Cognitive aging and flight performances in general aviation pilots

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ABSTRACT

Unlike professional pilots who are limited by the FAA's age rule, no age limit is defined in general aviation. Our overall goal was to examine how age-related cognitive decline impacts piloting performance and weather-related decision-making. This study relied on three components: cognitive assessment (in particular executive functioning), pilot characteristics (age and flight experience) and flight performance. The results suggest that in comparison to chronological age, cognitive assessment is a better criterion to predict the flight performance, in particular because of the inter-individual variability of aging impact on cognitive abilities and the beneficial effect of flight experience.

INTRODUCTION

The population of general aviation (GA) pilots is getting older in the USA (D. J. Hardy & Parasuraman, 1997) and in European countries like France where 41% of private pilots are more than 50 years old (BEA[1], 2008). Unlike professional pilots who are limited by the FAA's "age 65" rule, no such restriction exists for GA pilots. It is worth examining how age-related cognitive decline may impact piloting performance in GA.

[1] French Accident Investigation Bureau.

Casualties in GA

Contrary to commercial aviation (CA) pilots, GA pilots have not necessarily experienced a professional training, fly mostly on their own, without any co-pilot and with very few assistance systems. They have less support from the air traffic control and are more affected by weather conditions. Not surprisingly, in GA, the accident rate is considerably higher than in CA (Li & Baker, 2007). Li and coworkers (2001) analyzed NTSB[2] data files and showed that pilot errors were a probable crash cause in 38% of the airline crashes and of 85% in the GA. A main cause of accidents in GA is related to the loss of situation awareness of the aircraft position: since the light aircrafts' altitude is often relatively low, the loss of the aircraft's position awareness can provoke hazardous heading deviation (Gibson, Orasanu, Villeda, & Nygren, 1997). Indeed it is interesting to denote that the greatest part of the GA fatalities occurs on route, away from the airports, but 46% of the crashes occur at airports (Li & Baker, 1999) and are related to poor decision making by pilots who do not sufficiently take into account external cues (landing distance available, crosswind speed, traffic…).

Age and/or cognitive performance: casualty factors in GA?

Determining which factors are predictive of such errors is a great challenge to improve safety in GA. Several studies have revealed significant aging issues on accident rates in GA (Harkey, 1996; Kay, 2001; Taylor, Kennedy, Noda, & Yesavage, 2007), though these results are criticized (Li, Baker, Lamb, Grabowski, & Rebok, 2002; Rebok, Qiang, Baker, & Li, 2009). Hardy and colleagues (2007) examined the effect of age on pilot cognition in a 28-62

[2] National Transportation Safety Board: independent U.S. federal government agency responsible for civil transportation accident investigation.

years old sample and showed that cognitive performance began to decline very early, from 40 years old. Although this early decline could be partly related to a variety of medical issues, and in spite of the absence of a definitive consensus, the fall of cognitive performance is strongly suspected to be partly responsible for the increased accident rate with age. This raises the importance of monitoring the pilot cognitive functioning as long as the decline of these abilities represents a much higher risk of accident than a sudden physical incapacitation (Schroeder, Harris, & Broach, 2000).

Substantial literature focuses on the evaluation of the cognitive state to predict flight performance (Taylor, O'Hara, Mumenthaler, & Yesavage, 2000) or aeronautical decision-making (Wiggins & O'Hare, 1995), but its conclusions remain contradictory. Several reasons may explain the difficulty to draw a definitive conclusion on the effects of aging on flight performance in GA pilots. There is a great inter-individual variability in the deleterious effects of aging on cognition (Buckner, 2004); studies do not necessarily focus on the cognitive functions that are the most impacted by aging; few researches attempt to link, in the same sample, cognitive performance to flight abilities; a large part of the studies is interested on safety aspects like communications (Morrow, Menard, et al., 2003); few researches are exclusively related to the GA population; finally, another source of complexity arises from the suspected compensative role of flight experience on aging effects (Morrow, Menard, Stine-Morrow, Teller, & Bryant, 2001).

Different measurements of cognitive efficiency have been identified as crucial to the piloting ability, for instance: time-sharing (Tsang & Shaner, 1998), speed of processing (Taylor, et al., 1994), attention (Knapp & Johnson, 1996) or problem solving (Wiggins & O'Hare, 1995). One of the most promising approaches consists in administering a tests battery to pilots, such as Cogscreen-AE (Horst & Kay, 1991), and to correlate their score with their performance during flight simulator sessions or in real flight conditions (Yakimovitch, Strongin, Go'orushenko, Schroeder, & Kay, 1994). Taylor and colleagues (2000) were able to predict 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). However, the identification of the most relevant cognitive functions to predict flight performance remains a key issue.

Executive functions: early markers of age-related cognitive decline?

Contrary to studies that involved Cogscreen-AE, a large battery in terms of explored cognitive functions, we propose to focus specifically on executive functions (EFs). Indeed, these cognitive functions are among the earliest ones to be impacted by aging (Raz, 2000) and represent excellent clues of aging effects on cognitive performance.

Functional neuroimaging brings evidence that the brain is subject to anatomical and physiological modifications in normal aging (Cabeza, Anderson, Locantore, & McIntosh, 2002b). The prefrontal cortex appears to be the earliest affected region (Tisserand & Jolles, 2003) and may prominently account for age-related cognitive changes (West & Baylis, 1998). Because the prefrontal cortex plays a dominant role in the implementation of EFs, it is not surprising that aging provokes a selective alteration of reasoning (De Neys & Van Gelder, 2009) or inhibition, updating and set-shifting (Fisk & Sharp, 2004). However, the executive changes vary considerably across people. The complex interactions between the cerebral structures underlying EFs (Buckner, 2004), sociocultural background and genetic factors (Nagel, et al., 2008) may explain the heterogeneity of this decline.

