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When communication breaks down or what was that? – The importance of communication for successful coordination in complex systems

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Abstract

Automation is increasingly prominent in today's vehicles. Initial systems will likely have some limitations, such as highway only automation. Thus, the designers such systems rely on the driver to resume control of the vehicle when the limits are reached. Such a system introduce similar problems that have been prominent in aviation, relying on the pilot to safely resume control. To resume control of the vehicle, collaboration and communication is key, as most systemfailures are associated with breakdowns in communication and *"the single biggest problem in communication is the illusion that it has taken place"* (- George Bernard Shaw). The paper outlook is from an Automated Driving perspective and AF447 serves as an illustrative example of the application of the explanatory capabilities of theGricean Maxims in assessing Human-Agent communication in complex systems. Lastly, the paper discusses lessons learnt and potential application of the maxims in designing safe human-agent collaboration.

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*Keywords:*AF447; Communication; Human agent collaboration; Highly automated driving;Grice maxims

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1. Introduction

Driving automation technologiesarereceiving an increasing amountof media attention, presented as a panacea in driving safety, effectively reducing accidents and increasingroad network efficiency, whilst reducing the environmental impact of driving. Vehicle manufacturers such as Volvo, Jaguar, BMW, Google, Tesla and Mercedes are racing towards putting an automated vehicle on the road. Before fully automated vehicles can be seen on public roads, changes to current legislation will have to be made as it requires drivers to be able to control their vehicle at all times[1]. This will likely lead to an intermediate level of “Highly Automated Driving” (HAD) where the vehicle is able to act as an autonomous agent within certain areas such as highways where complexity is low[2, 3]. The vehicle will therefore have to hand back control to the driver when the operational limits of the automation is reached.Either due to geographical constraints being approached, deterioration of sensor readings due to weather, or to a driver takeover request orother external circumstances.

In handover situations it is crucial that driver and automation collaborate, providing contextual and temporally relevant information communicated in a safe and relevant manner in such a way that the mental model of the driver is kept up to date to be able cope with the task of taking over control of the driving task. This is a classic challenge in human automation interaction, where the operator is removed from the control loopfor extended periods of time which may cause a loss of situation awareness [4].In such a situation the operator does not know whether there has been a change in operational conditions and changes in the operation of the automated system might surprise the operator [5]. This may result in an escalation of the need for cognitive activities [6]which likely leads to a performance deterioration as the drivers’ attentional capacities have not had time to adapt to the needs of the situation, coming from a state of mental underloaddue to inactivity or low workload tasks [7-9].If the need for cognitive activities continues to escalate in such a way that the requirements surpasses the operator’s capacity,the operator is said to be in a mental overload condition.Thus, there seems to be an optimal workload level where operator performance is maximized [7, 9].

The aim of designing an automated system where the designer relieson an operator to intervene when the automation no longer can cope, should therefore be to ensure successful collaboration and information exchange between operator and automation. The process of collaboration and information exchange must be continuous in the sense that the operator hasaccess to sufficient context relevant information in such a way that any sudden escalation of cognitive activities may be avoided.

There is a vast body of literature from a multitude of domains describing when things go wrong.From the Therac-25 incident in the medical domain[10],in which an inaccurate presentation of information led to a skewed mental model was the cause of multiple casualties,to the aviation domain where an Air France operated Airbus A330-200 [11]crashed due to a breakdown in crew resource management, unexpected events in mentalunderload conditions and poor information communication and collaboration between pilot and automation. It has been shown that most breakdowns in communication and collaboration almost always lead to failure [12-16].

1.1. Human agent collaboration

Satisfactory communication has been implied as a crucial component for successful collaboration and co-ordination in human agent systems. To ensure satisfactory information transfer, communication must adhere to certain principles, one such principle is the principle of least collaborative effort(PLCE)[17]in which information transfers are designed in such a way as to minimize the effort required to send, receive and interpret information. To adhere to the PLCE, the agents must also adhere to the cooperative principle (COOP)[18]. The COOP, posited by Paul Grice in 1975 [18], entails four maxims one may adhere to, to ensure that communicative actsare successful. The four maxims proposed by Grice are the Maxim of Quantity (MoQa), Quality (MoQu), Relation (MoR) and Manner (MoM). MoQa states that any contributions should be made as informative as required without adding additional, unnecessary information. MoQu states that the information provided should be true and the information should not be based on information that one lacks evidence of. MoR states that the information provided should be contextually and temporally relevant to the current task. The MoMstates that obscurity and ambiguity in the presented information should be avoided and that information should be conveyed in a brief and structured manner.

