Cognition and piloting performance: offline and online measurements

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Abstract

In aeronautics, the notion that cognitive performance is correlated with accident rates raises the importance of implementing more efficient cognitive selection procedures for pilot candidates. The Cambridge Neuropsychological Testing Automated Battery (CANTAB) has established sensitivity to a range of cognitive functions and their neurobiological substrates. The ability of CANTAB to predict success during pilot training courses (notably based on the evaluation of flight performance) will be examined and compared to that of tests currently in use by one of the leading French civil aviation schools (ENAC) for their pilot candidate selection procedures. Ultimately, the goal is to develop an optimized pilot selection tool that taps into the cognitive functions and underlying neural circuitries required for successful piloting activities. Moreover, through the implementation of a dual-task paradigm, this study aims to provide guidelines for future cockpit instrumentation designs better adapted to the human brain, in a further attempt to reduce accident rates.

The neuroergonomics approach to human error

Evidence suggests that human error is a major contributing factor to accidents in commercial aviation (Wiegmann & Shappell, 2001). Li, Baker, Grabowski, and Rebok (2001) analyzed NTSB (National Transportation Safety Board) data files and showed that pilot error is a probable crash cause in 38% of the airline crashes. More specifically, Loss of Control In-flight (LOC-I) and Control Flight Into Terrain (CFIT) accidents are the two deadliest accident categories arising from human error. Common causes for these types of events include the aircrews not initiating the appropriate manoeuvres, failing to notice visual and auditory alerts, being unable to maintain good situation awareness (SA) and poor decision-making. Some errors may appear particularly surprising considering the hard-to-achieve selection criteria pilots have to meet to enter the training program and obtain their license and the pilots' high levels of expertise/experience.

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The notion that specific aspects of cognition play a crucial role in the chain of events leading up to aircraft crashes suggests that the implementation of efficient cognitive screening procedures for pilot selection and the development of cockpit instrumentations fitted for the human brain may decrease accident rates. A required first step in this direction involves characterizing the human cognitive limitations in complex environments such as piloting scenarios. The fields of integrative neurosciences and neuropsychology have in recent years provided a fruitful approach to further our understanding in this regard. Their application to human factors and ergonomics gave birth to neuroergonomics (Causse, Dehais, Péran, Sabatini, & Pastor, 2012; Parasuraman, 2003; Sarter & Sarter, 2003). Neuroergonomics aims to study the brain structures/functions involved in situations that trigger a high situational complexity. This approach is extremely promising for aeronautics and gives the opportunity to cross-fertilize the fields of ergonomics and neuroscience. For example, ecologically valid environments relevant to ergonomics provide enriched frameworks to test classical neurosciences principles and vice versa ergonomics can test its hypotheses using neuroscientific models and tools.

Bridging the gap between piloting activities and their underlying neural substrates

Identifying which cognitive factors and underlying neural circuitries are predictive of pilots' errors is a great challenge, as flying is a complex activity that takes place in a rapidly changing and uncertain environment. The pilot must not only know how to operate the aircraft, the procedures and the flight rules, but must also have accurate and up-to-date SA (Endsley, 1994). According to Hardy and Parasuraman (1997), the pilot flying performance is dependent on domain-independent knowledge (e.g. cognitive functions), domain-dependent knowledge (e.g. procedural knowledge), pilot stressors (e.g. adverse weather conditions) and pilot characteristics (e.g. age, expertise). Numerous studies have been conducted to link cognitive functioning with flight performance, and different measurements of cognitive efficiency have been identified as crucial to the piloting ability, including time-sharing (Tsang & Shaner, 1998), speed of processing (Taylor et al., 1994), attention (Knapp & Johnson, 1996) and problem solving (Wiggins & O'Hare, 1995). Cogscreen-AE (Horst & Kay, 1991), one of the most widely used cognitive test batteries, has been showed to be predictive of flight parameter violation in Russian CA (Commercial Aviation) pilots (Yakimovitch, Strongin, Go'orushenko, Schroeder, & Kay, 1994). Moreover, Taylor, O'Hara, Mumenthaler, & Yesavage (2000) were able to explain 45% of the variance of the flight simulator performance with four Cogscreen-AE predictors (speed/working memory, visual associative memory, motor coordination and tracking) in a cohort of 100 aviators aged 50–69 years.