The study of EFs has appeared recently in aeronautics, for instance, Hardy (2007) found very significant age-related differences in pilots' executive functioning (e.g. inhibition, set-shifting) and Taylor (2005) established a relationship between interference control and the ability to follow air traffic instructions. These cognitive functions underlie goal-directed behavior and adaptation to novel and complex situations (Royall, et al., 2002). They allow the inhibition of automatic responses in favor of controlled and regulated behavior, in particular when automatic responses are no longer adequate to the new environmental contingences. They also encompass decision-making (Sanfey, Hastie, Colvin, & Grafman, 2003) or reasoning abilities (Decker, Hill, & Dean, 2007). According to Miyake (Miyake, et al., 2000), three major low-level EFs are moderately correlated, but clearly separable: set-shifting between tasks or mental sets ("shifting"), inhibition of dominant or prepotent responses ("inhibition"), and updating and monitoring of working memory (WM) representations ("updating"). According to our hypotheses, EFs are crucial for piloting. Indeed, contrary to most jobs that are characterized by maintenance functions and very little integration of new information, which can hide effects of cognitive decline (Park, 1994), piloting activity takes place in a dynamical, uncertain and rapidly changing environment where new information must be integrated and updated continuously. EFs appear critical for handling the flight, monitoring engine parameters, planning navigation, maintaining an up-to-date situation awareness - SA - (Endsley, 1999), correctly adapting to traffic and environmental changes and performing accurate decision making by inhibiting wrong behavioral responses. In a light aircraft, the basic analogical and separated instrumentation requires mental effort and reasoning capabilities to maintain SA. Eventually, since EFs modulate mental flexibility, inhibition of inappropriate responses or the capacity to maintain up-to-date SA, they are critical to relevant aeronautical decision-making.

Aims and Hypotheses

In this experiment, we proposed to specifically evaluate three low-level EFs (shifting, inhibition and updating) and to link, in the same sample, their efficiency to flight navigation performance and decision making. Although it is little explored, decision making is a very important issue regarding pre-cited flight safety statistics and especially during the critical landing phase. This phase requires following an arrival procedure through several waypoints and implies formalized sequences of actions (e.g. to adjust engine parameters, to extend the flaps…). It also requires decision-making processes based upon rational elements like the maximum crosswind speed for a given aircraft. In spite of the presence of such formalized rules and procedures, numerous pilots make erroneous decision.

We have also taken into account a well established general ability: reasoning. Reasoning reflects fluid intelligence and supports processes relevant for many kinds of abilities (verbal, spatial, mathematical, problem solving etc.) and adaptation to novelty. It is a concept strongly related to executive functioning (Decker, et al., 2007; Roca, et al., 2009). We also assessed the speed of processing because it represents a reliable measure of general cognitive decline and it modulates the overall cognitive efficiency (Salthouse, 1992). Finally, we have also taken into account age to assess its participation to the flight performance variation and we have controlled total flight experience in the analysis. Indeed, experience is well known to improve flight performance and to protect against aging effects (Harkey, 1996; G Li, Baker, Qiang, Grabowski, & McCarthy, 2005; Morrow, et al., 2009; Taylor, et al., 2007). Our hypothesis was that the chronological age is not a sufficient criterion to predict piloting performance and decision-making relevance and that cognitive performance is a much more relevant criterion.

METHODS

Participants

The participants were 32 private licensed pilots rated for visual flight conditions. The pilots that had no longer flown during the past two years were excluded because of the potential impact on flight simulator performances. All participants had past experience with a computer-based flight simulator. Inclusion criteria were male, right handed, as evaluated by the Edinburgh handedness inventory (Oldfield, 1971), native French speakers, under- or post-graduate. A professionally trained clinical psychologist neuropsychologically examined all participants. Non-inclusion criteria were expertise in logics, airline pilots and sensorial deficits, neurological, psychiatric or emotional disorders and/or being under the influence of any substance capable of affecting the central nervous system. Due to their influence on decision-making processes, emotional disorders identification was based on impulsivity and anxiety assessment with the Barratt Impulsiveness Scale (BIS-10, Bayle et al., 2000) and the Spielberger state anxiety inventory (STAI Y-A, Bruchon-Schweitzer & Paulhan, 1993). All participants received complete information on the study's goal and experimental conditions and gave their informed consent.

Flight scenario

The flight scenario has been setup in collaboration with flight instructors to reach a satisfying level of difficulty and realism. To familiarize the participants with the PC-based flight simulator and to minimize learning effects in order to obtain reliable flight simulator performances, each volunteer underwent a training session. Before the navigation, they received the instructions, a flight plan and various technical information related to the aircraft (e.g. aircraft's crosswind limit). Basically, the scenario was to take off, reach a waypoint with the help of the aircraft radio navigation system and finally, land on a specified airport. The pilots were instructed that they were in charge of all the decisions and that they could only receive an informative weather report before landing. In order to increase the subject’s workload, on route, the pilots had to perform a mental arithmetic calculation of the ground speed (thanks to the embedded chronometer). Moreover, a failure of the compass was scheduled. After this failure, the pilots had to navigate thanks to the magnetic compass, which presents the particularity to be difficult to use as it is anti-directional. The flight scenario lasted for approximately 45 min.

Flight performance

The assessment of flight performance was founded on flight path deviations (FPD), expressed in terms of the amount of angular deviation in the horizontal axis from the ideal flight path. This measure is widely used as an indicator of the primary flight performance (Hyland, 1993; Leirer, Yesavage, & Morrow, 1989; Yakimovitch, et al., 1994). The deviation was measured from take-off to the waypoint before the landing decision, in order to assess the same flight segment for all the pilots. Indeed, after the waypoint, some pilots quitted the flight before others (because of the no-landing decision).

Crosswind landing decision

After the waypoint and before reaching the runway threshold, the pilots must state whether the meteorological conditions, as provided by the automatic information system of the arrival airport, were compatible with a landing or necessitated a go-around and a diversion. For this purpose, the pilots had to assess the crosswind component using a commonly utilized formula[3]. This formula is part of the basic knowledge of pilots and a rather important wind (i.e. 10-15 knots) systematically leads the pilot to consider it. The calculation result exceeded of 6 knots the aircraft's maximum crosswind limit specified in the documentation provided to the pilots at the time of flight preparation. The measured dependent variable was binary: correct when the pilot decided to divert before the runway threshold, incorrect when the pilots continued the landing beyond the runway threshold.

Neuropsychological test battery

Target hitting test

It provides a basic psychomotor reaction time (Loubinoux, et al., 2005). The instruction was to click as fast as possible on each target. The performance was measured by a velocity index inspired by the Fitts' law (1954). The index is the average ratio of the base 10 logarithm of the distance in pixels between two targets, divided by the time in seconds to go from the first target to the second. The index is considered as a measure of the speed of processing.

[3] Crosswind (in knots) = effective wind (in knots) * sin (angle between runway and wind direction). Moreover, pilots have mnemonic methods to simplify this calculation.

The 2-back test

It aims at assessing WM, in particular maintenance and updating abilities (Chen, Mitra, & Schlaghecken, 2008). Participants viewed a continuous stream of stimuli and had to determine whether the current stimulus matched on a specific dimension (shape, for our test) the stimulus 2-back in the stimuli sequence. The percentage of correct responses was collected. It is considered as a measure of working-memory updating ability.