By adhering to the Gricean Maxims, the system agents may reduce the *gulf of evaluation*, i.e. the effort required to interpret the state of the system, and determine how well the behaviour corresponds to expectation [13]. This would in turn reduce the likelihood of grounding problems [19] by ensuring that Common Ground is achieved [20]. Common Ground may be compared to agents' mental model, but, instead of being internalized, it is defined as the sum of the system agents' common beliefs, knowledge and suppositions. Thus, Common Ground may be compared to the mental model of the system as a whole.

2. Purpose

The purpose of this paper is to further illustrate the potential of the Gricean Maxims as a tool to assess human-agent communication in the context of HAD. Using the case of AF447 instead of a HAD case is justified by the fact that contemporary HAD is yet to be available on a commercial scale and therefore lacks the detailed case studies of automation related incidents that is available in aviation.

3. Method

The case study is based on the findings in the final report (2012), the third interim report (2011),as well as Cockpit Voice Recorder data and the Flight Data Recorder data (Appendix 1 & 2 of the final report)from the AF447 investigation published by the French Bureau of Investigation and Analysis (Bureau d'Enquêtes et d'Analyses pour la sécurite de l'AviationCivile; BEA)[11].

4. History of the flight

On May 31 2009 an Airbus A330-200 operated by Air France was scheduled to carry 216 passengers and twelve crew members on flight AF447 between Rio de Janeiro Galeão and Paris Charles de Gaulle. The captain was assigned Pilot Not Flying (PNF) and one of the co-pilots wasassigned Pilot Flying (PF). AF447 was in cruise at Flight Level 350 (FL350) in calm conditions at the start of the Cockpit Voice Recorder (CVR) recording, just after midnight. At 1:52 the captain woke the resting co-pilot and requested that he were to take his place as the PNF, 8 minutes later the PF briefed the newly arrived co-pilot. In the briefing the PNF mentioned that the recommended maximum altitude (REC MAX) was limiting their ability to climb above a turbulent area due to a higher than expected temperature. Following the briefing, the captain left the PF and the replacement PNF to continue the flight. At 2:08 the PNF suggested a heading alteration of 12 degrees to avoid a turbulent area, the crew also decided to decrease speed from Mach 0.82 to Mach 0.8 (~529kt) and to turn on engine de-icing.

At 2:10:05 the autopilot and the auto-thrust disconnected, likely due to the pitotprobes of the Airbus freezing over, resulting in unreliable speed readings. Following the autopilot disconnection the PF said "*I have the controls*" indicating he was in control of the aircraft. The PF simultaneously gave a nose up and left input as a response to the aircraft rolling to the right at the time of autopilot disconnecting. The actions of the PF triggered a stall warning as angle of attack increased beyond the flight envelope boundaries at Mach 0.8 (Fig 1. AOA >4°). This was the start of a series of events where communication between flight crew and between crew and aircraft failed to suffice. During the remaining 4 minutes and 23.8 seconds the aircraft continued to climb, leaving the lift envelope, trading kinetic energy for potential energy until it unavoidably started to descend. The PF, unaware of the situation, continued to apply nose up inputs which further increased the AOA which, from 2h 12m to the end of the flight were on average around 40°. The last recorded value of vertical speed was -10,912ft/min.

