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NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO LECTURE SERIES 220

Human Consequences of Agile Aircraft

(Cycle de conférences sur les facteurs humains liés au pilotage des avions de combat très manoeuvrants)

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Human Factors and Medicine Panel (HFM) of RTO presented on 20-21 March 2000 in Neubiberg, Germany, on 23-24 March 2000 in Preston, UK and on 19-20 October 2000 at WPAFB Ohio, USA.

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The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

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• SAS	Studies, Analysis and Simulation
• SCI	Systems Concepts and Integration
• SET	Sensors and Electronics Technology
• IST	Information Systems Technology
• AVT	Applied Vehicle Technology
• HFM	Human Factors and Medicine
• MSG	Modelling and Simulation

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Human Consequences of Agile Aircraft

(RTO EN-12)

Executive Summary

While historically agile flight was first seen as an issue of airframe agility with a consequent emphasis on acceleration issues, there has been an evolution in the understanding of agility. WG 27 adopted WG 19's recommendations that airframe agility is only one aspect of agility which when combined with weapons agility and systems agility results in "operational agility." The experienced pilots that we interviewed saw a real operational need for aircraft agility. They consistently rated both high angle-of-attack/nose pointing and off-boresight missiles/helmet-mounted display/sight systems as very important capabilities. They denied physiological problems related to acceleration or spatial disorientation, although their sorties to date have been with a clear sky, in active control. Also, experts predict an increase in spatial disorientation mishaps in super-manoeuvrable aircraft. In particular, there are significant gaps in our understanding of the effects of multi-axis accelerations.

With minimal constraints on angle-of-attack and expanded weapon launch envelopes, novel displays will be required that enable pilots to fly with references well beyond conventional fields-of-view. Decision aids, intelligent interfaces, and automated subsystems will be required to help pilots cope with the dramatic increase in the tempo of the tactical situation, while also maintaining situational awareness. Efficient controls are also needed to enable pilots to command and operate equipment quickly and accurately. The thrust-vectoring and post-stall operations should be fully integrated into the flight control system. Pilots still prefer controlling aircraft functions via HOTAS (hands-on-throttle-and-stick) although alternative controllers (e.g., voice and gaze-based control) may be worthwhile in the future. Current pilot protection systems will be inadequate in an unconstrained flight envelope and during ejection. The seat position relative to the aircraft's center of gravity will also impact the acceleration effects experienced by pilots.

The main aim of this Lecture Series is to provide a review of the physiological and psychological consequences of agile flight, as well as address considerations for the pilot vehicle interface design, pilot selection, training and simulation. These lectures are especially appropriate for scientific researchers and engineers involved in human-machine interaction and the design of crew stations for future aeronautical applications.

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Human Factors and Medicine Panel (HFM) and the Consultant and Exchange Programme of RTO presented on 20-21 March 2000 in Neubiberg, Germany, on 23-24 March 2000 in Preston, UK and on 19-20 October, 2000 at the Wright Patterson Air Force Base, Ohio in USA.

Cycle de conférences sur les facteurs humains liés au pilotage des avions de combat très manoeuvrants

(RTO EN-12)

Synthèse

Au départ, la manoeuvrabilité des systèmes aériens militaires n'a été étudiée que sous l'aspect de la souplesse de la cellule, avec, par conséquent, un accent mis plus particulièrement sur les problèmes d'accélération. L'approche du problème a maintenant considérablement évolué. Le groupe de travail WG 27 a adopté les recommandations du WG 19, à savoir qu'il y a lieu de prendre en compte également la manoeuvrabilité des armements et des systèmes et de parler d'agilité opérationnelle. Interrogés sur la manoeuvrabilité, des pilotes militaires expérimentés en ont confirmé la nécessité opérationnelle. Ils ont systématiquement accordé une grande importance aux caractéristiques d'angles d'incidence élevés/pointage du nez et de missiles dépointés/viseurs montés sur casque. Pour eux, rien ne laisse présager que les accélérations et la désorientation spatiale puissent entraîner des problèmes physiologiques majeurs, même s'il faut noter que la plupart de leurs missions avec des taux élevés de manoeuvrabilité ont été effectuées en ciel clair, le pilote disposant de tous les repères visuels habituels. Pourtant, les spécialistes du domaine prévoient une augmentation des incidents de désorientation spatiale en vol lors du pilotage des avions de combat à très grande manoeuvrabilité. En particulier il existe des lacunes considérables dans nos connaissances des effets des accélérations multiaxiales.

L'augmentation des domaines de tir des armements et la diminution des contraintes liées aux fortes incidences, rendra nécessaire l'emploi de nouveaux visuels, permettant aux équipages de piloter à l'aide de références se trouvant largement en dehors des champs de vision classiques. Des aides à la décision, ainsi que des interfaces élaborés et des sous-systèmes automatisés seront nécessaires pour permettre aux pilotes de faire face à l'évolution rapide de la situation tactique, tout en gardant pleinement conscience de la situation globale. Des contrôles efficaces sont également demandés pour s'assurer de la commande et de l'exploitation rapides et efficaces des équipements par les pilotes. Les opérations d'orientation de la poussée et de post-décrochage devraient être entièrement intégrées au système de pilotage. A l'heure actuelle, les pilotes privilégient le contrôle HOTAS (commande manuelle), mais admettent que les nouvelles technologies (vocales et visuelles) pourraient être intéressantes à l'avenir. De plus, il faudra tenir compte de l'inadaptation de certains systèmes actuels de protection des équipages dans des domaines de vol aussi étendus ou lors d'une éjection. La position du siège par rapport au centre de gravité de l'avion est un aspect important de la conception, qui aura une incidence directe sur les accélérations subies par le pilote.

Ce cycle de conférences a pour objectif principal de faire le point des effets physiologiques et psychologiques des vols avec des taux de manoeuvrabilité élevés, ainsi que des problèmes en matière de conception des interfaces homme-machine, de sélection et d'entraînement des équipages, y compris les moyens de simulation. Les présentations sont plus particulièrement destinées aux chercheurs et aux ingénieurs impliqués dans les interfaces homme-machine et dans la conception des postes de pilotage des futurs systèmes aériens.

Cette publication a été rédigée pour servir de support de cours pour le Cycle de conférences 220, organisé par la Commission des Facteurs Humains et Médecine (HFM) dans le cadre du programme des consultants et des échanges de la RTO du 20 au 21 mars 2000, à Neubiberg, Allemagne, du 23 au 24 mars 2000 à Preston, Royaume Uni et 19 au 20 octobre 2000 à Wright Patterson Air Force Base, Ohio, (Etats-Unis).

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Preface/Forward

Working Group #27 was formed under the former Advisory Group for Aerospace Research and Development (AGARD) in January 1997 to study the human factors implications of agile flight. As the Group was formed, it was believed that its focus would be aircraft maneuverability with a consequent emphasis on human physiologic issues related to the acceleration environment. Initially group members were chosen from the acceleration and vestibular research communities. Representatives from each of the nations with new fighter aircraft being developed were included as well as military pilot-physicians and acrobatic pilots. It was also planned to invite aeromedical input from Russian experts.

It soon became evident that the issue was much broader in scope. Among experts in the FMP Working Group #19 of AGARD, the definition of agility had evolved from one involving primarily aircraft maneuverability, to one including weapons and systems agility as well. It became evident that cognitive, control, and display issues also needed to be addressed. So additional representation from the human factors and psychology disciplines were added to the group. Also Mr. Patrick LeBlaye was included as a technical liaison to the engineering community.

Meeting sites were chosen to facilitate communication between the Working Group and aircraft designers, test pilots, and operational pilots. Because we wanted to base our work on real operational needs and realities, we had extensive interactions with NATO pilots from several nations. We interviewed pilots at our formal meetings; we asked them to fill our questionnaires; we were formally briefed by pilots on their concept of agility; we visited operational and test squadrons; we asked them to critique our briefings; and throughout the two and one-half years we consulted with pilots extensively. These pilots from France, the United States (USAF & NASA), Sweden, Germany, and the United Kingdom were indispensable contributors to the Working Group.

Conference Organization: During the first morning, both the pilot's and the engineer's views of agility will be discussed. Basic concepts of agility as well as history and definitions will be covered. During the afternoon of the first day potential physiological and psychological consequences of agility will be presented. Gaps in our scientific knowledge of agility and multi-axis accelerations will be highlighted. The second day will outline potential areas for intervention in the design of future aircraft and pilot-vehicle interface. Design considerations for displays and controls will be emphasised. During the last afternoon aircraft ejection, aircrew selection, and training considerations will be discussed. Finally we would like to discuss recommendations for design of agile aircraft and identify requirements for further research.

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INTRODUCTION

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1-1 A NEED FOR RESEARCH

> *"There is an inherent time-lag between the pace of evolution, and maturity, of new propulsion systems, and that of avionics/flight-control. While the former shifts into a "new generation" every ten to twelve years, it takes the latter only four to six."*
>
> *Dr. Benjamin Gal-Or, 1990 [1].*

Benjamin Gal-Or has been one of the leading proponents of high-agility propulsion. Many of his ideas, and those of his contemporary Wolfgang Herbst, are visionary, futuristic and controversial. In a relatively short period of time, these men, and others, have influenced the direction of fighter aircraft design. "High-agility" aircraft are now being tested and flown operationally. This new technology will offer new challenges, and threats, to human operators. Solving the inevitable human factors problems that will emerge will involve questioning established doctrine, and reaching for innovative and imaginative solutions.

The "inherent time-lag" referred to by Gal-Or could apply equally to the time-lag that now exists between the evolution of high-agility flight capability and current human protective/performance technology. There currently exists a technology gap, the precise nature of which is only partly understood. Typically, human factors are considered only after concept, design, and aircraft prototype development, and often after loss of life. Some human factors problems, identified years ago, have never been completely solved. Failure to identify the inevitably unique problems that will attend human exposure to the high-agility flight environment will unquestionably lead to needless loss of life and scarce resources.

High-agility flight will challenge every aspect of human protection and performance. Many old engineering designs and assumptions will be challenged. During the narrow window of opportunity that now exists between concept, test, and widespread operational deployment of high-agility aircraft such as the F-22 and JSF, aggressive research aimed at exploring the problems and solutions will enhance the value of the these weapons, and prevent needless loss of life.

1-2 HIGH-AGILITY FLIGHT

The merits of high-agility flight have been hotly debated since the concept was seriously explored by military planners several decades ago. Much emotion has been generated:

> *"And thrust-vectoring for high angle-of-attack airplanes? Hell, that's a bunch of crap....you slow down, and you're dead meat (46)."*
>
> *"All advanced fighters will be vectored ....prevent 60% of all flight accidents....racing cars, cars, buses, trucks, tractors, racing boats, and wheelchairs (25)."*

All opinions are based underlying assumptions regarding the nature of any future air war. The need for high-agility maneuvering may depend on whether future air-combat will occur at beyond visual range, or up close, or both. Short-range air-to-air combat capability may not be important in an era of beyond-visual-range weapons. However, the advent of all aspect missile technology might mean that survivability depends on "point-first" capability if combat occurs within visual range. To achieve a point-first capability, rapid pitch maneuvers will be required [1]. New tactics that trade energy for agility will emerge. If <u>both</u> long and short-range combat capabilities are needed, the successful future combat aircraft will need a design that incorporates the high speed capabilities of current fighters with high agility [2].

Paper presented at the RTO HFM Lecture Series on "Human Consequences of Agile Aircraft", held in Neubiberg, Germany, 20-21 March 2000; Preston, UK, 23-24 March 2000; WPAFB Ohio, USA, 19-20 October 2000, and published in RTO-EN-12.

The term "high-agility" has been loosely used, but often refers to an aircraft's ability to maintain controlled flight at speeds below that of the airframe stall speed. An agreed definition of "agility" remains elusive. Even among experts in the NATO Four Power Group, the definition of agility evolved from one involving primarily airframe maneuverability, to one including systems and weapons agility as well (see Chapter 3). Airframe Agility encompasses both maneuverability (speed and flight path) and controllability (attitude and thrust). Examples of System Agility would include datalink (Gripen, F-22), scanned array radars (Rafale, F-22), and helmet-mounted displays (Rafale, Gripen, Eurofighter, F-22). An example of Weapons Agility would be off-boresight missiles. These three aspects of agility will be described in more detail in Chapter 3.

By redirecting engine thrust, increased aircraft maneuverability can be achieved. Thrust vectored propulsion (TVP) was the term given to the redirection of engine thrust in flight. There is nothing new in this. TVP was designed into the Harrier many years ago. With the development of high thrust/weight ratios, it has been possible to use TVP systems more flexibly. High-powered TVP adds energy to directional control and can provide for tight, highly agile maneuvering of aircraft in flight. Thrust vectored control (TVC) has been used to describe this capability [3]. As well as "high-agility", TVP enhanced maneuvering has been termed "superagility," "supermanueverability," and "enhanced fighter maneuverability (EFM) [4]."

1-3 HISTORICAL PERSPECTIVE

The concept of high-agility flight was first described by Wolfgang Herbst and his colleagues at Messerschmitt-Boelkow-Blohm (MBB) during research conducted in the 1970s. This work was a logical progression in the evolution of fighter design and which began 1914. Practical flight experience started with civilian unlimited aerobatic competition pilots. In 1968, the world aerobatic scene was dominated by aircraft with non-symmetric, high-lift aerofoils and pressure carburettion, typified by the Zlin 526 and Yak 18 family. Those without state financial support or major sponsorship were seeking ways to break this stranglehold which reached its apogee at the Hullavington, England World Championships in 1970 with the Yak 50 and "barn-door" 2-aileron Pitts S1-A. Review of the Aresti aerobatic scoring system and theoretical consideration of every manoeuvre of which an air vehicle was capable suggested that symmetrical +/-Gz performance and a power/weight ratio better than the 5lb/hp then being achieved by Grand Prix/Formula 1 racing cars, would be essential.

Herbst and his group conceived the idea that controlled flight was feasible at high angles-of-attack (AOA) corresponding to airspeeds below the stall speed [5]. Using TVP, Herbst postulated that it would be possible to deeply penetrate this previously forbidden part of the flight envelope, and maintain control throughout. This capability was termed post-stall maneuvering (PST) [6]. High AOAs during PST would allow unprecedented maneuvering potential that could include the ability to quickly "point" the nose of the aircraft at an adversary while maintaining complete control. By redirecting the thrust vector into the yaw plane, it would be possible to introduce a lateral "pointing."

Gal-Or's work, consisting of proof of concept flights using a variety of unmanned scaled models, began in 1987 [7]. This work demonstrated that TVP could double pitch rate [8] and triple turning rate of the F-15 [7]. A manned flight research program involving the X-31 demonstrated several unique maneuvers, including enhanced PST flight, pitch-up from inverted flight, and the "Herbst" maneuver. In air combat maneuvering, the X-31 dominated comparable conventional adversaries by an exchange ratio of 3:1 and kill ratios in excess of 32:1 were reported in offensive mode.

High-agility flight gained popular attention at the 1989 Paris show when the Russian Su-27 demonstrated a maneuver that became known as the Cobra maneuver [9]. Subsequently, the Su-27 demonstrated previously unknown high levels of transient agility [9] [10]. A subsequent version of the Su-27, the Su-37, had fully independent, fully moveable thrust nozzles for each of its two engines. The Su-37 demonstrated superior agility that included backward flight during post-stall loops [11]. An additional maneuver, the 'hook' - or sideways Cobra, was introduced using the Su-35 [7].

In the United States, the Calspan NF-16D variable stability in-flight test aircraft (VISTA) [12], multi-axis thrust vectoring (MATV) demonstrated the Cobra, J-turn maneuver, split-S, and Herbst maneuvers [13]. Another maneuver, the "helicopter" consisted of a flat-spin that allowed continuous pointing at any adversary in any position in the sky [11]. Similar work was conducted on F/A-18 High Angle of Attack Research Vehicle (HARV) [14].

The F-22 Raptor, now in flight testing, will be capable of +/- 20 degrees of pitch thrust-vectoring (TV) [11]. The F-22 will open a new era in aviation that will be characterized by pitch rates 2-3 times those of conventional aircraft [15] and angles-of-attack (AOA) up to 70-degrees [16].

1-4 TACTICAL ADVANTAGES

Very little has been published on the tactical advantages of high-agility as the technology is still developmental and capabilities often classified. From what is available thus far, it appears that the following capabilities may emerge as tactical advantages:

a. Close-in Combat.

The tactical advantages of a point-first capability arose from the development of all aspect missiles [17] [18] [7], that is, missiles that could lock on the forward aspect of a target. Since fighter pilots would no longer need to tail-chase into a '6 o'clock position', just pointing at the adversary would be sufficient to achieve a kill [5].

b. Visual Reconnaissance and Ground Attack.

The advantages of high-agility would not be limited to short range, air-to-air combat. The majority of aircraft losses in recent wars have been due to ground attack [19]. Low level tactical maneuvering or automated systems, such as the Automatic Maneuver and Attack System (AMAS), would enhance high-agility capable fighters ability to escape ground or air threats. The dive attack would remain an important tactical option that would be improved by high-agility [19], and high-agility would allow strike fighters to avoid potential ground/air threats [20]. While future ground attack aircraft, such as the Joint Strike Fighter (JSF), might eventually use unmanned fighter versions in this role [21], no existing combination of computers and simulators of appropriate size can yet duplicate the capabilities of a pilot in real-world conditions [22]. Pilots will remain in the ground attack role for the foreseeable future.

c. Missile avoidance and Laser-break

d. High Altitude Operation

The ability to engage in tactical ceiling maneuvering, the requirement for high altitude visual identification and combat maneuvering above 20km/60,000' adds extreme altitude operations and the significant complexities they involve to the multi-role activities now expected of superagile aircraft. That the MiG-31 [designed for Vigilante and Valkyrie], despite all its difficulties, remains in service and is now being upgraded emphasizes the significance afforded by others to this sphere of operations.

e. Extremely short take-off and landings, ESTOL

All-weather, 'round the clock, extremely-short take-off and landings, ESTOL into remote strips and small carrier landings in worse weather conditions will involve either yawed approaches, totally automatic, aircraft-based landings or real-time, sensor-fused display directed heads-down finals and touch-down. The necessary velocity vectors and angles of attack will provide flight paths on finals in the blind sectors of even the most generous of "full vision cockpits", unless nose droop, Corsair II style cranked wings and stork-like undercarriages are re-introduced.

f. Automatic maneuvering

Automatic gun-laying, multi-target, single run air-to-ground nose pointing, missile and laser avoidance and "optimoving (optimum maneuvering, the instantaneous adoption of the optimum aerobatic figure to achieve the required tactical maneuvre from a given position, vector velocity and energy state with the performance available)" together with post-end gaming (the constructive use of GILOC], will all involve violent maneuvering and, for safety and economic reasons, require departure recovery from far out of envelope states rather than abandoning the aircraft by ejection as is now the rule.

g. Rules of Engagement

Superagility is mandatory if restrictive Rules of Engagement are imposed. Visual identification, VID and graded responses do and will place NATO aircraft and aircrew at immediate disadvantage and hazard.

h. Night

Though half the World is night, night operations using night vision goggles [NVGs], even with 120^0 FOV, fields of view, will increase rather than reduce the need for superagility as well as the opportunities for disorientation.

i. Multiple Roles Requirements

The carriage of ad hoc, asymmetric and incompatible loads, together with the retention of stores as long as possible, despite induced asymmetry by partial deployment as dictated by operational reality, require superagile aircraft capability and thrust vector control, TVC. Multi-roling, including ground attack, guarantees inadvertent close combat and being bounced under conditions of the opposition's choosing.

j. Stealth and Surprise

Stealth, surprise, ground attack and the use of forward, remote and exposed landing grounds in desperate situations, all inevitable in the light of the present strategic situation and NATO's need for economy, enhance the bouncing hazard, in which superagility is the only means of survival and of turning the tables on the bouncer who is now committed to attack. The reverse, achieving surprise by use of terrain, masking and weather, will depend on superagility.

k. Efficiency

Includes economy to extend tactical and strategic envelopes. Achieving trim symmetry and minimal aerodynamic drag despite asymmetric loads; corner speed optimization; range and endurance through fuel efficiency and economic supercruise under operational conditions are all facets of superagility.

l. Safety

The ability to exploit extreme aerodynamic envelopes also provides the means to recover from situations and departures, the present inevitable consequences of which are loss of aircraft and, at best, crew recovery by ejection. Just as in aerobatic aircraft parachutes should be unnecessary, all aerobatic aircraft departures being convertible into spin and therefore recoverable, so ejection in superagile aircraft should be solely to provide for combat damage occasioning major structural failure.

m. Superagile UAVs

Tactical un-manned air vehicles, TUAVs and the remote piloting of super-agile UAVs, where superhuman envelopes are essential to mission accomplishment, only remove the on-board human component of system agility. Not having a "man on the spot" and extended communications lag with the enhanced requirement for UAV autonomy actually increases the other demands of superagility.

1-5 TACTICAL DISADVANTAGES

There are two particular disadvantages associated with high-agility maneuvering: 1) low energy states following the PST maneuver, leaving the fighter vulnerable to re-attack; 2) the spin-like characteristic of the PST roll maneuver [17]. To prevent energy decay, Herbst has predicted average PST durations of 5 s [1].

With the possibility of pitch rotations of 400 degrees per second, it is possible that EFM maneuvers will involve completion of pitch-up to greater than 70 degrees AOA and recover to straight and level flight in considerably less than 5 s [1]. While the design of such a capability may be possible, the pilot will experience both impact and sustained acceleration and the effect of the combination of these accelerations is largely unknown. The effects of an abrupt spin-like maneuver, such as a rapid Herbst maneuver, during high and changing +Gz acceleration, is also unknown

1-6 PHYSIOLOGICAL STRESS

The principle physiological effect of high-agility flight on pilots will relate to abrupt changes in magnitude and/or direction of acceleration experienced by the pilot. Acceleration has been categorized as "impact" (less than 1-second duration) or "sustained" acceleration (greater than 1-second duration). Sustained acceleration is important in aircraft as a result of centrifugal force during high velocity turns. Previously, impact acceleration was associated with collisions (crashes), turbulence, or ejection escape. Pilots of high-agility capable aircraft will experience both impact and sustained acceleration during maneuvers that may be complete in several seconds [1].

While it is possible that peak Gz loads will be higher then those currently experienced, very short G durations might preclude physical harm [18] and some have claimed that peak +Gz may actually decrease during high-agility maneuvers [23]. Nevertheless, angular acceleration will be a new, potentially dangerous feature [24]. Herbst predicted the following maneuver characteristics: 1) 5 s PST average duration; 2) 10% of total engagement time in PST; 3) lower G-level by about 1 G, and; 4) lower maneuvering speeds by about 0.1 M [6].

Some prediction of the nature of acceleration stress can be made by considering several defined high-agility maneuvers. The Herbst maneuver consists of an abrupt pitch-up to a high AOA in the PST envelope followed by a 180 degree yaw leading to a nose-down inverted attitude and low airspeed. Recovery then allows the aircraft to reverse direction within a very short turning radius. The pilot would start the Herbst from +Gz, experience increased +Gz of short duration due to pitch, and experience additional increased +Gz due to aircraft decelerating profile drag. Then, depending on entry speed, seat back angle, and time at high alpha, the pilot would experience 0 Gz or -Gz before +/-Gy begins during the yaw phase. If stable velocity is achieved prior to yaw, the pilot would experience +1 Gx (gravity). Tamrat has compared the Herbst maneuver to a spin [17]. The magnitude of yaw-induced Gy would vary with the distance of the cockpit from the center of aircraft rotation [25]. On completion of the yaw, in the nose down attitude, the pilot would experience 0 Gz and increased +Gx during energy recovery, and +Gz during dive recovery (possible "push-pull" effect). Current aircraft attitude flight instrument depictions would make spatial orientation a problem during this maneuver, especially during low visibility conditions. These projected G changes are summarized in Table 1-1.

