PNT Resilience and the impact of satellite radio positioning disruptions on piloting teams

D. Castro (1), V. Conceição (2) e S. Campaniço Cavaleiro (2)

(1) Escola Naval, Instituto Universitário Militar

(2) CINAV, Escola Naval, Instituto Universitário Militar, Chalmers University of Technology

(3) CINAV, Marinha Portuguesa

Synopsis

The relevance of positioning, navigation, and timing for success in maritime operations has grown significantly. Yet, satellite-based PNT - GNSS - fallibility raises resilience concerns, especially in Navigation Warfare environments and confined water spaces. Therefore, we initiated an experimental study on resilience performance under GNSS disruption by understanding how navigation teams deal with those conditions. Participants are pilotage teams from the Portuguese Navy playing scenarios in a navigation simulator. The study intends to correlate performance with other measurements on experience, training, knowledge, attitudes, behaviors, cognition, and procedure compliance (for piloting and post-disruption actions). The study aims to provide insight into teams and success factors in the face of GNSS disruption, effectively appraising the positioning resilience of the Portuguese Navy.

Keywords: Navigation Safety; NAVWAR; PNT Resilience; Team Performance; Joint Cognitive Systems

1. Introduction

Resilience has been a topic that has increasingly driven scientific research (Janssen et al., 2006). The world is a volatile environment, especially because of the pace that just about everything seems to change (Notteboom and Siu Lee Lam, 2014). The maritime industry is no exception. Some of the most used and relied upon technologies used today aboard ships, whether civil or military, have been around for a relatively short time. Expanding this idea on the technology which the present study will tend to focus on: satellite radio positioning systems, GPS (Global Positioning System), the first of its kind, was introduced merely around 30 years ago and has been undergoing constant technology upgrades and changes both in the system itself and in other support systems such as DGPS (Differential GPS) technology. In addition, several other Global Navigation Satellite Systems (GNSS) are operated by other countries. This technology has profoundly impacted how maritime operations are conducted and is very much relied upon because of its accessibility and accuracy. Unfortunately, the pace of change has not only been impacting the technology positively but has the potential to disrupt it as well.

It is increasingly easier and cheaper to create disruptions to the GPS systems. The system itself is relatively fragile to intentional and unintentional interferences due to its working principles, mainly the low power of its radio waves. Although these disruptions have not been frequent enough to drive the mass use of alternatives, they have been enough to raise both awareness and concern about the topic and the need for resilience of Position, Navigation and Timing (PNT). The importance attributed to the issue is evidenced by the growing production, in the last couple of decades, of publications and other relevant scientific work (Janssen et al., 2006), inclusively being featured several times through different scopes in NATO (North Atlantic Treaty Organization) Review (Paulauskas, 2020).

Workgroups have also been established, civil and military, at a national and international level to tackle PNT resilience, such as the new DoD (Department of Defense) Task Force “Position, Navigation and Timing Control” or the Exploratory Team “NATO PNT Open System Architecture and Standards to Ensure PNT in NAVWAR (Navigation Warfare) Environments” (Goward, 2020). In addition, NATO consistently identifies resilience as a priority, emphasising the need to train to fail and anticipate disruptive challenges, acting to prevent or adapt to them (NATO, 2022).

The Portuguese Navy, given the importance of PNT in its operations, is naturally a stakeholder and therefore should be a part of the global effort of upholding a higher standard, more resilient navigation, as any ship of the Portuguese Navy today is, to a more significant or lesser extent, dependent on a rigorous PNT reference for the healthy functioning of most of its systems (Aresta, 2017). Therefore, it becomes essential that the institution seeks a deeper understanding of the tangible impact of the PNT systems and their possible shortcomings and vulnerabilities to identify solutions, improvements and new steps towards resilience in NAVWAR scenarios for which a highly reliable navy has to be prepared for. This work attempts to attain this knowledge by studying the impact of disruptions in teams and their relationship with the technology while performing a port entrance. This will, in turn, allow the identification of the success factors in overcoming such a disruption, giving way to a new perspective and perhaps new ideas for a better, more resilient navigation and, therefore, a better, more resilient navy.

2. Methodology

The study was based on six observations taking place in the navigation simulator (NAVSIM) of the Portuguese Navy. The study subjects were different piloting teams from various ships of the national fleet while performing a standard piloting exercise, PILOTEX or MISCEX 821A in NATO doctrine. The main goal of this exercise is to train the piloting team in conducting restricted waters navigation with the best possible accuracy and effectiveness. This means that the team should be able to continuously monitor the ship's position in compliance with the track line while monitoring and avoiding environmental hazards or possible collisions. The scenario was the port of Lisbon (Figure 1).

