Domain-Specific Interference Tests on Navigational Working Memory in Military Pilots

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INTRODUCTION: Human navigation is a very complex ability that encompasses all four stages of human information processing (sensory input, perception/cognition, selection, and execution of an action), involving both cognitive and physical requirements. During flight, the pilot uses all of these stages and one of the most critical aspect is interference. In fact, spatial tasks competing for the same cognitive resource cause greater distraction from a concurrent task than another task that uses different resource modalities.

METHODS: Here we compared and contrasted the performance of pilots and nonpilots of both genders performing increasingly complex navigational memory tasks while exposed to various forms of interference. We investigated the effects of four different sources of interference: motor, spatial motor, verbal, and spatial environment, focusing on gender differences.

RESULTS: We found that flight experts perform better than controls (Pilots*:* 6.50 ± 1.29; Nonpilots*:* 5.45 ± 1.41). Furthermore, in the general population, navigational working memory is compromised only by spatial environmental interference (Nonpilots*:* 4.52 ± 1.50*)*; female nonpilots were less able than male nonpilots. Also, the flight expert group showed the same interference, even if reduced (Pilots: 5.24 ± 0.92); moreover, we highlighted a complete absence of gender-related effects.

DISCUSSION: Spatial environmental interference is the only interference producing a decrease in performance. Nevertheless, pilots are less affected than the general population. This is probably a consequence of the need to commit substantial cognitive resources to process spatial information during flight.

KEYWORDS: interference, human navigation, visuo-spatial memory, aircrew, gender difference.

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This research compares and contrasts the performance of pilots and nonpilots of both genders performing increasingly complex navigational memory tasks while exposed to various forms of interference. The navigational tasks took place in navigational space beyond their local reach and the interference consisted of four scenarios that tasked various brain functions and skills involving motor, spatial motor, verbal, and spatial environments. In detail, motor interference involves motor activity that is believed to interfere with navigation performance in terms of an automatic behavior like walking. Spatial motor interference includes more complex motor activity in which movement is related to other voluntary or automatic movements that is believed to interfere with navigation performance in behaviors like marching. Verbal interference involves acoustic warning while answering a radio call during navigation. Spatial environmental interference includes locating different spatial cues in the environment regardless of our own position during navigation.

During flight, the pilot uses all four stages of the human information processing system (sensory input, perception/cognition, selection, and execution of action), involving both

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cognitive and physical requirements. Pilots must understand the data they are receiving, memorize them, and be able to recall those data, make decisions based on those data, and when the course changes, they are required to respond by physically using their hands to fly the aircraft.

Sometimes the pilot will be able to ignore the flying task while concentrating on the system monitoring task, but occasionally the situation may force the pilot to perform both tasks at once. This obviously creates some conflict, given that the sources of information are separated, as well as a cognitive conflict, since both tasks can simultaneously require all four processing stages. This is similar to what happens during flight when the adjustment of a course trajectory is needed and the system monitoring triggers a correction intervention.

Clearly, one of the most important aspect of flying involves the interference of visually presented tasks, visual monitoring, and cognitive processing. This is a crucial issue when determining how much mental workload the pilot is experiencing and how well she/he can be expected to perform. Specifically, during a flight mission, a pilot manages several multimodal stimuli, such as: 1) when air-to-ground communication via radio or with other aircraft are carried out, even during navigation instrument flight rules (IFR) or during instrumental cross-check; and 2) in a Ground Control Station, keeping a drone flying and checking the trajectory and the altitude.

In a study by Liu and Wickens,[12] pilots were required to perform a tracking task while simultaneously executing either a spatial decision task (predict the future position of a vector) or a verbal decision task (mental arithmetic). By manipulating the scanning distance (long/short), type of scanning (certain vs. uncertain target location), and decision codes (spatial/verbal), they were able to show that the inherently spatial visual scanning task produced more interference with a concurrent spatial task than with a concurrent verbal task, demonstrating that tracking error, decision accuracy, and workload all suffered more when both tasks involved spatial activities.[12]

In another study, Wickens et al.[28] showed that difficult and spatial tasks which compete for the same cognitive resource were more subject to distraction with a concurrent task compared to an easy or verbal task that uses different resource modalities. Furthermore, in a more recent study, Gugerty and Brooks[7] demonstrated that a concurrent cognitive side task causes more interference on a primary tracking task than simple monitoring tasks do, particularly when the cognitive task is visually displayed, involves spatial judgments, or is more demanding.

