The Differential Effect of Sustained Operations on Psychomotor Skills of Helicopter Pilots

Terry W. McMahon; David G. Newman

INTRODUCTION: Flying a helicopter is a complex psychomotor skill requiring constant control inputs from pilots. A deterioration in psychomotor performance of a helicopter pilot may be detrimental to operational safety. The aim of this study was to test the hypothesis that psychomotor performance deteriorates over time during sustained operations and that the effect is more pronounced in the feet than the hands. The subjects were helicopter pilots conducting sustained multicrew offshore flight operations in a demanding environment. The remote flight operations involved constant workload in hot environmental conditions with complex operational tasking.

METHODS: Over a period of 6 d 10 helicopter pilots were tested. At the completion of daily flying duties, a helicopter-specific screen-based compensatory tracking task measuring tracking accuracy (over a 5-min period) tested both hands and feet. Data were compared over time and tested for statistical significance for both deterioration and differential effect.

RESULTS: A statistically significant deterioration of psychomotor performance was evident in the pilots over time for both hands and feet. There was also a statistically significant differential effect between the hands and the feet in terms of tracking accuracy. The hands recorded a 22.6% decrease in tracking accuracy, while the feet recorded a 39.9% decrease in tracking accuracy.

DISCUSSION: The differential effect may be due to prioritization of limb movement by the motor cortex due to factors such as workload-induced cognitive fatigue. This may result in a greater reduction in performance in the feet than the hands, posing a significant risk to operational safety.

KEYWORDS: rotary, performance, tracking, hands, feet.

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There is an increasing demand for helicopter operations in difficult environments for both military and civil operators. A helicopter's unique flight and handling characteristics allow for operations in areas where there is no infrastructure and, unlike fixed wing aircraft, require no prepared airstrip for landing. Advances in technology enable helicopter operations to be conducted around the clock in an ever increasing, wide range of tasks and missions. Operations may be sustained in nature due to operational requirements or environmental seasonal restrictions. Sustained operations have been defined as an operation that spans multiple rotation cycles, or a single rotation extended in its duration.[7]

A helicopter pilot's psychomotor performance may be affected by a number of factors, including (but not limited to) fatigue, time on task, workload, environmental conditions, and operational stressors. Previous research has shown a correlation between the effects of cognitive fatigue and a decrease in both cognitive and psychomotor performance.[10,11,13] Deterioration of a pilot's psychomotor performance to any degree represents a significant risk to helicopter flight operational safety.

The first author observed that when pilots conducted high-risk sustained helicopter operations in a hostile mountainous environment in a highly fatigued state, they displayed a noticeable deterioration in fine motor control response. Furthermore,

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this appeared to occur mainly in the feet, with a lesser observed deterioration in hand motor response.

Following on from our previous studies into helicopter pilot psychomotor performance,[14] this study was conducted to test the hypothesis that psychomotor performance deteriorates over time during sustained operations and that the effect is more pronounced in the feet than the hands. This study represents an attempt to confirm the anecdotal experience of helicopter pilots and to examine possible mechanisms for the observed effect.

METHODS

Subjects and Operational Setting

Eighteen male helicopter pilots participated in this study, with an average age of 38 yr (range 25–55 yr). The pilots in this study all held valid Class 1 aircrew medicals, had no coexisting illnesses, were all nonsmokers, and were fully compliant with the company's drug and alcohol policy. The subjects were all experienced pilots with an average of 8000 flying hours (range 5000–14,000 h). The pilots were carrying out off-shore oil rig support operations from a remote land base with an average daytime temperature of 35°C (as recorded by the airport meteorology station). The highest temperature recorded during the study period was 39°C. The crews were conducting day instrument flight rules two-pilot operations in Augusta Westland AW139 twin-engine helicopters. Missions involved flights to and from an offshore oil rig some 90 nmi from their land base. Crews made several trips a day depending on operational requirements, with approximately 5 h flight time each day. The average flight time in this study was 25.5 h (range 20–30). Operations were restricted to daylight hours only for the offshore oil rig support tasks.

Pilots operated on a fly-in fly-out duty roster lasting for 12 d. The seventh duty day was designated as a nonflying day. As such, during a 12-d rotation, crews would fly for 6 d, rest on the 7th, fly an additional 5 d, and then be rotated out of the duty cycle.

