

Using Tactile Cueing to Enhance Spatial Awareness under Degraded Visual Environment

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ABSTRACT

Spatial orientation is critical for air operations. Perception of orientation is continuously maintained by accurate information from the visual, vestibular, and somatosensory systems in daily terrestrial activities. The various contributions of these senses can be significantly altered in variable gravito-inertial environments, or when one of the sensory cues is markedly reduced. The visual orientation system can be compromised during low visibility, or as a result of sudden loss of visual cues during 'brownout' while flying/landing in the desert or during 'whiteout' while flying/landing in snowy terrains. Current desert operations have led to an unacceptable number of terminal area aborts, mishaps and fatalities involving rotary wing aircraft throughout NATO due to "brownout". The use of a tactile interface as a "more natural" approach to convey position and motion perception was proposed some years ago [1]. Proof of concept studies has been conducted [2]. However, it is known that human perception of motion in 3 dimensional space involves roll, pitch, yaw, heave, sway and surge. Specifically, our ability to detect roll, pitch and heave are less sensitive. This study is to investigate if tactile cueing can enhance the detection and/or correction of roll, pitch and heave movements in degraded visual environments. A six degrees-of-freedom motion platform (MOOG 6DOF2000E) was used to generate the requisite motion in roll, pitch and heave separately. The tactile display system consists of a torso vest with a 3 rows by 8 columns array of tactors (EAI Inc C2 model), and tactors on two shoulder and two thighs straps respectively. Based on tactile cueing, blind-folded subjects were to 1) indicate motion perception when devoid of all visual, auditory and artificial tactile cues, 2) return to vertical from an offset, 3) maintain straight and level while the platform is continuously in motion. The first study examines the effects of tactile cues along the spinal axis (heave motion) and a second study examines the effects on the roll and pitch axes separately. The experimental design is a within subjects repeated measures. The variables are: with and without tactile cues and the axis of motion. In this manuscript, we will present the data on the effects of tactile cueing in detecting heave motion only. Results showed that the tactile navigation system improves subjects' performance in the ability to maintain neutral position along the spinal axis in the absence of visual and auditory cues. Tactile cueing also improves the subjects' confidence in being able to return to the original position from an offset and that tactile cues were rated to be useful consistently. In conclusion, it appears that tactile cueing in the absence of auditory and visual cues; was useful in providing situation awareness and limits the amount of error made in the roll, pitch and heave axes. Future studies are required to study its effectiveness under simultaneous motion from all three axes.

1.0 INTRODUCTION

Rotary wing (RW) operations are a critical part of mobility (insertion and extraction) and rescue missions. Several NATO countries are performing RW operations in Afghanistan and Iraq and are coping with dusty

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Spatial orientation is critical for air operations. Perception of orientation is continuously maintained by accurate information from the visual, vestibular, and somatosensory systems in daily terrestrial activities. The various contributions of these senses can be significantly altered in variable gravito-inertial environments, or when one of the sensory cues is markedly reduced. The visual orientation system can be compromised during low visibility, or as a result of sudden loss of visual cues during brownout while flying/landing in the desert or during whiteout while flying/landing in snowy terrains. Current desert operations have led to an unacceptable number of terminal area aborts, mishaps and fatalities involving rotary wing aircraft throughout NATO due to "brownout". The use of a tactile interface as a more natural approach to convey position and motion perception was proposed some years ago [1]. Proof of concept studies has been conducted [2]. However, it is known that human perception of motion in 3 dimensional space involves roll, pitch, yaw, heave, sway and surge. Specifically, our ability to detect roll, pitch and heave are less sensitive. This study is to investigate if tactile cueing can enhance the detection and/or correction of roll, pitch and heave movements in degraded visual environments. A six degrees-of-freedom motion platform (MOOG 6DOF2000E) was used to generate the requisite motion in roll, pitch and heave separately. The tactile display system consists of a torso vest with a 3 rows by 8 columns array of tactors (EAI Inc C2 model), and tactors on two shoulder and two thighs straps respectively. Based on tactile cueing, blind-folded subjects were to 1) indicate motion perception when devoid of all visual, auditory and artificial tactile cues, 2) return to vertical from an offset, 3) maintain straight and level while the platform is continuously in motion. The first study examines the effects of tactile cues along the spinal axis (heave motion) and a second study examines the effects on the roll and pitch axes separately. The experimental design is a within subjects repeated measures. The variables are: with and without tactile cues and the axis of motion. In this manuscript, we will present the data on the effects of tactile cueing in detecting heave motion only. Results showed that the tactile navigation system improves subjects performance in the ability to maintain neutral position along the spinal axis in the absence of visual and auditory cues. Tactile cueing also improves the subjects confidence in being able to return to the original position from an offset and that tactile cues were rated to be useful consistently. In conclusion, it appears that tactile cueing in the absence of auditory and visual cues; was useful in providing situation awareness and limits the amount of error made in the roll, pitch and heave axes. Future studies are required to study its effectiveness under simultaneous motion from all three axes.