In conclusion, several studies have shown greater interference between two tasks performed simultaneously and requiring processing by the same, rather than different modalities.[10,11,27] These findings in the flight environment suggest the importance of studying the interferences affecting human navigation skills. Indeed, human avigation is a very complex ability because the space around us is not a unitary construct and our brain represents it according to its distance from where a particular action is taking place.[9] Far or navigational space defines actions within walking distance, while near space defines actions within reaching distance.[13,17,20] By the means of an fMRI study, Nemmi et al.[13] demonstrated that different neural correlates underpin spatial learning within reach (near space within the arm's reach) and navigational (far space beyond the body space) space. In particular, these authors found that the calcarine cortex, the lingual gyrus, and the dorsolateral prefrontal cortex in the right hemisphere are selectively involved in learning within navigational space, while the middle occipital gyrus, the inferior temporal gyrus, and the lingual and fusiform gyrus in the left hemisphere are selectively involved in learning within reaching space.[13] Our brain not only codes and processes different distances as different spaces due to the action an individual can perform, but it attributes a different meaning to reaching and navigational space.

As recently demonstrated[16] for recalling a sequence in the navigational space, we mentally represent it like a pathway, while when we have to recall a sequence in the reaching space, we use a visual strategy. In the same study, the authors found that men did not show differences between the two spaces, while women are better in navigational than reaching space. This result is in line with other findings[6] which support the idea that behavioral gender-related differences in the performance of navigation can be due to differences in individual strategies adopted in performing the task (i.e., finding the exit in a virtual maze). Specifically, these authors found differences in the neural substrates activated during navigation. Women solve the task by engaging the right parietal and the right prefrontal cortex, whereas men cope with it by recruiting the left hippocampus. These authors[6] interpreted the activity of the prefrontal area observed in women as a consequence of the working-memory demand to hold the landmark cues "on-line," while the left hippocampal activity observed in men may be due to the processing of multiple geometric cues. In support of these gender-related differences, there is also evidence that hormonal changes during pregnancy affect memory in reaching distance, but not memory in navigation.[17] From a behavioral perspective, Coluccia and Iosue's model[2] explains the gender differences in navigational tasks, hypothesizing a disadvantage in women in visuo-spatial working memory load. In the general population, women perform worse than men when the navigational task requires holding "on-line" multiple visuo-spatial cues.

A very recent study investigated the interference effects on navigational working memory, demonstrating that only environmental interferences can hamper performance during navigation.[15] Specifically, the authors investigated the effects of four different sources of interference: motor, spatial motor, verbal, and spatial environmental, finding an interference effect due only to the environmental interference. Furthermore, focusing on gender differences, they also found that men were more proficient than women, regardless of the type of interference.[15]

In the flight environment, this specific kind of interference has not been investigated yet and we believe that it is important to understand how it comes into play during flying activities. A career as a military pilot, in fact, involves tasks that place demands on spatial cognition, focusing on human navigation,[22–24] as well as specific cognitive abilities, such as working memory, perceptual speed, pattern-matching ability, cognitive complexity, mental simulation, and attention sharing.[4,14]

So far, some studies have shown that a gender effect was not present in military pilots with regard to mental rotation tasks and navigational memory,[23,24] suggesting that in this specific population men and women use the same strategy to navigate. For this reason, we decided to investigate whether male and female pilots suffer from environmental interference during a concurrent navigational working memory task and whether the same gender effect observed in the general population was present.

In the classic studies on interference models to predict pilots' performance in the spatial decision tasks, a greater disruption emerged in the presence of a visual rather than a verbal conflict. Generally speaking, task interference is affected by task features and not just by the sum of the competitive task's overall difficulty. In other words, the secondary task hampers the primary task performances only when it requires sharing the same cognitive resource.[5] We hypothesized that military pilots could perform better than the general population in the sense that they were less sensitive to the environmental interference effect.