During a Cobra maneuver, the pilot would start from +Gz and experience rapidly increased +Gz due to pitch and drag (similar to the Herbst maneuver). When stable at high AOA, with no pitch movement, 0 or -Gz would occur. On recovery, nose down pitch would result in increased -Gz that would vary with the distance of the pilot from the center of pitch rotation [25]. The ability to recover from the Cobra may be limited by the pilot's -Gz tolerance. Negative AOA might occur during energy recovery with increased +Gz as the aircraft accelerates out of the maneuver (again, possible push-pull effect).

Table 1-1. Anticipated Acceleration Variations Associated with Currently Projected High-Agility Flight Maneuvers

Maneuver	+Gx	+/-Gy	+Gz (entry)	Angular Acceleration direction	Transitions	Comments
Herbst	| then ⌉	⌉ then |	⌉⌉ then | to 0 or -Gz	Lateral	1. 0 Gy ! +/-Gy 2. +Gz ! 0 Gz (or -Gz) ! +Gz 3. 0 Gx ! +/- Gx 4. +/- ang accel	1. Spatial orientation 2. Push-pull effect (PPE)
Cobra	| then ⌉	N/A	1. ⌉⌉ then | to 0 or -Gz 2. -Gz then +Gz	Pitch	1. +Gz ! -Gz ! Gz	1. Spatial orientation 2. PPE
Voll reversal	| then ⌉	1. ⌉ then | 2. | then ⌉	⌉⌉ then | to 0 or -Gz	Lateral	1. 0 Gy ! +/-Gy 2. +1 Gz ! +Gz ! 0 Gz (or -Gz) ! +Gz 3. 0 Gx ! +/- Gx 4. +/- ang/trans accel	1. Spatial orientation 2. Possible PPE
Pitch reversal	| then ⌉	N/A	1. ⌉⌉ then | to 0 or -Gz then ⌉ Gz 2. || to -Gz then ⌉ 0 or +Gz	Pitch	+Gz ! -Gz ! Gz	1. Spatial orientation 2. Possible PPE
Yaw reversal	N/A	⌉ then |	N/A	z-axis	0 Gy ! +/-Gy ! 0 Gy	
Roll reversal	N/A	N/A	N/A	Roll	Angular acceleration changes	
Axial reversal	1. || then ⌉⌉ 2. ⌉⌉ then ||	N/A	N/A	N/A	+/- Gx	
Lateral jink	N/A	⌉⌉ then ||	N/A	Inertial	+/- Gy	
Vertical jink	N/A	N/A	1. ⌉ then | to 0 or -Gz then ⌉ Gz 2. | to -Gz then ⌉ 0 or +Gz	Inertial	+/-Gz	

Depending on exit speed, the maneuver could be repeated, or the pilot might unload to 0 Gz to recover energy. These projected G changes are displayed in Table 1. As with the Herbst maneuver, spatial orientation will be a problem in poor visibility conditions. In-flight recordings from a TVP modified F-15 showed G variations during pitch of -1.5 Gz to +4 Gz, -1 Gy to +1 Gy, and - 1 Gx [26].

While +Gz will be less than current aircraft, and of shorter duration, it will be more frequent. Negative Gz exposure will be much more frequent than currently experienced. Zero Gz will be frequently experienced, both as an energy recovery tactic and during maneuver transitions. Gy exposure, now rarely experienced, will become frequent during pointing and escape maneuvers. Gx exposures will increase in magnitude as propulsion systems and air braking systems improve. Because of the unprecedented degree of controllability afforded by thrust vectoring, rapid changes in magnitude and direction involving these accelerations will occur. Superimposed on translational accelerations will be angular accelerations.

1-7 THE CURRENT KNOWLEDGE GAP

Virtually all of our current knowledge of aviation physiology comes from conventional, non-agile flight applications. Very little applicable published information exists related to the human consequences of exposure to agile flight. Most of what exists is found in the non-peer reviewed literature. It is evident that "surprises" will emerge as our knowledge and experience with this innovation increases. We will be challenged in areas as diverse as cockpit design, visual/vestibular illusions, instrumentation, escape system design, and human performance. Past assumptions in all of these areas will be reviewed.

A major problem will be protection against acceleration threats. The old g-suit designs, including recent innovations such as ATAGS and STING, may not work. In the past, laboratory tools used in acceleration research, such as the human centrifuge, were usually capable of generating +Gz only, and incapable of -Gz. Gx and Gy were generally uncontrolled and regarded as artifact. While a small fund of current knowledge might be applicable to high agility flight, with great caution, properly controlled studies on the effects of multi-axis acceleration that will be encountered have yet to be done.

Relatively little work has been conducted on the effects of -Gz. It has been estimated that about 30 good studies exist on the effects of -Gz, most conducted during WW II or soon after. These studies illustrate the role of the parasympathetic nervous system in adapting to -Gz. The physiology of -Gz was partly reviewed in 1992 in a discussion paper on bradycardia during –Gz [27]. A previously unidentified problem, persistent vertigo following -Gz (termed the “wobblies”), was recently described [28].

Almost no research had been done on transitions between +/- Gz. The recently identified “push-pull effect” [29] may be important in this regard. Although the push-pull effect was demonstrated in 1959 [30] and accidents were documented in civil aviation by Mohler in 1972 [31], no further work was undertaken until 1992. Since then several papers have confirmed the push-pull effect [32] [33] [34] [35]. Researchers in Canada, Israel, and the United States have implicated the push-pull phenomenon in causing the military aircraft accidents [36] [37] [38] and aside from education efforts, no new technology to solve this problem is in sight.

In terms of flight instrument design, pilots rely on flight instruments as their primary defense against visual and vestibular illusions and loss of situational awareness. The various heads up displays (HUD) designs, attitude indicators (AI), and associated primary flight instruments allow the pilot to determine spatial orientation relative to the earth in degraded visibility. Translational and rotational accelerations are known to affect spatial orientation through induced vestibular and proprioceptive illusions. Loss of spatial orientation can lead to loss of situational awareness. Never solved previously, aircraft crashes attributed to loss of situational awareness continue to occur [39]. Current AI/HUDs display a two dimensional depiction of the aircraft attitude relative to the horizon. Neither instrument effectively displays the yaw or velocity vector. Most airspeed indicators are pneumatically driven and become unreliable below the stall-speed. Thus, the pilot of an high-agility capable aircraft, flying at high-AOA during PST, employing current flight instrument displays, would receive inadequate orientation and velocity information. A HUD design in the X-31 depicting the velocity vector has proven confusing [5]. Vestibular illusions, not yet identified, will lead to pilot misperceptions of flight orientations that may be difficult to counter with existing instrument displays. Improved instrumentation will be needed to counter the severe vestibular illusions that will certainly be associated with high-agility flight [40]. Cord discussed the problem of situation awareness and the need to better integrate the pilot with the aircraft [18].

Spatial orientation of pilots will be especially challenged by lateral accelerations (Gy) that will be experienced during angular acceleration in maneuvers such as the Herbst maneuver. Similar forces are experienced by civilian light aircraft aerobatic pilots, with an important difference - high agility fighter pilots will experience lateral Gy in combination with long radius angular acceleration. The effects of this combination are unknown and will likely be associated with currently unidentified vestibular illusions [18]. While the natural tendency of any pilot might be to reposition the head in the direction of rotation (thus converting lateral angular motion to pitch motion), preoccupation with tactics may not allow orienting compensating movements. Thus, there will be a large combination of possible disorienting stimuli.

Short radius yaw rotational movements that occur in helicopter flight and vertical take off and landing (VTOL) fixed wing aircraft, subject pilots to rotation around the z-axis. The NF-16D MATV ‘helicopter’ maneuver is an example of a similar high-agility yaw maneuver [11]. The speed of rotation in high-agility capable fighters may be significantly greater than that seen previously, and may be combined with other acceleration stress. Head movements during z-axis rotation may provoke disorientation and motion sickness [39] [41].

Psychological challenges to pilots included faster information flow (estimated to be two to three times faster than conventional fighters). Although the requirement to think ahead is common to all aircraft, this becomes more urgent in agile aircraft due to the shorter time domain. Human factors and crew resource management will be redefined in the high-agility environment.

1-8 THE NEED FOR HUMAN RESEARCH

The lack of understanding of the physical demands imposed by high-agility flight has been described as the "forbidden human space-time agility domains." [25] "Understanding these complex rigid-body translational, rotational, gyration, and gyroscopic phenomenon, requires reassessment of well-established concepts." [25] While some speculation has occurred on the effects of G in high-agility flight [8], it is based on gradual or rapid G-onset studies not representative of high-agility accelerations. Gal-Or, one of the few engineer-researchers who has shown an appreciation of human factor limitations in these aircraft has strongly recommended DES-centrifuge research into these problems [8], and has included the need for research into pilot tolerances as part of his methodology [25]. Tedor has described the problems that could be anticipated and the lack of resources to solve them. He emphasized the problems of G-LOC and visual/vestibular illusion [42].

Several important illusions in non-agile aircraft were identified only after the loss of aircraft, a notable example being the somatogravic illusion which occurs during take-off or rapid acceleration in fighter aircraft. We can expect history to repeat itself if need for dedicated research is not understood, and work commenced.

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OPERATIONAL NEED

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2.1 PILOT SURVEY

Between April 1997 and October 1998, Working Group #27 conducted discussions with experienced military fighter pilots and test pilots concerning the human factor implications of agile aircraft flight. Aircrews interviewed included 23 U.S.pilots (consisting of 5 NASA Test Pilots, 13 USAF Air Warfare Center Pilots, and 5 USAF Pilot-Physicians), 11 Swedish Air Force operational pilots, 3 German Air Force test pilots, and 2 French pilots. After the discussions, the aircrews were asked to complete an anonymous questionnaire. (Note, the French pilots were interviewed before the questionnaire was completed and so their views are represented in the pilot comments, but not in the actual questionnaire results.) In addition to the questionnaire results, one-on-one interviews were conducted with many of the pilots. A world wide representation of most agile aircraft was achieved by surveying pilots experienced with the X-31, F-18 HARV, F-15 Active, MATV, Harrier, F-22, F-18, MIG-29, Rafale, Gripen, and Eurofighter.

As a part of the questionnaire, the aircrew members were asked background questions concerning their flying experience. The remainder of the questionnaire involved rating the utility of various aircraft capabilities (e.g., high AOA/post-stall maneuvering, negative G maneuvering, high (+12) Gz maneuvering) with regard to their contribution to air-to-air combat performance. A seven point scale was used to rate the perceived contributions to air combat effectiveness. Specifically, ratings ranged from 1 for "Not at all useful", 3 for "Slightly useful", 5 for "Moderately useful", to 7 for "Very useful."

The aircrews were, on the average, very experienced with an average flying time of 2,589 hours (range 900-9,000). A summary of the ratings for agility factors in shown in Table 2.1. Note that some pilots did not have experience with helmet mounted sights or advanced anti-G suits. Hence, they did not rate these systems. Combat Edge (the USAF positive pressure breathing system for G protection) and the Advanced Technology Anti-G suit were included as known benchmarks against which to judge the pilot responses.

Pilots rated helmet-mounted sights, high AOA maneuvering, and high G capability all highly. Ratings of negative Gs varied widely among the responders. Some interesting differences were noted in the responses of the Swedish pilots compared with the U.S. and German pilots (see Table 2.2). On the average, Swedish pilots valued airframe agility (capability to pull +12 Gz and –Gz) less. This could be due to several factors including (1) lower average flying experience (flying hours) in the Swedish pilots interviewed, (2) the Swedish pilots included mainly operational pilots rather than test pilots or (3) national differences.

In summary, the pilots surveyed viewed the capabilities afforded by agile aircraft as useful for combat. The following sections provide additional detail from the questionnaire data and debriefing comments that specifically pertains to human factors issues, including physiologic problems, the pilot-vehicle interface, selection, and training. The final section re-examines the pilots' view of agile flight.

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Table 2.1 Summary of Pilot Ratings of Agile Aircraft Capabilities

Aircraft Capability	Average Rating	Range of Ratings	Number of Responses
Helmet mounted sight	6.6	5-7	8
High AOA/nose pointing	6.2	1-7	35
+12 Gz	5.7	3-7	34
Negative Gz	3.2	1-7	34
Combat Edge	5.7	3-7	24
Adv. Technology Anti-G Suit	5.0	3-7	14

Table 2.2 Comparison of Pilot Ratings for Three Countries

Aircraft Capability	U.S.	Sweden	Germany
Helmet mounted sight	6.5	No responses	7.0
High AOA/nose pointing	6.2	4.8	6.7
+12 Gz	6.0	4.9	6.7
Negative Gz	3.7	2.1	3.3

2.2 PHYSIOLOGIC PROBLEMS

High AOA Flight: X-31 pilots described high AOA flight as feeling "unnatural" or "bizarre" at first, but they quickly adapted and denied any adverse physiologic sensations.

Acceleration Exposures: In the X-31, the +Gz exposure was generally limited to a brief +6 Gz pulse that decreased rapidly as airspeed decreased. X-31 pilots also experienced little negative Gs and almost no +/-Gy (side-slip).

Active Control of Aircraft: Pilots not in active control of the aircraft also related some adverse physiologic sensations. For example, Swedish pilots related some motion sickness symptoms related to automatic guns aiming.

+12 Gz: Pilots recognize that the G induced loss of consciousness (GLOC) problem has not yet been solved. Pilot predictions concerning the physiologic problems likely at +12 Gz also included discomfort, loss of situational awareness/disorientation, fatigue, degraded vision, decreased mobility, complaints about "cumbersome" equipment and concern about back/neck injury.

-Gz: The use of negative G's was controversial. Many of the test pilots saw definite operational applications of negative G flight. Comments included "Need to be trained to think of using negative Gs. Could be a life saver." Other pilots, including many of the operational pilots, did not see a need for negative G maneuvering: "I do not need negative Gs." "I do not use it".

We were impressed however, at the interviewed pilots' high level of negative Gs that had been experienced at sometime in their career. Listed below are the maximum negative Gs the pilots reported experiencing during several categories of maneuvers:

Collision Avoidance:	*4.8, 3.0, 2.3, 2*
Acrobatics, Spin test, "Fun":	*3.2, 3.0, 3.0,* --
Structural load testing:	*3.2,* -- -- --
Guns jink, missile avoidance:	*3.0 2.0, 1.6,* --
Lantirn bunt:	*2.7,* -- -- --

Thus, many of experienced pilots had actually experienced quite high levels of negative Gs. Pilot complaints concerning the physiologic problems at negative Gs included "Big time discomfort", red out, loss of situational awareness/disorientation, and an inability to "remain in the seat."

2.3 PILOT-VEHICLE ISSUES

Psychological Challenges: Psychological challenges to pilots included faster information flow. Pilots thought that the requirement to think ahead would become more urgent in agile aircraft due to the shorter time domain. Pilots predict that anticipation will become more difficult as aircraft agility increases.

2.3.1 Displays:

Head-up-Display: the HUD is "not useful when you're looking over your shoulder"– a helmet mounted display is needed.

Helmet-mounted Display (HMD): Pilots were enthusiastic in endorsing the requirement for HMDs, but requested that "clutter" on the display be kept to a minimum. "Vision is the most valuable sensor and should not be used for housekeeping."

Pilots were unanimous in demanding good visibility through the HMD – no "eye patch over one eye."

Test pilots felt that they were unable to adequately evaluate HMDs during short test programs. Like the HUD, pilots estimated that a HMD takes approximately 50 hours to get used to: "At first I never saw it."

Various possibilities for alternative displays were discussed with the test pilots that we interviewed. The pilots had mixed opinions on tactile and auditory displays. Positive comments were noted concerning three-dimensional auditory displays, although some stated that the pilot could easily ignore the aural tone. Others complained about too many "beeps" and "squeaks." The need for some additional cueing concerning aircraft energy state was the most frequently mentioned requirement anticipated by the pilots interviewed. Proprioceptive cues were mentioned as a possibility for use in cueing management. Requirements for cueing pilots on threats, ground proximity, fuel status, velocity vector, etc. were also noted. Cues need to be carefully chosen. For example, pilots said that for ground avoidance they would respond to a "break X", but might ignore more subtle cures (e.g., aural).

High AOA and Velocity Vector: One pilot related while descending into a scattered cloud bank at 11,000' he was "startled" by his rate of descent. Simultaneous display of nose position and velocity vector can be problematic (e.g. at AOA of 70 degrees). "The velocity vector between your feet can be a real problem."

Management of Energy State: Several pilots also commented that it was "Easy to command high AOA when you really do not want it." The X-31 was described as a "drag bucket." "No real sensation that you're coming down this fast (like a sky diver) ...need something that says that it is time to break off. Need some kind of cueing." Tactile cueing of high AOA state/post stall was incorporated into the X-31 for this reason. An improved method of conveying to the pilot his rate of descent was recommended.

Yaw Rates: Responses included comments concerning high yaw rates (guns tracking) and the need for wider horizontal field-of-view for the HUD.

2.3.2 Controls:

Integrated Flight Control System (IFCS): Pilots were also asked about "lessons learned" concerning high AOA flight. Many pilots commented on the importance of incorporating "Carefree Maneuvering" or integrated FCS into highly maneuverable/thrust vectored aircraft. Virtually all of the X-31 pilots commented that the integrated flight controls were very easy to learn – "Easy but radically different", "a dream for a test pilot,""Make it carefree then it allows you to do other things." Felt unnatural, very unnatural immediately ... "but easy to learn."

Conventional Controls: The experienced pilots stated that hands-on-throttle-and-stick concept (HOTAS), as it is, was not a limiting factor. Although the 50 functions on the control stick seemed formidable to the non-pilot, these experienced pilots did not feel that HOTAS represented a problem. Thus, the majority did not feel, based on their experience, that alternative controls were needed.

Alternative Controls: Pilots thought that current touch panel technology was not reliable enough; they called it "Fist on Glass" and suggested that it might be useful, for example, for an "on-off" function. For voice-based control, one pilot commented: "I can do it faster than I can say it." Pilots thought that current voice recognition technology was not reliable enough and worried about problems with surrounding auditory signals from anti-G straining maneuvers, oxygen breathing noises, etc.

Auto-GCAS: Regarding automatic systems for ground collision avoidance, pilots commented: "Nothing wrong with that." "Way of the future." "The Russians have done it for years." Pilots also saw a need for automated maneuvers in the future.

2.4 SELECTION, TRAINING, AND SIMULATION

The Harrier flight control system presents a high workload to the pilot. There is a consequent high risk of cognitive failure and a higher accident rate. Training for Harrier pilots takes 8 months compared to 4.5 months for other U.K. fighter pilots. Only those pilots who have performed well are selected for Harrier training.

This was in contrast to the X-31 Program with its integrated flight control system. The X-31 was "easy to learn", "not much training was needed", and "2-3 flights were sufficient" to get the most performance out of the aircraft. Pilots state that simulation of the agile environment may not be adequate: "inadequate visuals, no motion"; however, they felt it "...good for switchology."

2.5 PILOT VIEW OF FUTURE REQUIREMENTS

Need for Agile Aircraft: Whether future pilots will be able to avoid close in combat in the future is of course a controversial question. Off-boresight capability, while a distinct combat advantage, was noted to be of offensive utility only. Avoiding close-in-combat was noted to depend on successfully acquiring, identifying (visual ID), and subsequently destroying 100% of the targets. This might not always be possible in small arenas, with rapid aircraft closure rates, and with limitations imposed by politics and rules of engagement. Opinion about super manoeuvrability: "Every capability that the others do not have is a capability. Any capability is one to be explored and you do not have to use it every time."

The aircrew commented on the many potential advantages conferred by vectored thrust including improved close in air combat kill ratio, short take off and landing capability (STO), efficiency with asymmetric loads, availability of the full envelope for collision avoidance ("Half the world is negative"), and the ability to make tailless aircraft with stealth and other advantages. The test pilots that we interviewed were convinced that the weight and cost penalties for adding vectored thrust capabilities were minimal.

2.6 LIMITATIONS OF PILOT SURVEY

One limitation was that the sample included only 37 highly experienced pilots. Also, there was a wide variation in the individual responses, especially for high AOA maneuvering and negative Gs. Pilots generally responded with regard to their particular flying experience and the flight environment varied markedly from aircraft to aircraft. For example, the X-31 flight control system did not generate any side-slip and consequently X-31 pilots experienced minimal Gy accelerations. In the HARV, on the other hand, there was considerable side-slip. The HARV pilots commented that although it felt very unnatural, it was very controllable. In another example, the X-31 Program was characterized by only close in combat at speeds below 325 knots in the Mojave Desert with an IFCS. Thus, it may not be possible to generalize X-31 pilot responses to other scenarios.

During interviews, the pilots initially reported no adverse effects of high AOA maneuvering. X-31 pilots, for example, all stated that there were few adverse sensations experienced during agile flight regimes. On more detailed questioning, however, they related that although they experienced no adverse physiologic sensations when "flying in a clear sky", such sensations would be more likely in adverse weather conditions.

AGILITY : HISTORY, DEFINITIONS AND BASIC CONCEPTS

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SUMMARY

The purpose of this presentation is to provide some engineering basis of the concept of agility.

We'll see that the definition of agility has evolved across recent aviation history, from the well known area of airframe agility to a global concept of operational agility.

We'll give some consensus definition, some of which have been proposed by the working group 19 of the Flight Mechanics Panel of AGARD.

We'll briefly examine the concepts of agility relative to each component of the system (airframe, systems, weapons) and give some orders of magnitude of present and future weapon systems performances, which may have particular consequences on the human in flight.

We'll then examine the concept of operational agility and conclude with some perspectives for potential areas of preoccupation relative to the role of human pilots in the future combat scenarios and information environment.

1. INTRODUCTION

Recent aircraft prototypes such as the X-31or Su-35 have demonstrated impressive flying capabilities and astonishing maneuvers, which first come to mind when one speak of "agility". The technical feasibility of such agile airframe and its tactical utility under particular combat conditions is now widely acknowledged. Future aircraft will probably integrate some technologies directly derived from this prototypes, such as thrust vectoring and flight controls integrating new devices. Those technologies result in an extension of the flight envelope and possible maneuvers ; they may pose new requirements on the pilot.

Less spectacular but probably much more influent are the emerging technologies (calculation power, sensors, datalinks,...) and the new tactical environment (multi forces, multi role, multi targets,...) which contribute or push to enhance the agility of each component - airframe, but also avionics and weapons - of the combat system used by the human pilot.

This high level of agility of each component is obviously desirable and it should result in an increase of the global agility of the combat system, which require special attention from the engineers. Moreover, global agility results in an always increasing information flow made available to the pilot and which has to be efficiently used in order to fulfill the mission.

2. HISTORICAL DEFINITIONS

Generally speaking, agility is defined as the quick moving of a body or of the mind.

The historical background reveals an evolution of the concept of agility or similar concepts applied to highly maneuverable aircraft. This evolution is of course linked with the progress of aircraft technologies and with the consecutive extension of flying capabilities.

2.1 Supermaneuverability and post stall flight

Before agility, supermaneuverability was first defined, as the "ability to fly in the post-stall regime".

The post stall regime is the domain of flight at high angles of attack.

In the conventional regime, angle of attack is limited to low values, where lift increase almost proportionally with the angle of attack.

In the post stall regime, lift no longer increases but decreases with the angle of attack. So, the aircraft trajectory may go down while the aircraft nose is high, and the actual aircraft trajectory may become difficult to perceive for the pilot.

Also, aircraft capable of controlled flight at high angles of attack usually have very efficient control devices and demonstrate high angular rates, which make rapid changes of the flight trajectory possible.

These facts are illustrated in an other definition of supermaneuverability, which "refers to the unusual flight trajectories presently investigated by high performance fighter aircraft" [1].

Flying at high angles of attack raises difficult problems in term of aerodynamic behavior, propulsion and flight controls. It requires a powerful and sophisticated integrated control system so that the aircraft can be effectively flown by a human pilot. The progress in computer power was a sine qua non for opening this new domain of controlled flight.

It has to be noted that the post stall regime is necessary synonymous of low speed flight, which makes its practical utility somewhat questionable and probably limited to particular combat conditions, such as closed-in combat at one versus one.

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However, historically, the research necessary to extend the flight domain of some prototypes to the post stall regime has widely contributed to the progress in the reliability of the flight control systems installed on most modern aircraft and in their handling qualities at low speed, which is needed also in critical traditional flight phases such as take off and landing.