Another set of studies investigating associations between cognition and flight performance aimed to measure the predictive validity of pilot candidate selection tests, as determined by the relationship between students' performance on the selection tests for entry into the training program and the training outcome (indexed by flight performance) (e.g. Burke, Hobson, & Linsky, 1997; Carretta, 2011; Damos, 1993; Martinussen, 1996). Correlations between selection tests and training outcome tend to be weak, ranging between $r = .15$ and $r = .40$, leaving considerable room for improvement. The most robust predictors tend to be composite scores encompassing both cognitive and psychomotor variables (e.g. $r = .37$, Martinussen, 1996), followed by previous training experience (.30). The personality, intelligence, and academic tests yielded lowest mean validities (.14, .16, and .15, respectively).

According to a recent analysis of the French civil aviation pilot training system, the screening tests that are currently in use to recruit pilot candidates are insufficiently challenging, limiting the tests' ability to perform an efficient selection (Matton, 2008). The observed ceiling effects may be explained (at least partly) by the fact that candidates spend several weeks practicing the psychometric selection tests to increase their chances to be recruited, as the selection process is highly competitive. There is thus a need to implement cognitive tests designed to be challenging even for high performing subjects, that are either not readily accessible by students, or (preferably) are not prone to practice effects, being therefore suitable for repeated testing. As revealed by the same study, failure to be selected into the training program was often associated with difficulties in managing concurrent tasks simultaneously, a behaviour typically characterized by high EFs (Executive Functions) demands. On the basis on this outcome, EFs assessment seems particularly relevant in the context of pilot selection.

Carrying out goal-directed behaviours and adapting to novel and complex situations (Royall et al., 2002), inhibiting automatic responses in favour of controlled and regulated behaviour, notably when automatic responses are no longer adequate to the new environmental contingences (Kübler, Dixon, & Garavan, 2006), making decisions (Sanfey, Hastie, Colvin, & Grafman, 2003) and reasoning (Decker, Hill, & Dean, 2007) are all EFs without which a pilot would be unable to operate an aircraft successfully (e.g. monitoring the engine parameters, planning the navigation, maintaining up-to-date SA in such evolving and uncertain context where new information must be integrated and updated continuously, and correctly adapting to traffic and environmental changes).

Two recent studies provide further supporting evidence for the importance of assessing EFs in piloting activities. Research conducted by Causse, Dehais & Pastor (2011) showed that reasoning and updating in working memory were predictive of flight performance as indexed by flight path deviation in a flight simulator. In addition, updating in working memory was correlated with the relevance of a weather-related decision-making during the landing phase. In a 10 years longitudinal study in aviators, Yesavage et al. (2011) observed an interaction between EFs and flight simulator performance over time, such that high scores on tests of EFs at the beginning of the study were associated with slower rates of decline in flight performance. In other words, pilots with higher baseline EF scores showed slower rates of flight performance decline with aging than their same-aged counterparts. Intriguingly, processing speed was an even better predictor of decline in performance than EFs. In both aforementioned studies flight experience was positively associated with piloting performance, implying that levels of flight experience ought to be accounted for when investigating cognition in pilots.

Despite the growing evidence linking cognition and flight performance, we still have got a long way to go to fully understand which specific cognitive functions (or ensemble of cognitive functions) best predict flight performance, and how the observed links are explained in terms of neural substrates. Collectively, the here reviewed literature highlights the potential of EFs to predict flight performance, providing supporting evidence for the inclusion of prefrontal cortex-dependent EF tests in pilot candidate selection procedures. However, there are indications that other (non-prefrontal-cortex-dependent) cognitive and psychomotor functions may add distinct information regarding the subjects' piloting abilities.

Objectives

The primary aim of the current study is to further our understanding of which cognitive functions can best predict flight performance in pilots, taking into account other factors of likely impact such as level of flight experience or demographic variables (e.g. age). Results will be discussed in the light of the underlying neural substrates. Ultimately, the objective is to develop optimized pilot candidate selection tools. A further aim, also in an attempt to improve accident rates, is to provide guidelines for future cockpit instrumentation designs better adapted to the human brain.