The research was approved by Swinburne University's Human Research Ethics Committee (Protocol Number 2012/058). Each subject provided free and informed written consent before participation.

Equipment

A helicopter-specific psychomotor vigilance test (PVT) was used to conduct daily postflight testing of the pilots. The PVT consisted of a software program installed on a laptop computer, with a commercial off-the-shelf computer joystick and rudder pedals as previously described.[15] The compensatory tracking task software included a tracking ball (operated by the joystick), which moved randomly in all directions, and a second tracking ball which moved horizontally across the bottom of the screen (operated by the rudder pedals).

The 5-min test requires the pilot to keep both tracking balls centered despite their random tendency to move. A comprehensive integrated data management system analyzed the data recorded from the input of both foot pedals and the joystick and placed it in a user-specific, time and date-stamped spreadsheet file (Microsoft® Excel). The acquired data for the 5-min test consisted of the position of both balls relative to the posts and bullseye ring, respectively, on a per-second basis, as well as the raw time and the percentage of the total test time that each ball spent outside its target area during the test sequence.[15]

Procedure

All subjects were fully briefed as to the conduct of the study prior to commencement of testing. Subjects were given a 5-min practice session with the PVT (prior to commencement of formal testing).[15] Following the practice session an initial test was carried out on all subjects which formed the baseline or control data against which subsequent daily testing could be compared. Testing took place in a comfortable, quiet room with no distractions. Pilots completed the PVT test at the completion of daily flying duties over a period of 6 d (the longest continuous duty cycle). Testing took place as soon as practicable once the pilots had landed and completed their essential postflight tasks. All subjects were tested on average 30 min after flight, which also helped to ensure that all subjects were relaxed and there was no interference from any possible effect of flight arousal.[15]

Statistical Analysis

All 18 pilots underwent testing. While the pilots were tested every day for as many days as possible, the dynamic operational nature of their rosters and the fact that they were all at different points of their duty rotation cycle during the study meant that, at the conclusion of the study, only 10 pilots had undergone a minimum of at least 4 d of consecutive testing. As such, only the data from these 10 subjects are reported in this paper.

Daily PVT test data for 10 individual pilot subjects were tabulated in a PC-based spreadsheet program (Microsoft® Excel for Mac, 2011) and imported into a statistical software package for analysis (SPSS Statistics, version 23, IBM Corp, Armonk, NY). Linear regression analysis was conducted to determine if there was a correlation between PVT tracking accuracy and the subjects' age, total flight time, and study flight time. Due to the non-normally distributed nature of the PVT data, the Wilcoxon signed-rank test was used as the test of statistical significance. An alpha level of $P < 0.05$ was considered significant at the 95% confidence interval for all effects.

Each pilot acted as their own control. For each pilot, the change in PVT tracking accuracy for each limb group (hands or feet) was calculated as the difference between the final test score and the initial baseline test score. These values were averaged for each limb group for all subjects and compared across time and between limb groups for statistical differences.

RESULTS

A deterioration of psychomotor performance was evident in the pilots over time for both hands and feet. **Table I** shows the PVT tracking performance of each pilot's hands and feet over

Table I. PVT Tracking Accuracy (%) by Pilot, Limb, and Test Day.

PILOT & LIMB	DAY 1	2	3	4	5	6
P1						
Hands	45.7	31.0	28.7	31.0	72.0	29.0
Feet	31.3	33.0	39.7	39.0	36.3	30.3
P2						
Hands	60.3	50.3	60.7	49.7	41.7	47.0
Feet	53.3	38.3	48.3	49.3	34.7	19.0
P3						
Hands	51.0	33.0	38.3	32.3		
Feet	51.7	49.7	52.7	41.0		
P4						
Hands	59.3	61.3	34.3	43.0	43.7	40.3
Feet	49.7	63.7	25.3	53.7	46.3	17.7
P5						
Hands	2.3	16.0	16.7	8.7		
Feet	51.3	25.0	20.7	18.7		
P6						
Hands	34.3	46.3	45.7	42.0		
Feet	41.3	27.7	19.0	32.3		
P7						
Hands	64.7	66.3	59.7	55.3	53.0	
Feet	63.3	53.0	53.0	51.3	38.3	
P8						
Hands	42.3	54.0	45.3	41.7	38.0	34.7
Feet	19.3	26.3	23.0	12.3	7.0	9.0
P9						
Hands	19.7	19.7	45.7	8.7	8.0	19.7
Feet	10.0	2.3	52.3	1.7	2.3	4.7
P10						
Hands	29.0	7.0	12.3	9.7		
Feet	21.3	8.7	13.0	25.0		

the days that they were tested. Regression analysis did not demonstrate any statistically significant correlation between PVT tracking accuracy and the subjects' age, total flight time, or study flight time.