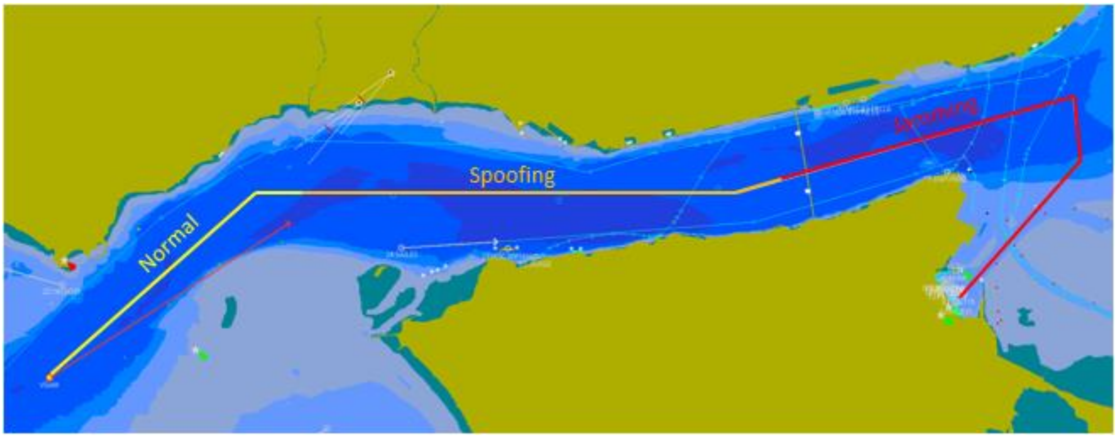

Figure 1 - Standard scenario used in the study

Up to now, six sessions with six different piloting teams were performed between the 1st of June and the 13th of July with piloting teams from different ships, from small patrol boats to corvettes. There were a total of 42 participants, and the main characteristics of the sample can be seen in Table 1. In all sessions, video and audio were recorded with one audio recorder, three cameras (with three backup cameras) and two chronometers for standard time reference.

	Team									
	D	E	F	G	H	I	Total			
Sex	7M/1F	5M/0F	5M/2F	7M/0F	7M/1F	7M/0F	38M/4F			
	Average	Average	Average	Average	Average	Average	Global avg	Stand. Dev	Max	Min
Age	33,9	33,0	31,0	32,0	30,4	29,6	32,1	1	34	30
Years in the navy	15,1	14,4	12,7	12,1	11,0	12,3	13,1	1	15	11
Experience aboard ships (years)	6,6	6,8	4,4	5,4	5,6	4,9	5,7	1	7	4
Hours at sea	5870,9	6700,0	971,4	3544,6	6282,9	5785,7	4673,9	1858	6700	971
Time on current ship (months)	17,4	6,2	11,0	13,7	14,0	12,4	12,5	3	17	6
Time on current team (months)	12,0	5,4	7,6	8,1	11,0	7,1	8,8	2	12	5
Months since last full training plan	42,0	78,0	20,0	24,0	2,0	2,0	33,2	24	78	2
Number of SIMPILOTEX's in 2022	11,0	6,0	2,0	2,0	6,0	14,0	5,4	4	14	2

M - Male ; F - Female

Table 1 - Demographic and Professional Background data of the study participants

Each series with each team had three distinct moments: The first, in the first leg, characterized by regular availability of GNSS signal; the second, in the second leg, undergoing a GNSS spoofing disruption and the third, in the remaining legs, undergoing a jamming disruption. The disruptions were always introduced when the ship's heading was steady, after the wheel over position (change of course point), to have minimal interference with the change of course.

The main research question was: "What are the success factors for resilient navigation in NAVWAR environments?". It is supported by three other questions (Figure 2) related to performance, the different factors chosen for measurement, and the differences between piloting as prescribed and as done. However, support is the key word, as performance measurement and the differences observed were meant to assess the resilience effectiveness of navigation functions rather than evaluate each team's proficiency or the reliability of the prescribed procedures.

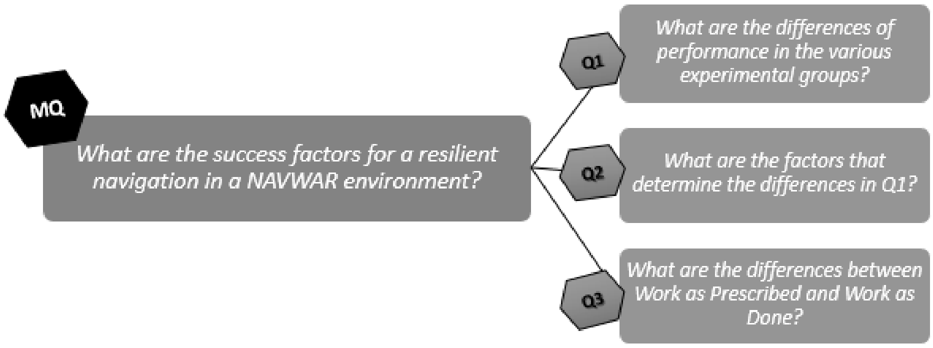

Figure 2 - Research questions

The study's data collection and measurements were adapted from the framework developed by Stowers (Stowers et al., 2017), using only quantitative measurements to effectively assess a human-machine system such as a piloting team.