2.2 Agility, super agility and hyper agility

The notion of agility appears with the generalization of naturally unstable flown-by-wire aircraft and the development of thrust vectored prototypes. Those aircraft exhibit high maneuverability and turn rates even at high angles of attack and an extended flight envelope, sometimes including the post stall regime.

Many similar definitions exist and are now well accepted to define the airframe agility [2] :

"Ability to shift from one maneuver to the other" (Col. Boyd, 1986)

"Time rate of change of the aircraft velocity vector" (W.B. Herbst, 1988).

Next, a more general definition emphasize the shift of the concept of agility towards global agility, including the role of each element of the system into its efficiency :

"Ability of the entire weapon system to minimize the time delays between target acquisition and target destruction" (A.M. Skow, 1989).

This recent concept of global agility was used in various studies on the practical impacts of agility, sometimes with slightly different denominations : weapon system agility, full envelope agility, practical agility, operational agility.

For instance, a parametrical study on the tactical utility of new technologies such as post stall flight, enhanced radar coverage and agile missiles addressed the full envelope agility ; its results emphasize the need for the balance and proper integration of the various components of the weapon system, including aircraft, armament, avionics and pilot [3].

Only a few references exist for the denominations of super agility or hyper agility [4]. These denominations could be understood as either augmented agility or supermaneuverability (post stall) plus agility, but it seems that they may lead to some confusion and that there is no need for new terms, unless they relate to a particular new technology or capability.

3. RECENT DEFINITIONS

In recent years, the Working Group 19 of the Flight Mechanics Panel of AGARD [5] made a considerable effort to synthesize the various and sometimes differing viewpoints on the topic of agility.

This group eventually identified several possible aspects of agility and provided some consensus definitions as follow :

Airframe Agility : the physical properties of the aircraft which relate to its ability to change, rapidly and precisely its flight path vector or pointing axis and to its ease of completing that change.

Systems Agility : the ability to rapidly change mission functions of the individual systems which provide the pilot with his tactical awareness and his ability to direct and launch weapons in response to and to alter the environment in which he is operating.

Weapons Agility : ability to engage rapidly characteristics of the weapons and its associated onboard systems in response to hostile intent or counter measures.

Transient Agility is a continuously defined property reflecting the instantaneous state of the system under consideration.

Operational Agility : the ability to adapt and respond rapidly and precisely, with safety and poise, to maximize mission effectiveness.

The quickness and precision are critical elements of all these definitions.

The concept of Operational Agility was established with the essential intent to provide definitions and metrics appropriate to capture the role of the component parts of the weapon system and their interaction, as the main contributor to the global effectiveness of a complex aircraft design.

The Working Group 19 also covers the pilot-vehicle interface and finally give some recommendations, two of whom are directly related to the human consequences of agility :

- Establish the Influences on Awareness of High Rate and Acceleration Maneuvers.
- Establish the Influence of Prolonged Exposure to Sustained 'g' at Moderate Levels.

In the following chapters, we will briefly examine the concepts of agility relative to each component of the system (airframe, systems, weapons) and give some orders of magnitude of nowadays and future weapon systems performances, which may have particular consequences on the human in flight. We will then examine the concept of operational agility and conclude with some perspectives for potential areas of preoccupation relative to the future combat scenarios and tactical environment.

4. COMPONENTS AGILITY

4.1 Airframe Agility

4.1.1 Two complementary considerations

Airframe agility relates to its ability to change, rapidly and precisely its flight path vector or pointing axis and to its ease of completing that change.

This definition covers two complementary considerations :

- maneuverability, the ability to change magnitude and direction of the velocity vector, and
- controllability, the ability to change the pointing axis through rotation about the center of gravity, independent to the flight path vector (Figure 1).

In the common sense, those considerations are sometimes conflicting and, indeed, they reveal that agility is the result of a compromise in the aircraft design : on one hand, it is desirable for the aircraft to be able of high peak velocities and turn rates, i.e. to have a high maneuverability, and in the same time it is highly desirable to be able to precisely control those parameters, which is obviously easier to obtain when the peak values are limited.

As such, airframe agility relates closely to, and may be regarded as an extension to, flying qualities. The considerations above are related to the distinction classically made in flight dynamics between, respectively, the study of aircraft performance and the study of handling qualities.

The airframe agility may or not include the aircraft ability to fly and to maneuver at high angles of attack, also described as the post stall flight region, which give rise to new problems to the designer (aerodynamic stall, propulsion ignition, non linear and non stationary behavior, unstable configuration, control of the possible departure).

This ability to fly at very high angles of attack may also pose some specific problems to the pilot, for instance to perceive what is the actual flight path of the aircraft. This problem is partially due to the technical difficulty to present the direction of the velocity vector on a display with a limited field of view. Some possible future solutions will be covered in the pilot-vehicle interface chapter of this lecture.

This problem is also clearly due to a necessary change into the basic flying habits of ordinary pilots. On light aircraft, the primary flight parameter is the aircraft body pitch angle ; it is visually controlled and the consequence of any change on the flight path is also visually controlled. On aircraft equipped with a head up display and an inertial navigation unit, the direction of the velocity vector is usually displayed. It is used for

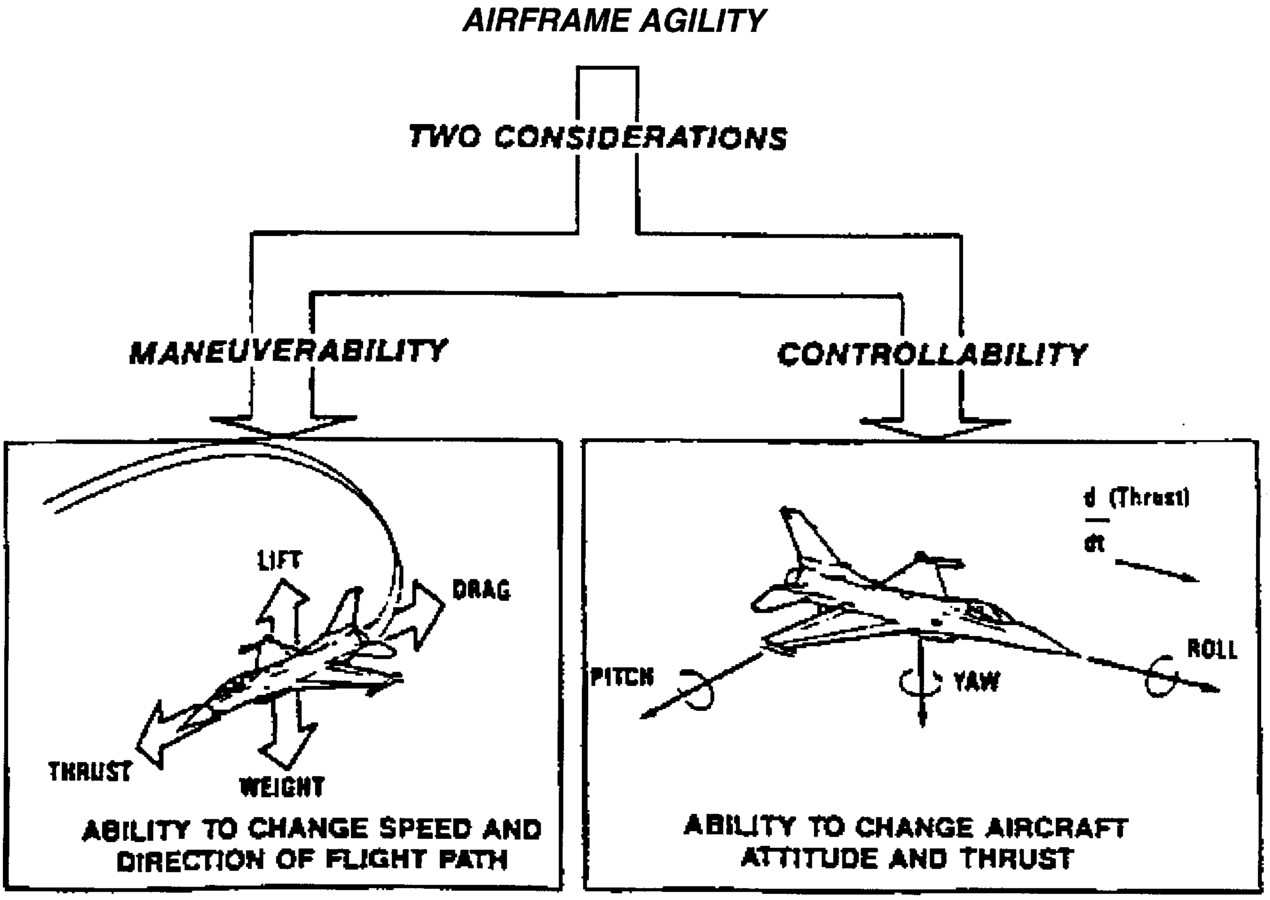

Figure 1 : Airframe agility : maneuverability and controllability.

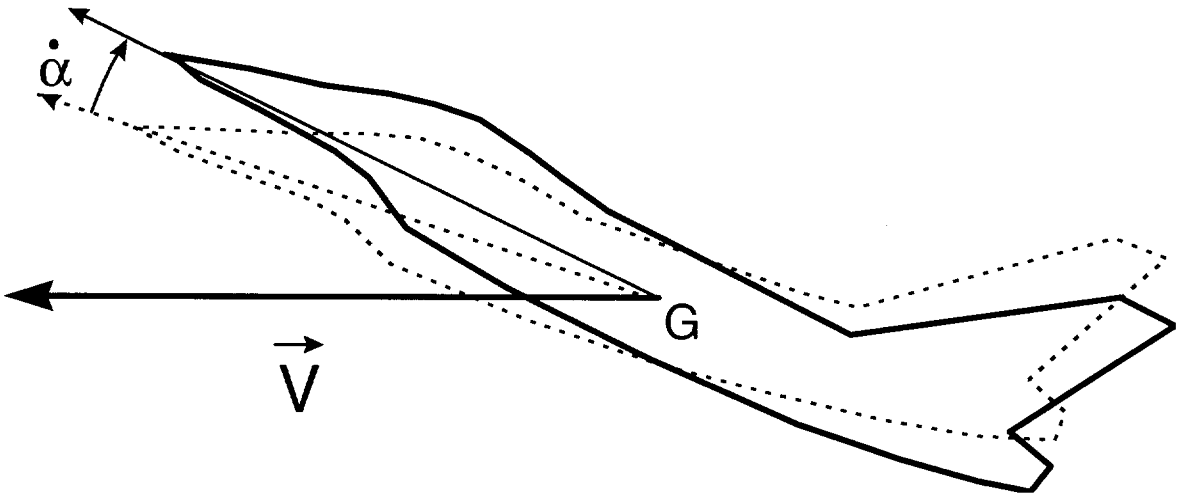

Figure 2 : Longitudinal agility.

instance when achieving a precise head up landing. Pilots usually get used quite easily to this new way of piloting, there is no deep conflict between body and velocity axis because the angular difference are still limited. On an agile aircraft flying at very high angle of attack, the body axis and the velocity axis may get completely decoupled, resulting in a complete difference between the perceived aircraft attitude and the actual path, which are no longer linked by the traditional flight equations.

Some similar problem may occur as soon as a technology is introduced that radically extend the possible solutions available for the pilot to achieve a given goal. This class of problem will be addressed in the chapters of this lecture dealing with psychological aspects, and selection and training.

4.1.2 Longitudinal, torsional and axial agility

In order to derive human consequences of airframe agility, it may be useful to consider separately some of the main components of this agility. Different definitions and reference systems are available to achieve this goal. They're introduced below.

Three axis are frequently used to describe the agility relative to the velocity vector rotation/change into the body axis :

- Longitudinal agility : rate of change of the angle of attack, up and down (Figure 2).
- Torsional agility : velocity vector roll rate (Figure 3).
- Axial agility : rate of change of the velocity.

Longitudinal agility (pitch up) is related with the ability to rapidly point the nose of the aircraft. This ability is necessary in air combat as it allows to align and shoot a target, once an appropriate relative position has been acquired. In the conventional regime, an increase of the angle of attack means a reduction of speed and an increase of the load factor. The rate of change of the load factor is called the G onset. G onset up to 15 G/sec might be obtained on modern fighters. The maximum G onset level is a critical parameter of a possible pilot's loss of consciousness, together with the duration of the exposure to the maximum G level.

Longitudinal agility (pitch down) is linked with the ability to quickly recover speed, for instance after a shooting maneuver has been achieved. This ability is

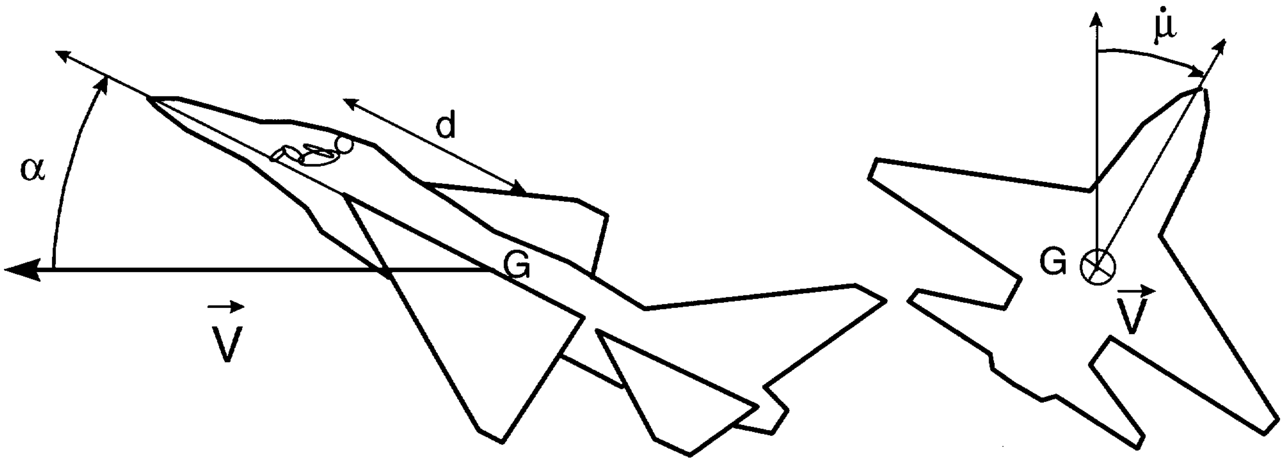

Figure 3 : Torsional agility.

absolutely necessary if high angle of attacks are to be used, because the aircraft at low speed is very vulnerable.

Torsional agility is relative to the roll rate around the velocity vector, with a constant angle of attack and with zero sideslip. The roll rate around the velocity vector is considered rather than the roll rate around the body axis. At small angles of attack, those rates are almost identical, but at high angles of attack, the control of the velocity vector roll rate allows a better decoupling of the aircraft attitude with the aircraft flight path. The velocity vector roll rate results from a combination of the body axis roll and yaw rates, which is achieved by the flight control system. The side slip angle is usually maintained at the value of zero, in order to reduce the aerodynamic drag. When the angle of attack is high, the velocity vector roll is perceived as a yaw by the pilot. Any change in the velocity vector roll rate results in a lateral load factor applied to the pilot. The value of this lateral load factor depends on the distance between the aircraft center of gravity and the location of the pilot's seat.

Axial agility is necessary in order to quickly accelerate, for instance once a target has been detected and has to be intercepted, or once a low speed combat maneuver has been achieved. It is obviously primary linked to the maximum thrust available and also to the engine response delay, from the time the throttle is pushed forward to the time the thrust actually reached the corresponding value. This delay depends on the engine regulation and inertia. Also, the tolerance of the engine to abrupt changes of the throttle position is certainly an important characteristic of axial agility.

Nowadays, the common design of aircraft control laws aims to give the pilot the direct control of those three components independently.

It has to be noted that each of these three components of agility is not directly linked with one particular component of the acceleration vector (noted Gx, Gy, Gz in the aerodynamic reference system). The relationship between one control component and the actual acceleration response depends on the flight control system. At a first glance, one can only give some general rules : the longitudinal command is usually the load factor/Gz acceleration at high speed and the angle of attack at low speed (below corner speed) ; the lateral command is the velocity vector roll rate, which results in a mix of Gy and Gz accelerations ; the engine command is primarily linked with Gx acceleration with a Gz component at high angles of attack or when thrust vectoring is available.

The effects of each acceleration component into the pilot's body axis of reference obviously depends on the position and on the inclination of his/her seat.

4.1.3 Nose pointing versus velocity vector pointing

Another distinction among the components of the airframe agility can also be introduced with some benefit in order to assess the practical influence of agility :

- the nose pointing agility is the primary effect of a change of the aerodynamics or thrust controls, and
- the velocity vector agility is a secondary effect of the nose pointing agility, chronologically speaking.

This distinction is particularly appropriate when evaluating the influence of agility on the weapons employment. When firing the aircraft gun, the pilot has to point the aircraft nose towards the target : the gun firing opportunities are obviously related to the nose pointing agility. When they are launched at a high - limited- angle of attack, conventional missiles "fall into the wind" because of their natural stability. So, the pilot trying to launch a conventional missile has to orient the velocity vector to the target otherwise the missile may break lock after launch : the missile launch opportunity are first dependent on the velocity vector agility.

These considerations are of course directly linked with the capability of the weapons. For instance, future missiles may be launched under adverse conditions (high AOA) or unlocked, which may modify the requirement to orient the aircraft or the velocity vector before launch.

4.1.4 Technologies for airframe agility

Among the enabling technologies for airframe agility, the following are of primary importance :

- Aerodynamic design (configuration, control surfaces),
- Propulsion design (air intakes, engine tolerance),
- Thrust vectoring (pitch only or pitch and yaw),
- High Thrust to Weight ratio, key characteristic for the aircraft capacity to quickly recover its energy,
- Flight Control laws and systems (fly by wire).

Now almost in operation, the thrust vectoring allows a substantial increase of the maximum pitch up and pitch down rate, as shown by the flight test results of the YF22 aircraft (Figure 4).

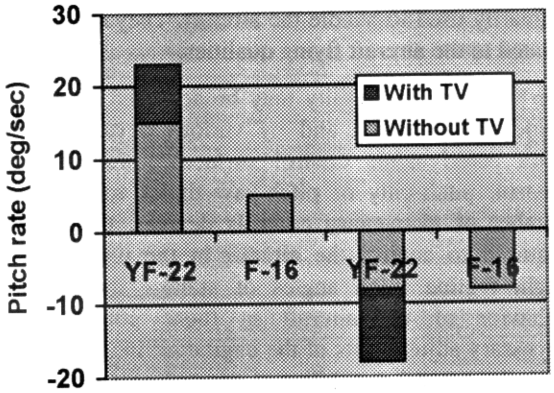

Figure 4 : Maximum pitch up, pitch down of the YF22 aircraft [6].

The thrust vectoring also contributes to an increase of the maximum roll rate (Figure 5). This is due to the fact that thrust vectoring, even if pitch only, allows a substantial relaxation of the constraints over the aerodynamic control surfaces, which can then be used to control the roll rate, while the pitch attitude is controlled by thrust vectoring.

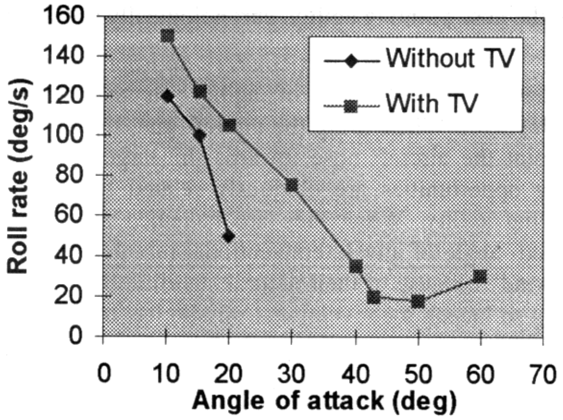

Figure 5 : Maximum roll rates of the YF22 aircraft, with and without thrust vectoring [6].

Thrust vectoring may be available on most future aircraft as a baseline or as an option. Studies and flight test are on the way for most programs currently under development (GRIPEN, F22, JSF, SU37 export).

In fact, the thrust vectoring technology has two main possible applications :

- improve the handling qualities and expand the flight envelope (high agility, post stall flight, STOL),
- or exploit this new control device to reduce traditional control surfaces (canards and tail) and thus, reduce drag and improve stealth.

One can suppose that a key concern for the aircraft manufacturers is to determine the best possible trade-off between agility and stealth.

4.1.5 Controls implications of airframe agility

The aircraft controls consist of the pilot's inceptors primarily used to handle the aircraft. They are primarily related to the aircraft flying qualities.

An high airframe agility may be achieved by adequate aerodynamic design and by various devices, such as extra aerodynamic control surfaces, forebody vortex control, pitch-only or pitch-yaw thrust vectoring. The number of elementary controls devices, the dynamics required to control the aircraft in the unconventional flight regime (high angles of attack), the non-linear behavior of the aircraft in those conditions, the necessary adjustments of the engine air intakes, together with the natural instability of the airframe necessary to achieve high maneuverability, are all numerous factors which require a sophisticated and integrated flight control system.

4.1.6 Towards a carefree handling system

Whatever the means used to obtain the airframe agility, the philosophy underlying the design of the flight control system may differ from one country or from one aircraft manufacturer to the other.

Some aircraft provide good examples of an original control philosophy :

- Thrust vectoring independent control (HARRIER, SU37 TV). In aircraft such as the Harrier/AV8, the ability to independently vector thrust was designed primarily to achieve vertical or short take-off and landing performance (STOL). Subsequently, the ability to vector in forward flight was also demonstrated as a possible combat technique which provides rapid deceleration and extra lift [7]. However, the requirements for post stall maneuverability are quite different : pitch and yaw axis moments generation is then required, together with rapid response rates which make an integrated flight/propulsion system mandatory. The ability to engage and disengage thrust vectoring may be required in particular situations, such as degraded flight modes, but pilots are probably most likely to benefit from integrated, rather than independent, control when it is engaged. This is demonstrated for instance by the research programs conducted on the basis of the HARRIER aircraft experience, involving integrated flight control of thrust vectored aircraft [8].
- Departure-tolerant aerodynamic design (MiG 29, SU 35). The preferred philosophy among these particular designs is to allow the pilot to fly in the post-stall region while being able to recover from the spin, rather than to build limiters into the flight control system [9]. The intent is to be able to use the entire envelope in combat and to teach the pilot how to recover from unstable situations (possibly with the help of an auto recovery system, as the panic button existing on the MiG 29 aircraft).

Having considered those particular designs, a general agreement is now that a system integrating flight and propulsion control is likely to bring substantial benefits in terms of ease of use of the aircraft and also in terms of safety and mission effectiveness.

Such a carefree handling system enables a limited number of controls (stick and throttle) to be used to maneuver the aircraft inside the whole flight envelope and it takes care automatically of the aircraft limitations.

For instance, once selected, operation of thrust vectoring is transparent with the flight control system dividing the required controls deflections between the thrust vectoring and conventional control surfaces. The system may also limit the stick inputs so that the load factor never exceeds the aircraft structural limits, given its current configuration.

The carefree system may improve flight safety, as it makes it possible to avoid aircraft departure and loss of control in most flight conditions.

Safety and flying accuracy can be further improved by implementation of advanced functions such as :

- automatic recovery from unusual situations,
- ground proximity warning,
- obstacle and collision avoidance,
- exit gate and aided post stall termination,
- optimized maneuvers, e.g. for energy recovery.

Carefree handling makes it easier for the novice pilot to fly the aircraft. This is now a key advantage as the formation and training flight hours are reduced. Also, a side effect of the carefree control system is that the aircraft can be flown more aggressively, without any limitations on the control stick input.

On the other hand, expert pilots have a tendency to find it frustrating because their flying proficiency is not recognized as it used to be. Anyway, the pilot job in the future will obviously comprise more management and decision tasks than basic flying.

As the basic flying workload is reduced, the pilot can better concentrate on the tactical decisions and actions. Spatial orientation and situation awareness are also supported by carefree handling, as less attention is required to the primary flight information displays.