Fig. 1 shows the changes in psychomotor performance of the hands and feet from baseline to the final test. The results demonstrate a statistically significant decrease in the PVT tracking accuracy of both the hands ($Z = -2.192$, $P = 0.028$) and feet ($Z = -2.599$, $P = 0.009$) over time.

Fig. 2 shows the baseline to final day trend in psychomotor performance for both hands and feet. The results show that the baseline PVT tracking accuracy for the hands and feet were very similar, but by the final test the PVT tracking accuracy of the feet had deteriorated more sharply than that of the hands. The hands recorded a 22.6% decrease in tracking accuracy, while the feet recorded a 39.9% decrease in tracking accuracy. The change in PVT tracking accuracy for the feet was 77% more than that of the hands.

Fig. 3 shows the mean PVT tracking accuracy for each limb group over the entire 6 d, with superimposed linear trend lines and R^2 values. In both limb groups the overall trend is a linear decrease, but the downward trend in PVT tracking accuracy is far more pronounced in the feet than in the hands.

Fig. 4 compares the mean PVT tracking accuracy over time for each of the limb groups. There was a statistically significant differential effect between the hands and the feet in terms of PVT tracking accuracy. This differential effect was statistically significant ($Z = -1.992$, $P = 0.046$).

DISCUSSION

The results of this study show that there is a general decrease in the psychomotor performance of helicopter pilots engaged in sustained flight operations. A key finding is that this general reduction in psychomotor performance displays a significant differential effect between the hands and feet, with the feet being affected much more than the hands.

These results support the first author's anecdotal experience of the adverse effects on psychomotor performance of sustained helicopter operations. The first author's experience involved operations based on a 30 d on, 28 d off, fly-in fly-out duty cycle, with a continuous 7 d/wk flying phase with a maximum 130 flying hours permitted in the 30-d period. A deterioration in fine motor control response in both hands and feet was seen among most of the pilot group and the deterioration was noticeably greater in the feet than the hands. The deterioration of the fine motor control response of the feet was observable after approximately 100 h of flying, with the effect accelerating beyond this time.

This adverse effect on psychomotor performance most commonly manifested itself during the landing phase. At the completion of daily flying activities, setting down of the helicopter onto the landing pad was generally done with a level of accuracy lower than typically expected. The helicopters were often not positioned properly into the wind and were misaligned with the edge of the rectangular helipads. This misalignment progressively worsened as pilot hours increased and was not considered intentional. The effect was common to all pilots regardless of experience or helicopter type. This anecdotal experience suggested to the first author that the normally subconscious response of the feet during the landing phase was becoming less automatic, requiring greater conscious effort and thought than usual, resulting in a lower degree of accuracy.

The significance of this in terms of its potential impact on flight safety is very clear. Helicopter pilots require a high standard of psychomotor coordination, as some maneuvers demand fine motor control and precise coordination of all control inputs simultaneously. Helicopters are inherently unstable and require constant control inputs unless aided by automatic flight control systems. Pilots may use different flying techniques for a variety of maneuvers. Landing a helicopter at the completion of a mission is carried out into the wind at an angle with a gradual reduction of airspeed to arrive at the landing point at zero airspeed and transition into the hover at approximately 3 ft above ground. The taxi phase to the parking area may require the helicopter to be in a cross or downwind position in close proximity to the ground. This may occur when a pilot is in a fatigued state at the completion of the mission and these maneuvers require simultaneous control inputs with fine motor control from both hands and feet.