Before the execution, each participant provided information regarding demographics and background/experience, as well as ship's details and the level of training of each team, by filling a Demographics and Professional Background Questionnaire (DPBQ). Pilot tests raised the possibility that specific knowledge of the impact of GNSS disruption on the bridge equipment could be a success factor. Therefore, the "GNSS-dependent equipment's/systems questionnaire" was developed and used for measuring this specific knowledge. In this questionnaire, participants were asked to identify out of a list of bridge equipment and systems which rely on GNSS information.

Trust in the bridge equipment was measured through the trust in automation survey developed by Koerber (2018), which is meant to be filled only by those operating directly with technology. Next, the behavior was appraised by analyzing the variation of interactions within the team and between each operator's and their respective equipment's, again building on the coding developed by Nepomuceno (2020). At last, cognition was assessed through situational awareness (SA) and cognitive workload (CW). At the end of each series, teams were requested to fill in the SART (Situational Awareness Rating Technique) and the Expanded NASA TLX (Task Load Index) questionnaire to assess SA and CW, respectively.

Navigational performance data was also collected from the NAVSIM Polaris instructor, the log of each bridge equipment and the session recordings. This data was processed to provide the following indicators, representing the compliance of both time and positioning, selected in cooperation with the PTC (Portuguese Tactical Center) specialists: Difference between ETA (Estimated time of arrival) and ATA (Actual time of arrival) to the end; Difference between ETA and ATA for each turning point; Time on and off the track line (with 50 yards tolerance) and both maximum and average distance to the track line.

The pilot tests also raised the possibility that compliance with procedures could be a success factor in the team's ability to attain superior positioning control, which means higher performance. Therefore, to measure general piloting procedure compliance, the study group was given access to the checklists and reports used by the evaluators in each session. However, the occurrence of a GNSS disruption is not provided for in these documents, and it was hypothesized that compliance to certain procedures, although they are currently not written in any navy doctrine document, in the face of one could again be a success factor for resilience. Therefore, a post-disruption procedure checklist was elaborated in cooperation with PTC specialists.

To provide an overview of the data collection process and the different data that will contribute to each category of measurements in the study, the following scheme summarises data collection in the study by category (Figure 3).

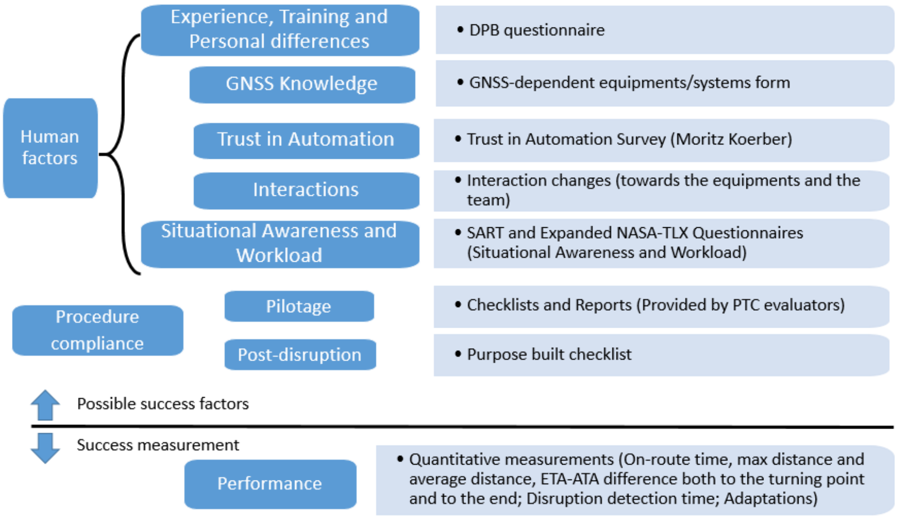

Figure 3 - Data collection scheme by category

The following summarises data collection time flux for the same purpose but intends to provide more of a chronological overview (Figure 4).

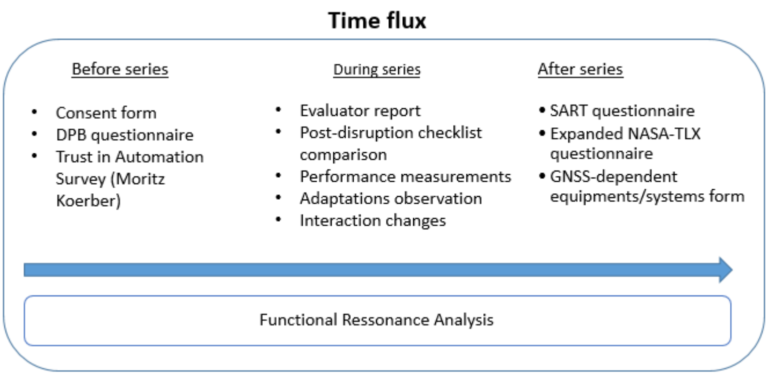

Figure 4 - Data collection scheme time flux

3. Results and Discussion

Regarding detection time, almost all teams were within the 3-minute detection criteria for resilience both in spoofing and jamming detection. The exception is team E which took 9 minutes to identify the spoofing disruption. On the other hand, teams G, H, and I detected both disruptions immediately. Therefore, immediate detection of the disruption can be considered a success factor.