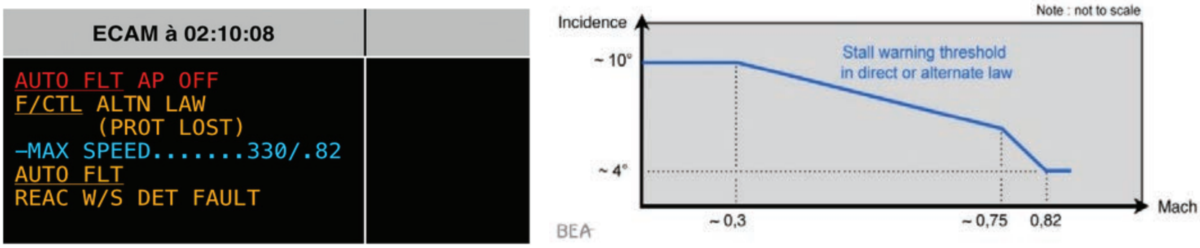

Fig. 1a). Information readily available for PNF at the time of autopilot disconnect.b) AOA threshold for stall warning at different speeds.Source: BEA www.bea.aero

5. Analysis

5.1. Auto-pilot disconnect

At 2h 10m 04.6s a Cavalry charge sounded in the cockpit of AF447, indicating that the autopilot had disengaged. An immediate change in roll angle from 0°–8.4° without any sidestick input followed the autopilot disengagement. The Pilot Flying (PF) responded appropriately by acknowledging the event by stating he had the controls, thereby making the Pilot Not Flying (PNF) aware that manual control was resumed. At this point the PF's task is to maintain control the aircraft and the PNF's task is to identify the fault and ensure that the designated flight path is followed. PNF does this by checking the instruments and the Electronic Centralised Aircraft Monitor (ECAM) display.

The ECAM is designed to provide pilots with information in a quick and effective manner as well as displaying the necessary corrective actions needed to resolve any errors. As the PNF tried to identify the reason for the unexpected disconnection of the autopilot by checking the ECAM messages in Figure 1a there was nothing to indicate that the autopilot disconnect had anything to do with the pitot probes freezing over, causing inaccurate speed readings. The only ECAM message indication that there was a speed-related error message indicating that the max speed was Mach 0.82, which, according to the BEA investigation, could be misinterpreted as the aircraft being in an over-speeding situation.

At the time of the transition of control of the aircraft from autopilot to pilot there was nothing to indicate why the transfer had occurred (Table 1, 2h 10m 04.6-6.4s), and what future actions need be taken to ensure a continued safe operation of the flight. According to Patterson & Woods [21], the main purpose of a transfer of control / handover is to ensure that the agent taking over control has got a correct mental model of the current process state and is aware of any changes to the process. The agent resuming control must also be prepared to deal with the effects from previous events and needs to be able to anticipate future events. These requirements failed to be fulfilled at the time of the transfer of control, as neither the PF, nor the PNF, succeeded in identifying the underlying cause of the autopilot disengagement in the initial period after control was transferred. As the PF and PNF failed to create an accurate mental model of the current system state the action responses to the events unfolding were erroneous, and thus resulting in a worsening rather than improvement of the situation.

Using a Gricean perspective it is possible to identify several violations of the Gricean maxims in the moments where control was transferred from autopilot to PF. The absence of any information related to the pitot readings being inaccurate is a clear violation of the MoQa as information clearly was not sufficient to provide the PF/PNF with the necessary information to assess the situation. The MoQu was also violated as the MAX SPEED information was of no help in resolving the situation as at the time of the incident, the aircraft was nowhere near an over-speeding situation, thus information indicating an overspeeding risk was provided of which no underlying evidence of such a risk was present. Furthermore, the MoR was violated as the MAX SPEED information was irrelevant to the context at hand and did not assist in creating an accurate mental model. The MoM was also violated as the ambiguous nature of the speed warning, giving an indication of the risk of over-speeding rather than the erroneous readings of the pitotprobes.

5.2. Stall warning

Five seconds after the autopilot disconnected a stall warning sounded in the cockpit as AOA values increased above the limit of 4° at Mach 0.8 (Fig 1b) due to the nose up inputs issued by PF. The sudden trigger of such a warning mid- cruise seems to have surprised the flight crew and especially PNF given the *"What is that?"* statement (Table 1) immediately following the stall warning. The stall warning then ceasedafter three seconds, just as sudden as it started, even though PF's input remained unchanged. The reason the stall warning ceasedwas due to a design feature that negates AOA readings at speeds below 60kt to avoid the occurrence of sporadic warnings. The consequence of this design feature was that as the speed readings rapidly decreased, reaching values below 60kt due to the frozen pitotprobes, the AOA values were no longer valid. As AOA values were invalidated, there was no data available for the flight computers to assess whether the current flight conditions were approaching stall.