4.1.7 Lessons learned from the X-31 experience

The X-31 program provides a good example of a carefree integrated flight control system : the design goal was to allow controlled flight and carefree maneuvering at and beyond stall boundary, without any additional workload in the post stall region [10].

This is achieved by use of three thrust-vector vanes, plus four trailing edges flaps and an all-moving canard. These control effectors were all integrated into an advanced flight control system.

The control law was designed to control the aircraft in the flight path axis system :

- load factor command up to 30 degrees AOA and angle of attack command when in post stall (PST), i.e. above 30 degrees AOA,
- velocity vector roll rate command (with zero sideslip),
- sideslip command (below 40 degrees AOA).

The handling quality requirements consist of high pitch and velocity vector rates (pitch rate up to 25 degrees/sec and velocity vector roll rate between 30 and 50 degrees/sec in PST, i.e. for an angle of attack ranging from 30 to 70 degrees) plus precise fine tracking for gun aiming.

Those objectives can be quite conflicting because of the large angle of attack domain ; they require a careful design of the control system and gains. For instance, the longitudinal stick sensitivity in the X-31 was so high that it was possible to command high AOA even when you really do not need it. This was corrected by the addition of a pilot selectable AOA limiter into the flight control software [11].

Also, a problem appear during the flight trials of the X-31, with the pilots hitting their legs with the stick when commanding high roll rates at high AOA. A scaled lateral stick command was implemented into the software to solve the problem.

Some possible alternatives may be to use special command devices or systems : long stick in use in the Russian aircraft, balance of the force-feel system design [12], multi-mode control laws depending on the task/phase of flight...

The X-31 control laws were designed to achieve zero sideslip maneuvers in PST. This design implies little Gy at the aircraft center of gravity and thus, small lateral accelerations are imposed to the pilot. Also, the normal load factor remains relatively low, because of the low airspeed in the PST domain. As the X-31 is a relatively slow aircraft when compared to modern fighters, high levels of +Gz may be attained only during the transient phase of increase of angle of attack, during a short time duration. Some transition between Gz and Gx also exist when entering PST, but they were not perceived as painful nor disorientating, as the aircraft quickly slowed down and the acceleration remained at moderate levels.

One possible problem of carefree handling may be the lack of sensory cues. Most of the conventional aircraft have some characteristics such as noise, buffet or wing rock which inform the pilot where his current status point is into the flight envelope. In the X-31, the sensory cues (buffet and stick force) are almost the same at 70 degrees as they are at 12 degrees AOA. This led most pilots to ask for a tone to provide them with AOA cueing. Some similar difficulties may exist with other key flight parameters (side slip angle, heading, flight path angle, speed and energy), especially under low visibility conditions. The problem may be more acute as airframe agility and post stall flight relate to parameters which are not primarily monitored under conventional conditions ; special displays and a special training may be required for the pilot to monitor those parameters.

The various unpredicted obstacles discovered and eventually solved during the envelope expansion of the X-31 program suggest that the development of a totally carefree handling system is still questionable, because of the lack of theoretical methods to demonstrate the complete robustness of the handling system, especially under non conventional flight conditions. The only solution, currently applied when expanding the flight envelope of a new aircraft is to proceed with extensive flight tests, which are designed to be as exhaustive as possible given the program cost and time constraints.

4.1.8 Agility metrics

The tools and methodologies currently used in the evaluation of handling qualities provide a large panel of solutions and viewpoints for the evaluation of the practical usability of the airframe agility.

The most easily usable metrics of airframe agility consist of the peak values of some key parameters, such as turn rates, angular rates, accelerations, instantaneous and sustained load factors.

For instance, the turn rate versus Mach number diagram (Figure 6) gives a good picture of the aircraft maneuverability envelope.

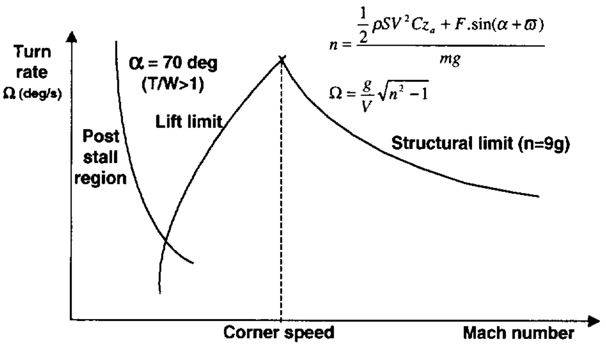

Figure 6 : Example turn rate diagram of a supermaneuverable aircraft.

Some typical orders of magnitude of these kind of parameters for existing and future fighter aircraft can be found in the literature [5, 6, 13, 14, 15].

However, the peak values are not sufficient for a precise analysis of the actual aircraft agility, as they give no information on the dynamics nor on the controllability of the aircraft.

So far, even though relationships between handling and flying qualities are already well-known for conventional aircraft and are subject to standard requirements (MIL-STD-1797 or ADS33), possible conflicts between flying qualities and performance have to be addressed at the design stage when high levels of airframe agility are to be achieved and operationally used [16].

The evaluation may address the following technical aspects : stationary and dynamic behavior of the aircraft under various flight conditions and configurations, ability and ease to perform particular tasks and maneuvers (gross or fine tracking, capture).

The available evaluation tools include numerical and man-in-the-loop simulation, and dedicated pilot's rating, such as the well known Cooper Harper rating scale which has often been adapted to capture the effects of particular features on pilot's control or workload.

The ability to fly at high angle of attack may also require some specific metrics and criteria, as it opens a new flight domain. Existing metrics have been extended for that purpose and new ones have been proposed [5, 16].

In a attempt to better capture the influence of the airframe agility on the combat effectiveness, some experimental metrics, pilot-centered or mission-oriented, have also been developed.

For instance, the Tamrat's combat cycle time is a measure of the total time duration of a typical combat, described as a cycle of state changes in the Mach number versus turn rate diagram [18]. It has been applied to aircraft capable of flight at high angles of attack and it is particularly useful to assess the aircraft ability to recover its energy after using a post stall maneuver (Figure 7).

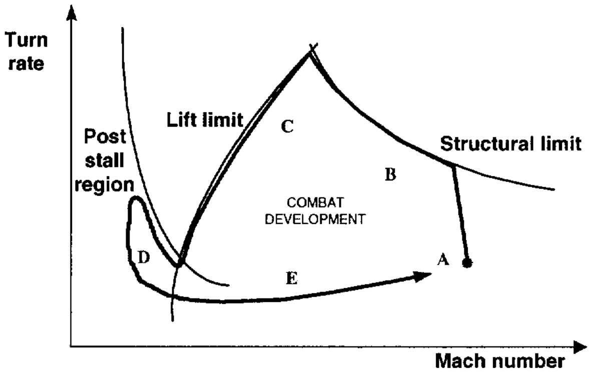

Figure 7 : Typical combat development in the Mach number / turn rate diagram.

This concept of combat cycle is an interesting viewpoint to better understand the cyclic nature of the physical constraints posed on the pilot during an actual fight :

- The combat cycle usually starts at the highest possible level of energy, which means high speed (supersonic) and high altitude, which are acquired as soon as the target is detected. The choice of this starting point (A) depends on the pilot's orders and experience, given numerous factors such as his role in the mission, the type of the target and the environmental conditions. A first shot may be decided at long range, weapons permitting.
- The combat cycle is first composed of one (or several) turns, from level flight at one gee and high speed to the maximum structural or sustainable load factor (B). The aim of this turn is to reach a favorable position relative to the target. It is a pre requisite of any modern engagement. During this turn, the pilot is submitted to sustained load factor at moderate to high level. The duration of this turn in recent fighters may be very long, as the engine power is sufficient to maintain speed even under high load factors.
- The maximum load factor is then maintained and speed decreased up to the maximum turn rate (corner speed), then the speed usually continue to decrease due to the high drag at high angle of attack (C).

- The post stall flight ability may then be used, for instance to point and shoot the target (D). The aircraft is very vulnerable then, as speed is low and maneuverability limited.
- This quick excursion into the post stall region is followed by the reduction of the angle of attack and by an acceleration phase, up to a speed sufficient to reengage a target (E).

The total time needed for the aircraft to cover this typical combat cycle is thought to be a good global indicator of its agility. The physical consequences of airframe agility on a human pilot should be regarded through the characteristics of each segment of this cycle.

4.2 Systems Agility

4.2.1 Definition and scope

The system agility is defined as the ability to rapidly change functions of the individual systems which provide the pilot with his tactical awareness and his ability to direct and launch weapons in response to and to alter the environment in which he is operating.

The systems considered here are individual systems which provide the pilot with tactical information and elaborated functions, rather than low level aircraft systems such as the flight control system which is usually considered as a component of airframe agility, at least in its basic functions.

As such, onboard sensors are of course concerned as they are the main sources in function of information gathering. The countermeasures and electronic war systems may be concerned also as their speed of response is a key of their efficiency.

The off board systems and the ability to share information may also be considered as they play an increasing role in modern scenarios.

The above definition emphasize the only objective of the systems agility which is to help the pilot to achieve his mission. Once again, the pilot-vehicle interface is actually a critical element for the contribution of systems agility to mission effectiveness.

4.2.2 Automation benefits and surprises

A high level of automation is necessary for the pilot to control the many complex systems of modern fighters, and it has proved to be mission effective most of the time.

For example, at the border between airframe agility and system agility, some advanced functions of carefree control systems have been developed, where aircraft limits are handled automatically. The automation of the aircraft limits may have some drawbacks under emergency or combat circumstances which require the full use of aircraft, but this problem is only the counterpart of the safety and mission effectiveness benefits, and the accurate design of the control laws makes it less and less sensitive.

More insidious may be the drawbacks of the automation of higher level functions, also sometimes referred to as automation surprises ; while developments in cockpit automation result in workload reduction and economical advantages, they also raise a special class of human-machine interaction problems [19].

These problems have been examined in research addressing the last generation glass-cockpit civilian transport aircraft. They involve confusion on the status of the automated control system and the subsequent behavior of the aircraft. The complexity of the control system is accompanied with a partial knowledge of the system ; the pilot's knowledge is focused on the most frequently used automated modes, which may represent only a relatively small part of all the possible modes. A possible mismatch between the pilot's understanding of the system and the actual function performed by the system may occur under unusual conditions. Special training and pilot adaptation are the only compensation for an ill defined automated system and a poorly designed interface.

Although a consensus exists about the need for a feedback of the complex aircraft system to the pilot, special attention should be given to the level of feed back, i.e. the nature and the amount of information concerning the system functions that should be provided, displayed or made sensitive to the pilot.

The complexity of modern systems makes it obviously impossible and undesirable to display every item of information to the pilot, but a minimum level of information is certainly desirable to keep the pilot on line, so that he can take a decision when needed. For instance, information is probably required about the following points : which system functions are actually in control, what are the goals aimed by the system, what to do if a system function fails, and what to do once a goal is achieved.

Also, the level of information provided to the pilot may be context-dependent, as for instance the pilot doesn't always want feedback from the system when the feedback can distract him from the tactical situation. The precise determination of the level of information which is required and sufficient to achieve a mission is not possible today without practical experiments. The research studies about the processes underlying the building of situational awareness could provide some guidelines for the design of future pilot/system interfaces and appropriate pilot aids. Alternative control technologies may also contribute to the enhancement of man-machine communication [20].

The recent approach and development of human-centered automation may help avoid these drawbacks. Nevertheless, the interaction of human with complex system and thus, the contribution of systems agility into mission effectiveness, is still a non trivial problem. The introduction of automation should be driven by actual operational needs rather than by market or economical considerations.

4.2.3 Emerging technologies

Some technologies contribute directly to increase the systems agility. These technologies provide new capabilities and have a potential to deeply modify the pilot's situation awareness and tactics :

- Extension of the sensors range and angular coverage (radar, infra red, video or laser)
- Fast search mode and reduced update rates (electronically versus mechanically scanned radar)
- Multi tracks and improved classification/identification capacity
- Helmet Mounted Sights/Displays and target designation
- Missile Launch Detector and Missile Approach Warner
- Improvements of Navigation (GPS)
- Communication (high rate datalink) and Collaboration (C3, Third Party Targeting)

For instance, the present days mechanically scanned radar is typically limited to +/- 60 degrees in coverage and cannot track numerous targets due to a relatively low update rate.

The electronically scanned radar and conformal antennas could provide substantial enhancements in terms of coverage, range and resistance to jamming, with direct consequences on the tactics. For instance, an angular coverage extended up to 120 degrees azimuth could allow the pilot to start going away from the target he has just shot, while still illuminating it (F-Pole maneuver).

Helmet Mounted Sights may allow an extension of the coverage to approximately . +/- 100 degrees in azimuth and -30 degrees to +80 degrees in elevation, which may considerably modify the way of conducting closed in combat, especially if a target designation is made possible, using head or eye pointing rather than aircraft nose or velocity vector pointing [21].

The improved capacity of future aircraft to automatically share information within the patrol or with other forces or ground support will probably have some very large implications on the way a mission is conducted and on the role of the pilot. The recommended number of seats in an aircraft for a given mission may of course change as a consequence of this new capacity.

More generally, new concepts of task sharing between the vehicles, systems and individuals involved in a combat scenario are being considered and they really have to be in order to get the full benefit from the increasing level of agility of future systems.

4.3 Weapons Agility

The weapons agility is defined as the ability to engage rapidly characteristics of the weapons and its associated onboard system. The precision is also mentioned as a critical element of this definition.

The emerging concepts for future weapons include [adapted from 22] :

- Air-to-Air Weapons
  - Expanded envelope (minimum & maximum range)
  - Hypersonic speed
  - Increased off-Axis capability (lock-after-launch using HMS information)
  - Midcourse guidance and improved guidance (seeker performance, thrust vectored control)
  - High angle of attack employment
- Air-to-ground weapons :
  - Enhanced standoff capability
  - All weather capability
  - Improved accuracy
- New weapons
  - Non lethal weapons (especially laser)
  - Multirole weapons (A/A & A/G missile)

For instance, the existing Russian AA-11 Archer short range missile provide some idea of the level of performance that may be obtained with modern air-to-air weapons [23] :

- Off boresight angle at launch up to 60 degrees
- Off boresight angular rate up to 60 degrees per second
- Launcher angle of attack up to 40 degrees

One tactical recommendation for a fighter against this new generation weapon is to avoid the short distance engagement.

Precise weapon agility data is of course usually classified, but one can expect that considerable progress has been made in air-to-air armament since the last large scale conflicts.

These progress are likely to strongly reduce the potential benefits of airframe agility, especially in the close in combat area.

5. OPERATIONAL AGILITY

Operational agility is close to the concept of weapon system agility proposed by Boyd in 1988 [5].

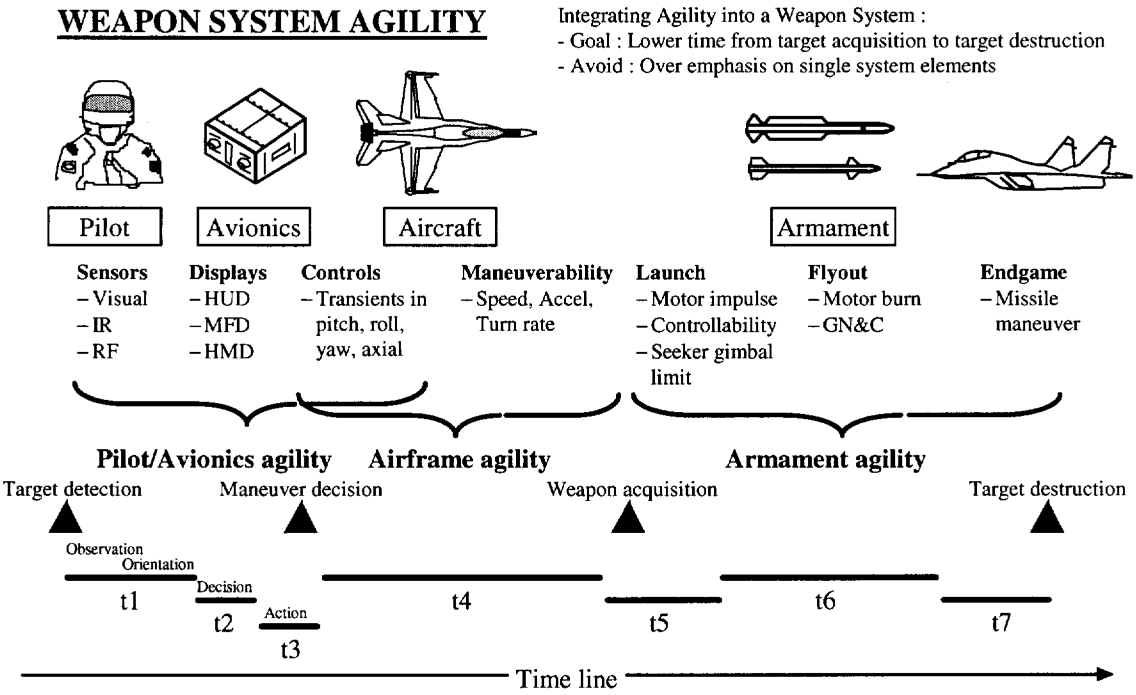

Figure 8 : Weapon system agility [18].

His model (Figure 8) includes seven time delays in the sequence of events between target detection and target destruction, including the Observe-Orient-Decide-Act (OODA) model for the pilot/avionics element.

This simplified model is of course valid only in a given mission context ; it also lacks the role of external support and environmental factors.

However, it illustrates the fact that any gain in the time delays from the detection to the target destruction may be of crucial importance.

Although they are depicted as sequential, the time delays are actually not independent, as all the elements of the weapon system are closely interacting. For instance, the pilot's reaction time depends on the information displayed and maybe from physical factors such as the acceleration level ; also, the attack maneuvers and thus the time required to get a shooting solution depends of the type of missile on board.

A hierarchy of the various components that contribute to operational agility was proposed by Working Group 19 (Figure 9).

The respective agility of each element of the global weapon system contributes at a similar level to the operational agility

In reality, the operational agility results from the correct interactions of all the elements rather than from the high agility of one single element.

Airframe, systems and weapons agility should not be considered separately, as the main contributor to mission efficiency is probably the consistency of the global combat system.

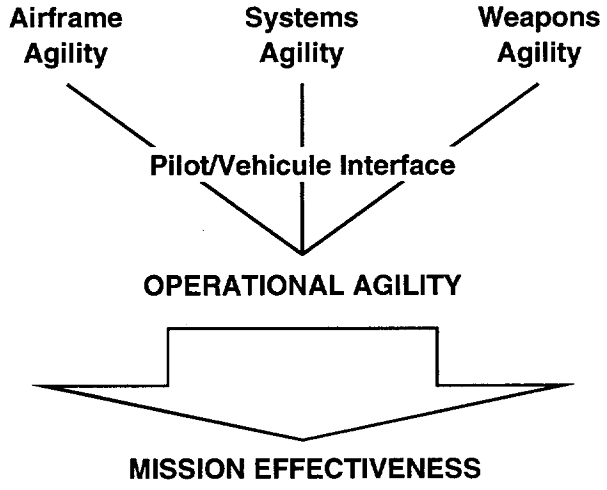

Figure 9 : Hierarchy of operational agility [5].

For instance, enhancing airframe agility by a post stall flight capacity may be useless if the firing systems are too slow to allow a quick shot or if the missiles cannot be launched at high angles of attack. Airframe agility may also become less useful if missile could be shot unlocked at very high off boresight angles, using an HMS.

The balance of the final weapon system and the best trade off between investment and efficiency is the main driver of an aircraft design. Many interesting technologies do exist and will not be applied despite their value because they cost too much and are simply not immediately consistent with the current needs or design philosophy.

Moreover, as long as the pilot is in control of the main tactical decisions, the pilot-vehicle interface will remain a key element into the operational agility hierarchy.

In particular, the potential benefits of high technologies may be impaired if the pilot is not given the tools to use them at best. Also, the introduction of automated functions requires a deep analysis of their potential implications as they may reveal unsuspected drawbacks once in operations.

Ergonomics should be given special attention at the design stage, to ensure that the objective level of operational agility will be attainable by a normally proficient air force pilot.

The following areas of preoccupation related to the issue of pilot-vehicle interaction and operational agility can be listed as follow :

- Physiological : pilot comfort, G protection, angular rates, spatial disorientation,...
- Ergonomics : cockpit, information, displays, controls,...
- Cognitive : workload, situation awareness, pilot assistance, task sharing,...

The operational agility may also require some particular approaches of selection, instruction and training for the next generation pilots.

The human consequences of operational agility have to be considered in the context of the present and possible future operational scenarios.

Those scenarios may present the following characteristics :

- Complex tactical environment with several forces involved : large quantity of information to be displayed and treated ;
- Mission achieved in collaboration with allied forces : flexibility, communication ability and precision required ;
- Various rules of engagement and political pressure : positive identification is usually required which increases risk taking and time pressure ;
- Rapid reaction and localized conflict scenarios, generalization of multirole aircraft concepts with several mission objectives and targets of opportunity : need for a fast decision making ;
- Possible new concepts about the role of the pilot : team work or unmanned aircraft to reduce the exposure to danger ("leave the pilot's head in the aircraft, not the body").

Those characteristics are at the same time a consequence and a motivation for an enhanced operational agility : agility is definitely a requirement in the information era, and its human implications have to be addressed.

Short glossary

A3A	Aircraft, Armament, Avionics Agility
AOA	Angle Of Attack
BVR	Beyond Visual Range
FEA	Full Envelope Agility
HMS	Helmet Mounted Sight
IRST	Infra Red Search and Track
PST	Post stall flight
SM	Supermaneuverability
STOL	Sort Take Off and Landing
T/W	Thrust to Weight ratio
WG	Working Group
WSA	Weapon System Agility

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PSYCHOLOGICAL CONSEQUENCES AND PILOT "SITUATIONAL AWARENESS" SURVEY

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1. INTRODUCTION

The technological design and developments already applied to a number of aircraft, which represent the basis of tomorrow's aircraft, tend to change the tasks performed by pilots. Since the 80's, automation and computerization have invaded cockpits, leading to a change in the role of pilots. Whereas pilots used to need competencies directed towards handling and navigating the aircraft, what is now increasingly required of them is the ability to manage complex systems. With the arrival of new concepts like supermaneuverability and superagility, it seems extremely important to try and understand the psychological consequences these concepts will have on pilots. Enabling new types of operation, supermaneuverability and superagility alter existing tasks and will probably create new ones, which will have their own psychological constraints. What makes these constraints different from those existing on present aircraft, and what consequences could they have on pilot performance? These two questions can be addressed by two preliminary comments:

- As of today, supermaneuverability and superagility are still extremely novel concepts. Various "prototype" aircraft point to the developments, which will eventually make these concepts a reality in the near future, but there still is no such thing as "real" operational experience. The difficulty in accurately studying the consequences these future aircraft will have on pilots, lies in trying to define the exact role the pilot will be asked to play aboard.
- The psychological consequences studied in this chapter will be limited to the consequences borne by the pilot in terms of taking and processing information. This chapter does not take into account psychological aspects based on personality or motivation.

2. EXPERIENCE ON CURRENT FIGHTER AIRCRAFT

Determining the psychological consequences on crews of flying agile aircraft is not an easy task, because of the lack of operational feedback regarding missions performed with these aircraft. The only way to envisage potential psychological consequences is to transfer the experience acquired on agile aircraft prototypes and on last generation combat aircraft to the operational situations these future agile aircraft are expected to meet.

To this end, the Working Group carried out a questionnaire survey with pilots of last generation combat aircraft flying in the Air Forces represented in the working group. The questionnaire was developed to address the following topics:

- Physiological constraints and psychological consequences,
- Cognitive constraints,
- Situational awareness and human performance,
- Aid systems,
- Crew training and practice.

The 15 question questionnaire was anonymous and made up of open and closed questions. The questionnaire is in Annexe 1. Twenty-nine pilots, representing 5 countries answered it:

- 3 pilots from Germany,
- 12 pilots from Sweden,
- 5 pilots from the Netherlands,
- 1 pilot from the US,
- 8 pilots from France.