Team	Spoofing detection time	Jamming detection time
D	2 min	Immediate
E	9 min	2 min
F	2 min	Immediate
G	Immediate	Immediate
H	Immediate	Immediate
I	Immediate	Immediate

Figure 5 – Disruption detection time

Regarding the control of time performance measurement, there were no significant differences between the ETA-ATA at the wheel-over positions performed with regular availability of GNSS signal and the wheel-over positions performed while undergoing the disruptions. Therefore, results from this experimental study do not support the claim that GPS jamming or spoofing impacted the team's control of time. Besides, the ETA-ATA differences in wheel-over positions did not significantly differ between the participating teams (Figure 6). Only team F was the stand-out, demonstrating superior control with a result close to zero. Nevertheless, this did not hold up as the inverse happened regarding ETA-ATA differences to the NAVPLAN end, being several minutes late in comparison (Figure 7).

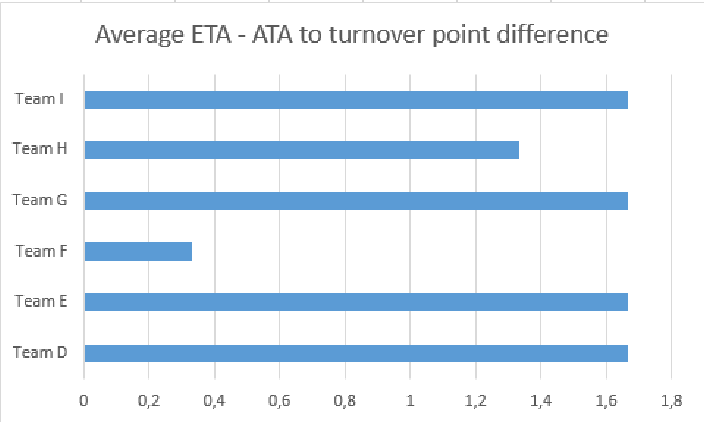

Figure 6 - Average ETA-ATA to wheel-over point difference

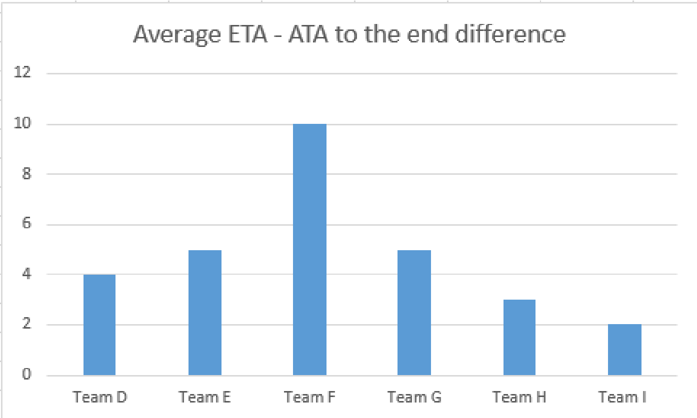

Figure 7 - Average ETA-ATA to wheel-over point difference

Although the difference was relatively short, teams H and I ended up being the superior performers regarding time control, arriving only 3 and 2 minutes late, respectively. This superior performance was confirmed concerning positioning control. Team H and I were the best performers in all three parameters measured. Besides, as mentioned in the previous section, the two teams were the only ones who performed above average in every parameter (Table 2). Therefore, they were selected as the success cases, with the study pursuing the identification of success factors within the different possibilities raised by the study's measurements.

	Average distance	Maximum distance	Time on track
Team D	164	142	70
Team E	155	405	29
Team F	58	240	59
Team G	76	100	49
Team H	42	100	74
Team I	23	29	91
Average	71	169	62

Table 2 - Average results for each team for all positioning performance measurements (above average resuls are highlighted in green)

Regarding positioning control throughout the series, the data shows strong evidence that, on average, the GNSS disruptions were directly related to a worse positioning control, sometimes by several hundred yards compared to the usual signal availability. However, results also present evidence that this is only the case for the worst performing teams, as three teams were able to attain an equal or even better positioning control, as was the case of teams H and I. These claims were supported by the average and maximum distance to the track line measurements in which clear differences were found between the Normal and Spoofing and Jamming situations. However, the percentage of time on track measurement was somewhat inconclusive. The average result in all situations was very similar, and each team's result did not reveal significant variation either. Surprisingly, most teams registered higher values while undergoing the disruptions.

Finally, in terms of the different adaptations that teams made while facing the disruption, they were mainly made at the level of the ECDIS operator. Considering that the two clear best performers made the same decisions in adapting the role of the ECDIS, which weren't followed by any other teams, it is likely that these are successful adaptations. Therefore, the adaptation of the ECDIS operator on station and reporting based on the information from the visual fixes should be considered a success factor. In table 3, it is possible to see the successful and unsuccessful adaptations to the disruption based on this analysis.