The reasoning test

It has been used in a previous study to assess executive functioning (Causse, Sénard, Démonet, & Pastor, 2010). The goal of the task is to solve syllogisms by choosing, among three suggested solutions, the one that is a logical conclusion. Syllogisms are based on a logical argument in which one proposition (the conclusion) is inferred from a rule and from another proposition (the premise). We used four existing forms of syllogisms: modus ponendo ponens, modus tollendo tollens, setting the consequent to true and denying the antecedent. Each participant had to solve 24 randomly displayed syllogisms. The measurement was the percentage of correct responses.

The Wisconsin Card Sorting test – WCST – (Berg, 1948)

It gives information on the subject's abstract reasoning, discrimination learning and shifting abilities (Eling, Derckx, & Maes, 2008). The test version here is a computer implementation that is very similar to the clinical version of the WCST (Heaton, 1981). Participants had to sort cards according to three different unknown categories (color, shape, number); an audio feedback indicated whether the response was correct or not (yes/no). When the participant categorized successfully ten cards, the target category was automatically changed. The task ended when six categories were achieved (color, shape, number, color, shape, number) or when the deck of 128 cards was used. The total numbers of errors was derived from the individual cards' records. This number is considered as a measure of set-shifting ability.

The Spatial Stroop test

It assesses the conflict between the meaning of a location word (e.g. "left") and the location where the word is displayed. The ability to restrain a response according to the localization of the word gives information on inhibition efficiency. This conflict appears to be provoked by the simultaneous activation of both motor cortices (Desoto, Fabiani, Geary, & Gratton, 2001). Our test encompasses four control conditions. "Stroop neutral meaning" (SNM): a motor answer is given with the appropriate hand according to the word meaning displayed centrally on the screen; "Stroop neutral position" (SNP): the response is given according to the location of a string of XXXXX, displayed at the left or the right of the screen; "Stroop meaning incompatible/compatible" (SMI/SMC): the response is given according to the meaning of the word, compatible or incompatible with its location at the screen. In order to get the pure effects of inhibition, the interference score was calculated to control reading and localization effects by: SMI - (SNP*SNM) / (SNP+SNM).

RESULTS

Statistical analysis

The relationship between age and neuropsychological variables and the ability of the neuropsychological variables to predict piloting performance was tested using regression analyses. The Bonferroni-Holm (Holm, 1979) correction was applied to control the familywise error rate. The landing decision being a Boolean variable, we performed one-way ANOVAs using decision as a categorical variable to examine whether the cognitive efficiency differed according to the pilot's decision relevance.

Pilot characteristics

The mean age of our sample was 47.28 years (SD = 15.87). The mean level of education was very high (15.4 years, SD = 2.25) and did not significantly correlate with age ($p = .462$, $r = -.14$). In all pilots, impulsivity and anxiety trait level were within a normal range (respectively, mean = 40.81, SD = 9.29; mean = 36.42, SD = 7.60). The mean total experience was of 1545 hours of flight (Range = 57-13000). As expected the Bravais-Pearson correlation revealed that there was no significant correlation between age and total flight experience ($p = .117$, $r = .28$). This is an important outcome as it helps to disentangle between aging and experience impacts on piloting performance.

Aging effects on cognitive variables

Table 1 shows aging effects on all assessed cognitive variables. With the exception of reasoning performances, Bravais-Pearson correlation demonstrated that all the neuropsychological abilities declined with age. Reasoning performances solely showed a trend to diminish. The rather steep slope of the decrease of velocity with age (see Figure 1) existed also in the other cognitive abilities that showed a marked decline around 55 years of age. For instance, regarding the update in WM, ten participants out of eleven of more than 55 years of age had a correct response rate below 70%, which was never the case for any younger participants. Similarly, set-shifting strongly declined after 55, where five pilots had a higher interference index than any other pilots.

Figure 1 about here

Table 1 about here

Explanatory variables of piloting performance

The mean FPD amplitude was 29.36 (SD = 11.92). We first examine the predictability of age and neuropsychological performances on the piloting ability. We conduct flight experience-partialled correlation to control for flight experience effects, see Table 2.

Table 2 about here

It is interesting to note that flight experience-partialled correlation between reasoning and FPD was the most significant (see Figure 2), suggesting that this general ability was among the most critical to reach a good piloting performance. In addition, speed of processing and updates in WM were also significantly predictive of FPD. The higher the reasoning, the speed of processing and updates in WM abilities were, the smaller the FPD was. In contradiction with our expectations, analysis showed that age was correlated with piloting performance. We therefore conducted 5 others partial correlations between age and piloting performance and we controlled flight experience plus cognitive effect. None of these 5 correlations remained significant. This outcome showed that age effect on piloting performance was mediated by the cognitive performance decline.

Figure 2 about here

Cognitive variables related to the crosswind landing decision

Results showed that 50% of the pilots erroneously kept on landing in spite of adverse wind conditions. ANOVA revealed that pilots who were more akin to make the good decision to go-around demonstrated better updating in WM and set-shifting score (respectively, $F(1,30) = 9.76$, $p = .003$, $\eta^2p = .25$; $F(1,30) = 5.33$, $p = .027$, $\eta^2p = .15$), see Figure 3 and Figure 4. These results suggest that these two abilities were particularly critical for decision-making process.

Figure 3 about here

Figure 4 about here

DISCUSSION

A first objective of this study was to assess the effects of normal aging on cognitive functioning. Our sample of pilots was submitted to a neuropsychological battery that taped three crucial low-level EFs (Miyake, et al., 2000). EFs analysis on GA pilots is rather uncommon and is of interest as this specific population usually presents a high level of education, which is supposed to be protective from aging effects. However, in spite of this high level of education, analysis revealed that pilots demonstrated a significant decrease in every considered EF. Consistently with literature (Gregoire & Van Der Linden, 1997; Taylor, et al., 2007; Verhaeghen, 1993; Yesavage, Dolhert, & Taylor, 1994), updating in WM was sensitive to age effects. The decline was particularly obvious from 55, where ten out of eleven pilots had a lower performance than all the younger ones. In the same way, set-shifting and inhibition were also significantly impacted by age. Various studies have highlighted that older adults demonstrate lower mental flexibility (Ashendorf & McCaffrey, 2008; Fristoe, Salthouse, & Woodard, 1997) and a greater sensitivity to interference compared to younger adults (Bruyer, Van der Linden, Rectem, & Galvez, 1995; West & Baylis, 1998). Taken together, these results confirmed that the three taped executive functions are vulnerable to aging effects (Fisk & Sharp, 2004).