Table 1. Voice Data Recording transcript and Flight Data Recording temporally aligned between 2h 10m 04s to 2h 10m 17s into the flight coupled with an analysis of the human-machine and human-human communication from a perspective of the individual Gricean maxims.

Time	Voice Data Recording		Flight Data Recording	MoQu	MoQa	MoR	MoM
2h10m	PNF	PF					
04.6s		*Do you us to put it on ignition start*	Cavalry charge Autopilot disconnection warning	✓	✓	✓	✓
05s			Autopilot disconnects Roll angle changes from 0° to 8.4° in 2 seconds, sidestick neutral Pitch attitude is 0°				
06s			Flight control law changes to alternate	✓	✗	✓	✗
06.4s		*I have the controls*		✓	✓	✓	✓
07s			PF sidestick positioned at 75% nose up Pitch attitude increases to 11° Vertical speed increase to 5200ft/min				
07.5s	*Alright*			✓	✓	✓	✓
08s			Flight Director 1 & 2 becomes unavailable Auto thrust is disengaged CAS changes from 274 to 156kt	✗	✗	✗	✗
09s			CAS is 52kt	✗	✗	✗	✗
09.3s		*Ignition start*					
10s			Stall warning is triggered AOA 1, 2 & 3 is 2.1°, 4.9°, 5.3°	✓	✓	✓	✓
11.3s	*What is that?*						
12s			CAS is 55kt	✗	✗	✗	✗
13.5s			Stall warning seizes	✗	✗	✗	✗
14s		*We haven't got a good..*					
15.1s		*We haven't got a good display…*		✓	✓	✓	✓
15.9s	*We've lost the the speeds so… engine thrust A T H R engine level thrust*	*… of speed*		✓	✓	✓	✓
17s			Flight director 1 & 2 becomes available again; active mode is HDG/ALT CRZ; CAS is 80kt	✗	✗	✗	✗

From a Gricean Perspective the aircraft system fail to adhere to the Maxims, as the stall warning initially adheres to the maxims by providing brief, understandable and unambiguous context relevant information. It is arguable that underlying systemic factors may have contributed to the confusion with regards to the stall warning in cruise conditions. In normal law operation, the in-flight computers ensure that the aircraft stays within its protective flight envelope by analysing and modifying pilot input before applying the commands to the ailerons. This make it impossible to stall an Airbus A330 by applying full nose inputs in such conditions. However, as the pitot probes froze, the conditions for remaining in normal law changed, switching the mode to alternate law. Alternate law lacks these flight envelope protections which, in controlling nose up/down inputs, only provides warnings when the flight envelope limits are exceeded. The mode change from normal to alternate law occurred as the autopilot disconnected. The information of the change was displayed to the pilots on the ECAM display.However, according to the official investigation, the pilots failed to understand the significant impact such a change in mode would have on the handling of the aircraft. From a Gricean perspective, the mode display was in compliance with the MoR and MoQu, but failed to comply with the MoQaand MoM as the information provided with regards to the consequences of the change in mode was insufficient.

The deviation from normal to alternate law remained unnoticed to the pilots.Thus, the PF acted in a way that would put the aircraft in a protective state in over-speeding conditions (as indicated in the ECAM display) by applying a nose up input.The consequence of this action was that the AOA values exceeded the warning threshold at Mach 0.8, triggering a stall warning. As the speed rapidly dropped below 60kt the stall warning seized. The sudden interruption of the stall warning did not adhere to the MoRas context relevant information needed to get out of the stall condition ceased to be provided. Furthermore, the MoQu, MoQa and MoM was violated as the ending of the stall warning indicates that the aircraft has left stall conditions, even though PF gave continuous nose up input for the duration of the warning. Thus, the warning should have remained active until AOA was within the flight envelope limitations.