Methods

The study will be conducted on French civil aviation pilot students recruited from the ENAC (Ecole Nationale de l'Aviation Civile). Students will be administered the tests that are currently part of the ENAC's pilot candidate selection procedures, as well as selected tests from the CANTAB (Cambridge Neuropsychological Testing Automated Battery, www.cantab.com). The ability of CANTAB to predict students' success over the course of the training program (and as a consequence their flight performance) will be examined and compared to that of the ENAC's selection tests. We propose to use a broad CANTAB battery covering a wide range of cognitive domains and implement an exploratory factor analysis on the acquired data in order to determine the extent to which different cognitive and psychomotor factors provide unique vs. overlapping information with regard to the candidates' flying abilities.

In addition, correlations between individual performances on ENAC's tests vs. the CANTAB tests will be calculated. Given the substantial body of evidence on the neurobiological substrates of the CANTAB tests, it is hoped that this approach may further our understanding of which specific cognitive functions and neural substrates the tests currently used for pilot selection by the ENAC are tapping into.

To gain insight on how cockpit instrumentation could be optimized to improve safety, a subset of CANTAB tests will be integrated in a cockpit display in the context of a dual-task paradigm.

Participants

Subjects recruited from the ENAC are likely to be high performers on the tests to be administered as part of this study due to a selection bias: all of ENAC's pilot students come from preparatory years for competitive admission to the "Grandes Écoles", representing the top 15% of the French General Certificate of Education A-Level students, and are admitted into the pilot training program based on their scientific grades as well as their cognitive abilities assessed through part of the pilot selection tests described below. For example, on a widely used fluid intelligence test (Raven Advanced Progressive Matrices), these pilot students had a mean score (M = 30.05, sd = 2.98) that corresponded to the 90th percentile rank of a population of UK and Australian students (Raven, Raven & Court, 1998).

Pilots' Characteristics

Pilot characteristics have been shown to present a strong influence on flight performance (Causse, Dehais, & Pastor, 2011; Parasuraman, 2003). As a consequence, age and total flight experience will be collected to assess their effects on flight performance. The level of impulsivity of the pilots will be measured by the French version of the Barratt Impulsiveness Scale (Bayle et al., 2000). This test includes 34 items that can be scored to three first-order factors: cognitive (quick decision, 11 items), motor (acting without thinking, 11 items) and nonplanning impulsiveness (present orientation, 12 items).

Assessment of the results of the student pilots during their formation

Beyond the obvious binary variable (success or failure) which has the strong disadvantages of being poorly distributed in the group (around 5% of failure only), a composite performance score will be calculated for each student regarding his results during the formation. This composite score will notably include the flight experience necessary to perform the first solo flight and the ratings from their instructors for each of their flying lesson (at least 20 data points per participants).

Comparing the predictive power of some official selection tests with a variety of CANTAB tests

This step will allow us to uncover the precise cognitive abilities tapped into by the official pilot's selection tests and to compare their respective predictability of success during the training. Below we describe the current official selection tests and the selection of CANTAB tests that will be used.

Current official selection tests

The actual ENAC pilot selection process consists of the assessment of five cognitive abilities: multitasking ability, spatial ability, reasoning ability, attention ability and numerical ability. Each dimension is evaluated through three tests, but in order to reduce the test administration duration, only one test for each dimension will be selected. All these tests will be computer-based and time-limited.

Multitasking test. The multitasking test is composed of six stages in which the participants had to manage one to four tasks, *Ta*, *Tb*, *Tc* and *Td*. At stage 1, the participants have only to perform *Ta*. At stage 2, the participants have to perform two tasks simultaneously, *Ta* and *Tb*. At stage 3, a third task, *Tc*, to perform concurrently is added. At stage 4, a fourth task, *Td*, was added. At stage 5 and 6, no task is added but the relative prescribed importance of the four tasks is varied. Except for the two last stages, each stage is composed of a familiarisation step and a testing step. *Ta* is a monitoring task, where the participants have to check whether four gauges were in acceptable zones. When the gauges are in an unacceptable zone, the participants have to readjust the gauge level with the help of a joystick. *Tb* is a pursuit task, where the participant has to keep a cross in a moving circle with a second joystick. *Tc* is a visual detection task where participants have to press on corresponding function keys when target letters appeared on screen. *Td* was a calculation task where participants have to enter the results of simple arithmetical problems. The whole test lasted 40 minutes approximately.