We also assessed two well-established general abilities that modulate many kinds of cognitive functions: reasoning and speed of processing. Reasoning did not appear to be consistently impacted by aging, the decline of correct responses in the syllogism resolution task was only near significance threshold. De Neys (2009) showed that reasoning performances begin to drastically decline only after 65. It makes sense that the linear regression was not significant given the large age range of our sample (22-78). Finally, the observed reduced speed of processing was also a classical effect of normal aging (Birren & Botwinick, 1955; Houx, Jolles, & Vreeling, 1993; Salthouse, 1996). According to Salthouse (1991), the speed at which the neural connections are performed determines the number of nervous centers that cooperate at the same time, and therefore, modulates intellectual performance. Thus, speed of processing is considered as a factor of cognitive deterioration, and not as a symptom of such degradation. This overall cognitive decline, despite a high mean level of education (15.4 years) may appear counterintuitive. However, Tucker-Drob (2009) showed that a high level of education has no consistent neuroprotective effect. According to him, education increases cognitive skills in advanced age, but does not influences the rate of cognitive decline. In other words, higher cognitive performances in advanced age associated with a high level of education are allowed by preexistent superior cognitive abilities. The rate of cognitive decline remains the same as for less educated people. In this perspective, it was coherent that, in spite of inter-individual variability, linear regressions could reveal age related cognitive decline in the tested pilots.

Our results suggest that EFs are crucial for piloting. Indeed, the pilot's activity takes place in a dynamical and changing context where new information must be integrated and updated continuously. Update in WM appeared to be essential in this context, most likely to maintain up-to-date SA as suggested by a previous work that showed that losing SA provokes hazardous heading deviation (Gibson, et al., 1997). Besides, a study by Taylor and coworkers (2000) found that WM and speed of processing are predictive of the piloting performance. We are in line with these results as the index of speed of processing, which is a reliable measure of general intellectual performance (Salthouse, 1992), was also related to piloting performance in our study. In addition, our results suggest that reasoning ability appeared to be one of the most predictive functions of piloting ability. This latter outcome confirmed previous results of Causse and coworkers (in press) and Wiggins & O'Hare (Wiggins & O'Hare, 1995) that showed strong links between reasoning and piloting performance. This is particularly interesting as this function was not clearly correlated with age in our study. In this perspective, the assessment of reasoning performance appears to be critical for safety and not only in older pilots. Reasoning processes are very close to EFs and reflect fluid intelligence, a central cognitive ability linked to various types of mental activity (calculation, problem solving etc.) and is essential to adaptation to novel problems. Complex and novel problems cannot be solved directly by referring to a store of long-term knowledge but require analytic or fluid reasoning. The complexity of our flight scenario with unexpected events such as compass failure may have contributed to a strong involvement of reasoning abilities. The pilots had to perform numerous operations during the navigation to estimate their position and they must use radio navigation systems to reach waypoints. In addition, the scheduled compass failure required pilots to use the anti-directional magnetic compass as backup. The use of this instrument is counterintuitive and may have caused additional difficulties.

According to our hypotheses and other authors (Li, et al., 2002; Rebok, et al., 2009), analysis that controlled for cognitive effects showed that chronological age per se was not a relevant variable to predict piloting performance. Schroeder (2000) has pointed out the necessity to use neuropsychological tests rather than relying on age. We must admit that a more extreme sample size including a great proportion of pilots aged of more than 60 would have increased the strength of our conclusions. Unfortunately we had difficulties to recruit several pilots of this category as they were reluctant to take part to the experiment. We plan to perform a future study focused on such a population (60+) in collaboration with airfield medical staff to facilitate recruitment. Nevertheless, our results tend to confirm the limitation of using the chronological age as a single criterion to decide whether a given pilot is able to fly or not.

We also addressed weather-related decision-making. In agreement with several authors (Causse, et al., in press; Dehais, Tessier, & Chaudron, 2003; Goh & Wiegmann, 2002;

Muthard & Wickens, 2003; Orasanu, et al., 2001), our results confirmed the difficulty of pilots to revise their flight plan, especially during the final approach where a great number of them keep on landing in adverse meteorological conditions (Rhoda & Pawlak, 1999). Indeed, this was the case for 50% of our volunteers. ANOVAs showed that updating and set shifting may have been particularly related to accurate decision-making. These abilities were probably particularly essential to integrating the degradation of meteorology during the course of flight scenario and to recollect the aircraft's maximum crosswind limit at the time of the approach. In our experiment, this inability to call to mind critical information, to maintain an up-to-date SA and to inhibit the no more appropriate flight plan seems to lead pilots to erroneously persist on landing. In this sense, Muthard (2003) has shown the great difficulties encountered by some pilots to integrate critical contextual changes such as deteriorating weather, and a survey of Ebbatson (2007) has demonstrated that 30% of the pilots are unable to recall the crosswind limit of their aircraft. Given that the 2-Back task also assesses the maintenance in WM, another additional explanation is that the participants did not keep in mind the whole radio-communicated message, in particular the critical wind speed data. This is consistent with the prior findings of Morrow (2003) and Taylor (2005) which showed that poor WM performances degraded the ability to follow ATC radio communication. These outcomes provide new insight for a particular category of accidents called Plan Continuation Errors - PCE - when pilots fail to perceive the changing context of the airspace and subsequently to inhibit the flight plan and consider alternative ones. This phenomenon has been demonstrated both in CA (Rhoda & Pawlak, 1999; Orasanu, et al., 1998) and GA (BEA, 2000). The BEA revealed that these pilots' trend to land (called the get-home-itis syndrome in the study) has been responsible for more than 41.5% of casualties in light aircrafts (BEA, 2000).

The identification of the brain mechanisms related to pilot errors requires much progress. However, the results of this study confirm that neuropsychological evaluation is a reliable means for predicting piloting and decision-making performances. This is an important issue as long as the cognitive decline is subtle and may impact flight safety. These types of experiments pave the way to the development of dedicated software including neuropsychological tests that could be administered for pilot certification and during their medical examination. This could help preventing dangerous behaviors, in particular by detecting subtle, though crucial, cognitive impairments. In addition, cognitive decline can reflect the onset of a certain neuropathology or be transient, and reflect the adverse effects of substance consumption (medication, alcohol…), chronic stress, mental fatigue, depression etc. In such cases, its early detection could help pilots, by advising them and directing them to a medical staff.

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References

Ashendorf, L., & McCaffrey, R. J. (2008). Exploring Age-Related Decline on the Wisconsin Card Sorting Test. *The Clinical Neuropsychologist, 22*(2), 262-272.

Bayle, F., Bourdel, M., Caci, H., Gorwood, P., Chignon, J., Ades, J., et al. (2000). Factor analysis of french translation of the Barratt impulsivity scale (BIS-10). *Canadian journal of psychiatry*, 45(2), 156.