Team	On station	Reporting	Intentionally reported GPS	Reported fixings instead
D	No	No	No	No
E	No	No	No	No
F	Yes	No	No	No
G	Yes	Yes	Yes	No
H	Yes	Yes	No	Yes
I	Yes	Yes	No	Yes

Table 3 – ECDIS adaptations

	Team						
Question	D	E	F	G	H	I	Total
Time on current team (months)	12,0	5,4	7,6	8,1	11,0	7,1	8,8
Months since last full training plan	42,0	78,0	20,0	24,0	2,0	2,0	33,2
Number of SIMPILOTEX's in 2022	11,0	6,0	2,0	2,0	6,0	14,0	5,4

Table 4 - Experience and training data

As seen in Table 4, when it comes to time working together in the same team, from the two best performing teams, one is on the higher end of the specter while the other is on the lower one. Concerning the other teams, the assumption that teams with a higher average would be better performers also did not hold up. However, as expected, the results show convincing evidence that training can be a decisive success factor. Both teams H and I were the teams that went through a complete training plan more recently, with a decisive difference from all the other participants.

However, when analysing the number of similar exercises to the one performed in this experiment, we could not derive any conclusion since teams' availability to do so is very much dependent on their operational planning. Yet, neither of the best performing teams is on the lower side of the specter in this parameter, with team I performing the highest number of these exercises. However, team D, the runner-up, did not perform so well; therefore, the number of SIMPILOTEXs performed in 2022 does not seem to be a success factor.

The specific knowledge of the impact of a GNSS disruption on the bridge equipment was raised as one possible success factor. The reason was that teams would continue to rely on the information from AIS on ECDIS (Electronic Chart Display and Information System) and RADAR. However, all teams, both the Navigation Officers (NAVO) and the ECDIS operators, as well as on average, were able to identify that these two equipments worked with GNSS information successfully. So the problem of trusting the information did not hold up as a matter of lack of technical knowledge but remains to be explained.

It is possible that the focus of the teams and its members on the task and the positioning error does not allow them to access this knowledge, or habit might also play a role in overriding their knowledge with "what they usually do". However, the best performing teams had the highest number of correct answers for the questionnaire, both for NAVOs and ECDIS operators, as well as on average. Nevertheless, the difference was minimal; therefore, given the sample, it cannot be considered a success factor.

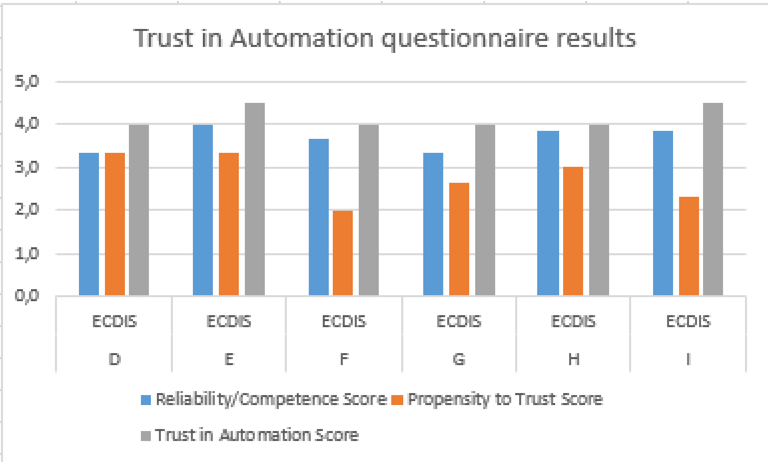

Figure 8 - Chart with the Trust in automation questionnaire results for the ECDIS operators

While the pilot tests provided interesting evidence that lower values of reliability, the propensity to trust and trust in automation, could be linked to better performance, this was not true for the experimental study (Figure 8). For ECDIS operators, the trust in automation parameters was similar across the board, with relatively high values of 4 and 4.5. The best-performing teams did not register lower values of propensity to trust and fell somewhat in the middle of the table in both parameters. Therefore, the results of this experiment suggest that ECDIS operators' trust is not a success factor for more resilient navigation.

NAVO interactions/min				ECDIS interactions/min			
Team	Normal	Spoofing	Jamming	Team	Normal	Spoofing	Jamming
D	0,7	0,3	1,0	D	0,4	0,1	0,3
E	0,2	0,5	0,3	E	0,3	0,6	0,2
F	0,4	0,3	0,6	F	0,2	0,2	0,2
G	0,3	0,6	0,4	G	0,2	0,2	0,2
H	0,0	0,3	0,1	H	0,1	0,3	0,3
I	0,4	0,1	0,3	I	0,1	0,3	0,1
Single interactions/min				**Report cycles/min**			
Team	Normal	Spoofing	Jamming	Team	Normal	Spoofing	Jamming
D	0,9	0,6	1,6	D	0,2	0,2	0,2
E	0,4	0,8	0,4	E	0,4	0,2	0,1
F	0,4	0,5	0,9	F	0,3	0,3	0,1
G	0,5	0,8	0,8	G	0,1	0,2	0,2
H	0,2	0,4	0,3	H	0,2	0,2	0,2
I	0,4	0,4	0,5	I	0,2	0,3	0,2