METHODS

Subjects

We investigated 34 pilots (PIL, 17 men and 17 women) and 40 non-pilots (NON-PIL, 18 men and 22 women). A few of them were students of the Italian Air Force Academy who were in the final stage of the training course and most of them were already assigned to operational units (with experience on the following aircraft: C-130, Falcon 50, G-222, and P-180 Avanti). The recruitment included almost the totality of female pilots in the Italian Air Force at the time of the study.

The mean flight hours for men was 1760.53, SD = 1935.64, and for women was 782.11, SD = 588.19 [$t(33) = -1.22$; $P = 0.12$]. Non-pilots were college students with no flight experience. They were matched with the pilots for age [$t(73) = -1.23$; $P = 0.11$], sex, and educational level (i.e., third year of University or with basic degree) [$t(73) = 1.23$; $P = 0.89$]. Only right-handed subjects were included in both groups,[21] all with no history of neurological or psychiatric illness. The protocol met the criteria of the Declaration of Helsinki and was approved by the Institutional Ethical Board. All subjects signed an informed consent form before entering the study and undergoing the protocol, which did not include any invasive procedures. Subjects were grouped for the analysis as pilots and non-pilots; demographic details are provided in **Table I**.

Table I. Demographic Details of the Subjects.

GROUPS	AGE (YR)	EDUCATION (YR)	FLIGHT HOURS
Male Pilots (*N* = 17)	30.41 (7.91)	16.88 (1.58)	1250.00 (1064.42)
Female Pilots (*N* = 17)	30.71 (6.17)	18.29 (2.20)	774.12 (564.15)
Male Non-pilots (*N* = 18)	28.78 (3.46)	17.28 (2.27)	—–
Female Non-pilots (*N* = 22)	27.95 (4.95)	17.96 (1.09)	—–

Equipment

We followed the same procedure and the same apparatus used in Piccardi et al.[15] The WalCT[18,19] is an extended version of the Corsi Block-Tapping test (CBT) (3 × 2.5 m; scale 1:10 of the CBT Corsi, 1972;[3] see **Fig. 1A**) and consists of nine squares placed on the floor, in the same position as in the standard Corsi Block-Tapping test,[3] in an otherwise empty room. During the test, the subject is asked to walk and reach different locations.

Procedure

WalCT. The WalCT was administered to assess topographical short-term memory (TSTM) and was administered to all participants in four different dual-task conditions, with four different interferences. Different span sequences, balanced for degree of difficulty, were used in different conditions. The administration order was counterbalanced across subjects to avoid the effect of familiarization with the experimental apparatus.

During the WalCT (single task-condition), the investigator illustrated the sequence by walking across the carpet and stopping on each square for 2 s. The subject then had to repeat the same sequence as the investigator by walking and stopping on the squares included in the sequence. The sequences gradually increased in length, as in the CBT (starting from a two-block sequence), and the score was calculated by the number of squares in the longest sequence remembered correctly (square span).

TSTM: dual task conditions. The WalCT was administered under four interference conditions, during which the participants were asked to perform an additional task while the investigator was illustrating the sequence. As in the standard WalCT, the square sequences gradually increased in length and the score was calculated by the number of squares in the longest sequence remembered correctly (square span). Different sequences were developed for each WalCT interference condition.

The procedure was the same as the standard TSTM assessment. During the motor (M) interference, participants were required to walk on the spot while the investigator was illustrating the sequence. Then they were asked to repeat the same sequence as the investigator, as in the standard WalCT administration. During the spatial motor (SM) interference, participants were required to repeatedly make a sequence of leg movements (i.e., the participant had to bend his/her leg at knee level and then stretch it out backward, alternating the left and right leg, always standing in the same place) while the investigator was illustrating the sequence. They were then asked to repeat the same sequence as the investigator, as in the standard WalCT administration.