BEA (2000). The get-home-itis-syndrome. Retrieved from http://www.bea.aero/etudes/objectifdestination/objectifdestination.pdf.

Berg, E. A. (1948). A simple objective technique for measuring flexibility in thinking. *The Journal of general psychology, 39*, 15.

Birren, J. E., & Botwinick, J. (1955). Speed of response as a function of perceptual difficulty and age. *Journal of Gerontology, 10*(4), 433.

Bruchon-Schweitzer, M. L., & Paulhan, I. (1993). Le Manuel du STAI-Y de CD Spielberger, adaptation française. Paris: ECPA.

Bruyer, R., Van der Linden, M., Rectem, D., & Galvez, C. (1995). Effects of age and education on the Stroop interference. *Archives de psychologie(Genève), 63*(247), 257-267.

Buckner, R. L. (2004). Memory and Executive Function in Aging and AD Multiple Factors that Cause Decline and Reserve Factors that Compensate. *Neuron, 44*(1), 195-208.

Burian, B., Orasanu, J., & Hitt, J. (2000). *Weather-related decision errors: Differences across flight types.* Paper presented at the HFES 2000, Santa Monica, CA, USA.

Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002b). Aging gracefully: compensatory brain activity in high-performing older adults. *Neuroimage, 17*(3), 1394-1402.

Causse, M., Dehais, F., & Pastor, J. (in press). Executive functions and pilot characteristics predict flight simulator performance in general aviation pilots. *The International Journal of Aviation Psychology*.

Causse, M., Sénard, J., Démonet, J., & Pastor, J. (2010). Monitoring Cognitive and Emotional Processes Through Pupil and Cardiac Response During Dynamic Versus Logical Task. *Applied psychophysiology and biofeedback, 35*(2), 115-123.

Chen, Y. N., Mitra, S., & Schlaghecken, F. (2008). Sub-processes of working memory in the N-back task: An investigation using ERPs. *Clinical Neurophysiology, 119*(7), 1546-1559.

De Neys, W., & Van Gelder, E. (2009). Logic and belief across the lifespan: the rise and fall of belief inhibition during syllogistic reasoning. *Developmental Science, 12*(1), 123-130.

Decker, S. L., Hill, S. K., & Dean, R. S. (2007). Evidence of construct similarity in executive functions and fluid reasoning abilities. *International Journal of Neuroscience, 117*(6), 735-748.

Dehais, F., Tessier, C., & Chaudron, L. (2003). *GHOST: experimenting conflicts coutermeasures in the pilot's activity.* Paper presented at the IJCAI, Acapulco, Mexique.

Desoto, M., Fabiani, M., Geary, D., & Gratton, G. (2001). When in doubt, do it both ways: Brain evidence of the simultaneous activation of conflicting motor responses in a spatial Stroop task. *Journal of Cognitive Neuroscience, 13*(4), 523-536.

Ebbatson, M., Harris, D., & Jarvis, S. (2007). Crosswind Landings in General Aviation: A Modified Method of Reporting Wing Information to the Pilot. *The International Journal of Aviation Psychology, 17*(4), 353-370.

Eling, P., Derckx, K., & Maes, R. (2008). On the historical and conceptual background of the Wisconsin Card Sorting Test. *Brain and cognition, 67*(3), 247-253.

Endsley, M. (1999). Situation awareness in aviation systems. *Handbook of aviation human factors*, 257-276.

Fisk, J., & Sharp, C. (2004). Age-related impairment in executive functioning: Updating, inhibition, shifting, and access. *Journal of Clinical and Experimental Neuropsychology, 26*(7), 874-890.

Fitts, P. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology: Applied, 47*, 381-391.

Fristoe, N. M., Salthouse, T. A., & Woodard, J. L. (1997). Examination of age-related deficits on the Wisconsin Card Sorting Test. *Neuropsychology, 11*(3), 428.

Gibson, J., Orasanu, J., Villeda, E., & Nygren, T. (1997). *Loss of situation awareness- Causes and consequences.* Paper presented at the International Symposium on Aviation Psychology, 9 th, Columbus, OH, USA.

Goh, J., & Wiegmann, D. (2001). Visual flight rules flight into instrument meteorological conditions: An empirical investigation of the possible causes. *The International Journal of Aviation Psychology, 11*(4), 359-379.

Goh, J., & Wiegmann, D. (2002). Human factors analysis of accidents involving visual flight rules flight into adverse weather. *Aviation, Space, and Environmental Medicine, 73*(8), 817.

Gregoire, J., & Van Der Linden, M. (1997). Effect of age on forward and backward digit spans. *Aging, Neuropsychology, and Cognition, 4*(2), 140-149.

Hardy, D., Satz, P., D Elia, L., & Uchiyama, C. (2007). Age-Related Group and Individual Differences in Aircraft Pilot Cognition. *The International Journal of Aviation Psychology, 17*(1), 77-90.

Hardy, D. J., & Parasuraman, R. (1997). Cognition and flight performance in older pilots. *Journal of Experimental Psychology: Applied, 3*, 313-348.

Harkey, J. A. Y. (1996). Age-related changes in selected status variables in general aviation pilots. *Transportation Research Record: Journal of the Transportation Research Board, 1517*(-1), 37-43.

Heaton, R. (1981). A manual for the Wisconsin card sorting test: Odessa, FL: Psychological Assessment Resources.

Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics, 6*(2), 65-70.

Horst, R., & Kay, G. (1991). *COGSCREEN- Personal computer-based tests of cognitive function for occupational medical certification.* Paper presented at the International Symposium on Aviation Psychology, 6 th, Columbus, OH, USA.

Houx, P. J., Jolles, J., & Vreeling, F. W. (1993). Stroop interference: aging effects assessed with the Stroop Color-Word Test. *Experimental Aging Research, 19*(3), 209-224.

Hyland, D. (1993). *Experimental evaluation of aging and pilot performance.* Paper presented at the International Symposium on Aviation Psychology, 7 th, Columbus, OH, USA.

Kay, G. (2001). *Effects of aging on aviation-related cognitive function in commercial airline pilots.* Paper presented at the In *Proceedings of the 72nd Meeting of the Aerospace Medical Association,* Aviat Space Environ Med 2001; 71:241.

Knapp, C., & Johnson, R. (1996). F-16 Class A mishaps in the US Air Force, 1975-93. *Aviation, Space, and Environmental Medicine, 67*(8), 777.

Leirer, V., Yesavage, J., & Morrow, D. (1989). Marijuana, aging, and task difficulty effects on pilot performance. *Aviation, Space, and Environmental Medicine, 60*(12), 1145.