One factor that, according to the official investigation [11], could have assisted in diminishing the gulf of evaluation created by the violations of the Gricean maxims in relation to the stall warnings was an instrument that showed the values of AOA to the pilots. Had such information been readily available to the pilots as soon as a stall warning is triggered, the additional information available might be sufficient to reduce the gulf of evaluation, thus giving the pilots a chance to recover from stall conditions where current cockpit instruments are not able to provide such information.

6. Discussion

The analysis shows that information flow between aircraft and pilots were insufficient and further deteriorated immediately following the autopilot disconnect. The sudden change in flight conditions, caused by the pitot-probe freezing over causing the autopilot to disconnect and put the aircraft in alternate law, forced the pilots to move from a low workload, standard procedure scenario to a high workload, time-critical scenario. This sudden escalation of cognitive workload had a significant negative impact on crew performance and decision making.

The analysis show that the information available to the crew were both irrelevant in the context in which the autopilot disconnected as well as incoherent with regard to the stall warnings that followed. It is reasonable to state that if context relevant information had been available, such as AOA values and correct ECAM messages relating to pitot-probe issues, the crew could have succeeded in recovering from the situation.

6.1. Recommendations

This paper has established several aspects in which human-machine communication failed in different aspects of the Gricean maxims. Therefore, some recommendations will be made that may improve human- machine communication in future flight decks.

- Ensure that ECAM messages are presented in the relevant context of the flight as to avoid inappropriate action.

- Display the angle of attack values in the interface at the onset of a stall warning to reduce the gulf of evaluation. The angle of attack display should be displayed until the PF/PNF acknowledges and cancels the displayed information similarly to how ECAM messages are acknowledged and cancelled.
- Increase the signal clarity of significant changes in critical flight parameters, such as changes in flight law, to allow for quick identification and consideration by flight crew.

6.2. Lessons learnt for highly automated driving

The results from this case study may have implications for the design of contemporary automated vehicles,as contemporary vehicle automation is likely to have several restrictions based on geographical, sensor and driver state conditions. The consequence of the limitations imposed by such restrictions is that vehicle control will be passed between the vehicles system agents, i.e. the driver and the automated agent, when such limits are approached.

Such a procedure is strikingly similar to how automation in aviation is designed, where routine low-complexity tasks are automated, leaving the complex situations to be handled by pilots (e.g. take-off and landing). In automated vehicles drivers may be engaged in other activities such as reading or working during the time when automation is engaged. Thus, the driver is likely to have little knowledge of what has transpired up until the time of transfer of control and what actions the automation has taken to adapt to changes, as most failures occur during control transitions resulting from a lack of, or insufficient communication with a resulting inaccurate mental model [15].

To mitigate these issuesdesigners must ensure that drivers are supported with information relevant to handle such situations. The transfer of control procedure leading up to the moment of transfer must therefore ensure that the driver is ready by ensuring that the agent taking over control has got a correct and up-to-date mental model of the current process state and is aware of any recent changes to the process. As shown in the AF447 analysis, the human-machine communication failed, causing a conflict between pilot mental models and system state, resulting in a negative feedback loop that ultimately led to the loss of the aircraft. Therefore, to mitigate such situations, it is argued that the transfers of control must be designed as to ensure a structured and unambiguous bidirectional transfer of information between driver and automation to create a coherent mental model, by adhering to the constraints imposed by the Gricean maxims.

Continuous bidirectional information flow facilitates driver automation interpredictability[19, 22] as transient information will be available for both driver and automation of their respective states. Having a continuous flow of information between driver and automation also enables the possibility of utilising a question and answer style of presenting and requesting information as part of the control-transfer process. Such a communication protocol may be used to enable communication to be tailored to what information is needed by the driver and at what level; strategic information to support long term decision making such as route redirection/planning, tactical information to support short term decisions such as lane changes/overtaking manoeuvres and operational information such as speed adaptation.

7. Conclusion

When applying the Gricean Maxims one is able to identify several problems in the human-machine communication of AF447, and to attribute these problems to different aspects of the maxims. Most problems were caused by a lack or surplus of information, and ambiguity in the information and warnings presented. Some problems were also associated with inaccurate information presentation and contextually irrelevant information.