Table 5 - Interactions between team members results

The pilot tests raised the possibility that teams that felt more at ease having interactions between the team members outside the reporting cycle could be better performers. However, in the experimental study, this possibility was not confirmed (Table 5). The results do not really lean in one direction, with the single interactions of the NAVO and the ECDIS operators' results being extremely varied among the different participants. Furthermore, the reporting cycles per minute registered very similar results in all teams and, therefore, cannot be considered a success factor. However, contrarily to the pilot tests, the total number of single interactions per minute on the bridge data does seem to indicate that the high-performing teams actually had fewer interactions outside the reporting cycle, also registering the lower variation of single interactions between the normal and spoofing or jamming situations.

Therefore, a less interactive bridge and more procedural-focused, although allowing some level of single interactions, seems to be a success factor for more resilient navigation. Similarly to the pilot tests, there were no expressive differences between the number of single interactions or report cycles per minute between the normal and spoofing or jamming situations. It should be noted that the interactions were measured in terms of the number of times they occurred and were then transformed into an indicator related to the number of times they occurred per minute to provide a standard time frame in which the results could be compared.

ECDIS - Obtained position through fixings			
Team	Normal	Spoofing	Jamming
D	4	0	0
E	4	2	1
F	0	0	0
G	1	0	0
H	5	5	3
I	5	3	6

Table 6 - Number of fixings performed

ECDIS - total interactions/min			
Team	Normal	Spoofing	Jamming
D	1,4	0,2	0,0
E	0,5	0,4	0,2
F	0,6	0,6	0,1
G	0,3	0,2	0,1
H	0,6	0,5	0,5
I	0,3	0,4	0,6

Table 7 - Total number of interactions with ECDIS

Contrary to the interaction between team members, there were robust differences between the number of interactions per minute with the ECDIS equipment in normal navigation and undergoing the GNSS disruptions. A much higher number of interactions in the normal situation progressively declined throughout the series. This could be explained by the fact that the ECDIS operator would frequently give up interacting with the equipment or leave it entirely, as mentioned in the FRAM analysis. Besides, the teams that were able to sustain or even increase their level of interaction with ECDIS were precisely the best performing teams, H and I. This happened for the use of fixings (Table 6), which allowed the ECDIS to remain in the reporting cycle, and for the total number of interactions (Table 7), with many associated with troubleshooting. Therefore, there is solid evidence that a higher interaction level with ECDIS is a success factor for more resilient navigation.

Team	Weighted TLX	Team efficacy	Team support	Team dissatisfaction
Average D	61,7	10,4	14,2	6,2
Average E	61,6	10,4	15,7	4,7
Average F	66,1	10,4	16,8	4,6
Average G	63,9	10,5	16,8	9,9
Average H	62,3	10,5	16,3	8,4
Average I	60,1	16,3	15,8	10,3

Table 8 - Average Expanded NASA-TLX results

The Expanded NASA-TLX questionnaire results did not reveal any intriguing tendency. On average, they were very similar among the participating teams (Table 8). The same is true for the ECDIS operators (Table 8). A somewhat unexpected result was that the best performing was on the higher specter of team dissatisfaction, but there were not so well-performing teams in the same circumstance. Therefore it cannot be considered a success factor.

Regarding the NAVO, the two best-performing teams recorded higher values of mental workload, with a considerable difference (Table 10). This contradicts the literature, as it would be expectable for them to have a lower mental workload as they dealt more easily with the situation. However, it could indicate that they performed a higher effort than the other participants, achieving higher results despite the increased mental workload. It appears to be a success factor, although it should be looked at with skepticism. As for the NAVO's results in team perception (Figure 9), the best performing teams had higher values of team efficacy and team support and lower values of team dissatisfaction. Thus, a positive team perception by the NAVO seems to be a success factor for more resilient navigation, even more so as the NAVO has the role of being the team leader.

Team	Function	Weighted TLX	Team efficacy	Team support	Team dissatisfaction
D	ECDIS	68,7	5,0	9	9
E	ECDIS	63,7	20,0	19	2
F	ECDIS	56,7	5,0	8	10
G	ECDIS	75,0	14,0	14	8
H	ECDIS	56,7	17,0	17	2
I	ECDIS	83,3	17,0	20	19

Table 9 - ECDIS' Expanded NASA-TLX results

Team	Function	Weighted TLX	Team efficacy	Team support	Team dissatisfaction
D	NAVO	72,3	17,0	13	7
E	NAVO	64,7	15,0	15	5
F	NAVO	73,3	2,0	12	16
G	NAVO	72,0	12,0	14	16
H	NAVO	85,0	19,0	19	3
I	NAVO	81,0	17,0	16	2