Li, G., & Baker, S. (1999). Correlates of pilot fatality in general aviation crashes. *Aviation, Space, and Environmental Medicine, 70*(4), 305.

Li, G., & Baker, S. (2007). Crash risk in general aviation. *Jama, 297*(14), 1596.

Li, G., Baker, S., Grabowski, J., & Rebok, G. (2001). Factors associated with pilot error in aviation crashes. *Aviation, Space, and Environmental Medicine, 72*(1), 52.

Li, G., Baker, S., Qiang, Y., Grabowski, J., & McCarthy, M. (2005). Driving-while-intoxicated history as a risk marker for general aviation pilots. *Accident Analysis & Prevention, 37*(1), 179-184.

Li, G., Baker, S. P., Lamb, M. W., Grabowski, J. G., & Rebok, G. W. (2002). Human factors in aviation crashes involving older pilots. *Aviation, Space, and Environmental Medicine, 73*(2), 134-138.

Loubinoux, I., Tombari, D., Pariente, J., Gerdelat-Mas, A., Franceries, X., Cassol, E., et al. (2005). Modulation of behavior and cortical motor activity in healthy subjects by a chronic administration of a serotonin enhancer. *Neuroimage, 27*(2), 299-313.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49-100.

Morrow, D., Menard, W., Ridolfo, H., Stine-Morrow, E., Teller, T., & Bryant, D. (2003). Expertise, cognitive ability, and age effects on pilot communication. *The International Journal of Aviation Psychology, 13*(4), 345-371.

Morrow, D., Menard, W., Stine-Morrow, E., Teller, T., & Bryant, D. (2001). The influence of expertise and task factors on age differences in pilot communication. *Psychology and Aging, 16*(1), 31-46.

Morrow, D., Miller, L., Ridolfo, H., Magnor, C., Fischer, U., Kokayeff, N., et al. (2009). Expertise and age differences in pilot decision making. *Aging, Neuropsychology, and Cognition, 16*(1), 33-55.

Morrow, D., Ridolfo, H., Menard, W., Sanborn, A., Stine-Morrow, E., Magnor, C., et al. (2003). Environmental support promotes expertise-based mitigation of age differences on pilot communication tasks. *Psychology and Aging, 18*(2), 268-284.

Muthard, E., & Wickens, C. (2003). *Factors that mediate flight plan monitoring and errors in plan revision: Planning under automated and high workload conditions.* Paper presented at the 12 th International Symposium on Aviation Psychology, Dayton, OH, USA.

Nagel, I. E., Chicherio, C., Li, S. C., von Oertzen, T., Sander, T., Villringer, A., et al. (2008). Human aging magnifies genetic effects on executive functioning and working memory. *Frontiers in Human Neuroscience, 2*.

Oldfield, R. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia, 9*(1), 97.

Orasanu, J., Martin, L., & Davison, J. (1998). *Errors in Aviation Decision Making: Bad Decisions or Bad Luck?* Paper presented at the Fourth Conference on Naturalistic Decision Making, Warrenton, VA, United States.

Orasanu, J., Martin, L., & Davison, J. (2001). Cognitive and contextual factors in aviation accidents: Decision errors. *Linking Expertise and Naturalistic Decision Making*, 209-225.

Park, D. (1994). Aging, cognition, and work. *Human Performance, 7*(3), 181-205.

Raz, N. (2000). Aging of the Brain and Its Impact on Cognitive Performance: Integration of Structural and Functional Findings. *The handbook of aging and cognition*.

Rebok, G., Qiang, Y., Baker, S., & Li, G. (2009). Pilot Age and Error in Air-Taxi Crashes. *Aviation, Space, and Environmental Medicine, 80*(7), 647.

Rhoda, D., & Pawlak, M. (1999). An assessment of thunderstorm penetrations and deviations by commercial aircraft in the terminal area, Massachusetts Institute of Technology, Lincoln Laboratory, Project Report NASA/A-2.

Roca, M., Parr, A., Thompson, R., Woolgar, A., Torralva, T., Antoun, N., et al. (2009). Executive function and fluid intelligence after frontal lobe lesions. *Brain, doi:10.1093*.

Royall, D. R., Lauterbach, E. C., Cummings, J. L., Reeve, A., Rummans, T. A., Kaufer, D. I., et al. (2002). Executive Control Function: A Review of Its Promise and Challenges for Clinical Research. A Report From the Committee on Research of the American Neuropsychiatric Association. *J Neuropsychiatry Clin Neurosci, 14*(4), 377-405.

Salthouse, T. A. (1991). *A theory of cognitive aging*: Elsevier.

Salthouse, T. A. (1992). Working-memory mediation of adult age differences in integrative reasoning. *Memory and Cognition, 20*(4), 413–423.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological review, 103*(3), 403-427.

Sanfey, A. G., Hastie, R., Colvin, M. K., & Grafman, J. (2003). Phineas gauged: decision-making and the human prefrontal cortex. *Neuropsychologia, 41*(9), 1218-1229.

Schroeder, D., Harris, H., & Broach, D. (2000). Pilot age and performance: an annotated bibliography. Oklahoma City, OK: Federal Aviation Administration, Civil Aeromedical Institute. *Human Resources Research Division*.

Taylor, J., Kennedy, Q., Noda, A., & Yesavage, J. (2007). Pilot age and expertise predict flight simulator performance: A 3-year longitudinal study. *Neurology, 68*(9), 648.

Taylor, J., O'Hara, R., Mumenthaler, M., & Yesavage, J. (2000). Relationship of CogScreen-AE to flight simulator performance and pilot age. *Aviation, Space, and Environmental Medicine, 71*(4), 373.

Taylor, J., O'Hara, R., Mumenthaler, M., Rosen, A., & Yesavage, J. (2005). Cognitive ability, expertise, and age differences in following air-traffic control instructions. *Psychology and Aging, 20*(1), 117-133.

Taylor, J., Yesavage, J., Morrow, D., Dolhert, N., Brooks III, J., & Poon, L. (1994). The effects of information load and speech rate on younger and older aircraft pilots' ability to execute simulated air-traffic controller instructions. *The Journal of Gerontology, 49*(5), P191.

Tisserand, D. J., & Jolles, J. (2003). Special issue on the involvement of prefrontal networks in cognitive ageing. *Cortex, 39*, 1107-1128.

Tsang, P., & Shaner, T. (1998). Age, attention, expertise, and time-sharing performance. *Psychology and Aging, 13*, 323-347.