Spatial visualisation test. The spatial visualisation test is a mental rotation test composed of 60 items to be treated in 15 minutes maximum. Each item consisted of an object to be mentally rotated following the instructions (three to four successive mental rotations of various angles and directions). The participants eventually have to choose the correct answer among 5 propositions.

Abstract reasoning test. The abstract reasoning test was a syllogistic reasoning test composed of 20 items to be treated in 28 minutes maximum and divided in two stages. At the first stage the participants have to solve various syllogisms. At the second stage two syllogisms are interlinked, so the participants have to memorise the premises of one syllogism while solving another syllogism. For each syllogism, the participants have to choose the correct response among 3 to 5 propositions.

Visual perception test. The visual perception test is a sustained attention test, composed of 20 items to be performed in 10 minutes. Each item consists in counting the number of target signs among distractors.

Numerical ability test. The numerical ability test is a mental calculation test, composed of 40 items to be performed in 20 minutes.

CANTAB battery, tests of executive function:
Attention Switching Task (AST). AST is a test of the participants' ability to shift attention between the direction and the location of an arrow displayed on-screen associated with high prefrontal cortical demands (Aarts et al., 2009). Task duration is approximately 7 minutes.

Stop signal task (SST). The stop signal task test is a classic test which uses staircase functions to generate an estimate of stop signal reaction time. This test gives a measure of an individual's ability to inhibit a prepotent response and has been found to be dependent on the right inferior frontal gyrus (Owen 1990, 1996). Arrows appear on the screen and the participant learns to press the button corresponding to the direction in which the arrow points. When a stop signal – an auditory tone – is presented, the participant must inhibit their response. A stop signal occurs on 25% of trials. The task duration is 15 minutes.

One-touch Stockings of Cambridge (OTS). One Touch Stockings of Cambridge is a spatial planning task. Performance on this test activates a neural network of structures including the dorsolateral prefrontal cortex (Baker et al., 1996) and is impaired in patients with frontal lobe damage (Owen et al., 1990). The participants are shown two displays containing coloured balls held in stockings or socks suspended from a beam. The participants must use the balls in the lower display to copy the pattern shown in the upper display following specific rules. OTS is a variant of the Stockings of Cambridge task and places greater demands on working memory as the participant has to work out in their head how many moves the solutions to these problems require. The time taken to complete the pattern and the number of moves required are taken as measures of the participant's planning ability. Completion of the test takes approximately 10 minutes.

Spatial Working Memory (SWM). SWM is a test of the participant's ability to retain spatial information and to manipulate remembered items in working memory. It is a self-ordered task with executive function demand and is a highly sensitive dorsolateral prefrontal cortex measure (Owen 1990, 1996; Manes 1996). The test begins with a number of coloured squares (boxes) being shown on the screen. The aim of this test is that, by touching the boxes and using a process of elimination, the participant should find one blue 'token' in each of a number of boxes and use them to fill up an empty column on the right hand side of the screen. The number of boxes is gradually increased. The colour and position of the boxes used are changed from trial to trial to discourage the use of stereotyped search strategies.

CANTAB battery, Test of reaction time

Reaction Time (RTI). RTI is a measure of simple and choice reaction time, movement time and vigilance during simple and 5-choice reaction time trials. The participant must hold down a button until a yellow spot appears on the screen, and then touch the yellow spot as quickly as possible. The spot appears in a single location during the simple reaction time phase and in one of five locations in the 5-choice reaction time phase. The RTI task is a direct analogue of the rodent 5-choice serial reaction time test (5-CSRT), one of the most well-studied animal behaviour paradigms. In the rat, 5-CSRT shows sensitivity to discrete lesion sites in the prefrontal cortex and to cholinergic lesions in basal forebrain (McGaughy et al., 2002). The task duration is 5 minutes.