These pilots flew last generation high performance aircraft, equipped with the latest weapons, navigation, communication and interface systems. These 29 pilots gave feedback on the following aircraft:

- Falcon 15,
- Falcon 16,
- Falcon 18,
- MiG 29,
- JAS 39,
- Mirage 2000 C-RDI, and
- Mirage 2000-5.

All pilots had an extensive aeronautic background, with an average flying time of 2,490 hours (standard deviation of 1,080 hours).

Questionnaire answers were processed by content analysis to draw out major trends. Given the sample polled, a qualitative analysis was more relevant than a quantitative one. This sample is not representative of the crew population flying last generation aircraft from NATO countries. Furthermore, for strict statistical purposes, the specificities of each aircraft

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(combination of aerodynamic capacities, on-board systems and interfaces), as well as pilot experience should be taken into account.

3. PHYSIOLOGICAL CONSTRAINTS AND PSYCHOLOGICAL CONSEQUENCES

3.1. Questionnaire results

The connection between cognitive and physiological constraints caused by load factors clearly appears in the answers to the questionnaire. This dimension is taken into account when assessing the mental effort required, since Gz acceleration has a direct impact on the pilot's mental resources. Acceleration impacts information processing at three levels:

- Part of the attention potential is mobilized by the mere activity of flying, to reach and maintain a high level load factor,
- Another large part of the attention potential is earmarked to off setting the physiological consequences of acceleration: applying anti-G maneuvers and having a proper body position in the cockpit,
- The field of vision is reduced because of the limitations in possible head movements and the physical consequences of acceleration on visual functions (restricted field of vision, greyout, etc.). Pilots only maintain central vision.

The crew is then forced to allocate the remaining resources to manage parameters essential to survival, to the detriment of weapons management, which inevitably becomes simplified.

Gy acceleration was not mentioned by pilots as penalizing in close combat situations.

3.2. Data from literature

Supermaneuverability refers to the unusual flight trajectories presently capable by high performance fighter aircraft (1). The trajectories illustrating supermaneuverability show that stress is mainly experienced by the pilot in terms of rotational and linear accelerations. These maneuvers are usually performed at low or medium altitude, and at low speed, under 450 kts, generally in a range between 70 and 265 kts. Vectorial thrust allows for pitch and yaw in ways impossible with more traditional aircraft. In terms of acceleration, supermaneuverability does not create any new stress that hasn't already been studied for physiological consequences. Linear acceleration amplitude and jolts are below the values generating serious physiological symptoms, such as blackouts or loss of consciousness. However, pilots can sometimes experience rotational acceleration that they are not used to, or combinations of accelerations they find unfamiliar. Psychologically, these accelerations can have two different consequences:

- Psychophysiological consequences due to the way information is perceived (i.e., trouble with perception), and the generation of sensory illusions and disorientation. These aspects developed in the previous chapter.
- Psychomotor and cognitive consequences.

The psychomotor and cognitive consequences of linear acceleration have not been studied in depth yet. A review of the available literature shows that most of the work is centered on the loss of consciousness under +Gz acceleration: description of psychological symptoms leading to loss of consciousness and return of intellectual capacities after a loss of consciousness (2). For our purpose, the consequences on vision for medium intensity accelerations (3–5G), which are well known to pilots need to be noted: progressive reduction of field of vision, progressive loss of colored vision, drop in visual acuity, and the ultimate symptom, total blackout. These are all symptoms, which can directly alter the pilot's capacity of capturing information. The visual consequences of –Gz accelerations are also well known in the pilot community: a decrease in perceptual capacities, and negative scotoma in the visual field.

On the motor side, heaviness in head and limbs, associated to the difficulty of moving them, must be taken into account in all motor activities to be performed by the pilot, especially since these motor tasks can be further degraded because of the stress induced by the equipment worn.

Little work has been done on the effects on psychomotor and cognitive activities at acceleration rates that are lower than the thresholds associated with loss of consciousness. Brown and Lechner's survey (3) insists that acceleration has a negative impact on simple motor activities, complex activities (putting on a parachute) and cognitive processes (reaction time in choice making, time required to stabilize the aircraft after loss of control, etc.). But, as noted by the authors, there are few experiments and little data is available to check the real effects acceleration has on the various steps involved in information processing. Hendler's work, quoted by Forster and Cammarota (4) is interesting for maneuverability. It shows that performance during a tracking psychomotor task decreases as the time during which acceleration is applied increases. These authors conclude by saying that the change in acceleration level is more disabling to the performance of a psychomotor task than the acceleration level actually applied. Albery (5), aware of the fact that cockpit tasks are becoming increasingly cognitive in military aircraft, carried out a survey aimed at assessing workload during acceleration. Using Subjective Workload Assessment Technique, mental workloads during cognitive tasks performed in a centrifuge significantly increased acceleration plateaus (1,4G, 2,75G and 3,75G). This study is one of the few investigating the cognitive consequences of accelerations, but, as mentioned by the author, it is limited by the assessment method, which is global and hardly analyzes the underlying cognitive processes. In practice, such studies have strong methodology limitations for the generalization of results to real flight. The tasks easily accomplished in the centrifuge (target tracking, choice reaction time, etc.) to assess cognitive performance have a poor ecological validity for flying and real mission tasks. Albery and Chelette (6), in an experiment examining the effect of G-suits on cognitive performance, pointed out these limitations and encouraged the use of more realistic tasks.

For +Gx accelerations, the available data in the literature involves high acceleration values, greater than 5G (2). Symptoms include limited head and limbs mobility and loss of peripheral vision. Starting at 7G, a psychomotor decrease is described, without any further detail. Effects of Gy acceleration are better known. It mainly generates problems of head support and limb mobility.

Effects of rotational acceleration on performance have also not been studied in depth (2). The main results describe diminution of psychomotor performance with high acceleration. Applying acceleration across time is also associated with human effects. The majority of the research addressing rotational acceleration, either alone or in combination with other accelerations, has focused on the effect of sensory illusions and disorientation.

3.3. Implications for supermaneuverability

What bearing can this have, in terms of supermaneuverability? The psychological consequences of low and medium intensity accelerations have hardly been studied. The few available studies tend to show that psychomotor and cognitive capacities decrease under acceleration, without any details as to the nature of the degradation. On the other hand, these results were obtained with acceleration profiles different from those usually encountered in supermaneuverability. Caution is therefore required when generalizing the above mentioned results.

These two remarks illustrate the need to develop specific work in order to better grasp what psychological effects low and medium intensity accelerations may have. Such research should take into account the specifics of supermaneuverability, including acceleration combinations for which there is no available data. Investigating cognitive functions requires developing methodologies going beyond mere global performance analysis. These methodologies need to measure the changes in mechanisms involved in perception, analysis, understanding, decision-making and risk taking. Furthermore, in addition to analyzing the consequences which may be observed during the execution of specific maneuvers, it seems important to also take into account the tiredness or fatigue which may occur when such maneuvers are repeated several times during a single mission. Physical and psychological fatigues are closely linked, and the fact that fatigue alters human reasoning capabilities is well known (7). These recommendations underline how important it is to take operational realities into account in designing any research on this topic.

From a practical point of view, the lack of data requires investigation into what actually happens in squadrons. Despite the new stress of supermaneuverability, the pilots reported that they are not experiencing any increase in psychologically disabling stresses over that already occurring in non-supermaneuverable aircraft. Today, pilots report they empirically manage psychological consequences. Relying on their experience, pilots develop management, anticipation or avoidance strategies, which help them carry out their tasks. When faced with supermaneuverability, this acquired experience will probably be used to transfer strategies or adapt new ones. However, from a preventive point of view, the only way to develop effective management techniques is to have a better knowledge of psychological consequences.

4. COGNITIVE CONSTRAINTS

4.1. Questionnaire results

Close combat with modern aircraft generates numerous cognitive constraints. Pilots mentioned both the constraints generated by aircraft capacities and those generated by systems capacities. For 65% of the pilots, these constraints are experienced as increased workload, but this feeling is not shared by all. This difference of opinion depends on what systems and interfaces are on-board, because they can make situation management more or less convenient. Analyzing the various cognitive constraints shows that:

- Time pressure is seen as the lowest constraint. This judgment seems strange, given the very short response time available to manage situations. In fact, responses are supposed to be so quick that time is not available for management purposes. Rather, responses must be reflexive. Thinking is considered a waste of time. The pilot "feels" rather than "understands" what is going on; assessing trends and reacting according to experience.

- Loss of information was rated a slightly higher constraint than time pressure, without being truly penalizing since it often has no consequence on the immediate time frame. The information lost usually involves non-priority issues. It is unusual to lose track of high priority items, since the pilot's attention is totally focused on them. However, when priority information is lost, situational awareness seriously deteriorates and consequences on performance can be far-reaching.

- The complexity of the information supplied by on-board systems or by outside communication media represents a severe constraint for crews. Information complexity raises the issue of human/machine relationships, and of the phrase "the right information at the right time in the right format." With today's systems, the crew has a better grasp of its environment. But the information provided has been pre-processed and is not always compatible with the crew's immediate mental representations. There is a gap between an equipment manufacturer's design rationale and the crew's logic of employment. This complexity is further compounded by the lack of transparency surrounding the way the data were obtained and the processing applied to it. Weapons systems are becoming increasingly sophisticated and even though their implementation is facilitated by aids, using them presents a significant mental load for the crew.

- Information flows also constitute a strong constraint. These flows result from the increasing number of sensors and communication networks. They open up the pilot's "field of perception", but on the other hand also flood the aircrew with a mass of information difficult to handle given the lack of information management systems.

- The strongest constraint is the quick pace at which situation change. This is directly linked to the maneuverability of agile aircraft. Visual contact with other aircraft is an absolute priority to manage engagement and combat. Aircraft aerodynamic capabilities make it almost impossible to predict flight trajectories, and it becomes increasingly easy to suddenly have a turnaround in a given situation, and lose an advantage, which had previously been acquired. The extension of flight envelopes multiplies tactical opportunities and makes anticipation more and more difficult. Anything can happen faster than ever, and the situation changes rapidly. Agility helps achieve unexpected moves, which can surprise an opponent, but can also at any time lead to losing the upper hand. Combat is fought in a more demanding spatial and dynamic environment, requiring greater mental effort (often done subconsciously during combat) to observe, predict, fly and fight.

4.2. A frame to describe cognitive constraints of agile aircraft

In order to extend these results to agile aircraft, a frame to identify and describe cognitive constraints is required. Aeronautical situations are complex. But what does complexity actually mean, and how can a situation be described in connection with its complexity? The complexity of a situation involves several dimensions (8):

- The task characteristics,
- The knowledge required to complete the task, and
- The difficulty experienced by the pilot to implement the required knowledge in order to fulfill task goals.

Orasanu (9) describes a complex situation as a situation characterized by:

- Ill-structured problems,
- An uncertain and dynamic environment,
- Shifting, ill-defined, or competing goals,
- Action/feedback loops,
- Time stress,
- High stakes,
- Multiple players, and
- Organizational goals and norms.

These characteristics can all be found in aeronautical situations. The following question remains: is the complexity of air-to-air combat involving agile aircraft identical to the same combat situation with non-agile aircraft, and if not, what makes it different, and what consequences may this have on pilots? To answer these questions, it is necessary to look into the various elements of complexity.

4.3. The task characteristics

The task and its characteristics are commonly referred to as complexity factors. They are description elements external to pilots, and help compare the complexity of various situations. Several categories of factors can be used to describe the complexity of a given task.

4.3.1. Time factors

Task dynamics

Task dynamics are defined by the average length of time taken by the various steps in a task, and by the transition speed between steps. Combat tasks are eminently dynamic tasks. With agile aircraft, dynamics are increased during specific flight phases (attack and escape maneuvers), and during some sequences of systems use (arming or countermeasure systems). Increased task dynamics reduce the possibility of reversing actions performed by pilots, thus also reducing the possibility of detecting or correcting errors made.

Time pressure

Time pressure is the time available to understand, decide, and take action. It is a deadline. With agile aircraft, it seems that some flight phases and systems involve more time pressure than air-to-air combat schemes with traditional aircraft. For the pilot, an increase in time pressure means less time to analyze, alternative solutions envisaged before making a decision, and assess the consequences of these decisions for the medium and long terms. Time pressure is a factor, which increases pilot workload and stress.

Time references
Pilot activity is organized around three time references (10):

- Physical time, i.e. the time frame used to keep track of developments in threat and environment. It is the time given by the clock.
- Systems time, i.e. non-compressible time units, which represent the operating or transition time of aircraft or on-board systems. For example, to execute a "post-stall" maneuver, aircraft aerodynamics requires an amount of time over which the pilot has no power. Another example: the transition time it takes to go from one weapon mode to another cannot be faster than what is required by the system. Systems time is important, because it is forced upon the pilot. The pilot must organize its activity around it.
- "Pilot" time is a kind of internal clock, specific to the pilot. It is the perception by the pilot of time passing by. This feeling is very different from physical time. Everyone knows that when you are bored, time is very long, whereas when you are busy, time flies. In aeronautics, pilot time is developed by experience; it is structured around memorized time sequences. It helps in adapting to changes in the environment and knowing: (i) when to take action, (ii) when control is possible, and (iii) when reasoning is possible.

The pilot lives with the continual difficulty of simultaneously managing these three time frames. With more and more automated and computerized systems in agile aircraft, systems time is an increasing constraint on the pilot. Successful combat requires systems time to coincide with clock time, which means having a proper time-based mental picture of the way systems operate, and of the way the environment changes.

Schedule of relevant information
Flying an aircraft is a task where information continuously flows in. Some information has an immediate relevance to the task, the moment it is perceived by the pilot. It is then integrated into the task underway. Other information has no specific value at the moment it is perceived by the pilot. However, it may be of value later on during further task developments, or may never be of any use (11). Managing the schedule of relevant information is an important factor of complexity in aeronautics, because unexpected situations are part and parcel of tasks performed. It is therefore difficult to know ahead of time what information will be of value during the mission. Since pilot memorization capacities are limited, pilot cannot remember everything. However, managing the schedule of relevant information does not seem to be more of a challenge with agile aircraft than in more traditional combat situations.

4.3.2. Task dimensionality
This term represents all the paths available to the pilot to reach the goal involved in the task. By creating new operational possibilities, agility multiplies the pilot's possibilities of action: more maneuvers are possible, which can all be coupled to different systems use. Each solution has its pros and cons, which the pilot must be aware of. Compounding this with time pressure, it becomes difficult to comprehensively assess all the available alternatives. Preference-based behavior often appears, favoring a solution readily "in mind", rather than one which would be ideally appropriate for the situation.

4.3.3. Multiplicity of goals
Air combat is a task which may be broken down into sub-tasks, each having specific goals. Managing goals, or giving priority to specific sub-tasks, is not always easy, especially since sometimes some goals compete with each other. For example, in air-to-air combat, success and security can be contradictory, in terms of the choices made by the pilot. Agility introduces nothing new in the management of goals than what is observed in more traditional air-to-air combat situations.

4.3.4. Risk-linked factors
Moving around in four dimensions generates risks. In air combat, this risk is very high, because it is linked to the scope of possible aircraft movements and to the presence of one or more hostile elements, over which the pilot has no power. Amalberti (8) makes a distinction between two kinds of risks: objective external risks, illustrating the probability of having an accident, or failing the mission, and subjective internal risks, specific to the pilot, and representing its fear of not knowing how to perform, of not having the situation under control. In agility, the first risk depends on the operational capacities of hostile elements. But the second risk may be increasing, since the pilot might find it more difficult than usual to assess the situation and obtain satisfactory situational awareness. Risk is another element increasing workload and stress.

4.3.5. Multiple players and organizational norms
These factors have no agility-related specificity in close combat except the choice between one-seat or two-seat agile aircraft. Now, agile aircraft are one-seat aircraft. In order to identify the role of this factor, a question on the possibility of adding a second crewmember (pilot or Weapon System Officer) to help relieve situation complexity was included in the questionnaire. Pilots had different opinions on this, since:

- 52% believed a second crewmember would not improve performance, and could even deteriorate it. They argued that the time constraint involved in the situation does not leave enough time for an effective dialogue. Perception-action cycles are too short to allow for real coordination.

- 38% believed this could help, allowing task sharing and providing relief in highly strained psychological situations (four eyes are better than two). The cockpit should however then be designed to accommodate task sharing. Collective work rules also need to be developed to offer the best synergy possible. Some pilots see a second crewmember as a useful operator, not necessarily in combat situations, but in order to ensure aircraft survivability, should the pilot lose situational awareness.
- Finally, 10% had mixed feelings; they believed a second crewmember would add effectiveness, but remained very doubtful as to the feasibility of such a cockpit and on the definition of really effective collective work rules.

4.3.6. Factors specific to systems and their design

Aids systems on current modern aircraft

On current modern aircraft, questionnaire responses indicate that close combat is not possible without aid systems. The physical and cognitive constraints described by pilots are so demanding that the pilot alone will find it difficult to handle the complexity of the situations encountered.

Modern aircraft are equipped with a great number of different systems designed to aid pilots. As a rule, pilots are quite satisfied with them. The small number of criticisms related more to the systems interface than functionalities. When pilots were asked what additional aids they would like to have, they mention technical systems. However, the main point raised in their answers is that it is important to ensure that the functionality and operability of the systems are complementary, with efficient, pilot-centered interfaces. However this is not easy to achieve, given the extent to which technology and human factors research have addressed human performance in complex systems. The shortcomings mentioned by pilots involved limitations in these two areas, which will obviously require further research works.

Aids on board modern aircraft (see also Pilot-Vehicle Interface Chapter) can be grouped into two categories:

- Aids providing relief for part of the pilot's activity, even if final control is required,
- Aids helping the pilot perceive and understand the situation to make better decisions and to carry out programmed actions.

Among the aids providing relief in various pilot activities, are the following:

- Navigation and flying aids,
- Protection systems management,
- Electric Flight Control System: they free the pilot from various flying constraints, but must be "care free" to be optimum. "Care free handling" system is a system that integrates flight and propulsion control, and enables a limited number of controls (stick and throttle) to be used to maneuver the aircraft inside the whole flight envelope and takes care automatically of the aircraft limitations.

Among the aids enhancing information processing:

- Improved sensor performance: radar, optronics, Identification Friend or Foe, and low ground clearance alarm systems all provide improved information on the environment.
- Displays: HMD/HMS, 3-D audio, wide field-of-view HUD. The purpose of these displays is to minimize pilot head movement for retrieving information during combat phases, and help maintain watch outside of the cockpit (acquiring visual items, and never losing track of them).
- Voice or data transmission communication media to obtain information known by the system or by people outside the cockpit.
- Information presentation more in line with the pilots' cognitive needs: analog rather than digital displays, presentation of aircraft energy state, integration of information from various sources on a same medium, and preliminary processing of data displaying safe and dangerous zones.
- HOTAS concept for facilitating control of multiple systems while reducing reaction time and maintaining the hands on the throttle and on the stick.
- Direct voice input for hands-free control.

Challenges for implementing aids systems in agile aircraft

Behind current aid systems advantages and limitations, some questions due to cockpit automation and computerization raise and have consequence on cognitive constraints. Aid systems define the conditions under which pilots are required to complete tasks. On-board systems are more and more computerized. Automation has invaded the cockpit to increase performance. The basic flying tasks can be totally performed by systems (e.g. piloting, navigating). For other tasks (e.g. weapons, countermeasure management), systems partially support the pilot (see also Pilot-Vehicle Interface Chapter). Besides assisting the pilot, automation can cause problems. For instance, if the pilot only manages systems and does not directly pilot the aircraft, the pilot's flying ability can deteriorate and be inadequate should the automatic system fail. Moreover, automated systems can misrepresent a situation or provide erroneous data when they are not programmed correctly. Woods and al (12) expounded at length on these factors in the framework of human error, and spoke about “a clumsy use of computer technology". Since sufficient information on systems equipping future agile aircraft is still lacking. It is impossible to fully explore "systems ergonomics." However, it is possible to identify several factors which will increase the complexity of the pilot's task onboard agile aircraft:

- Systems logic. Systems operate according to mathematical and physics logic and do not always follow operational procedures, or use logic. This can result in additional complexity for the pilot, as the system's rationale, or the way the system arrived at the solution may not be obvious (13). "Transparency" of systems is often mentioned. For the pilot, this means, on the one hand, an increase in workload to understand or verify the way the system operates, and on the other hand, a confidence in the system (which is only relative, because its logic is sometimes “surprising”). Automation is likely to increase in agile aircraft to help the pilot handle task dynamics and time pressure and keep the pilot's workload compatible with mental capacities.

- Multiplicity of information. Agility can only be envisaged with aircraft equipped with an ever increasing number of sensors, along with communication networks, which integrate all the aircraft in a fleet and the command and control systems. This information comes in addition to the data already available in the cockpit, to update aircraft and system status. The pilot is confronted with multiple pieces of information that are difficult to manage. The pilots especially found this a problem in the various screens displaying tactical situations. However, some data on weapons status, countermeasure management and aggressive hostile capacities are absolutely necessary. There are several kinds of pilot aids possible: more widespread use of the various sensory channels with multimodality displays, and the pre-processing of data either by an assistant or human operator. Designing such aids is a challenge, and represents an open field of research for human factors. The consequence of this multiplicity of information is the risk of inadequate situational awareness with the potential of erroneous decision making.

- Multiplicity of controls. In parallel with the multiplicity of information, many new controls have appeared in cockpits with multi-role combat aircraft. The number of controls has considerably increased to use the different systems for both air-to-air and air-to-ground missions. For instance, Switches are more numerous, closer together, and often incorporated as a multifunction control, whereby the function of the switch changes, depending on the flight phase. The increasing complexity of the dialogue between the pilot and the systems increases the risks of making mistakes or of forgetting something, especially since pilot workload and stress are also on the increase.

- Access to information. Multifunction displays are also more prevalent because it is impossible to simultaneously display all the information pertaining to the environment, aircraft, and systems. With the hierarchical organization of information, the displayed page may not correspond to the current functional needs of pilots. Moreover to access data on a different page, the pilot has to remember where the information is stored and have the time to perform the steps (usually button presses) to retrieve the desired information. These requirements are not always compatible with the task. To try to minimize workload, careful design of the dialogue is needed and the provision needs to be made for the pilot to pre-select desired functions, based on anticipated requirements in an upcoming complex flight phase. The display location in the cockpit is also import to relate to the current mission phase. Information needs to be displayed in the most convenient location for the pilot's current task. Any conflict between head-up and head-down displays for information retrieval could decrease pilot performance.

- Feedback. Information feedback is a factor which Sarter and Woods (11) consider as essential for situational awareness. Feedback makes it possible to stay inside the control loop to make sure the desired goal is reached after the implementation of appropriate actions. It also makes it possible to detect errors made, and therefore to possibly remedy them. Another kind of feedback, just as important for the pilot, is the feedback provided by systems when they automatically change modes (e.g., when automatic pilot id engaged or during automatic changes of weapon system state during a delivery sequence). Feedback is also necessary on the state and potential possibilities of systems. There again, feedback allows the pilot to stay inside the monitoring loop, and to maintain adequate situational awareness. Feedback on the aircraft aerodynamics is especially important for agility management because many of the typical sensations are no longer available with integrated digital flight control systems.

4.4. Knowledge required to execute a task

These factors involve the qualification of agile aircraft mission personnel. The qualification level is determined by psychomotor and cognitive abilities required of the pilot to successfully carry out missions. The identification and definition of these abilities is accomplished by analyzing tasks and pilot activity. Pilots can obtain the required abilities in two different ways:

- Through training, be it theoretical, by simulation, or in real life situations,
- Using existing pilot experience.

Now, it is difficult to accurately determine the psychomotor and cognitive abilities required to successfully carry out missions with agile aircraft. However questionnaire responses give pilots opinions on this topic. The questionnaire was aimed at assessing two items:

- Physiological and psychological abilities required by aircrew to fly modern aircraft in situations of close combat,
- Specific training developed for these crewmembers.

According to the pilots' answers, it seems that a good physical condition is essential. This fitness must be supplemented by regular acceleration training in centrifuges and in real life situations.