Table 10 – NAVO's Expanded NASA-TLX results

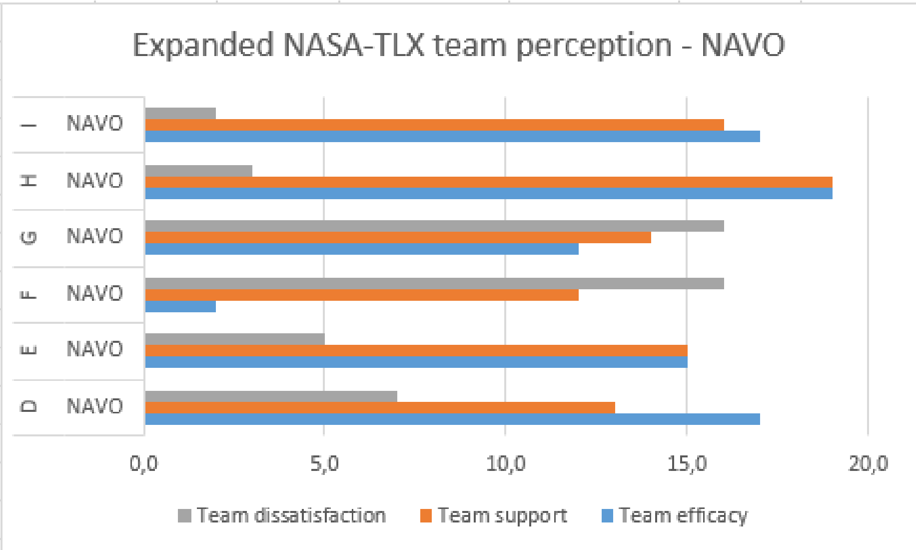

Figure 9 – NAVO's Expanded NASA-TLX results

Although the results were limited to two series due to the unavailability of PTC evaluators for the remaining ones, the data collection points to a strong influence of piloting procedure compliance on team performance. The team with the best global evaluation and the lower number of critical and significant AtI's was largely the best performing team, both in time and positioning control (Table 11). Therefore, the comparison is strong evidence that piloting procedures compliance is, in fact, a resilient navigation success factor.

PTC Report		
Parameter	**Team F**	**Team G**
Global Evaluation	Below Standard	Marginally Satisfactory
Critical Atl's	3	1
Significant Atl's	8	5
Minor Atl's	1	6

Table 11 - Piloting procedure compliance results

The same was found to be true for executing the recommended post-disruption actions. Although the checklist elaborated for the study was not previously given to the teams beforehand, the teams with higher compliance did so somewhat instinctively, following what can be called common sense best practices, as they are not written in navy doctrine or the ships' bridge cards. However, the teams that registered higher compliance were precisely the best-performing ones, with a considerable difference from all the other teams (Table 12). Therefore, the data collected presents robust evidence that more direct and correct actions in the face of a GNSS disruption in maritime navigation are a success factor for managing it. It also provides compelling evidence that the checklist built in collaboration with the PTC specialists is a practical set of actions to respond to either jamming or spoofing.

	Post-disruption actions		
	Detection and reporting	**Impact Acknowledgment**	**Global**
D	2	1	3
E	4	1	5
F	3	1	4
G	6	1	7
H	8	2	10
I	6	4	10

Table 12 - Post-disruption actions compliance results

4. Conclusions

The proposed methodology aimed to address the issue of PNT resilience through the scope of Joint Cognitive Systems, measuring teams' performance, procedure compliance, as well as human factors, namely interactions both with technology and other team members, trust in automation, as well as situational awareness and mental workload, when faced with a GNSS disruption. As an experimental study and somewhat of a pioneering one, the scope was broad, as one of the main concerns was not to leave out any factor that could impact resilience, which would consequently be discarded in future, more narrow, focused studies.

Throughout the series, teams sequentially navigated with regular availability of GNSS signal, undergoing spoofing and jamming. The performance was measured through quantitative measurements of time and positioning control, and procedure compliance was assessed with the support of evaluators from PTC. The human factors were primarily measured using questionnaires. The FRAM framework (Functional Resonance Analysis Method) supported studying the differences between Work as Done and Work as Prescribed. The study intended to provide extensive insight into the piloting teams' ability to navigate in the face of adversity and effectively upraise the knowledge on the resilience of the PNT function in the Portuguese Navy to pave the way to technological and human solutions for better, more resilient navigation.

The study is meant to constitute a constructive outlook on the impact of the GNSS disruptions on piloting, as well as the study of the success factors for coping with them, contributing with knowledge in different areas both to science and the Portuguese Navy as presented in Figure 11. GNSS spoofing and jamming were found to impact both performance and human factors, namely behavior, with teams on average registering a slight increase in distance to the track line but with some teams registering a significant difference of more than 100 yards. The impact on behavior, on average, seemed to be only identifiable in terms of the general increase of single interactions per minute, but several also registered differences in the report cycles and the single interactions of NAVO and the ECDIS operator.