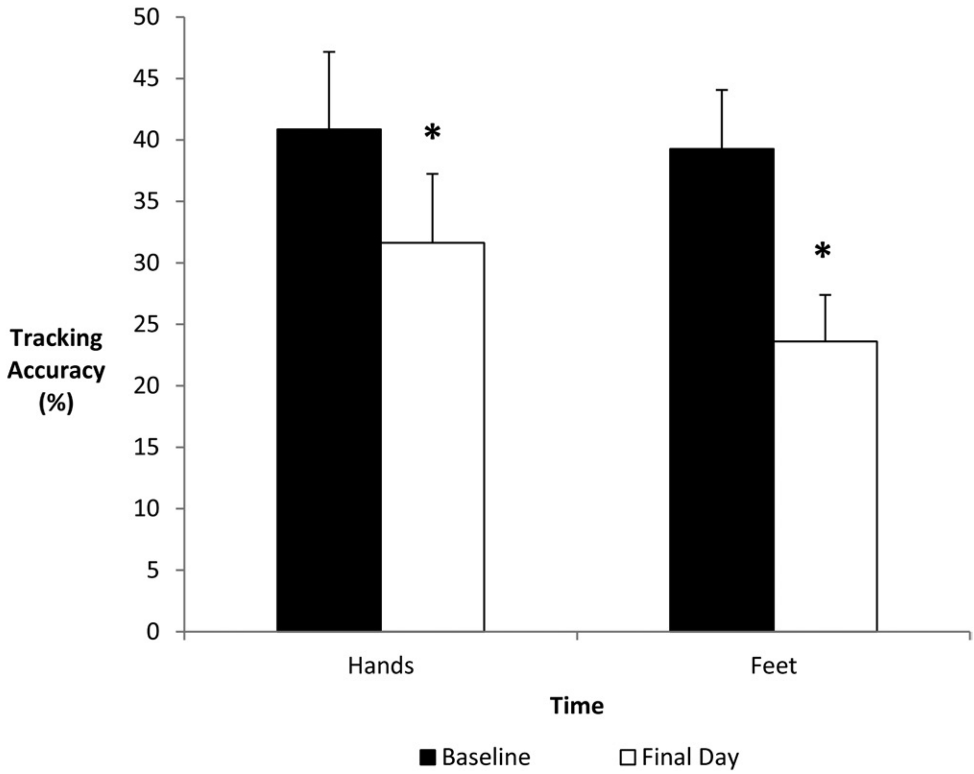

Fig. 1. PVT tracking accuracy of hands and feet over time. Data are mean (± SEM) values. * = Significant difference ($P < 0.05$) from baseline.

likelihood of an undesirable event occurring, particularly during takeoff or landing.[18]

Sustained helicopter operations in hostile environments may produce high levels of cognitive fatigue because of time on task, prevailing environmental conditions, the nature of the task, high cognitive workloads, operational or individual stressors, and poor quality and quantity of sleep.[19] Deployments into unfamiliar areas of operation with limited resources may occur at short notice with little preparation. Indeed, the demands of the operation may change such that initial deployed resources (aircraft and personnel) may become inadequate for the required task, thus placing additional workload on the in-situ pilots.

Long duty times can also be an issue. Modern helicopter operations may see missions lasting up to 12 h or longer. Hot refueling, where the pilot remains at the controls on landing while pressurized fuel is pumped into the helicopter over a brief period may give little respite to the pilot. Some military helicopters are capable of in-flight refueling, resulting in extended flight times.[4] Offshore oil rig support operations may require long transit flights over featureless terrain in adverse weather conditions and in some cases at the maximum edge of helicopter performance. Landing on oil platforms may require out of ground effect approaches with variable winds and multiple threats such as small landing areas, oil rig cranes, and other obstacles.

Lateral movement (drift) on landing, particularly in helicopters equipped with landing skids, may result in a dynamic rollover condition, or a poor landing technique may also induce a harmonic vibration. The rapid onset and unpredictability of both of these potential problems may result in a catastrophic event. Operations involving degraded visual environments in both white-out and brown-out conditions in combination with decreased pilot psychomotor performance may increase the