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landing conditions. Desert operations have led to an unacceptable number of terminal area aborts, mishaps and fatalities involving rotary wing aircraft and warriors throughout NATO due to "brownout". Brownout is the condition in which sand (or snow - "whiteout") stirred up by the "rotor downwash" and renders out-the-cockpit visibility impossible. There have been various technology evaluations in rotary wing with emphasis on new radars, ladars, flight control systems, advance technology for the pilot-vehicle interface, display symbology, mathematical modelling, dust abatement, crew coordination techniques, simulation and development of tactile cueing systems to avoid potential mishaps due to brownouts.

A tactile cueing system uses the sense of touch to provide spatial orientation and situational awareness information to pilots. In general, such system contains tactile stimulators called "tactors" that are embedded in a garment (e.g., vest) worn by the pilot. When activated, these tactors will vibrate (buzz or tap) to warn the pilots when they need to change the aircraft position because of a potentially dangerous drifting or manoeuvre. For example, in many situations, a helicopter pilot does not have any visual cues and can not watch the helicopter instruments because he/she is task-saturated. When the helicopter inadvertently begins banking to the right, the tactile system in the garment starts to warn the pilot on the right side of his/her torso so he/she instinctively corrects the helicopter position by moving the control column to the left. Furthermore, if the helicopter is going too far forward, the system is going to buzz the pilot on the front of his/her chest, the pilot, then, instinctively pulls back.

The use of tactile cues to convey position and motion perception and to overcome inadequacies of other sensory systems is based on the fact that the tactile system is the first sense to develop in a human fetus. The tactile system exploits the sensitivity of the body's largest organ, the skin, for providing continuous feedback signals from the skin to the central nervous system (i.e., brain). The total surface area of the human skin is about 1.8 square metres. It contains a variety of sensory organs called receptors and has about 1.1 million axons (nerves) terminating in the central nervous system [3]. In addition, the tactile system has a well-defined midbrain architecture, fast robust responses, and minimal demands on cognition.

There have been a number of demonstrations and proof of concept studies on using tactile cues in navigation (Cheung et al. 2004). Human perception of motion in 3 dimensional space involves roll, pitch, yaw, heave, sway and surge. Specifically, our ability to detect heave motion is less sensitive. For example, it has been well documented by Malcolm and Melvill-Jones [4] and Melvill-Jones and Young [5] that oscillatory gravitational acceleration along the spinal (z) axis of the body, which primarily stimulates the hair cells of the saccule, leads to uncertain and usually erroneous perception of the direction of motion. In this study, the tactile system will be assessed for performance benefit along the spinal (z) axis, i.e. heave motion, by human subjects using a six degree-of-freedom motion platform. An ultrasonic distance sensor was used to determine the subject's ability to return from an off-set to initial "zero" position and to maintain a pre-determined level position during constant oscillation.

2.0 METHOD

2.1 Subjects

Twelve male and female volunteers (military/civilian) between the ages of 18 and 55 were recruited from DRDC Toronto and the surrounding university communities with the aid of a call for subjects. Subjects were informed fully of the details, discomforts and risks associated with the experimental protocol and were required to sign the Consent Form before their participation.