The psychological qualities of competent combat aircrew listed were: aggressiveness, willpower, enthusiasm, ingenuity and cunning. Pilots mentioned various cognitive abilities: good spatial capacities, excellent eye-to-hand coordination, quick reaction time, and efficient information management. The comments also stressed that pilots need to be reactive, flexible, accurate, cautious (knowing importance of verification), and able to make decisions under stress.

Beyond these abilities, strictness and professionalism were considered as the two essential qualities of a good fighter pilot. These two qualities help pilots know their aircraft and its systems inside out, as well as enemy aircraft. Knowing all these automated and computerized systems is extremely time-consuming given the great number of available functions, and implementation options, and sometimes the difficulty encountered by the pilots to totally understand the functioning of these systems. The qualities of a fighter pilot must be developed by training, in simulators as well as in flight. "Full-scale" mission simulators are essential to acquire this know-how, but cannot replace practice in real life conditions. This practice must be regular and frequent, because the abilities developed are complex and require permanent reinforcement. The final goal of this training and practice is to make pilot's behavior automatic so they can react as quickly as possible any given situation and its constraints.

4.5. Difficulty experienced by the pilot

Task difficulty is subjective feeling, specific to each pilot. The more difficult the task is felt to be, the more the pilot will assess it as being complex. Difficulty can also be thought of as the outcome that reflects a person's experience, knowledge, and ability to manage situations and fulfill task goals (8). The pilot's performance results from the interaction between the situation, acquired expertise and stress level, “difficulty” being the way the pilot experiences this interaction. Performance is guided by the overwhelming concern to save cognitive resources, i.e. not to exceed their limits, and also the need to keep some in store to maintain a margin for adaptation (14).

In addition, stress generated by the mission stakes effects the way the pilot processes information. Cognitive effects of stress are well known and have to be taken into account to assess the pilot's performance. They include: reduced thinking, "tunnel vision", excessive hurry, mental regression, "act at any cost" and mental block (15). Knowledge of these stress effects is important for training pilots and designing stress-resistant interfaces.

Fatigue is also an important factor to define the way the mission is difficult for the pilot. Mental and physical fatigue is closely linked in combat mission where physical and mental requirements are high. Fatigue has several effects on information processing mechanisms. Perception, memory, attention, understanding, decision making, risk making and action accuracy may be decreased (7)

In the framework of agile aircraft, it is difficult to know ahead of time how difficult things will be for the pilot. It will depend on aircraft ergonomics, pilot experience and, pilot's stress and fatigue states. But it is obvious these factors need to be taken into account in the design agile aircraft man-machine interface.

5. SITUATIONAL AWARENESS AND HUMAN PERFORMANCE

In order to cope with agile aircraft, pilots also need to be "agile". Human agility can be defined like the cognitive mechanism helping pilots answer questions on the status of the situation at hand. It also helps them make choices in order to reach the goals they set for themselves. During air-to-air close combat, pilots have to answer many questions:

- Where am I?
- Where am I going?
- Where are the enemies?
- Where are the enemies going?
- Where are friendly aircraft?
- Where are friendly aircraft going?
- What is the aircraft's energy status
- What is the status of on-board systems?
- What is my weapon delivery envelope?

The pilot will make the choices it feels are best adapted to meet the objectives, after integrating the answers to all these questions. It could seem that these questions contribute towards developing a solution that guarantees successful pilot performance. However, the reality is that in real world missions:

- The pilot has limited perception, memorization, information processing and action capacities,
- All the information is not available,
- Some information is uncertain,
- Other information is there, but difficult to perceive and understand,
- The situation changes rapidly, and unexpected or unknown events may occur, and
- The aircraft and its systems have their own limitations.

Despite all this, the pilot must face the situation, and develop cognitive strategies. Believing that the challenge of pilot performance lies within these strategies, the human factors community has decided to study them, and to address two specific aspects: situational awareness and decision making.

5.1. How to define situational awareness?

Vogel (16) mentions that the term “situational awareness” was used in United State Air Force pilot manuals even before being defined. The "situational awareness" notion being absolutely crucial to mission success, human factors specialists have looked into it, to offer a definition and to assess and describe what mechanisms come into play to build up and maintain situational awareness.

First distinction is necessary between situational awareness and spatial orientation. As Menu and Amalberti point out (17), spatial orientation is the capacity to position oneself in relation to a given fixed reference, represented by the horizontal and vertical directions in space. Situational awareness is the capacity to position oneself in relation to a relative reference system made up of the dynamic properties of the objects located in the geographical and tactical environment. Spatial orientation is a mechanism underlying situational awareness.

The literature provides two different approaches to research on situational awareness (18):

- One approach deals with the components of situational awareness. It is a “product” centered approach. One of the most comprehensive definition comes from Wickens (19): "situational awareness is a continuous extraction of environmental information about a system or environment, the integration with previous knowledge to form a coherent mental picture, and the use of that picture in directing further perception, anticipating and responding to future events". Through this definition, Wickens underlines that:

a) situational awareness does not just involve perception, but also integrates understanding and anticipation (20),
b) there is situational awareness of environment as well as of the aircraft and its systems,
c) situational awareness not only helps to anticipate, but also to appropriately react to situations.

- The second approach studies the mechanisms by which cognitive resources are managed and adapted so the pilot can form a understandable and coherent mental picture representing the situation, continually updated with recurrent situation evaluations (11). This is a “process” centered approach, which stresses:

a) the interdependence and non-linearity of memory, perception and action (18),
b) the importance of time awareness and feedback (11), and
c) the link between situational awareness, decision making and action (21).

The description of situational awareness properties and mechanisms helps to better understand the difficulties, which may be encountered in flying agile aircraft. Upon entry into a combat situation, the key challenge to pilots is how best the update their situational awareness:

- On the one hand, situational awareness needs to be sufficiently valid in time to avoid not being able to act and having to allocate all resources available into merely updating situational awareness,
- On the other hand, the pilot must be able to continuously integrate information, to update situational awareness and avoid working with mis-adapted situational awareness.

The answers to this conflict depend on the abilities of pilots to operate at various levels of understanding (22). For some situations, an abstract or "big picture" awareness is adequate, minimizing cognitive demands. The details to which situational awareness is updated can also vary, depending on the time and other resources available. Also, the pilot may decide to only attend to updating aspects that are critical to the situation. For example, in an air-to-air combat phase, having only a rough picture, or no picture at all, of the state of the inertial navigational system has no disabling effect on the ability of the pilot to engage in combat.

5.2. Agility and situational awareness

Situational awareness is defined by pilots as having sufficient perception and understanding to be able to predict future changes occurring in the situation, from the information supplied by the outside, on-board systems and links connecting the aircraft with the outside. For pilots, situational awareness in a close combat situation involving modern aircraft is a major issue. In the survey, 78% of the 29 pilots surveyed said they had sometimes lost situational awareness during these flight phases.

The physiological and psychological constraints mentioned above influence the situational awareness developed by pilots. In addition to just having situational awareness, pilots also raise the question of having the right situational awareness. Is it necessary to have total situational awareness, or is partial awareness sometimes sufficient? The realities of air combat show that when engaging in combat, situational awareness needs to be as comprehensive as possible. However, once combat is engaged, the predictability of the situation changes and the time constraints, information flows, and lack of critical information (such as identification of external link targets) make it difficult if not impossible, for pilots to acquire comprehensive situational awareness. It can only be partial, and can range from high to low. The difficulty is then for the pilot to assess the relevance of this partial awareness to the situation, decide whether it is sufficient or not, and decide to continue the combat or stop. In practice, under specific situational awareness threshold, combat should be stopped, but in real life things are never this simple. This is a very important issue for pilots.

The questionnaire also tried to identify whether different components of situational awareness are easy or not to acquire and maintain in modern air combat. According to the pilots' answers, it seems that:

- Knowledge of the energy situation of modern agile friend or foe aircraft is more difficult to acquire and maintain than in older combat circumstances. Pilots explain this by referring to the frequent and rapid changes occurring in the physical and tactical environment. It is no longer easy to assess and predict the speed, banking rate, altitude, and potential acceleration of enemy aircraft. In regards to the pilot's own aircraft, several factors contribute to this decreased perception of the aircraft's energy situation. For instance, the information displayed in the cockpit is often illegible or difficult to access. Also electronic flight control systems minimize the feeling and other feedback cues on the aerodynamic state that were available with older flight control systems.
- Identifying the envelope for weapon delivery and knowing the present and future position and trajectory of friend or foe aircraft are also more difficult to accomplish than in former combat situations. This opinion also shows that despite the increasing number and sophistication of on-board systems, the information supplied to pilots does not greatly contribute to enhancing situational awareness in highly complex combat environments. The pilots did not directly mention root causes. However, one reason may be that the nature of the information displayed and/or the way it is displayed does not meet pilots' cognitive requirements.
- On future aircraft, pilots do not envisage to acquire good situational awareness without high level of automation for support systems and man-machine interfaces This feeling reflects the constant efforts made by designers. A great number of on-board systems are now perceived as being essential and crucial to achieve the mission. However, pilots mentioned the functional coherence between systems functions, aids, aircraft properties and interfaces do not always exist. Future aircraft design has to be users' need-centered and not a technology "patchwork".

Regarding human agility, pilots need to be able to maintain adequate situational awareness, while optimizing resource allocation. However, in reality, one or more of the following are plausible for agile aircraft flight:

- Pilot has inadequate situational awareness due to the lack of information or because the knowledge required is not available,
- Pilot retains and outdated situation representation, because it does not have the resources necessary to change it,
- Pilot adopts too abstract of a representation leading to imprecise situation management,
- Pilot is not aware that its situational awareness is outdated. Captain Peeples (23) of United States Air Force talks about an "ultimate situational awareness" to describe a pilot's capacity of being aware that he does not have an adequate situational awareness.

5.3. Decision-making

Decision-making has been extensively studied in aeronautics. At first, research work was carried out within normative approaches, trying to define an optimal decision making model. The work of Jensen (24) on Aeronautical Decision Making models must be mentioned. Extensively used to train pilots on decision-making, these models quickly proved their shortcomings, when trying to explain how pilots made decisions. Under Klein's lead (21), a new approach to the modeling of the mechanisms involved in decision making, in real work situations, was developed: Naturalistic Decision Making. These studies, like recent studies on situational awareness, belong to the research movement focused on "situated" cognition.

Decision-making is not simply an algorithmic process analyzing all possible hypotheses to choose the best one. A decision is a cognitive mechanism constrained by the task at hand and the pilot's expertise. Klein's recognition-primed decision model (21) suggests the following:

- The more complex the constraints in a situation, the more decision strategies will be based on situation recognition, and not on analytical processes.
- Recognition of the situation generates an option, which then undergoes evaluation. If the option is deemed not valid or feasible, the pilot carries out a diagnosis to generate a new solution, and so forth. This is a serial process of option evaluation.
- If the situation is a familiar one, actions are carried out without further evaluation.
- The main difference between experienced pilots and more junior ones is not that the former have better reasoning, but that they have a better capacity at having a mental picture of the situation.
- The more expert the pilot, the quicker the situation will be recognized.
- The pilot is more likely to choose and execute an option that it is familiar with. In other words, the right decision is the decision the pilot knows how to implement.

Performance is the result of pilot behavior. It involves tactical aspects (shooting the enemy or flying away) as well as mission safety aspects (managing separation with other aircraft, managing aircraft movements in relation to ground or to ground-air threats). The complexity of close combat makes the simultaneous and comprehensive management of all these goals difficult. Pilots have to prioritize issues, and set a number of activities aside. Another solution is to simplify operations by lowering control precision, and only using familiar routines or a portion of the functions or capabilities of each system.

The higher the constraint, the more the pilot will operate sequentially, processing one single goal after another. Goal prioritization then becomes a key element in mission success. Of course in the background, the pilot must also stay on the lookout to detect any alarm signal, which could challenge the priority list established. The difficulties entailed by goal management are especially noticeable when managing the energy situation of the aircraft, acquiring and maintaining contact with enemy aircraft, and using the weapon systems. Yet, the closer the target, the more dynamic and unpredictable the situation becomes, ever decreasing the time available to perceive, understand, and act. Conversely, a pilot must be able to use the aircraft's movement potential and systems changes to surprise the enemy. Tactics are now less predictable than before and their implementation is increasingly reactive.

The impact for pilots stems from the level the pilot is in control over the situation. The pilot is in control when there is enough capacity to anticipate situation developments. Loss of control results in a reactive behavior. The pilot no longer controls events, but becomes subject to them, and is always trying to catch up with the aircraft. In modern close combat, tactical patterns are more numerous and more diverse, given the increased options allowed by aircraft maneuverability and by weapons system performance. The pilot cannot anticipate all possible tactics, but even if this was possible, it would require an in-depth knowledge of the possibilities offered by enemy aircraft and systems. Because of this, some pilots say that although modern aircraft have a higher performance level than older ones for close combat, they require the adoption of an increasingly opportunistic behavior since it is very difficult to anticipate situation developments and the pilot is less and less frequently in control of the situation.

The questionnaire answers also stated that agility cannot only be envisaged in terms of aircraft maneuvering capacities. In addition to airframe agility, systems and weapons agility must also be taken into account. Agility is the capacity to minimize the time required to acquire and shoot an enemy and systems and weapons play a role as important as the airframe itself. The agile aircraft must be a coherent entity, within which the "intellectual" agility of the pilot is integrated.

In conclusion, the demands of agile aircraft missions will further constrain decision making in numerous ways:

- There may be insufficient time to generate more than one or two options, making it more critical that these few options are appropriate for the situation;
- The situation can change very rapidly, making the assessment of options more difficult;
- Consequently, there is increased likelihood that options, will be executed that have not undergone preliminary evaluation;
- Given the agility of the airframe and weapons, it is more difficult to develop a three-dimensional picture of the situation and perform mental simulation of candidate options.

Having a better understanding of decision-making mechanisms makes it possible to envisage what could be done to enhance decision making. Beyond decision making aid or assistance systems, a very important aspect is to help pilots retain a greater number of previously evaluated tactics in their memory. This could help pilots react faster when there are insufficient resources to assess options in real time.

However, There is also a danger in allowing reasoning to be so rigid that it allows options to be executed without full evaluation as to whether they are appropriate. This mechanism is found in routine errors or “slips”, as mentioned by Norman (25). Thus, additional techniques that can facilitate "agile decision making" are needed that enable pilots, while taking into account the ongoing dynamics of multiple aspects of a situation, are able to arrive and execute timely solutions which culminate in mission success.

6. CONCLUSION

The experience acquired on last generation combat aircraft and on "supermaneuverable" aircraft prototypes can be used to predict the consequences these concepts will possibly have on pilots' intellectual capacities and on information processing mechanisms.

Existing data show that the decrease in psychomotor capacities occurs mainly during changes in acceleration rates, and that there is an overall reduction in information processing capacities when the pilot passes through acceleration plateaus (perception, understanding, decision making). However, these results were obtained with experimental protocols having little in common with the acceleration profiles encountered in supermaneuverable aircraft. Thus, they must only be considered as a basis on which to conduct more specific research work. This research, in a first phase, should quantitatively and qualitatively assess the effects of accelerations on psychomotor and cognitive capacities, and in a second phase, assess these same capacities in the framework of supermaneuverability. The effects of acceleration on psychological capacities are not well known, but it is important to realize that pilots already experience these effects in traditional aircraft, and have probably learned to manage them, without any further formalization. There is no reason for the psychological consequences of supermaneuverability to be more serious than those already experienced in traditional aircraft. Of course, a better knowledge of this stress could help pilots develop better management techniques (training), and could help the design of adapted aids.

Superagility refers to the human/aircraft relationship, in view of reaching a goal. Beyond the mere agility of the airframe and its systems, human agility needs to be taken into account. Human agility results from information processing mechanisms, which lead to situational awareness and decision making. Analyzing the complexity linked to agility helps identify the various factors involved, and envisage the consequences they may have on information processing. The effects of these factors are analyzed through a "situated" approach of pilots at work, where pilot performance results from the interaction between the situation and pilot's expertise and within which the pilot manages cognitive compromises. Agility does not create new psychological constraints for the pilot, at least as such. But it amplifies the constraints already existing in aeronautical situations. With agility, the pilot will find it increasingly difficult to manage cognitive compromises, and will tend to use information processing strategies, which increase the risk of mistakes or mis-adapted choices. The in-depth study of these mechanisms will help develop new training schemes for pilots, innovate systems and interface design, and provide assistance to pilots.

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ANNEXE 1

SITUATIONAL AWARENESS QUESTIONNAIRE FOR AGILE AIRCRAFT PILOTS

1- Background

Current assigned aircraft type:

Assigned aircraft hours:

Total flying hours:

Flying hours on agile aircraft: What type?

Age:

2- During close-in combat with agile aircraft, what are the main constraints to manage to have a good situational awareness?

3- In comparison with current fighter aircraft, are the following items more or less difficult to acquire with agile aircraft?

	more difficult	**no difference**	**less difficult**
Where I am?			
Where am I going?			
Where are enemies?			
Where are enemies going?			
Where are friendly aircraft?			
Where are friendly aircraft going?			
Knowledge of aircraft energy status?			
Knowledge of weapon delivery envelope?			

Comments to explain your responses:

4- Are there Gz and Gy accelerations constraints to maintaining situational awareness during close-in combat with agile aircraft? Could you explain your response?

5- Are there Gz and Gy accelerations constraints to handling the man-aircraft interface commands during close-in combat with agile aircraft? Could you explain your response?

6- Close-in air-to-air combat is a complex dynamic situation. Among the items characterising a complex situation, which are relevant for close-in air-to-air combat with agile aircraft?

	no relevance	**relevant**	**very relevant**
Time pressure			
Sudden changes			
Sudden loss of information			
More complex information			
Increased information flow			

Comments to explain your responses:

7- Have you lost situational awareness during close-in air-to-air combat with agile aircraft?

If yes, could you explain the circumstances?

8- Do you think that anticipating tactics during close-in air-to-air combat is more problematic with agile aircraft?

Could you explain your response?

9- Do you think your mental effort is increased fighting with agile aircraft?

Could you explain your response?

10- Do you have the feeling that if you lost situational awareness with an agile aircraft, it is more difficult to retrieve it in comparison with current fighter aircraft?

Could you explain your response?

11- Have you already been surprised by the behaviour of agile aircraft during close-in air-to-air combat?

Could you explain your response?

12- Which support systems might improve situational awareness during close-in air-to-air combat with agile aircraft? (for instance: helmet mounted display, head down display with tactical situation, 3-dimensional auditory, pilot's assistant, etc.). Could you justify your responses?

13- Do you think a second pilot or a weapon system officer would be useful in the agile aircraft to have better situational awareness and effectiveness?

Could you explain your response?

14- For you, what are the skills to be an effective agile aircraft pilot?

15- To train future agile aircraft pilots, what changes would be useful to introduce in the pilots' training courses?

16- If you have other comments on the human consequences of agile aircraft, you can explain them below:

We thank you for your co-operation

PHYSIOLOGICAL CONSEQUENCES: CARDIOPULMONARY, VESTIBULAR, AND SENSORY ASPECTS

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SUMMARY

Discussing the physiological consequences of enhanced fighter manoeuvrability (EFM), aspects of cardiopulmonary reactions will be seen during high G manoeuvres, especially the combination of negative G-load followed by high G-onset manoeuvres ("push-pull"). The aicrafts' capability to reach high altitude within a very short time (due to the lift to weight ratio of more than 1) may produce new problems even during normal aircraft operation, e.g. decompression sickness (DCS). The incidence of vestibular problems may be increased by unconventional acceleration exposures. Sensory stimulations may be induced by high acceleration alterations in the roll, pitch, and yaw axis. The support by an advanced G-protection garment will be needed. For the "care free" handling the advanced G-protection device must work without any delay in time even during high acceleration transitions, must secondly include high altitude protection, and thirdly must ensure pilot comfort. Furthermore special training devices are required such as the human centrifuge as a dynamic flight simulator (DFS) with a fully gimballed system, and a spatial (dis)orientation device with a fully three-axes gimballed system. Pilot selection and medical survey with high sophisticated diagnostic tools will become more and more important. Last not least the need of special physical training will be required to enhance the aerobic endurance and the anaerobic power, to train the cardiovascular reflexes, and to increase psychomotoric stability and mental mobility.

INTRODUCTION

In respect of possible physiological consequences superagility includes first of all the aircraft's capability to change its velocity vector in all directions and dimensions in a very short time. This does not only includes new technologies to improve the post stall capability of the aircraft by vectored thrust and electronically flight control system with fast alterations in the roll, pitch and yaw axis, low to medium altitude and low speed. It also concerns the capability of the aircraft to reach high G-loads, high altitude, and supersonic speed.

Physiological consequences may not only occur in the normal operation range of the agile aircraft, but also in extreme edges of the flight envelope and in emergencies. For safe operations with agile aircrafts it will be necessary to consider special procedures in the process of pilot selection, survey, and training. Especially manoeuvring in the post stall regime requires new mental and physical abilities.

Paper presented at the RTO HFM Lecture Series on "Human Consequences of Agile Aircraft", held in Neubiberg, Germany, 20-21 March 2000; Preston, UK, 23-24 March 2000; WPAFB Ohio, USA, 19-20 October 2000, and published in RTO-EN-12.

CARDIOPULMONARY ASPECTS

So far very few pilots have experienced high-agility flight with extreme acceleration stress. Therefore there is very little data in the literature that relate to the effects of G associated with EFM flight. However, it is possible to speculate about the acceleration stress hitting the pilots during enhanced fighter manoeuvrability by transferring the observations from human centrifuge exposures in the dynamic flight simulation mode.

Cardiopulmonary effects during high-agility flight will be induced primary by magnitude, direction, duration, frequency, and onset of acceleration exposure. During high agility flight pilots will experience both impact acceleration with less than 1-second duration and sustained acceleration during manoeuvres that may be completed in several seconds.

To withstand acceleration forces blood pressure has to be increased up to 300 mmHg by the left ventricle of the heart to reach blood pressure at heart level of more than 200 mmHg (figure 1).

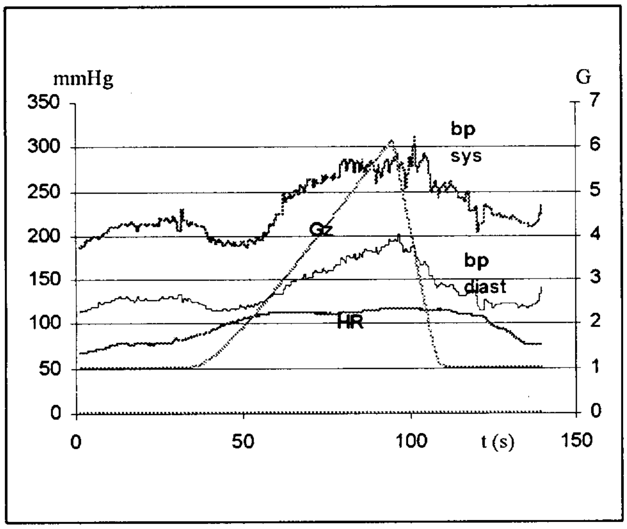

Figure 1: blood pressure (systolic and diastolic) measured by porta pres method during a linear acceleration profile with 0.1 g/s onset up to +6 Gz.

Positive pressure breathing assisted by a breathing regulator or induced by the pilot with active breathing techniques increase the intrapulmonary pressure up to 70-100 mmHg.

There is no doubt that this cardiopulmonary stress – even if the exposure time and frequency is short – demands healthy cardiopulmonary system, confirmed by special medical selection procedures and continuous medical monitoring.

Cardiovascular Aspects of EFM

Despite lower peak Gz levels to be expected during enhanced fighter manoeuvrability, G-induced loss of consciousness (G-LOC) as a result of cardiovascular decompensation during +Gz will become a greater threat. EFM will involve more frequent changes from negative Gz to greater than +1 Gz. Transitions between zero or –Gz and +Gz are known to reduce human +Gz tolerance [1], termed the "push-pull effect" [2]. The decrease of blood pressure and heart rate by vasodilatation during any "push" phase less than +1 Gz will diminish human +Gz tolerance. The Canadian Forces reported that 17% of all G-LOC episodes have been related to push-pull effect, several of them involving F-18 pilots who had been in control of the aircraft [3]. A review of United States Air Force (USAF) accident records determined that F-16s, F-15s and even one A-10 and one T-37 were likely lost because of G-LOC due to push-pull effect.