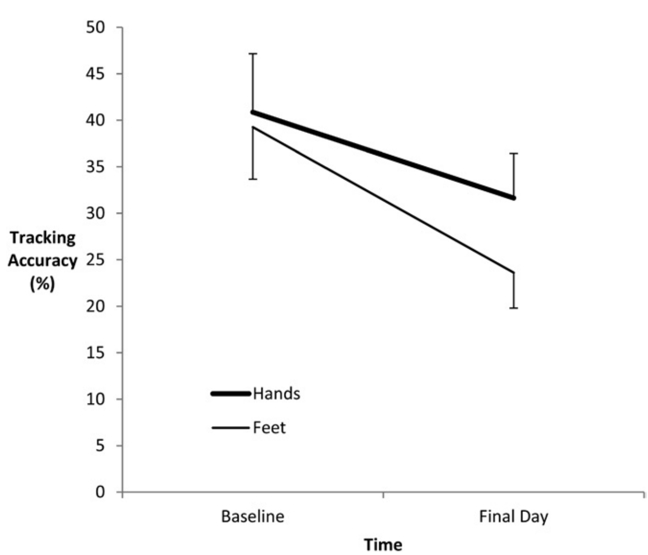

Fig. 2. Trend analysis of mean change in PVT tracking accuracy over time for hands and feet.

Deployments involving sustained helicopter operations may lead to significant levels of fatigue. Mental fatigue may be defined as a change in psychophysiological state due to sustained performance.[23] A reduction in mental or physical performance may impair a pilot's alertness and the ability to operate a helicopter or perform a mission in a safe manner. The change in psychophysiological state has subjective and objective manifestations, which include an increased resistance against further effort,[16] an increased propensity toward less analytic information processing,[20] and changes in mood.[3,9]

Despite decades of research into the subject of cognitive fatigue, the subject remains complex and is yet to be fully understood. This is particularly the case in terms of the link between cognitive fatigue and its behavioral manifestations.[3,9,23] A study involving sustained muscular contractions showed a corresponding increased functional activation of various cerebral cortical areas, which may lead to development of cognitive fatigue.[22] Several studies have used psychomotor reactions to

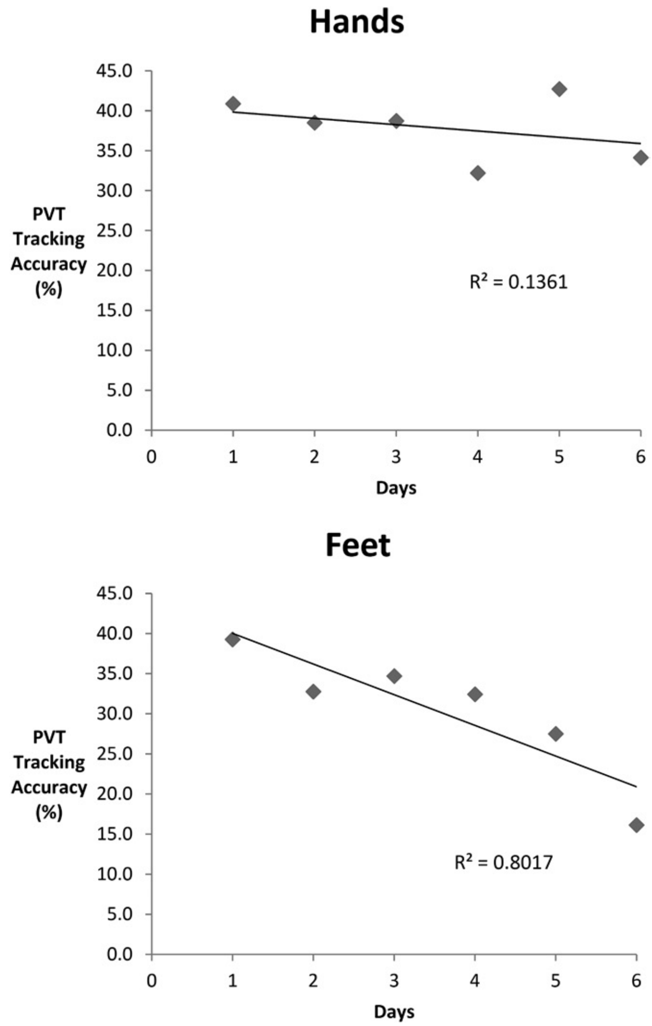

Fig. 3. Mean daily PVT tracking accuracy and linear trend lines for each limb.

quantify the effects of cognitive fatigue. The results of these studies have demonstrated reductions in alertness, vigilance, and attention, as well as psychomotor impairment as a consequence of cognitive fatigue.[12,21,22] A study involving a 60-min Go/NoGo task found that fatigue scores indicated mental and physical fatigue after 60 min of testing. The study showed a decrease in reaction times, reaction time variability, and error rate. The results suggest that cognitive fatigue causes deteriorations in motor performance which may be due to reduced allocation of mental resources to the task.[10]