2.2 Tactile Orientation System

The tactor used was a vibro-mechanical electromagnetic tactor (C2 model from Engineering Acoustics, Inc (EAI)). These tactors are essentially acoustic transducers that transmit 200 to 300 hertz (Hz) sinusoidal vibration onto the skin. The mass of each tactor is 17 grams. For this experiment, these C2 tactors were used at a frequency of 250 Hz, a value that exploits well skin sensitivity and that creates good perception with sine waves. A nylon canvass vest lined with three strips of Velcro that hold 8 x 3 matrixes of vibrotactile tactors served as the tactile orientation system. There was one tactor located under each thigh strap and shoulder strap. The 24 tactors were in a chest-distributed arrangement (Figure 5). Each group of 8 tactors (i.e., each row of the 8 x 3 matrix) were wrapped around the participant's chest in a horizontal line. The 3 front-middle tactors (first column of the matrix) were placed vertically in line with the belly button while the back –middle group of tactors (fifth column of the matrix) was vertically in line with the spine. The right and left groups of tactors (third and seventh column of the matrix) were located on the right and left sides of the ribcage, at an angle of 90° and 270° from the first column respectively. The other four columns of tactors were placed at an equal distance between the first four columns, at 45°, 135°, 225° and 315° from the first column respectively. The shoulder tactors were located on the vest straps, and the thigh tactors were located on thigh straps. The thigh tactors were located on back of the thigh, between the subject's legs and the pilot seat.

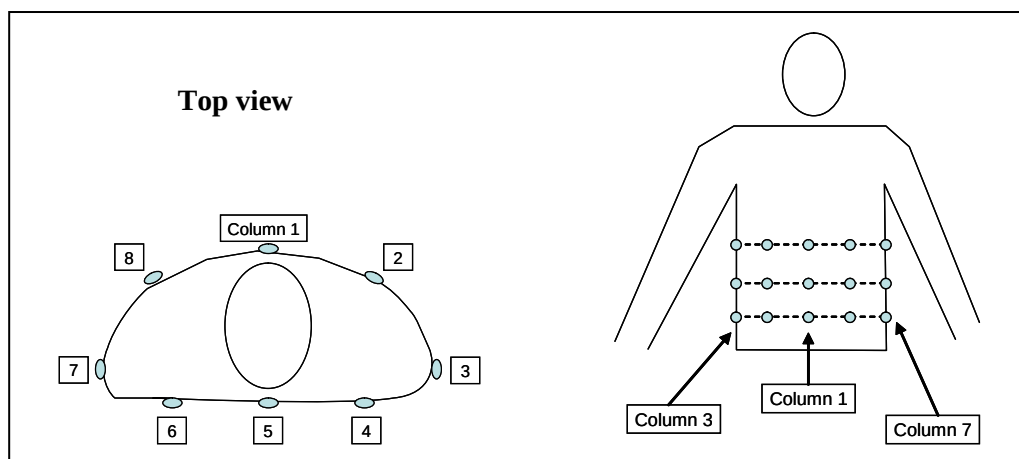


Figure 1: Tactors arrangement (Chest-distributed).

2.3 Motion Platform

An aircraft seat, with a five-point harness to secure the subject, was mounted on a six-degrees-of-freedom motion platform (MOOG 6DOF2000E motion system, MOOG, New York). The platform is equipped with a control column and a collective (similar to the basic helicopter flight control system) so that the subject can control the motion of the platform in the heave (using the collective), roll and pitch axes (using the control column). The following figure illustrates the subject wearing the tactile vest and controlling the motion platform. The motion of the platform can also be controlled independently by the experimenter.