During the verbal (articulatory suppression: AS) interference, participants were required to repeat an irrelevant speech sound (e.g., COLA–COLA–COLA–COLA) while the investigator was illustrating the sequence. They were then asked to repeat the same sequence as the investigator, as in the standard WalCT administration.

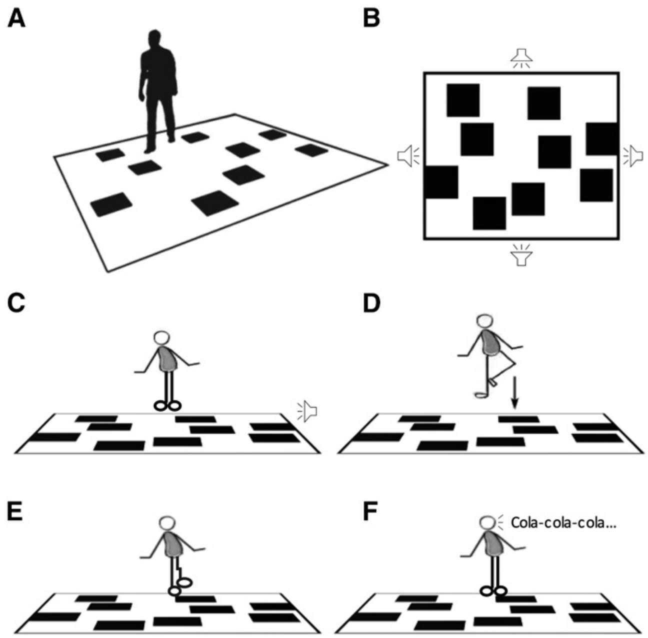

Fig. 1. Experimental design and paradigm. A) WalCT layout. B) Sources of sound used during spatial environmental interference. C) Spatial environmental interference. D) Spatial motor interference. E) Motor interference. F) Articulatory suppression.

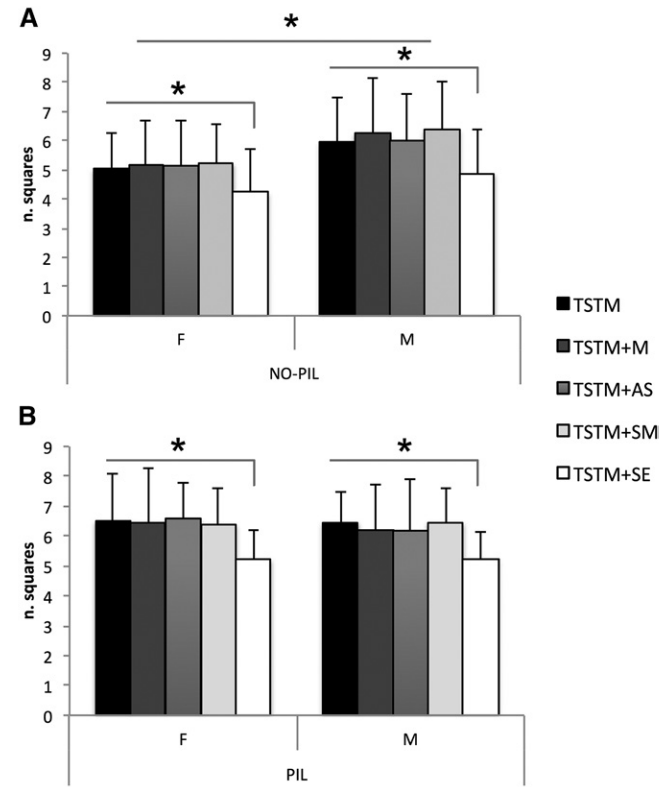

Fig. 2. Main effect of the task and Group-by-Gender interaction. Averaged performances and standard deviation in the different experimental conditions in A) NON-PIL and B) PIL. PIL = Pilots; NON-PIL = Non pilots; F = Females; M = Males; single task: TSTM, topographical short-term memory; dual task: TSTM + AS, topographical short-term memory + articulatory suppression; TSTM + M, topographical short-term memory + motor interference; TSTM + SM, topographical short-term memory + spatial motor interference; TSTM + SE, topographical short-term memory + spatial environmental interference.