Increase of ±Gx and ±Gy during enhanced fighter manoeuvrability might not be followed by cardiovascular problems.

Threat of G-LOC

G-induced loss of consciousness will not only be caused by frequent transitions between -Gz and +Gz and the push-pull effect, but will also happen due to the capability of high agility aircraft to reach high +Gz levels within less than 1 second.

Normally there is no risk of G-LOC during accelerations lasting less than 1 second (impact) even with normal G-protection garment and even during push-pull manoeuvres. The cardiovascular system is too slow to react. If the oxygen reserve of the brain is not exhausted by previous high +Gz manoeuvres there will be enough capability to withstand high +Gz acceleration forces of short duration.

Figure 2 shows a push-pull manoeuvre in the interactive steering mode of the German human centrifuge, actively performed by a pilot with conventional anti-G trousers.

This push-pull manoeuvre is executed within 6 seconds. It starts at +1 Gz, reaches –0.5 Gz after 1 second, about another 2 seconds later the peak level of +9 Gz is reached. The duration of the G-level above +8 Gz lasts about 1 second. Finally +1 Gz is reached 2 seconds later again. No G-induced visual impairment like peripheral light loss was reported.

But there is no doubt that G-LOC would have occurred if the G-level of more than +8 Gz would have lasted for more than 1 second.

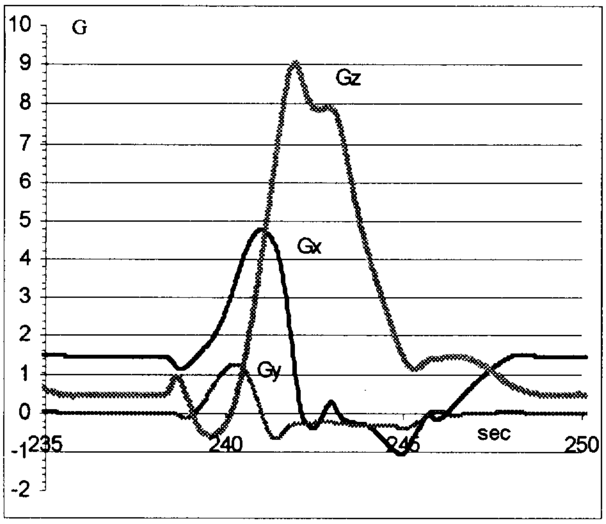

Figure 2: active "flown" push-pull manoeuvre on the dynamic flight simulator (human centrifuge).

Problems with current anti-G suits

Pilots of current EFM-capable aircraft are to wear anti-G suits designed for previous, non-agile aircraft. The original anti-G suit design remains operational today, with minor changes only. Even with an electronically controlled anti-G valve that regulates the flow of pressurised air into inflatable compartments in the G-trousers, the pressure delivery to the trousers requires 1 to 3 seconds to achieve the demanded pressure for cardiovascular protection. The addition of positive-pressure breathing during +Gz (PBG) is a means to decrease fatigue and to enhance the effectiveness of anti-G protection garment. However, currently there is no G-suit that is designed for enhanced fighter manoeuvrability conditions. Even new anti-G valves that will realise rapid and continuous changes in the G-suit pressure in order to adapt to frequent changes of G will have some disadvantages. As the cut-in of the pressure schedule does not cover the total Gz-envelope, a delay will remain between the pressure in the anti-G suit and the immediate change of the pilot's physical state.

Current research in ±Gz protection

For about three years a liquid filled anti-G suit (prototype "Libelle" of *Prospective Concepts AG*, Switzerland) is evaluated in the dynamic flight simulator (human centrifuge) at Koenigsbrueck. With this prototype pilots were able to perform any flight manoeuvre within the limits of +0.9 Gz and +10.4 Gz and a maximum G-onset/offset of ±5 g/s. They could use the HUD, HDD, throttle and stick in order to chase a target-A/C or perform clinical manoeuvres (aerobatics) like in a normal flight simulator or in the real aircraft. The evaluation of the suit was done under clinical and operational conditions, especially during profiles of a simulated A/C with high agility capability and frequent change of acceleration levels from base level up to maximum +Gz. In 34 runs pilots reached G-levels of at least +9 Gz without any arm-pain and with remarkable less fatigue than expected. Simulated air combat manoeuvres (SACM) were performed up to 10 minutes with G-levels up to +10.4 Gz. There was no decrease in situational awareness. Physiological parameters (e. g. ECG) showed no abnormalities.

Prototypes of the new hydrostatic suit "Libelle" demonstrated the ability to help the pilot to perform extreme agile manoeuvres. Excellent anti-G-protection was ensured without time delay during high-G-onset and –offset rates. The avoidance of arm-pain was the most impressive result. Even as there is a wide individual spread in the reached G-levels during the passive acceleration profiles evaluation (due to "learning effects" and perhaps not exact custom fit), the operational benefit of the prototypes was convincing.

Need for research and training

Up to now there is only little information about physical demands imposed by high-agility flight. Understanding these complex translational, rotational, and gyroscopic phenomena requires reassessment of well-established concepts. While some speculation has occurred on the effects of G in high-agility flight, this is mostly based on gradual or rapid G-onset studies which are not representative for high-agility accelerations. The human physiology will be the limiting factor in high-agility flight. Pilot's G-tolerance in this environment will be limited by G-LOC mishaps, visual problems, and vestibular illusions.

Acquiring and understanding of human factors in enhanced fighter manoeuvrability flight will be central topic in future. Validated laboratory tools and proven experimental methods are needed as well as acceleration devices capable of ±Gz, ±Gy, and ±Gx. These modern human centrifuges should be able to simulate the acceleration profiles of enhanced fighter manoeuvrability. The capability of reliable transitions between -Gz and +Gz, active powered gimbals to reach angular velocities of at least 10 rad/s^2, and acceleration onsets of more than 10 g/s will be the technical requirements to understand the human physiology in the envelope of forth generation aircraft and to optimise crew protection systems.

France, Sweden, and Great Britain undertook great effort to construct new advanced human centrifuges.

Today the German Air Force is planning to upgrade its human centrifuge to meet the specified requirements.

Furthermore, physical fitness training and education must have high priority for Eurofighter "Typhoon" (EF) aircrew. Training facilities should be collocated with EF squadron accommodation. Aerobic endurance, anaerobic strength, and the capability of co-ordination is a must for efficient anti-G protection.

Cardiopulmonary effects of decompression bubbles

Raising the ceiling of current flight operations will lead to an increase in altitude exposure hazard and consequent incidence of decompression sickness (DCS) symptoms. Agile aircraft like the F-22 and the EF are capable to reach a flight altitude up to 60,000 ft with a climb rate of 50,000 ft/min. With the current cockpit pressurisation schedule there is more than a theoretical chance for the pilot to be hit by decompression sickness, when wearing the common aircrew equipment [4, 5].

A pressure altitude of 21,500 ft seems to be the critical threshold where the incidence of DCS increases rapidly and the chance to experience decompression sickness symptoms is greater than 50%. With the normal cockpit pressurisation schedule the critical cockpit pressure altitude of 21,500 ft will be reached at FL 480 (48,000 ft flight altitude).

Using of 100% oxygen is necessary to provide additional protection. It is highly recommended that the cabin pressure differential should be increased to at least 6 PSI instead of current 5 PSI. For escape or in case of rapid decompression in a flight altitude above 50,000 ft the pilot has to be equipped with a (partial)pressure suit. There is no doubt, that a partial or even a full pressure suit will decrease pilot's mobility and comfort. New concepts for protective garment have to be developed.

Venous gas emboli (VGE) and DCS

Bubbles are routinely detected in the venous blood (venous gas emboli) after decompression at altitudes above 12,000 ft. As the more common occurrence of decompression sickness relates to limb pain (bends), cardiovascular effects of decompression bubbles should be discussed. The scope and the magnitude of the problem are proportional related to the gradient of decompression (pressure/time relationship) and hence the amount of gas bubble formation. Not only after rapid decompression, but also during ascend in a altitude chamber with a climb rate of 4,000 ft/min bubble formation can be detected. Knowing this it is to be assumed that gas bubbles formation will occur during high performance take-off or rapid cabin pressure changes during maximum climb rate manoeuvres in an air combat scenario.

The cardiovascular effects of decompression bubbles are presented by symptoms ranging from local blood flow abnormalities, due to mechanical blockage of minor blood vessels, to complex neural effects or complete circulatory collapse.

Intrapulmonary shunts and PFO

Normally the pulmonary microcirculation in the lungs is the filtering mechanism of the bubbles. No bubbles can reach the left ventricle of the heart, no bubbles become arterial gas emboli (AGE). The condition whereby venous bubbles cross pulmonary capillaries might be pulmonary hypertension – induced by anti-G breathing techniques or positive pressure breathing during G-load (PBG) or in high altitude (PBA). In addition to that, pulmonary hypertension might open extra-alveolar arteriovenous shunts, allowing VGE to spill over and to become AGE [in 4].

The prevalence for a patent foramen ovale (PFO) is 20-30% in the human population [in 4]. A PFO is essential for fetal life since it allows blood to pass from the right heart to the left heart in order to bypass the collapsed fetal lungs. Usually within the first year of life this foramen will be closed. Even if there is no anatomical closure by fibrous adhesions the foramen is usually functionally closed because the pressure in the left atrium of the heart is generally higher than in the right atrium.

Venous gas emboli induced by altitude decompression may pass the PFO even in normal pressure environments. The functionally atrial right-to-left shunt allows the gas emboli to cross over when rapid and substantial venous flow to the right heart occurs. Typical situations are:

- G-offset
- Cessation of positive pressure breathing,
- Cessation of the L-1 or M-1 anti-G straining manoeuvre
- Valsalva manoeuvre
- Coughing.

With the new envelope of modern agile fighters the exposure of the pilot to extreme physiological stress is not only likely but probable. Exposure to extreme low pressure without the benefit of denitrogenisation or full protective coverage is likely to be capable of producing silent or overt decompression sickness symptoms. Exposure to assisted positive pressure breathing (PPB) in excess of 60 mmHg in a population likely hiding a 25% incidence of PFO may produce right-to-left atrial shunting as a consequence.

One consequence is discussed and it is recommended that an extension of the echocardiographic examination will be introduced at pilot selection for fourth generation aircraft. The German Air Force Institute of Aviation Medicine has already established the transoesophageal echocardiography for the medical examination of EF pilot. Candidates.

VESTIBULAR AND SENSORY ASPECTS

Discussing the sensory consequences of enhanced fighter manoeuvrability, the ability to execute manoeuvres in the post-stall regime, with controlled side slip (lateral acceleration) and with high angle of attack (AOA) far beyond the maximum lift and aerodynamic limits is most relevant. This "supermanoeuvrability" is enabled by thrust vector control, aerodynamic design, fly-by-wire flight control system, and a thrust-to-weight ratio exceeding 1.

The human complex stress envelope in supermanoeuvrable flight is discussed controversial. In the post-stall regime it is expected that maximum +Gz will be less than in current aircraft, but 0 or −Gz will be much more frequent due to negative AOA in the energy recovery phase. However, agile flight includes also high speed turns like defensive or avoidance manoeuvres even during supersonic speed. Positive accelerations peak levels up to +15 Gz and in the negative Gz-regime up to −10 Gz have to be expected. Although of a very short duration, high G-onset, G-offset and possible G-transition between negative and positive G-load (push-pull manoeuvres) will have to be faced. In addition to the cardiovascular effects sensory and vestibular symptoms will increase and may become the limiting factor during agile flight.

Albery [6] estimated that maximum Gx values are within the limits of ±6.5 G with a maximum G-onset and G-offset of ±5 g/s. The yaw authority may increase lateral accelerations during agile flight up to ±4 Gy with the maximum G-onset and G-offset of ±2 g/s. X-31 test flight results however showed nearly no ±Gy acceleration forces. Lateral G's decrease the pilot's handling capability. To avoid this, these "yaw-looking" manoeuvres were flown by high roll rates (up to 240°/s) with high AOA. Nevertheless when initiating the roll input impact-like Gy's due to the high angular acceleration can't be avoided.

The linear acceleration transitions and the high angular accelerations (pitch: ± 180°/s, roll: ± 360°/s, yaw: ± 90°/s) with extremely high onsets and offsets may increase vestibular disturbance and possible spatial disorientation.

Consequences of supermanoeuvring for semi-circular canals and otoliths

The magnitudes of angular accelerations as provided by Albery [6] are not beyond the normal sensory function of the semicircular canals. One may even expect that the canal responses as for instance during the Cobra- or the Herbst-manoeuvre, will rather accurately reflect the actual angular motion, because of the fast rotations over a limited angle. Simply said, acceleration will deviate the cupula, and the deceleration will erect the cupula back in the original position. This happens faster than the 2nd-order canal characteristics are able to neutralise the response during the rotation. This implies that most of the time the nystagmic response will be adequate as well during post-stall manoeuvring. However, linear accelerations in supermanoeuvring aircraft are most probably different to those of conventional aircraft as they affect the pilot from all directions. Moreover, the magnitude of the acceleration vector will vary, but will be most of the time exceeding 1G, perhaps up to 4G during post-stall manoeuvring. In that case, the gain of the canal response in terms of nystagmus or in terms of motion perception may be different from the optimum response at 1G. Evidence for these interactions is available from parabolic flight experiments.

The G-loads encountered will not destroy the otolith system, as the G-loads in the post-stall regime will be smaller than pulled in conventional high-performance aircraft. On the other hand, G-loads > 3G will generate nystagmus which will be inadequate given the situation [7].

It is also of interest that the intersubjective variability in the magnitude of this nystagmus is considerable, as is the capability to suppress the nystagmus by visual fixation. There is not much known about the horizontal nystagmus following stimulation along the Gy axis, because of unpleasant attitude for subjects in conditions of Gy > 2G. This would require further research.

For a more detailed analysis of the perceptual consequences of the sensory system involved, the combined recordings in linear and angular encountered accelerations should be available for model simulation.

Subjective vertical and spatial orientation

The central vestibular system will have problems in accurately interpreting the otolith input if it concerns a sustained G-load. Present motion perception concepts believe in low pass filtering of the otolith output to preserve gravity, while the canal response is also involved in the internal reconstruction process of the gravity vector, the subjective vertical. In view of increased G-load and its changing directions - even without a detailed analysis - it is obvious that this will result in a subjective vertical that does not correspond to the gravity vector.

For current spatial orientation, the system has to relay on the visual information. According to the present models on visual-vestibular interactions, the post-stall manoeuvring should not pose insolvable problems to the data processing of the sensory systems involved in maintaining spatial orientation. But this is only true as long as there is ample vision position and motion information available. This is in accordance to the verbal reports of the test pilots.

It is feasible that the movement of the aircraft as such is more provocative for the vestibular data handling when the head is fixed to the head rest compared to the pilots in air-to-air combat manoeuvring trying to keep their gaze and consequently their head fixed on the adversary. In this case the angular motion of the head is much more natural than the motion of the aircraft, and therefore more easily and accurately to handle.

Although one would imagine that a high AOA causes a difficult perception of the flightpath, X-31 pilots consider it to be no problem in visual air combat, because the target is used as the reference.

Pilot reports

No additional human factors or physiological limitations were encountered on X-31, after flying the F-16 or F-18, even the F-4 aircraft. Disorientation was not encountered. But all X-31missions were flown in daylight, in visual meteorological conditions (VMC), with excellent sight and good horizon. And all the missions were flown after hours and hours in the flight simulator.

One single episode, spiralling down into and through a cloud layer, suggested that poor weather, poor visibility with no horizon, intermittent instrumental meteorological conditions (IMC), few cues and alternating „head down“ conditions could pose problems. „Head inside“ was not enjoyed. „Care free“ handling and manoeuvring is important in all fighter aircraft. It allows full attention to be paid to the adversary and the tactical situation: full situational awareness without the distraction in the melee one's own aircraft may depart its own control envelope.

X-31 flight control system (FCS) was set up to provide post-stall manoeuvring with zero side slip. This gave little Gy and very comfortable manoeuvring.

The reports of the pilots were encouraging in view of the predicted problems due to the complex sensory stimulation. However, it might be that clear visibility is a prerequisite for this achievement. Therefore it was assumed that at least the adversary as a referent point - even as a virtually picture in the primary flight instrument - must be integrated into the leading sense, the vision, to avoid spatial disorientation in VMC.

Research tools

Because of the G-loads applied to the pilot from different directions, a research tool with centrifuge capabilities and a fully gimballed system is required, as well as full visual displays. Dependent on the particular goal of the research, choices can be made between several systems available (Table 1). Another brand new system, located in the Netherlands, seems to be capable to do research in this area. It is a fully three-axis gimballed system with visual displays, called "Desdemona". It also allows heave over 2 meters, and may displace itself along a 8 meter track, which is placed on a rotator, allowing centrifugal forces up to 3G.

Vision and vestibular illusions

Pilots rely on flight instruments as their primary defence against visual and vestibular illusions and loss of situational awareness. The various head up display (HUD) designs, attitude indicators (AI), and associated primary flight instruments allow the pilot to determine spatial orientation relative to the earth in degraded visibility. Translational and rotational accelerations are known to affect spatial orientation through induced vestibular and proprioceptive illusions. Loss of spatial orientation can lead to loss of situational awareness.

Current AI/HUDs display a two dimensional depiction of the aircraft attitude relative to the horizon. Neither instrument effectively displays the yaw or the velocity vector. Most airspeed indicators are pneumatically driven and become unreliable below the stall-speed. Thus, the pilot of an EFM-capable aircraft, flying at high-AOA during post stall manoeuvring, employing current flight instrument displays, would receive inadequate orientation and velocity information. A HUD design in the X-31 depicting the velocity vector has proven confusing. Vestibular illusions, not yet identified, will lead to pilot misperceptions of flight orientations that may be difficult to counter with existing instrument displays. Improved instrumentation will be needed to counter the severe vestibular illusions that will certainly be associated with enhanced fighter manoeuvrability especially in poor weather conditions.

Off-boresight targeting may pose problems in terms of a second visual frame reference, which will affect the situational awareness of the own aircraft. Since this depends also on the visual information, off-boresight targeting may easily lead to disorientation. Weather specific symbology in the HUD or the helmet mounted displays (HMD) will enable the pilot to remain fully aware of his situation, remains to be investigated.

Vestibular illusions

Spatial orientation of pilots will be especially challenged by lateral (Gy) and longitudinal (Gx) accelerations that will be experienced during angular accelerations and high AOA. High agility fighter pilots will experience lateral G in combination with long radius angular acceleration. The effects of this combination are considerable unknown and will likely be associated with currently unidentified vestibular illusions. While the natural tendency of any pilot might be to reposition the head in the direction of rotation , preoccupation with tactics may not allow orienting compensating movements. Thus, there will be a large combination of possible disorienting stimuli. The speed of rotation in EFM-capable fighter aircraft may be significantly greater than that seen previously, and may be combined with other acceleration stress. Head movements during yaw manoeuvres may provoke disorientation and motion sickness.

Several important illusions in non-agile aircraft were identified only after loss of aircraft. A notable example being the somatogravic illusion which occurs during aircraft carrier take-off or rapid acceleration in fighter aircraft. Spatial orientation can be expected to be a serious limitation in EFM-capable fighter aircraft.

Motion sickness

As discussed above, based on the vestibular information the vertical will differ in magnitude and in direction from the gravity vector. Current motion sickness modelling is based on the concept that the main conflict causing motion sickness is the difference between the vertical as determined from the sensory inputs and the vertical as determined on the basis of previous motion information. Beside this sensory caused mismatch situation the misperception from sensory cues and delayed visual cues, independent from the vertical, may cause motion sickness, like simulator sickness.

In view of the fast manoeuvring it is unlikely that the internal model of “passenger” can keep up with the sensory side, giving sufficient conflict to provoke motion sickness. Since expectancy plays a large roll in motion perception, and the pilot is in control of the manoeuvres, this will enable the internal model of the pilot to keep up with the sensory side. More-over, as indicated by the pilot reports, the sorties flown so far were in good visual conditions, allowing the visual system to correct for the vestibular insufficiencies in determining the vertical. These two factors should reduce the chance on motion sickness considerably.

In view of the above one should avoid conflicting frames of reference, for instance symbology on the HUD in the helmet (HMD) should be consistent during head movements. In general, dissociation between the reference frames of the head, helmet, display and airframe should be avoided. Although motion sickness may be encountered in conventional aircraft, supermanoeuvring is thought to have an even more provocative character. Extensive training and gradual acquaintance with this type of manoeuvres should be considered using (dis)orientation trainers, advanced centrifuges (Table 1), inverted time (ground: gyro-wheel, triplex, somersault- swing, and in the air), aerobatics in aerobatic aircraft.

Countermeasures

Spatial Disorientation (SD) in superagile aircraft is a threat which is not different from the threat in conventional aircraft. Just as in normal aircraft, spatial disorientation is threat because it may occur unexpectedly. This applies also to the superagile aircraft when they are not engaged in supermanoeuvring. During supermanoeuvring a Type 1 (unrecognised) SD is highly unlikely to occur, but Type 2 (recognised) can occur easily in bad viewing conditions. Also it will be recognised easily, it may be difficult to recover, because of the dissociation between the velocity vector of the aircraft and the aircraft attitude.
It is obvious that normal procedure training and training of additional skills (such as recovery from Type 2 SD) is required.

Several of the items discussed above are at present time under investigation. A survey of the relevant items to be studied for supermanoeuvrable aircraft handling is useful, as is joined research since the research tools are expensive and therefore scarce.

Until more ground based research has been done on the effects of superagile manoeuvring on motion sickness provocation, one should restrict conversion to superagile aircraft to those pilots who have a history free of motion sickness.

Demonstrations and training of supermanoeuvres in ground based devices give responses similar to what is encountered in the air. Otherwise an internal model will be build up which does not correspond to the real situation. Since the real conditions may cause motion sickness as well, one should carefully differentiate between motion sickness and simulator sickness in the ground based devices. One should be aware that G-seats are of limited value in supermanoeuvring aircraft simulators because of the G-load coming from other directions than the pilot’s z-direction.

Tactile cueing and 3D-audio could be tools that are helpful in maintaining spatial orientation during supermanoeuvring, and therefore help to prevent motion sickness. Whether this is true indeed, requires a considerable research effort.

SUPERMANEUVERABILITY SIMULATOR MATRIX (GROUNDBASED)

FACILITY	TYPE DEVICE	NUMBER OF X, Y, Z AXES SIMULATED	MAX G ONSET	VISUAL DISPLAY	RATING
DES (WPAFB)	Gimballed Centrifuge	Two	20 G (1 G/s)	120° x 60°	Good-7
DFS (VEDA)	Gimballed Centrifuge	Two	40 G (13 G/s)	90° x 30°	Excellent-9
GAF IAM (Koenigsbrueck, Germany)	Gimballed Centrifuge	Two	12 G (5 G/s)	24° x 32°	Good-8
Singapore AF	Gimballed Centrifuge	Two	15 G (6 G/s)		Good-7
US Navy (Lemoore NAS)	Gimballed Centrifuge	Two	15 G (6 G/s)		Good-7
LAMARS (WPAFB)	5 DOF Flight Simulator	Three	(1.6 G/s)	266° x 108°	Good-5

Table 1: Albery, W.: ASMA-Meeting Seattle, 1998

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PILOT-VEHICLE INTERFACE

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SUMMARY

Agile aircraft introduce new requirements and performance standards for the pilot-vehicle interface. This lecture will address these ergonomic issues as they pertain to agile aircraft. Specifically, controls and displays will be discussed, followed by design issues relevant to intelligent interfaces. The concepts and technologies proposed as candidate solutions for creating pilot-vehicle synergy are, for the most part, untested at present. It is hoped that this lecture will provide the impetus for the research required to realize a pilot-vehicle interface that will enhance the operation of agile aircraft.