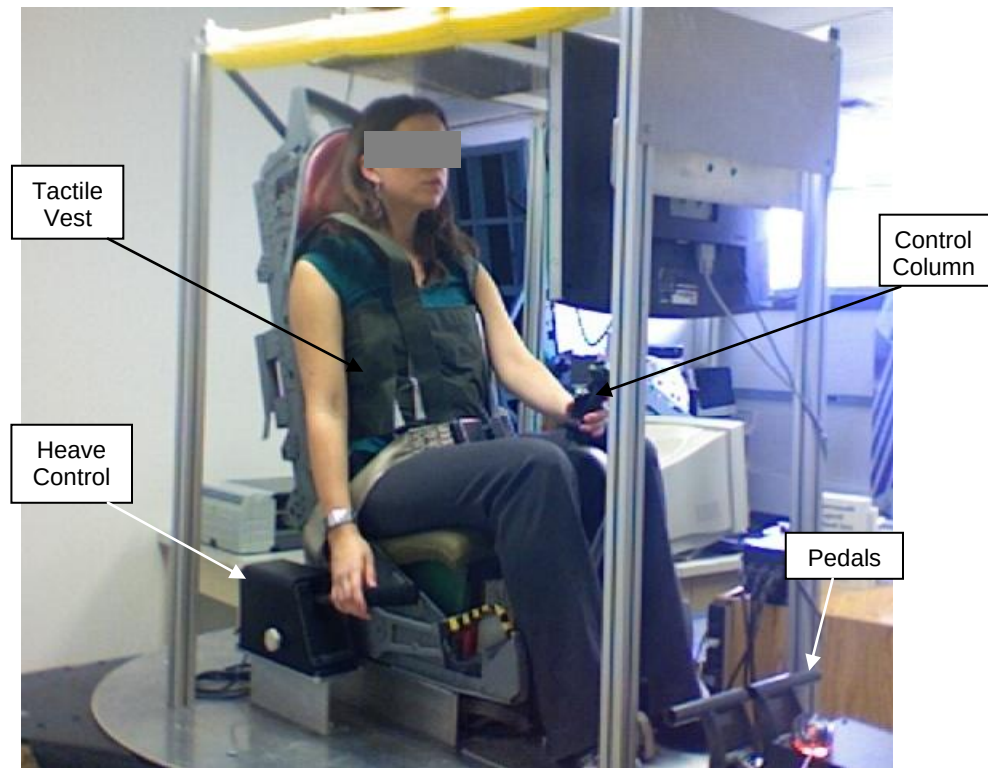


Figure 2: Subject wearing the tactile vest and controlling the motion platform.

2.4 Procedure

As indicated above, in this manuscript only heave motions will be reported. The subjects wearing the tactile system, a blindfold, earplugs and earmuff were exposed to three different manoeuvres in a random order. Prior to the trials, subjects were given opportunities to become familiar with the motion platform and the control column and the collective. Upon activation, the resting motion platform will reach a “zero position” from which further off-set for the particular manoeuvre will be adjusted.

2.4.1 Manoeuvre 1 – Perception of Heave, Roll and Pitch Motion

The sensitivity of the subject in detecting heave, roll and pitch motion was investigated separately. During the trial, the subject was fitted with a blindfold, earplugs, hearing protection device but without the tactile system. At the start of each trial, prior to the onset of motion, the subject was signalled (by a light tap on the knee by the investigator) to indicate that he or she must start a stopwatch in order to record the time that it took to perceive the movement of the platform in each of the axes of motion presented randomly. Once the subject was certain of the movement and the direction, he was instructed to stop the timer and immediately reported the direction of motion that he/she experienced. Each of the manoeuvres was repeated with five different motion frequencies at 0.001 Hz, 0.005 Hz, 0.01 Hz, 0.025 Hz, and 0.05 Hz presented randomly.

2.4.2 Manoeuvre 2 – Performance of Return to Zero Position from a Heave Offset Using Tactile Cues

This manoeuvre begins with the motion platform reaching a pre-defined offset (either in the up or down direction) from the zero position along the heave axis. Once the platform stops moving, the subject was

instructed to return the platform back to the zero position using the collective. In one trial, the tactors were activated and the goal for the subject is to stop the tactors from vibrating by using the collective to control the position of the motion platform and bring it to the zero position. As the frequency of the tactor vibration increases, the farther the subject is to return to their original zero position. The manoeuvre lasted for a maximum of five minutes, with a cut-off time being ten minutes. The subject's path with and without tactile cues will be recorded and then compared.

2.4.3 Manoeuvre 3 – Maintaining Level at the Zero Position Using Tactile Cues while the Platform is in an Oscillating Heave Motion

The motion platform will follow a predefined profile that changes the heave position continuously; it oscillates up and down from the offset position. The subjects were instructed to maintain the zero position while the motion platform is oscillating. The manoeuvre was repeated with five different motion frequencies presented randomly at 0.001 Hz, 0.005 Hz, 0.01 Hz, 0.025 Hz, and 0.05 Hz with resting period in between. The maximum duration of each test was 5 minutes. The subject completed a 2.5 minute profile without tactile cueing first, and then completed the same task (2.5 minutes) with tactile cueing enabled. This manoeuvre lasted for a maximum of one hour.