CANTAB battery, Tests of visual memory

Pattern Recognition Memory (PRM). This is a test of visual pattern recognition memory in a 2-choice forced discrimination paradigm. The participant is presented with a series of abstract patterns, one at a time, in the centre of the screen. These patterns are designed so that they cannot easily be given verbal labels. In the immediate and delayed recognition phases the participant is required to choose between a pattern they have already seen and a novel pattern. Test duration is about 5 minutes.

Delayed Matching to Sample (DMS). DMS assesses forced choice recognition memory for novel non-verbalisable patterns, and tests both simultaneous and short term visual memory. Lesion and neuroimaging studies, in both humans and non-human primates, indicate that DMS performance is associated with activity in the medial temporal lobes (particularly hippocampus) and frontal lobes (e.g. Sahgal and Iversen, 1978; Curtis et al. 2004; Porrino et al. 2005; Elliot and Dolan 1999). Approximate time of administration is 8 minutes.

Dual-task paradigm

CANTAB tests will be simultaneously administered to pilots during the performance of a flight scenario on a 3-axis motion flight simulator. In this dual-task paradigm, flight performance will be the primary task, while CANTAB tests will be administered as the secondary task. Such a paradigm allows the online in-flight monitoring of the recruitment of specific cognitive functions, following the well-established assumption that the interference between two concurrent tasks is greater when they compete for the same cognitive resources. Future design may preferentially engage cognitive functions that have been shown to be not strongly engaged by piloting activity.

Discussion and future research

It is now well established that neuropsychological test batteries are a reliable means to predict activities crucial for piloting, although the limited predictive validity of pilot candidate selection tests currently in use suggest that there is scope to refine and improve the neuropsychological screening tools. This position paper describes a viable methodology to determine which cognitive function(s) (as measured by a selection of computerized neuropsychological tests) predict pilots' abilities to fly an aircraft. The aim is for this information to guide the development of an optimized cognitive screening tool well-suited for the successful selection of pilot candidates. Experiments like the one described here pave the way for the development of dedicated software designed for the selection and certification of pilots capable of reducing the risk of accidents.

Another goal of this study is to help to provide recommendation on future cockpit instrumentation designs, better adapted to the human brain. Indeed, despite rigorous selection, even improved by more suited selection tests, pilot's errors will probably still be a major contributive factor to accidents. When human brain constraints are well recognized, human error turn out to be the logical consequence of the nominal brain functioning placed in an inappropriate context. In short, human error is also a symptom of the system deficiency. The administration of CANTAB tests during flight performance in a flight simulator in a dual-paradigm context will provide will provide an integrated platform dedicated to the online monitoring of cognitive workload. Whereas physiological measurements (electrocardiogram, EEG) can be extremely informative on this point, their use remains quite complex. In addition, their ability to assess a single cognitive ability is very low. Dual-tasks paradigms are a very simple way to assess cognitive load and are informative of the precise cognitive mechanisms (reasoning, working memory…) involved at the time of testing. For instance, this method would help to assess the effects of the introduction of a new type of display, with the observation of its impact on the performance to the secondary task.

The growing body of literature concerning the neural substrates underlying the CANTAB tests will serve in a first instance to shed light on the neural mechanisms required for diverse piloting activities. In a follow-up experiment, it is planned to use functional near infrared spectroscopy (fNIRS) to measure cortical activation during both CANTAB test performance (to replicate in pilots previous literature on the neural mechanisms involved during CANTAB performance) and piloting activities performed in a flight simulator. fNIRS is a field-deployable non-invasive optical brain monitoring technology that provides a measure of cerebral hemodynamics within the prefrontal cortex in response to sensory, motor, or cognitive activation. Its application in the aforementioned contexts will allow monitoring and localizing the hemodynamic changes associated with relative cognitive workload during performance of the diverse tasks, helping to bridge the gap between piloting and its underlying neurobiological mechanisms. In a recent study, this technique was successfully employed in pilots of unmanned air vehicles to measure cortical hemodynamic changes associated both with the performance of classical neuropsychological tests and with performance of piloting-related complex cognitive and visuomotor tasks (Ayaz et al., 2012)

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