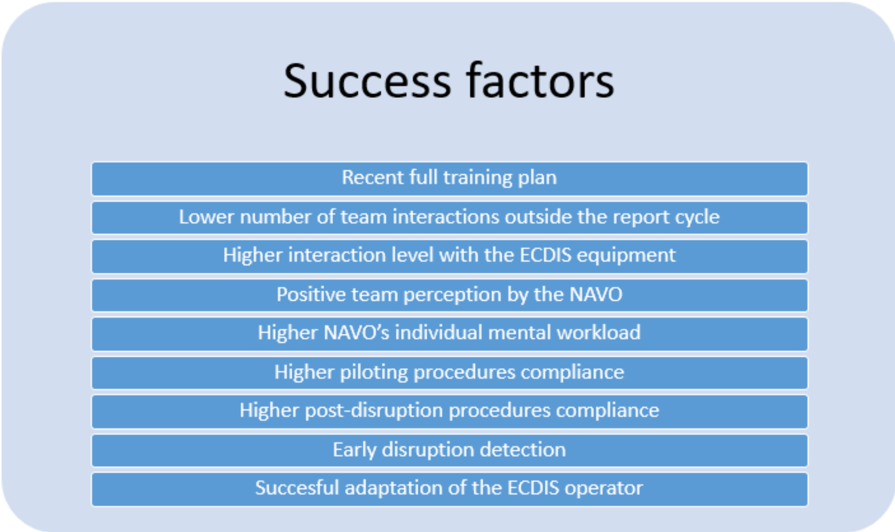

Figure 10 - Success factors results summary

In terms of the success factors for more resilient navigation, they are presented in figure 10, while the remaining factors and measurements are either inconclusive or simply not success factors. Although the study provides an interesting comparison between the different teams' performance and measurements, the small sample size doesn't allow for statistical significance. Therefore it is recommended that the developed protocol is used to collect more data for a new analysis to attain more robust conclusions.

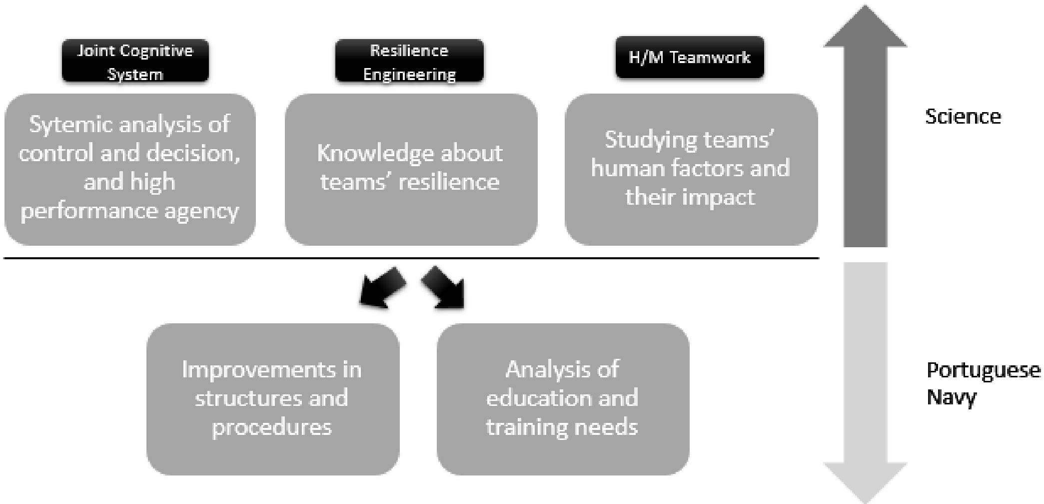

Figure 11 – Intended contributions of the study

Acknowledgements

To the Fleet Command by supporting the study with the vessel's navigation teams and the PTC. The infrastructures and staff were essential to the study, both from a technological perspective with the direct support of SES (Serviço de Engenharia de Sistemas), and on an organisational one in close cooperation with the GNFM (Gabinete de Formação de Navegação e Manobra) and the DTA (Departamento de Treino e Avaliação). Their members were also of precious help as navigation experts.

References

Janssen, Marco A, Michael L Schoon, Weimao Ke, and Katy Börner (2006). "Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change". In: Global environmental change 16.3, pp. 240–252.

Notteboom, Theo and Jasmine Siu Lee Lam (2014). Dealing with uncertainty and volatility in shipping and ports.

Paulauskas, Kestutis (2020). "Space: NATO's latest frontier". In: NATO Review.

Goward, Dana (2020). DoD PNT Task Force Charter: Best investments may be nonGPS

NATO (2022). 2022 NATO resilience symposium - key discussions and takeaways.

Aresta, Catarina Matos (2017). "Resilience of the PNT Systems". MA thesis. Escola Naval

Nepomuceno, Guilherme Polainas (2020). "Estudo sobre a utilização do ECDIS na execução da navegação em águas restritas". MA thesis. Escola Naval.

Stowers, Kimberly, James Oglesby, Shirley Sonesh, Kevin Leyva, Chelsea Iwig, and Eduardo Salas (2017). "A framework to guide the assessment of human-machine systems". In: Human factors 59.2, pp. 172–188.

Körber, Moritz (2018). "Theoretical considerations and development of a questionnaire to measure trust in automation". In: Congress of the International Ergonomics Association. Springer, pp. 13–30.