2.5 Objective and Subjective Measurements

An ultrasonic distance sensor attached to the platform was used to measure the subject's vertical motion trajectory. The sensor is a TS-15s model from Senix Corporation. The output signals (voltages) from the two devices were sent to a computer running MS Windows XP. A Labview program converts the data to distance in both centimetres and inches. The values of the voltage and distance can be viewed in real-time. In addition, each subject was given a subjective rating questionnaire at the end of the three manoeuvres where they can rate various criteria on a scale from 1 to 10. These factors include: vest and tactor vibration discomforts and workload using the NASA Task Load Index (TLX) Questionnaire [6]. The NASA TLX rating provides an overall workload score based on the relative importance of six dimensions: Mental Demands; Physical Demands; Temporal Demands; Own Performance; Effort and Frustration. In addition, subjects were asked to express their opinion on the design of the tactile system and possible improvements.

3.0 RESULTS

The effects of tactile cueing and frequencies of motion on the position accuracy, duration and subjective rating for the tactile system, vibration discomforts and workload was analyzed using a repeated measures analysis of variance (ANOVA) for any significant differences in the dependant variables. When statistical significance is obtained, Tukey's HSD post hoc analyses were used to assess main effects and interactions. Statistical significance was accepted at $p < 0.05$ level. The results in the text and figures are means $\pm$ standard error of the means (SEM).

3.1 Manoeuvre 1 – Perception of Heave, Roll and Pitch Motion

The latency in detecting the movement of the platform across frequencies and axes of motion is illustrated in Figure 3 (left).

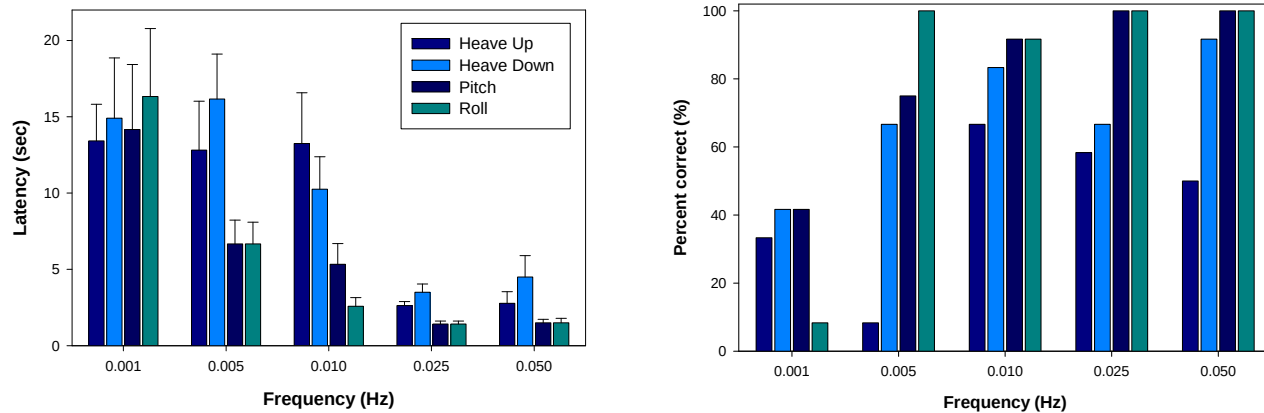


Figure 3: Effect of motion frequency and motion direction on the latency in detecting movement (left) and the correct guess of motion direction (right).

With the exception of 0.001 Hz, the latency in detecting motion was significantly higher ($p < 0.001$) for the heave-up or heave-down motion than pitch and roll.

A post-hoc test for direction revealed that the latency was significantly longer for heave-up vs. pitch ($p < 0.001$), heave-up vs. roll ($p < 0.001$), heave-down vs. pitch ($p < 0.001$), heave-down vs. roll ($p < 0.001$). Overall, there were no significant differences between the latencies in the two heave directions and the latencies between pitch and roll motion, regardless of the motion frequency. Similarly, post-hoc test for motion frequency showed that there were no significant differences between the latencies at 0.025 and 0.05 Hz, regardless of the direction.

The number of correct guess of motion direction by the subjects is illustrated in Figure 3 (right). For all motion frequencies with the exception of 0.001 Hz, the heave movement in the up direction generates significantly higher mistakes number than any of the other three directions ($p < 0.001$). There were no significant differences between the numbers of correct response in heave-down and pitch or roll. However, the number of correct guess was lower in the heave down direction.

