, semi-supervised label type. ML modeling parameter combinations were identified for accurate prediction of SD. The goal of phase 2 was to create a ML model parameter selection guide for SD prediction, such that SD researchers in aviation can readily use these proven parameters with real flight data. Finally, the relationship between physical sickness symptoms and motion disorientation were investigated to identify potential physical markers for SD; physical sickness was quantified using a generalized disorientation test for humans called the Simulator Sickness Questionnaire (SSQ) [**?**], [**?**]. We hypothesized that participants who correctly detected motion, implying they do not have SD, will additionally not have physical sickness.

2 Reference