Tucker-Drob, E. M., Johnson, K. E., & Jones, R. N. (2009). The cognitive reserve hypothesis: A longitudinal examination of age-associated declines in reasoning and processing speed. *Developmental psychology, 45*(2), 431.

Verhaeghen, P. (1993). Marcoen, A, & Goossens, L. Facts an& fiction about memory aging: A quantitative integration of research findings. *Journal of Gerontology: Psychological Sciences, 48*, 157-171.

West, R., & Baylis, G. C. (1998). Effects of increased response dominance and contextual disintegration on the Stroop interference effect in older adults. *Psychology and Aging, 13*, 206-217.

Wiggins, M., & O'Hare, D. (1995). Expertise in aeronautical weather-related decision making: A cross-sectional analysis of general aviation pilots. *Journal of Experimental Psychology: Applied, 1*(4), 305-320.

Yakimovitch, N., Strongin, G., Go'orushenko, V., Schroeder, D., & Kay, G. (1994). *Flight performance and CogScreen test battery in Russian pilots.* Paper presented at the 65th Annual Scientific Meeting of the Aerospace Medical Association, San Antonio, TX, USA.

Yesavage, J., Dolhert, N., & Taylor, J. (1994). Flight simulator performance of younger and older aircraft pilots: effects of age and alcohol. *Journal of the American Geriatrics Society, 42*(6), 577.

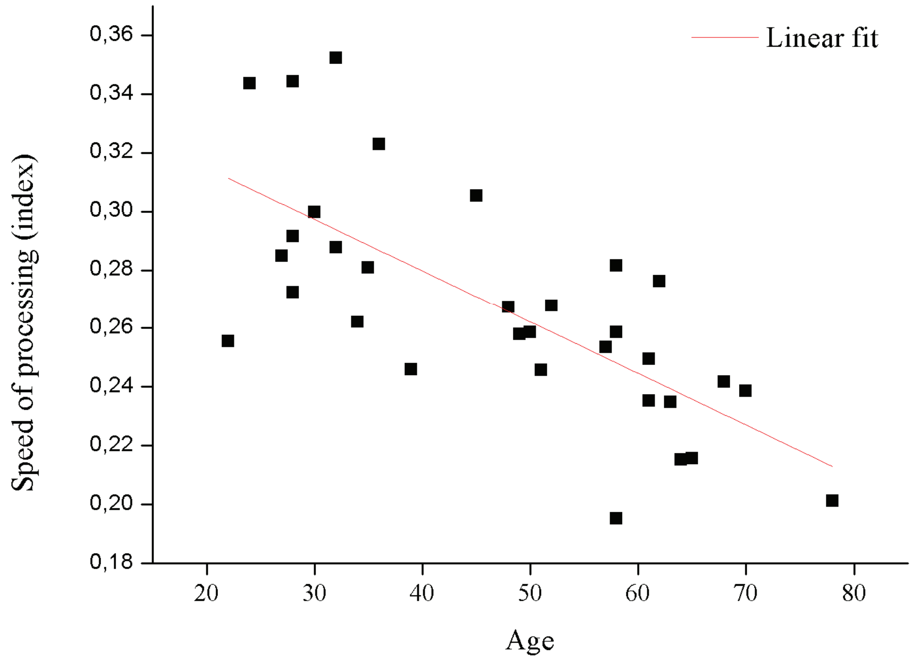

Figure 1. Speed of processing index regressed on age (n = 32).

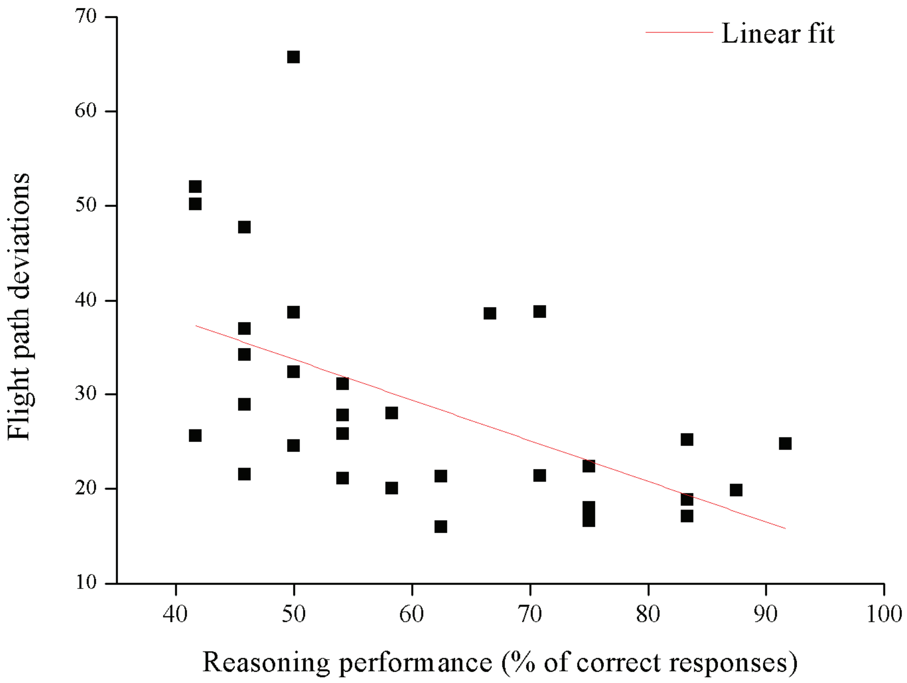

Figure 2. FPD regressed on reasoning performances (n = 32).