3.2 Manoeuvre 2 – Return to Zero from Offset

For the heave movement in the up direction, the subjects obtained an average final displacement of 0.67 ± 0.13 cm with the use of tactile cues, and an average final displacement of 2.54 ± 0.65 cm without the use of tactile cues. In other words, subjects performed better with tactile cues (Fig. 4). The final displacement is defined as the distance from the zero position at the time when the subject stopped moving the motion platform. Similarly, for the heave movement in the down direction, the subjects obtained an average final displacement of 0.83 ± 0.17 cm with tactile cues, and an average final displacement of 5.83 ± 1.05 cm away from the zero position without tactile cues. The increased accuracy for the with tactors condition over without tactors condition was statistically significant ($p < 0.001$). In addition, the increased accuracy for heave up movements over heave down movements was statistically significant with a p-value of 0.026. However, a post-hoc test for the interaction between direction and tactors revealed that there were no significant differences between the displacements in the two heave directions when the tactors were ON.

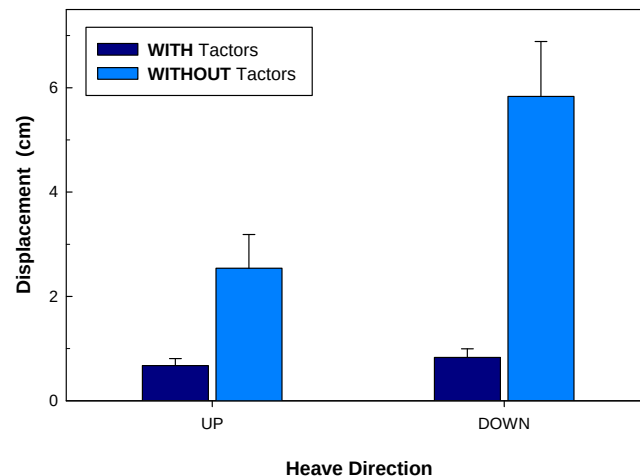


Figure 4: Final displacement with and without tactors in the two heave directions.

Based on subjective reports where 100% would indicate the highest confidence and 0% would indicate the lowest. The average confidence level for the heave motion in the up direction was $91.3 \pm 2.2\%$ with tactile cues and $44.4 \pm 7.3\%$ without tactile cues. The average confidence for the heave motion in the down direction was $87.9 \pm 2.8\%$ with tactile cues and $50.9 \pm 7.2\%$ without tactile cues. The difference in confidence level between the two directions was not statistically significant, nor was the interaction between the direction and the presence of tactile cues. However, there is a significant difference ($p < 0.001$) with and without tactile cues.

3.3 Manoeuvre 3 – Maintaining a Level Position while the Platform is in Motion

The displacement root mean square error (RMSE) was calculated for each trial (i.e., over 2.5 minutes) and averaged across subjects. For each of the five different frequencies of vertical motion: 0.001 Hz, 0.005 Hz, 0.01 Hz, 0.025 Hz, and 0.05 Hz, there is a significant ($p < 0.001$) improvement in the displacement RMSE with tactile cues (Figure 5). The displacement was calculated as the distance of the platform position from the “zero” position. There were no significant differences between the frequencies of motion nor were there any interaction between the state of the tactors and the direction of motion.

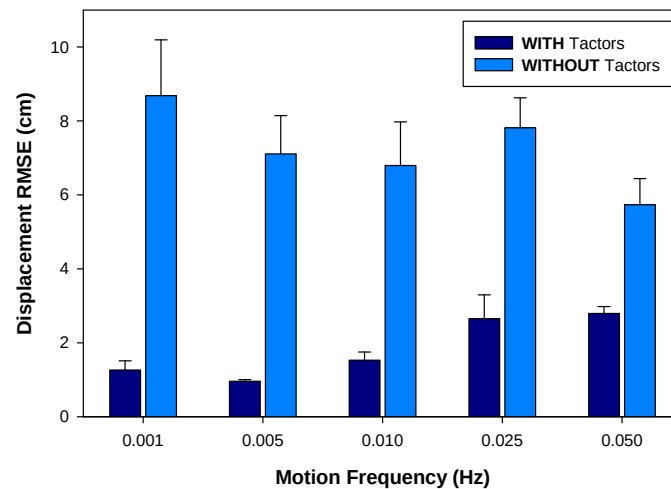


Figure 5: RMSE of the displacement with and without tactors as a function of the motion frequency.