A possible explanation for the cognitive fatigue-induced changes is that such fatigue affects those control processes that are involved in the organization of actions that play a major role in deliberate and goal-directed behavior. Simple or well learned tasks can be performed for long periods of time in a highly fatigued state without a decrease in performance and that complex tasks may be more difficult and show signs of decreased performance.[8,9,12] The different levels of information processing and the disorganization of behaviors occurring during fatigue studies indicate that cognitive fatigue may be a result of deterioration of executive control.[23] Furthermore, it has been postulated that mental fatigue compromises executive control and suggested that there is an increased tendency for more automatic regulatory processes to accomplish reduced goal activation which are triggered by situational or external cues, even when this is inappropriate.[23]

Executive control within the brain refers to the ability to regulate perceptual and motor processes to respond in an adaptive way to novel or changing task demands.[2,17] Executive functions include verbal and design fluency, ability to maintain and shift set, planning, response inhibition, working memory, organizational skills, reasoning, problem-solving, and abstract thinking. In addition to the primary projections noted above, the frontal lobes have multiple connections to cortical, subcortical, and brain stem sites and should be conceived as one aspect of an executive system involving many structures of the central nervous system. The basis of higher level cognitive functions such as inhibition, flexibility of thinking, problem solving, planning, impulse control, concept formation, abstract thinking, and creativity often arise from much simpler, lower level forms of cognition and behavior. Thus, the concept of executive function must be broad enough to include anatomical structures that represent a diverse and diffuse portion of the central nervous system.[1]

There appears to be no definitive model for the complete function of executive control and its association with other parts of the brain. One important function of executive control is to coordinate goal-directed behavior and to keep goal-related information active in the mind. During compromised executive control, it is not the mental representation of the goal itself that is affected. Rather, it appears that it is the activation level through which a goal can influence the selection of actions that is reduced.[5] During periods of reduced goal activation, actions are guided by more automatic processes, which are triggered by situational or external cues, even when this is inappropriate.[6] This may lead to goal neglect and may be the major source of problems with executive control, which may manifest as slowed reaction time, decrease in accuracy, and delayed decision making.

What possible mechanisms could explain the deterioration in psychomotor performance seen in this study, particularly the differential effect between the hands and feet? High levels of cognitive fatigue achieved during sustained helicopter operations may result in a reduced capability of executive control. This may in turn lead to a reduction in the available mental resources needed to control psychomotor tasks and a subsequent prioritization of how these resources are allocated. Driven by the relative weighting of the cortex devoted to each body part, the hands exert more demand for these resources due to their greater cortical representation within the motor cortex. As a result, the psychomotor performance of the hands is preserved far more than that of the feet.

While we did not directly measure fatigue in this study, it is perhaps noteworthy that all the individual pilots subjectively reported symptoms of fatigue to varying degrees during and after daily flying operations as a result of workload and time on task. In some cases, pilots had not slept well the previous night