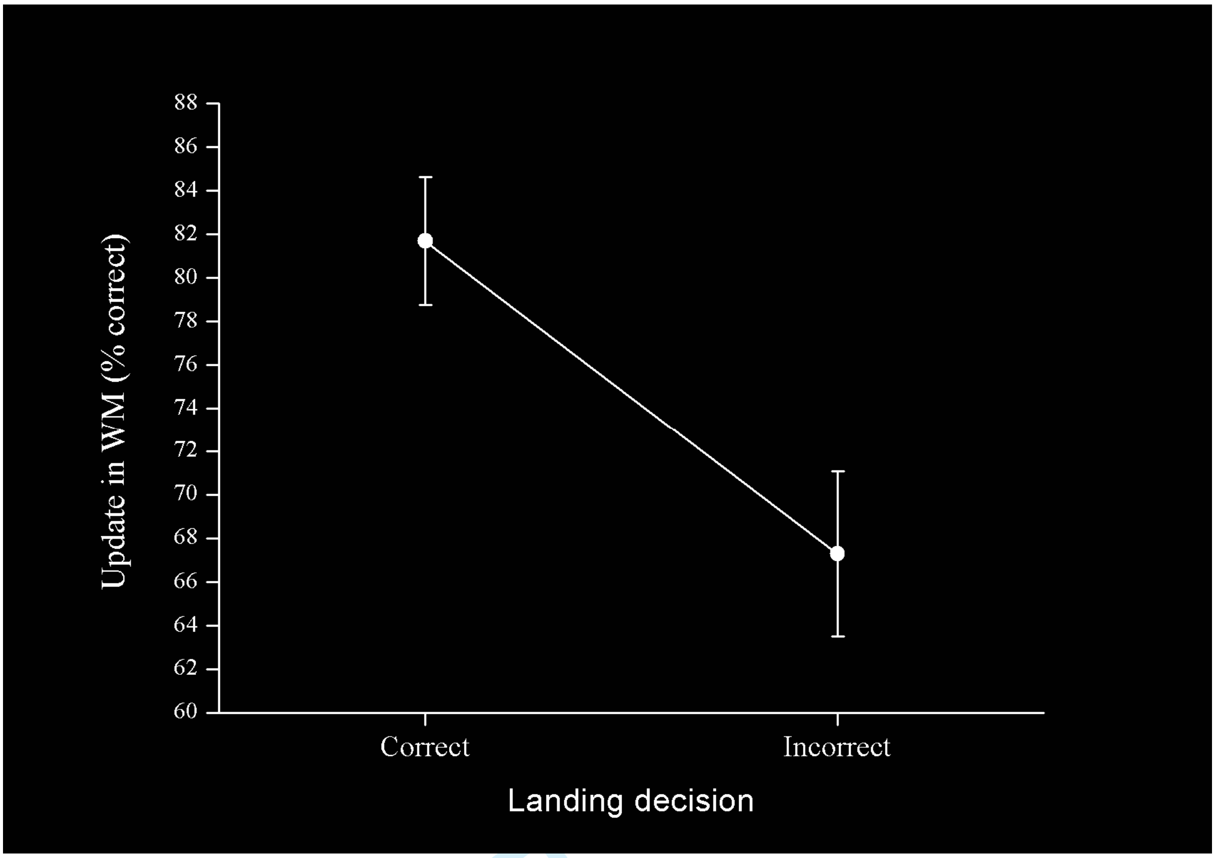

Figure 3. Update in WM performances according to the landing decision (n = 32).

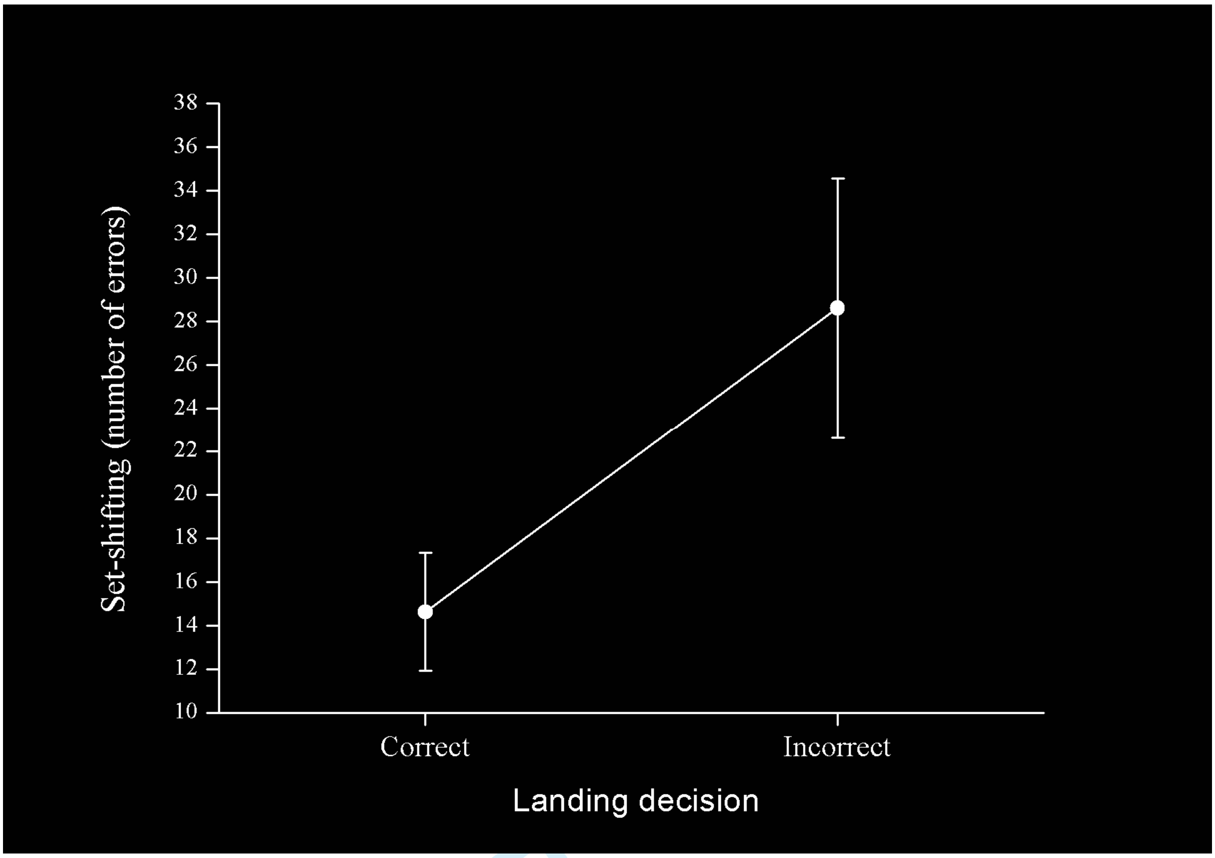

Figure 4. Set shifting performances according to the landing decision (n = 32).

Table 1. Neuropsychological performances regressed on age (n = 32) (* p ≤ .05; ** p ≤ .01;*** p ≤ .001).

Variables	r	R^2	Corrected p-value
Update in WM	-.65	.42	<.001***
Set-shifting	+.40	.16	.042*
Inhibition	+.57	.32	.002**
Reasoning	-.31	.09	.0829
Speed of processing	-.72	.52	<.001***

Table 2. Flight experience-partialled correlation between age and neuropsychological performances with piloting performance (n = 32) (* p ≤ .05; ** p ≤ .01).

Variables	r	R^2	Corrected p-value
Age	50	.25	.020*
Update in WM	-.41	.17	.022*
Set-shifting	-.23	.5	.452
Inhibition	+.19	.3	.322
Reasoning	-.54	.30	.006**
Speed of processing	-.45	.20	.050*