3.4 Questionnaire Results

The results of the questionnaire are shown in the following figure. The vertical axis shows the weighted TLX subjective workload rating, a value which varied from zero to one hundred, zero being the lowest workload rating and one hundred being the highest workload rating. An overall workload score was computed using a weighted average of ratings on six dimensions: Mental Demands; Physical Demands; Temporal Demands; Own Performance; Effort and Frustration level.

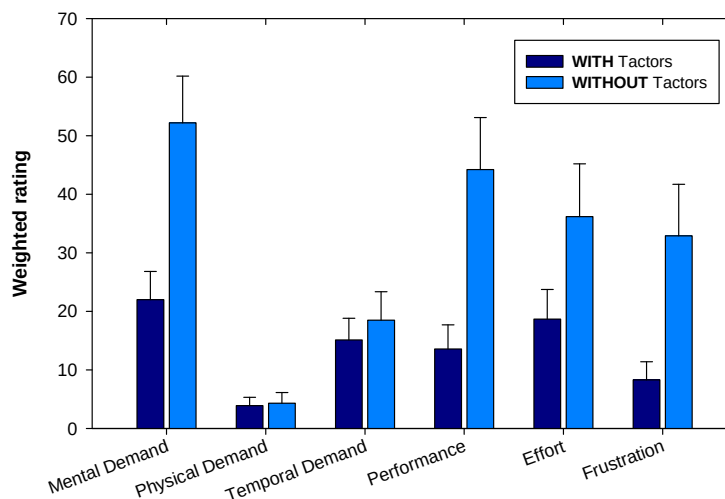


Figure 6: Weighted average workload ratings with and without tactors.

A paired t-test was used to test the significance of these results for each of the six dimensions as well as for the overall workload. The factor tested was the tactor condition. The computed overall workload of 27.2 ± 3.8 with the use of tactile cues was significantly lower than 62.8 ± 5.4 without the use of tactile cues ($p < 0.001$). With the exception of the physical demand and the temporal demand, the difference between the tactile conditions was significant with a p-value lower than 0.001 for the mental demand, $p = 0.011$ for performance, $p = 0.043$ for effort, and $p = 0.003$ for the frustration item.

4.0 DISCUSSION

Posture maintenance and the perception of self-motion are based on the simultaneous stimulation of the visual, vestibular, and somatosensory systems, and to a lesser extent, the auditory system. The somatosensory system refers to non-vestibular proprioceptors (muscle, tendon, joint sense) and tactile mechanoreceptors. Early studies [7-8] suggested that there is an influence of touch and pressure cues on spatial orientation. A more recent study showed that tactile mechanoreceptors could indicate the direction of gravity via patterns of pressure within and at the surface of the body [9]. Recent study by Cheung and Hofer [10] suggested that tactile cueing delivered by a tactile garment provides a sense of direction, but it does not affect any concomitant vestibular responses.

Our results are consistent with earlier studies suggesting that human motion perception along the spinal (z) axis is poor and ambiguous with longer latency in perceiving heave motion. The results also indicate that with the activated tactile system, all subjects performed better in returning to the initial “zero” position and were able to maintain level position while the platform is in constant oscillation along the spinal (z) axis, which suggested that the tactile stimulus serves as an excellent directional cueing. The sensation of touch has a well-defined midbrain architecture, fast robust responses, and minimal demands on cognition. It might be an ideal candidate to provide continuous, intuitive veridical (true vertical) orientation information. There are many potential application of tactile cueing in operational environments. For example, in environments that demand high levels of information transfer, increased workload and situational awareness (SA), visual and auditory pathways may be easily overloaded and significantly altered. For example, in a search and rescue (SAR) mission at sea during poor weather, the helicopter pilot is unable to maintain visual sighting of the survivor. In addition, the constantly changing wind and water currents will cause both the helicopter and the survivor to drift in different directions. The pilot is required to be in continuous communication with the flight engineer and SAR Technicians, and in the same time make constant flight control changes and position adjustments to maintain hover or attempt to follow the drifting survivor. As a result it takes longer than necessary to rescue survivors, which put them to greater risk and injuries such as severe seasickness, excessive loss of fluid and potential hypothermia. An alternative orientation and navigation system such as a tactile cueing system can supplement the auditory and visual input to provide continuous, intuitive and true orientation and SA information to pilots during high workload and time sensitive SAR missions such as whiteout/brownout landing and rescue at sea.

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