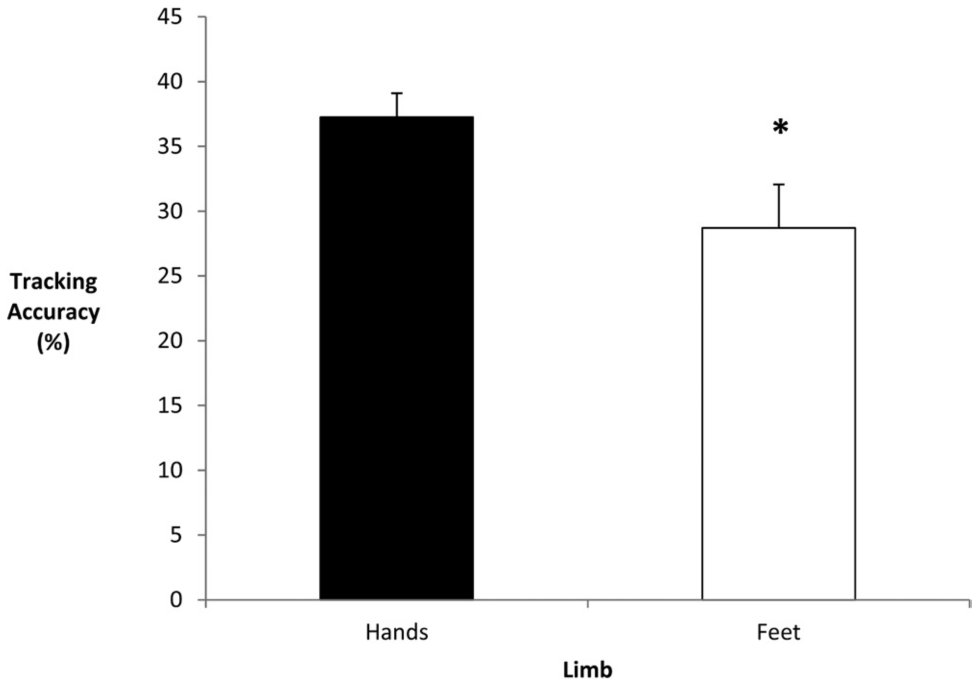

Fig. 4. Comparison of limb PVT tracking accuracy. Data are mean (± SEM) values. * = Significant difference ($P < 0.05$) from hand value.

In particular, PVT tests such as the one used in this study could have a role in monitoring (on a daily basis) the psychomotor performance of helicopter pilots to ensure that they stay within safe operating limits (which would need to be defined). This testing may provide some insight as to when a pilot has become too cognitively fatigued, particularly during sustained flight operations. The use of PVT tests in such a way could also be incorporated into an organization's integrated Safety Management System for a more complete and holistic approach to fatigue management and flight safety. Clearly more research is required before this would be possible.

There were certain limitations with this field research which should be acknowledged. For various operational requirements, pilots either moved to another base or in some cases were near completion of their tour of duty during the study period. As a result, the sample size in this study was somewhat limited. Furthermore, the extent to which the subjects were physically fatigued was unknown. Although field studies such as this one present a number of restrictive difficulties, particularly in an operational environment, it is difficult to replicate environmental conditions, geographic isolation, and the normal aviation stressors in laboratory-based studies. The effects of cognitive fatigue on psychomotor performance may only manifest themselves fully during field studies conducted over extended periods of time in which subjects gradually achieve a substantial level of fatigue.

The objective of this research was to examine the anecdotal evidence that helicopter pilots conducting sustained helicopter operations who acquire high levels of cognitive fatigue may experience a significant effect on their psychomotor performance. As flying a helicopter requires the complex coordination of psychomotor skills the effect on psychomotor performance due to sustained operations may result in a deterioration of motor response within the hands and feet. The results of this research show that automatic psychomotor responses may be compromised during sustained flight operations and that there is a decline in psychomotor performance in both hands and feet. Specifically, the study shows there is a differential effect of psychomotor performance with the feet deteriorating more rapidly than the hands. The differential effect may be due to prioritization of limb movement by the motor cortex due to factors such as workload-induced cognitive fatigue. This may result in a greater reduction in performance in the feet than the hands, posing a potentially significant risk to operational flight safety.

due to poor quality or quantity of sleep and had acquired a sleep debt at the commencement of duty the following day. Some individual pilots also reported being fatigued for the first 2 d on arrival at work for the commencement of their tour of duty. Additionally, a small number of pilots had traveled from east to west across the Australian continent through multiple time zones, and in some cases over a number of days from New Zealand (five time zones).

A number of fatigue countermeasures were employed in this commercial helicopter operation as part of the company's Fatigue Risk Management System (FRMS). This consisted of compliance with regulatory flight and duty flying hours, a crew rostering matrix, a fatigue management software system, and environmental controls in the form of air conditioned aircraft. Despite these countermeasures, the results of this study show a significant deterioration of psychomotor performance.

For sustained helicopter operations, particularly in challenging environments, general fatigue risk management systems and reliance on fatigue software models as an indication of fatigue levels may not be sufficient and it may be necessary to further enhance the FRMS with additional monitoring capabilities such as daily psychomotor performance testing. The implications for flight safety remain to be further investigated. Currently there is insufficient research into the effects of fatigue on helicopter pilot psychomotor performance and more work is required. Building on this and our previous laboratory studies, further field studies with larger sample size and using real world conditions may provide a greater understanding of the effects of fatigue on helicopter pilots and provide greater insight into safer sustained helicopter operations.

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