Some of the problems in communications that occurred in the case of AF447 may be anticipated on as automation gets a prominent role in contemporary vehicles. This paper highlights some of these problems and how they may be mitigated in a highly automated driving context. Like pilots, drivers are facing an increasingly advanced environment. This environment must be designed in such a way as to support the work of the driver rather than replace the driver until full autonomy is a reality. This may be done by using the Gricean maxims as a tool in designing human machine communication by providing a means to identify whether information is presented in a contextually relevant way, whether the information is sufficient, accurate and unambiguous.

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References

[1] United Nations, Vienna convention on road traffic, in 37, U. Nations, Editor. 1968.
[2] Gasser, T.M., et al., Legal consequences of an increase in vehicle automation. 2009.
[3] National Highway Traffic Safety Administration, Preliminary Statement of Policy Concerning Automated Vehicles, N.H.T.S. Administration, Editor. 2013.
[4] Endsley, M.R., Automation and situation awareness. Automation and human performance: Theory and applications, 1996: p. 163-181.
[5] Sarter, N.B., D.D. Woods, and C.E. Billings, Automation Surprises, in Handbook of Human Factors & Ergonomics, G. Salvendy, Editor. 1997, Wiley.
[6] Woods, D.D. and E.S. Patterson, How Unexpected Events Produce An Escalation Of Cognitive And Coordinative Demands, in Stress Workload and Fatigue, P.A. Hancock and P. Desmond, Editors. 2000, NJ: Lawrence Erlbaum Associates: Hillsdale.
[7] Young, M.S. and N.A. Stanton, Attention and automation: New perspectives on mental underload and performance. Theoretical Issues in Ergonomics Science, 2002. 3(2): p. 178-194.
[8] Young, M.S. and N.A. Stanton, Malleable attentional resources theory: a new explanation for the effects of mental underload on performance. Hum Factors, 2002. 44(3): p. 365-75.
[9] Young, M.S., et al., State of science: mental workload in ergonomics. Ergonomics, 2015. 58(1): p. 1-17.
[10] Levenson, N., Medical Devices: The Therac-25, in Software: System Safety and Computers. 1995, Addison-Wesley.
[11] Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile, Final Report: On the accident on 1st June 2009 to the Airbus A330-203 registered F-GZCP operated by Air France flight AF 447 Rio de Janeiro - Paris. 2012.
[12] Christoffersen, K. and D.D. Woods, How to Make Automated Systems Team Players. Advances in Human Performance and Cognitive Engineering Research, 2002. 2: p. 1-12.
[13] Norman, D.A., The Design of Everyday things. 2013, New York: Basic Books.
[14] Inagaki, T., Traffic systems as joint cognitive systems: issues to be solved for realizing human-technology coagency. Cognition Technology & Work, 2010. 12(2): p. 153-162.
[15] Sarter, N.B. and D.D. Woods, Team Play with a Powerful and Independent Agent: Operational Experiences and Automation Surprises on the Airbus A-320. Human Factors: The Journal of the Human Factors and Ergonomics Society, 1997. 39(4): p. 553-569.
[16] Sheridan, T.B. and R. Parasuraman, Human-Automation Interaction. Reviews of Human Factors and Ergonomics, 2005. 1(1): p. 89-129.
[17] Clark, H.H. and D. Wilkes-Gibbs, Referring as a Collaborative Process. Cognition, 1986. 22(1): p. 1-39.
[18] Grice, H.P., Logic and Conversation, in Speech Acts, P. Cole and J.L. Morgan, Editors. 1975, Academic Press: New York. p. 41-58.
[19] Brennan, The Grounding Problem in Conversations With and Through Computers, in Social and cognitive psychological approaches to interpersonal communication, S.R.F.R.J. Kreuz, Editor. 1998, Lawrence Erlbaum: Hillsdale, NJ. p. 201-225.
[20] Clark, H.H., Using Language. 1996: Cambridge University Press. 432.
[21] Patterson, E.S. and D.D. Woods, Shift changes, updates, and the on-call architecture in space shuttle mission control. Comput Support Coop Work, 2001. 10(3-4): p. 317-46.
[22] Miller, T., et al., Foundations of Human-Agent Collaboration: Situation-Relevant Information Sharing. The AAAI 2014 Fall Symposium on AI for Human-Robot Interaction, 2014, 2014.