Finally, during the spatial environmental (SE) interference, as in Wen et al.,[25] participants were required to point with their index finger to the source of a sound coming from a PC every 2 s from four random different positions (in front, behind, on the right, or on the left) while the investigator was illustrating the sequence. They were then asked to repeat the same sequence as the investigator, as in the standard WalCT administration.

Statistical Analyses

Statistical analyses were performed using SPSS (IBM SPSS Statistics 20). A 2 × 2 × 5 mixed factorial ANOVA was performed on the participants' square span, with Group (PIL vs. NON-PIL) and Gender (Male vs. Female) as between factors, and Task as repeated measure (TSTM, TSTM + S, TSTM + SM, TSTM + AS, TSTM + SE). Post hoc comparisons were performed using Bonferroni's correction for multiple comparisons. For the Pilot group we also performed a 2 × 5 mixed factorial ANOVA, with Gender (Male vs. Female) as the between factor and Task as the repeated measure, in order to directly investigate the existence of gender differences in the PIL group in the single and dual task experimental conditions. Furthermore, we performed a Pearson's correlation analysis to investigate whether flight hours correlated with the PIL group performance.

RESULTS

The 2 × 2 × 5 mixed ANOVA revealed a main effect of the Group [$F(1, 70) = 9.674$, $P = 0.003$; partial Eta-squared = 0.121], with PIL performing better than NON-PIL (**Fig. 2A** and **2B**). We also found a main effect of the Task [$F(4, 280) = 15.152$, $P = <0.0001$; partial Eta-squared = 0.178]. Post hoc comparisons showed that participants performed significantly worse on the TSTM + SE dual-task condition ($P < 0.001$, Bonferroni's correction for multiple comparisons) as compared to the other conditions (Fig. 2A and 2B). Interestingly, we also found a significant Group × Gender interaction [$F(1, 70) = 5.064$, $P = 0.028$; partial Eta-squared = 0.067]. Post hoc comparisons showed that only Males and Females of the NON-PIL group differed ($P = 0.005$, Bonferroni's correction for multiple comparisons) in performing the experimental tasks (Fig. 2A and 2B). No other significant effect was observed.

The 2 × 5 mixed ANOVA on PIL's performances confirmed the absence of any gender effect in this group, but also confirmed a main effect of the Task [$F(4, 128) = 7.591$, $P < 0.001$; partial Eta-squared = 0.192]. Post hoc comparisons showed that the PIL group performed worse on the TSTM + SE dual-task condition ($P < 0.05$, Bonferroni's correction for multiple comparisons) as compared to the other conditions (Fig. 2B). The Task × Gender interaction was not significant [$F(4, 128) = 0.276$, $P = 0.893$; partial Eta-squared = 0.009]. Pearson's correlation analysis did not show any significant correlation with flight hours (**Fig. 3**).

	Flight Hours	WalCT	WalCT + M	WalCT + AS	WalCt + SM	WalCT + E
Flight Hours						
Pearson's Correlation	1	−0.148	0.087	−0.054	0.203	0.112
P-Value		0.402	0.623	0.760	0.249	0.529
N	34	34	34	34	34	34
WalCT						
Pearson's Correlation	−0.148	1	0.337	0.510	0.156	0.255
P-Value	0.402		0.052	0.002	0.378	0.145
N	34	34	34	34	34	34
WaltCT + M						
Pearson's Correlation	0.087	0.337	1	0.414	0.457	0.068
P-Value	0.623	0.052		0.015	0.007	0.702
N	34	34	34	34	34	34
WaltCT + AS						
Pearson's Correlation	−0.054	0.510	0.414	1	0.280	0.224
P-Value	0.760	0.002	0.015		0.108	0.203
N	34	34	34	34	34	34
WaltCT + SM						
Pearson's Correlation	0.203	0.156	0.457	0.280	1	0.014
P-Value	0.249	0.378	0.007	0.108		0.939
N	34	34	34	34	34	34
WaltCT + E						
Pearson's Correlation	0.112	0.255	0.068	0.224	0.014	1
P-Value	0.529	0.145	0.702	0.203	0.939	
N	34	34	34	34	34	34

Fig. 3. Correlation matrix.

