Executive functions and flying performance in pilots

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Introduction:
Flying was predominantly a physical and sensory-oriented task in the first generation of aircrafts. In contrast, flying is nowadays more a cognitive task requiring the pilot to act as a supervisory system manager and decision maker. This shift has led to the inclusion of cognition as a predictor for flying performance, in particular so-called executive functions (EFs). EFs is an umbrella term encompassing a broad range of separate, but interrelated higher cognitive functions (Friedman & Miyake, 2017). Despite their broad nature, four core EFs have been established based on behavioural and neural studies: working memory updating, set-shifting, response inhibition, and conflict monitoring (Miyake et al., 2000; Enriquez-Geppert et al., 2010). In this study we systematically review the current knowledge regarding the relationship between EFs and flying performance in pilots (Enriquez-Geppert et al., 2021, *under review*). Understanding the precise nature of this relationship has the potential to fuel research on tailoring neuropsychological diagnostics for the selection of pilots, cockpit design, and enhancing EFs with brain training approaches, to ultimately improve flying performance and safety.

Method:
A systematic search in PsycInfo, PubMed, Web of Science, and Cochrane resulted in ten eligible studies (Causse et al., 2011a; Causse et al., 2011b; Causse et al., 2017; Kennedy et al., 2013; Morrow et al., 2003; Taylor et al., 2000; Taylor et al., 2005; Van Benthem & Herdman, 2016; Van Benthem & Herdman, 2017; Yesavage et al., 2011). Inclusion criteria were: peer-reviewed articles published in English, inclusion of a behavioural EFs measure, inclusion of a measure assessing flying performance, inclusion of pilots as study subjects, and year of publication between January 2000 and July 2020. Data regarding the sample, EFs measure(s), flying performance measure(s), and statistical results were extracted from these studies.

A comprehensive overview was created using a framework of EFs and flying performance (EF-Fly) based on two models. First, the EFs measures were categorized as complex or specific tasks (Miyake et al., 2000). Complex tasks require a wide variety of cognitive processes, including multiple EFs and other cognitive abilities. In contrast, specific tasks focus on one of the four core EFs. Second, the flying performance measures were categorized into the aspect Flying, Navigating, or Communicating, following the golden rule: 'fly, navigate, and communicate' (Owens, 2013).

Results and discussion:
Regarding the EFs measures, the included studies primarily used complex tasks, such as the computerized Wisconsin Card Sorting Test, assessing both multiple EFs and other cognitive abilities simultaneously. Some studies also included tasks measuring specific EFs, such as the Two-back task for working memory updating or the Stroop task for conflict monitoring. The core EFs set-shifting and response inhibition were not assessed in any study. Regarding flying performance, in all studies, except

the one from Morrow and colleagues (2003), a flight simulator was used. The aspect Flying was measured with a flight summary score, flight path deviation, or crosswind landing decision, Navigating was measured with a diversion management score or staying on course score, and Communicating was measured with an aviation communication task.

As most studies used complex tasks, the main results indicate that multiple EFs together with other cognitive abilities are associated with most of the measures of Flying, Navigating, and Communicating, and furthermore can predict its performance. This suggest a general involvement of cognition (including EFs) in flying performance. However, these results do not permit the identification of a specific EF crucial for flying. Fortunately, some studies focused on the core EFs, measured with specific tasks, which hint for more specific relationships, for instance between working memory updating and the aspects Flying (i.e., crosswind landing decision) and Communicating (i.e., aviation communication task). Working memory updating significantly predicted a correct crosswind landing decision (Causse et al., 2011a) and could dissociate pilots making a correct or incorrect decision (Causse et al., 2011b). Studies show that pilots have the tendency to continue landing despite adverse conditions and poor crosswind landing decisions are the reason for most incidents (Ebbatson et al., 2004), making it critical for safe flying. Furthermore, working memory span demonstrated significant correlations with aviation communication performance both in- and outside a flight simulator (Taylor et al., 2005; Morrow et al., 2003). This was expected, as aviation communication strongly involves working memory (Durantin et al., 2016): pilots have to memorize information from air traffic control, read back the details, and subsequently adapt their trajectory and speed. Air traffic control messages represent a common source of errors, as they could be misunderstood or even executed incorrectly (Molesworth & Estival, 2015). These hints for a relationship between working memory and aviation communication display an important finding, as direct training of working memory capacity and span could potentially prevent errors in communication. In contrast, conflict monitoring could not predict and was not associated with Flying (i.e., flight path deviation and crosswind landing decision). The relationships between conflict monitoring and Navigating or Communicating were not assessed, making it an interesting direction for future research.

Overall, the current review demonstrates that research on this topic is still in its early stages as only some studies assessed the relationship between specific EFs and flying performance. For future research we propose the following general directions:

- Conceptualization of EFs and flying performance measures based on existing theoretical frameworks (e.g., the proposed EF-Fly framework)
- Usage of multiple sensitive and specific tasks to assess core EFs (i.e., working memory updating, set-shifting, response inhibition, and conflict monitoring)
- Assessment of flying performance in simulated or real flights
- Control for or take into account factors affecting EFs and/or flying performance (e.g., age, experience, gender, and personality)
- Investigation of ways to improve EFs (e.g., brain training approaches)

Table 1: References

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