DISCUSSION

In most circumstances, a pilot's task involves a continuous stream of activities. Many of these activities are overt and easily observable, such as movement of the flight control sticks, communications with air traffic control, or manipulating switches. Others tasks are much more covert and less observable, such as planning, diagnosing, or monitoring. A skilled pilot will selectively choose which tasks and actions to perform at the appropriate time, knowing which tasks to emphasize and which ones to ignore when the workload is high. The skilled pilot will also execute those actions smoothly and appropriately, the most important of which is control of the aircraft.[26] Therefore, pilots represent the ideal population to observe and study the effects of interferences during a navigational working memory task.

When we refer to navigational working memory, we intend the system responsible for the transient holding and processing of new environmental information. For instance, an individual used navigational working memory while finding his/her way back out of a shopping center where he/she had never entered before. However, if a blackout intervenes, it interferes with the temporarily stored environmental information useful for finding the way back. This is similar to a flight environment in which a pilot has to approach a new airport and finds everything suddenly covered by volcanic ash.

In the general population, navigational working memory is compromised only by a spatial environmental interference, demonstrating that the motor aspects in navigation, even when present, do not interfere with the normal acquisition of environmental information.[15] Similarly, verbal interference, when the task is not landmark-based, does not interfere with the processing of navigational information.[15] Furthermore, female non-pilots were less able than male non-pilots and in both women and men performance was affected by spatial environmental interference. This finding suggests that at least people without experience of flight are subjected to the same mechanism of interference. In the present study, we compared the performance of the general population with that of flight experts. We found a reduced effect of interference in the experts and the complete absence of gender-related effects.

This result demonstrates that even if spatial environmental interference is the only one that produces a decrease in performance, pilots, because of their experience in handling simultaneous tasks, are less jeopardized compared to the general population. In addition, in the present study, we did not observe any gender-related effects in female pilots, which is consistent with previous data by Verde et al.[24] The lack of gender-related effects in pilots compared to non-pilots is partially due to the strict criteria used during the selection testing for entering the Italian Air Force Academy.[23] In fact, women who pass the trials are already strongly selected for their high spatial abilities, which might explain the reason female pilots behaved differently from women from the general population. Furthermore, in the present study, we did not observe an advantage due to the hours of flight experience; this suggests that in some way navigational competencies in military flight experts were already developed when they were submitted to the initial screening for the Air Force Academy. Another explanation could be that we investigated the resistance to the spatial environmental interference in expert military pilots with many flight hours. Since there was a small variability in flight hours, in a future study it would be interesting to compare expert pilots with military cadets to better investigate the effect of experience on environmental interference.

Only few studies have investigated gender-related effects in military pilots. For instance, Koonce and Berry[8] found that female cadets were faster than male cadets on perceptual tasks during flight training performance in simulators. Conversely, male cadets were quicker on visual memory, spatial orientation, spatial scanning tasks, and psychomotor tasks. However, Koonce and Berry[9] did not find general differences between men and women in basic flying abilities. In line with these results, Carretta,[1] looking at gender differences in the selection tests of U.S. Air Force pilots, did not find any reliable evidence of such differences in skill between male and female pilots. Similarly, Verde et al.[24] did not observe any gender differences in the mental transformation of an object and, in a very recent study,[23] the same authors did not find any gender effects in navigational working memory or in navigational long-term memory.

Taken together this evidence strongly suggests that, once selection has taken place, female and male pilots are equally competent in their job activities. Furthermore, as recently demonstrated by Sutton et al.,[22] the spatial updating performed by pilots during flight is transferred to a nonaviation context. This suggestion is in line with the evidence that pilots, differently from the matched group without flight experience, suffered less from spatial environmental interference during navigational working memory tasks. Very likely, this is a consequence of the need to commit substantial cognitive resources to process spatial information during daily flight activities.

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