6.1. OVERVIEW

Agile aircraft have the potential to provide enhanced speed, range, flexibility, and lethality. In order to exploit these benefits, the warfighter must be able to assess situations, decide tactics to be employed, and execute responses under rapid, highly uncertain and temporally demanding combat conditions. Unfortunately, improvements to date have all tended to *complicate* cockpit design. This increased complexity may overload pilots' perceptual and cognitive processing capabilities, increase workload, and ultimately degrade mission effectiveness.

For pilots to realize the benefits afforded by agile aircraft, crew station designs must facilitate the potential synergy between situational awareness, the maneuverability envelope, and systems [1]. For instance, enhanced maneuverability will not increase survival rates if pilots do not realize that a change in flight path is recommended. Moreover, if pilots on a flight path ending with ground impact have real-time updates of their situation, they can choose when to alter their flight path – they can choose whether to change the path immediately, or wait until the final moment the envelop allows escape. Likewise, if pilots are cognizant of a threat, but weapon selection is time consuming, they may not be able to exploit the advantages of increased maneuverability. On the other hand, simple and direct means of changing weapon settings may achieve a tactical advantage without arduous maneuvering.

These examples show that it is the communication between the crew station and the pilot that is the limiting factor in the ability of pilots to exploit the advantages afforded by agile systems. Although there are some specific design issues presented by new capabilities, it is the *multitude* of systems that constitute agile aircraft that make the pilots' information management task the primary challenge and key determinant of successful deployment. Crew station design with the goal of pilot-cockpit synergy has the potential to provide the flexibility to maximum mission effectiveness.

6.2. AGILE AIRCRAFT IMPLICATIONS

The pilot-vehicle interface used in agile aircraft determines how fast and accurately the pilot can assimilate the required information and execute control procedures. Although the pilots interviewed indicated that special devices are not required to exploit the advantages of agile airframes, they did raise several interface design issues for agile aircraft systems. These are discussed below.

6.2.1. HIGH ANGLE-OF-ATTACK (AOA)

Conventional attitude displays can not simultaneously present both the nose position and vertical velocity during high AOA maneuvering. Moreover, when a pilot is recovering from a high AOA maneuver (e.g., over 45 degrees), there is an initial feeling that the aircraft is not reducing its AOA in response to nose down pitch commands. This makes it even more difficult for the pilot to maintain awareness of the flight path vector. Pilots need a display format that provides a rapidly interpreted indication of the flight path response for agile aircraft.

6.2.2. NEW COMBAT MANEUVERS

Agile airframes have enabled a new range of combat maneuvers (e.g., Herbst Maneuver), especially since pilots no longer have to point the aircraft's nose in the direction of the target. The ability to rapidly change flight path has also allowed an advantage during flat scissors maneuvers. These two exemplary maneuvers present corresponding display challenges. First, the pilot must receive a clear indication of the approach of a "terminal exit time" – that point in flight when the pilot must leave the post-stall domain to avoid reaching a hazardous altitude. Second, additional indication of yaw, in addition to flight path, is needed for the pilot to maintain spatial orientation. A visual reference that provides an accurate orientation cue is especially needed during automatic guns aiming or missile avoidance, to help avoid disorientation and sickness from the abrupt maneuver changes. Also, means of maintaining sight and situational awareness of the target during high angle-of-attack flight is required.

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6.2.3. HIGH SPEED/EXPANDED ENVELOPE

The anticipated speed that can be achieved by agile aircraft will mean that information in front of the pilot will unfold two to three times faster than in non-agile aircraft. Thus, some conventional symbology (pitch ladder and digital readouts) may change too rapidly to be useful to the pilot. The pilot has to "think ahead" more, given there is less turning time involved in getting in position to launch weapons. These agile operations require decisions to be made in "microtime" or less time than one typically would want to spend weighing options, making decisions, and executing actions. The ability of the system to provide the right information at the right time, and assist the pilot in determining the right course of actions, is the crux of the cockpit designers' challenge.

6.2.4. NEED FOR TAILORING

With increasing onboard processing capabilities, agile aircraft will have a concomitant increase in the number of systems and possible data views. The pilot's time can be consumed just programming the numerous options available. Cockpit design and standard operating procedures should focus solely on those options essential to mission requirements. One mechanism is to have one command or input automatically activate the systems and set up the tasks relevant to the current flight segment (e.g., air-to-air versus landing). Only those options required for that flight segment would be readily accessible.

6.2.5. TUNNELLING OF ATTENTION

It cannot be assumed that pilots will scan all available information sources in a timely manner. Presenting information on head up displays, together with the demanding agile aircraft mission, can result in a tunneling or channeling of the pilot's attention such that vital head down information is missed. It is also possible for a situation (e.g., changing threat scenario) that attracts the pilot's attention to head down displays and delays the pilot from returning to a head up posture. Therefore, some cueing mechanism is required to inform pilots of critical information or a change in aircraft or mission state that needs attention.

6.2.6. ENERGY MANAGEMENT

Given the complex maneuvers possible with agile aircraft, anticipated use of carefree handling, and decrease in sensory feedback (noise and buffet), the pilot needs to have precise timing and perception of any change in the aircraft's energy state. Moreover, the pilot needs information pertinent to energy management to weigh the advantages of different maneuvers that can be employed. For instance, the pilot needs information on the goodness of the launch condition to assess the tactical situation and determine whether to accept a low confidence launch or maneuver to a more favorable launch position. This is especially important since using the advantages of an agile airframe to point the nose at a target may leave the aircraft too slow to recover speed quickly for a missile defense maneuver.

6.3. HEAD UP CONTROLS/DISPLAYS

Providing and controlling information "head up" maximizes the amount of time the pilot spends looking out the canopy for threats. To date, this advantage is primarily realized with a head up control concept and a head up display (HUD). Head up control is achieved with the pilot's inceptors which can be operated with the head up. Agile airframes make a sophisticated system that integrates flight and propulsion control a definite requirement. With such a carefree handling system, the stick and throttle can be used to maneuver the aircraft inside the whole flight envelope, automatically taking into account aircraft limitations. Head up control is also facilitated with additional switches located on the flight controls; this hands-on-throttle-and-stick (HOTAS) concept enables selection of many sensor, navigation, and weapon systems without redirection of the pilot's gaze point.

A HUD presents symbology projected onto a transparent combiner. Some information, such as a pitch ladder that relates directly to the world, can be seen superimposed on the real scene to facilitate display interpretation. The display can also relay a sensor image, providing a view of the scene ahead at night or bad weather. Because the HUD combiner is fixed to the top of the instrument panel, the pilot must look forward along the aircraft longitudinal axis to see the symbology. Moreover, targets often lie outside its limited field-of-view.

Helmet mounted displays (HMDs) have been developed as one means of extending the advantages of the head up transparent display concept and overcoming limitations of current HUDs. An HMD can provide a wider area of visual information. Moreover, with a HMD, displayed information is within the pilot's field-of-view regardless of head movement and orientation. Because of their utility when the pilot looks both along and away from the fore-aft axis of the aircraft, HMDs are predicted to eventually eliminate the need for HUDs.

When implemented with a head/helmet position tracker, a HMD system can also provide target cueing and sensor guidance. In addition, these Helmet Mounted Display/Tracker (HMD/T) Systems have tremendous capability compared to earlier Helmet Mounted Sights (HMS) that combined a tracker with a sighting reticle to provide a simple aiming mark to pilots. HMD/T systems, along with other "head up" control and display devices (e.g., HOTAS and auditory systems), enable pilots to focus attention out the window and minimize manual control and head down glances which can cause disorientation and/or vertigo, especially in extreme

+/-G. This is even more critical for agile aircraft to support maneuvering, weapons launch, and evasion/survival.

The following describes candidate head up controls and displays. This presentation will focus on pilot usage of these devices for agile aircraft applications, rather than on the mechanics of each technology.

6.3.1. HELMET MOUNTED DISPLAY/ TRACKER SYSTEMS (HMD/T)

Candidate HMD/T systems have three major components: 1) a head or helmet mounted visual display, visually directed, 2) a means of tracking head pointing direction (based on the assumption that the pilot is looking in the general direction that the head is pointing), and 3) a source of visual information which is dependent on the head viewing direction [2]. Information displayed on the HMD can be referenced to head axes, aircraft axes, earth axes, or any combination of these three. Advances in several display technologies (miniature cathode ray tubes, etc.), make HMDs a definite candidate for agile airframes [3]. With further development, other hardware may provide additional advantages over conventional approaches. For instance, the Virtual Retinal Display^{TM} scans a lower power beam of light to "paint" rows of pixels onto the retina of the eye, creating a high resolution, full motion image without the use of electronic screens [4].

The concept of HMD/T operation (Figure 6.1) is as follows: the pilot looks in a particular direction, the head tracker determines what the direction is, and the visual information source produces appropriate imagery to be viewed on the display by the pilot. The direction of the head can also be used as a control signal for a variety of aircraft systems, in addition to controlling what information is displayed. Thus, the HMD/T system serves as both a head up control *and* display, with an instantaneous field-of-view around 25-40 degrees subtended visual angle.

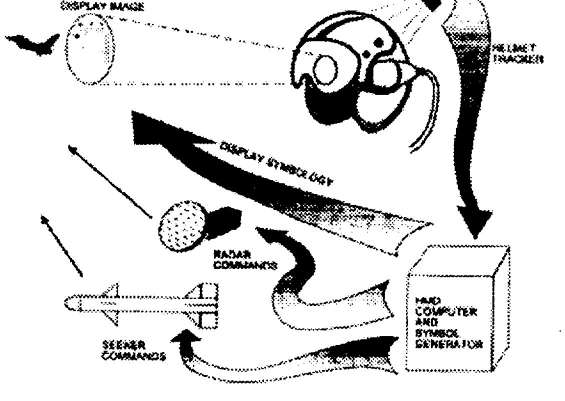


Figure 6.1. Schematic of Helmet Mounted Display/Tracker System Concept.

(Reprinted with permission from *Helmet-Mounted Displays and Sights*, by Mordekhai Velger. Artech House, Inc., Norwood, MA USA. www.artechhouse.com)

With a HMD, the pilot has a global view of information through the whole range of head positions [5]. Head up, visually coupled information will assist the pilot in looking out of the cockpit to maintain situational awareness in a highly dynamic flight environment. For instance, research has shown that an off-boresight HMD enhances the pilot's search capability, tracking performance and survivability in a simulated low-level, high-speed airborne surveillance/reconnaissance mission [6] and facilitates high angle target search and intercept during a simulated air-to-air engagement [7]. With a HMD, both the angle and duration of off-boresight visual scanning were increased. The extent to which this advantage can be realized depends on the information presented on the HMD, as the symbology can occlude the outside world view.

For combat, the combination of agile aircraft and HMD/T systems may offer important tactical advantages when used in conjunction with guided missiles. A tracker determines the position of the pilot's head as the target is followed through the display on the helmet visor. The tracker relays critical information to the computer that, in turn, communicates the location of the target to the missile system. When the weapons lock on the target, the pilot receives feedback and pulls the trigger located on the control stick to fire the missile. This scenario represents a total paradigm shift in the way within-visual range air-to-air combat is fought. The nose of the aircraft is no longer the sighting reference for cueing the weapon, but rather the pilot's helmet. As long as the target is within range and can be viewed by the pilot through the display in the helmet visor, the relative position of the aircraft to the enemy is not critical. Since a hostile contact averages only 30 seconds to 2 minutes, any time saved by not needing to repoint the aircraft helps give a quicker first shot capability to pilots. This capability also facilitates engagement of multiple adversaries. Using a HMD/T system, a pilot can designate and launch a missile or lock the radar and immediately turn to the next target, designating sequentially several targets within seconds without having to reposition the aircraft [5].

Another advantage of a HMD/T system is the ability to designate targets and hand off their location to other sensors and the theater communications system, in general. For example, the pilot can steer a FLIR system mounted on a steerable gimbal in the nose of the aircraft. Likewise, a threat detected by a sensor can be used to cue the pilot by showing directional information to the threat location on the HMD. The pilot can also designate a ground position and then call up cues to reacquire the target, should the pilot lose sight of it during maneuvering [5].

These potential tactical advantages were demonstrated in several simulated scenarios by operational F-15 pilots employing a HMD/T system [8]. The simulation pilots reported that the HMD/T: made it easier to accomplish within-visual range radar acquisition and get visual sighting of acquired targets, saved time in attacks, provided helpful weapon data while visually tracking a target, added tactics capability by easing simultaneous AIM-9 and AIM-7 attacks, and avoided sacrificing basic fighter maneuvers to launch an AIM-9 or perform a full system gun attack. The ability to accomplish a visual missile attack without sacrificing positional advantage was viewed a key advantage of the HMD/T. The pilots commented that the HMD/T provided as many improvements to air-to-air operations as weapons computers have provided to air-to-ground operations. There was also a marked exchange ratio advantage for the pilots with the HMD/T.

6.3.1.1 Visual Illusions with HMD/T Systems

Certain vision conditions (empty field myopia and accommodation convergence micropsia) can be problematic with HMD/T usage [9]. For example, even if symbology is presented on a HMD focused at infinity, overlaying the sky, some individuals' eyes will tend to focus two feet out from the display. Problems such as this can result in misjudgments of sizes and distances to external objects.

6.3.1.2 HMD/T Symbology Size/Location

Symbology size needs to be optimized for the HUD field-of-view viewing and the goal of minimizing obstruction of the outside view. Plus, the resolution of the HMD will impact the size and legibility of presented text and symbols. One study [10] has shown that recognition of symbolic aircraft presented on a collimated display deteriorated with increased eccentricity (5, 9, and 13 degrees). Aircraft in the periphery had to be displayed for a longer time than targets near the fixation axis, for viewers to classify them successfully. Response latencies were also longer in the lower and left visual fields.

6.3.1.3 HMD/T Symbology Format

Most of the information requirements for agile aircraft are the same as non-agile aircraft. For flight control, pilots need to know where the aircraft is actually going, rates of change, energy management, and how to recover to straight and level flight. Given the dynamic and expanded weapon envelopes realized by agile weapons, pilots will need enhanced estimations of the probability of detection and or launch as well as accurate information on the threat situation, ownship susceptibilities, and sensor ranges. Information is also needed to assess avoidance maneuvers and use of decoys.

Advances in display technologies make it possible to present pilots with formats that span from simple lines and symbols to high fidelity, geo-specific perspective scenes. Having the HMD format attempt to duplicate the organization and content of the real world is attractive in the sense that the pilot would have *everything* needed (Figure 6.2 [2]). The optical flow of objects could give natural cues as to altitude, attitude, and airspeed. For conditions in which view of the outside scene is poor or absent, such a display can provide a "virtual cockpit." [5].

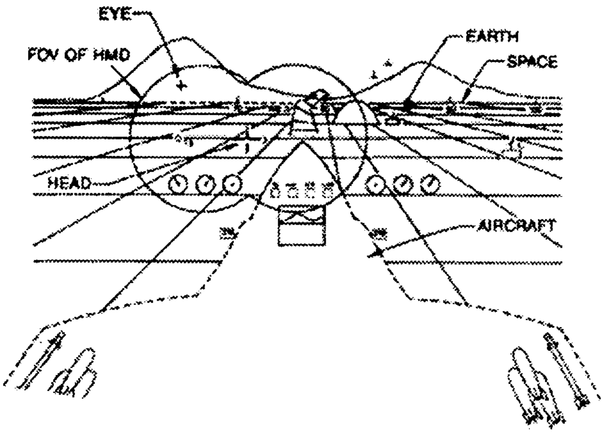


Figure 6.2. Example Candidate HMD Symbology.

For flights where the outside scene is visible, it remains to be determined whether providing this abundant amount of information is in the pilot's best interests. Contrary to viewing a HUD, the symbology remains constantly in front of the pilot's eye.

For any proposed format, systematic evaluations of candidate symbology sets are required. These evaluations should start by examining features of individual symbology elements. Indeed, experience has shown that the usefulness of elements depends on the pilot's current flight segment and information needs. For example, consider the use of digital, tape, and dial indicators of flight parameters. Some research has indicated that analogue displays are easier to process than digital displays since the analog information is extracted more intuitively, maps more directly on the response system (i.e., analog control inputs), and requires few mental transformations. Moreover, if the digits (e.g., vertical velocity) are changing very rapidly, the blurry readout is useless, especially when the pilot only needs to have a general indication of the rate and extent of change. It may be the case that a dial format (e.g., with arc scribing the outside of the altitude dial relative to changes in vertical velocity) is assimilated more easily than vertical formats [11]; however, initial results using a HMD presentation failed to support this notion [12]. With a perspective format, quantitative estimates are even more difficult to discern and adding scaled reference marks as a remedy tends to defeat the objective of providing the pilot the impression of flying into the perspective scene [13].

Besides the requirement to evaluate how conventional flight information should be presented for agile aircraft operation, the unique information needs for these missions also needs to be considered. For instance, pilots will need to monitor the more extreme angles-of-attack that can be achieved by agile aircraft. HMDs will help keep the flight path vector within view, except when the aircraft is at an extreme angle (e.g., 60 degrees). New symbology might be useful. One candidate HMD symbology set evaluated for the X-31 utilized two triangles, superimposed and appearing as one triangle for 0-30 degrees of angle-of-attack. For 30-70 degrees angle-of-attack, one triangle stayed fixed and the second grew to match a point on a scale inside the attitude reference symbology [14].

There have also been several evaluations to determine what symbology helps exploit the advantages affording by using a combination of HMD/T devices and precision weapons. One experiment investigated how the target location information should be related to the pilot [15]. Three symbology orientations were evaluated. In one, the symbology was relative to the nose of the aircraft, indicating the most efficient pursuit vector between the ownship and an airborne target location. A second orientation referenced head movement, indicating the most efficient line between the pilot's line-of-sight and a target. The third orientation evaluated included symbology that simultaneously presented ownship and head information. The results indicated that the ownship coordinate information may have more merit than traditionally believed and that pilots favored the combination which presented both "look-to" and "fly-to" locator lines when the target was outside of the HMD field-of-view.

Consideration of HMD symbology with respect to weapons needs to consider the exact flight mission anticipated, as information needs may differ depending on whether the pilot is engaged in air-to-air combat, air-to-ground attacks, or missile evasion (in addition to navigation and landing piloting tasks). The designer's objective is to provide the information required for each flight segment, yet minimize the pilots' training burden by keeping symbology sets as similar as possible. For instance, there have been several studies addressing how and when ownship information should be presented. One experiment [7] examined if ownship status information within the HMD symbology set is necessary for air-to-air applications. Several ownship status formats were evaluated, including the Standard Attitude Reference, the Arc Segmented Attitude Reference (ASAR) and the Theta Attitude/Direction Indicator (Theta). In the standard format developed by the US Air Force, the attitude set includes a helmet fixed inverted "T" climb/dive symbol oriented as an inside-out flight path reference, as well as an artificial horizon line and pitch bars.

The German-developed ASAR ("orange peel") includes a fixed climb-dive symbol that represents climb/dive angle by its relation to a half-circle arc surrounding the symbol [16]. The upper portion of the circle is invisible during straight and level flight. The visible portion of the circle represents the area below the horizon and the invisible portion represents the area above the horizon. The amount of visible orange peel translates to aircraft pitch (e.g., for positive pitch attitudes less than half the circle is visible, while for negative pitch attitudes more than half is visible). As the climb angle increases, the visible negative angle area of the arc begins to narrow in proportion to the climb angle. With an increase in dive angle, the arc closes to forms a more complete circle (Figure 6.3). At a 90-degree dive angle, the arc forms nearly a complete circle, leaving a small gap to cue the pilot of the most efficient direction to recover from the dive. During a roll, the arc rotates about the climb-dive symbol.

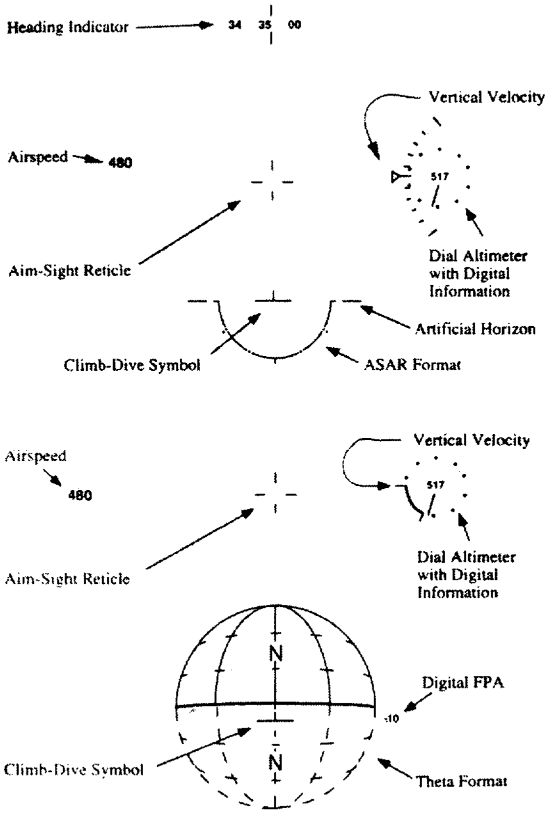


Figure 6.3. Example ASAR (top) and Theta (bottom) HMD Symbology [12].

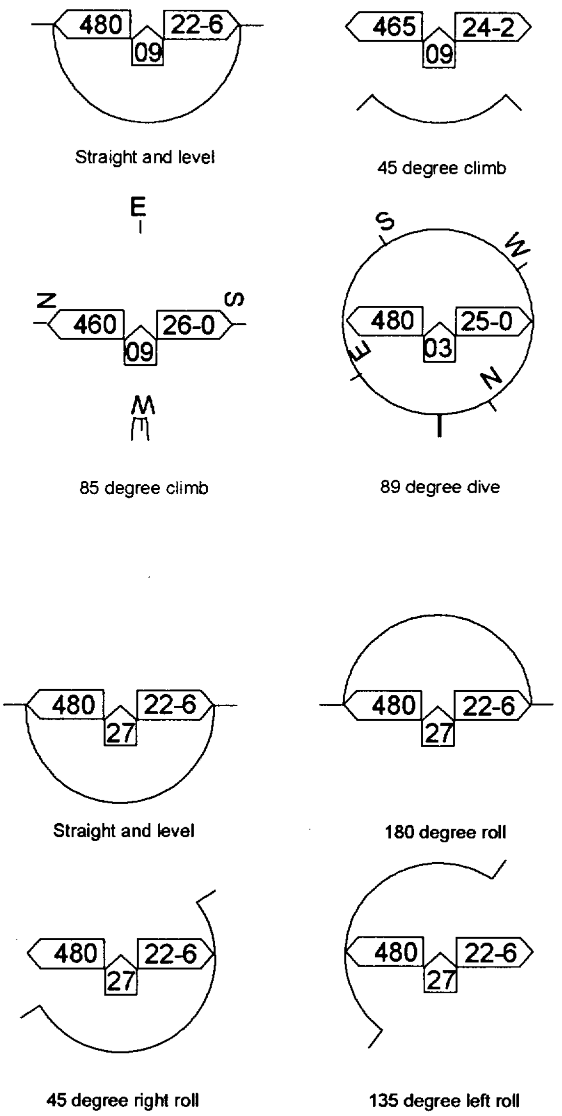
Another format featured a Theta Attitude/Direction Indicator [16] developed at the Air Force Research Laboratory (Figure 6.3). The symbology integrates heading information and attitude symbology with a simulated three-dimensional, transparent, wire-frame half-ball consisting of arced lines. The longitudinal lines serve as an azimuth (heading) position reference in 45-degree increments. The ball is free to rotate about all three of its axes to represent rotation of the aircraft in those axes. Continuous lines on the upper portion and segmented lines on the lower portion represent climb and dive areas, respectively. Within the ball there is a climb/dive symbol and the cardinal headings are marked by letters. The format is mechanized like a standard, three-axis attitude direction indicator ball. The results of this experiment failed to show any interpretation or usability differences among the formats used to present ownship information. However, the pilots definitely preferred that ownship status be included in the HMD symbology set [7].

Another study specifically examined the ASAR and Theta symbology suites for a HMD used in the X-31 [17]. The pilots commented that for close-in-combat, attitude symbology was less critical, because the pilot flies relative to the opponent aircraft. Pilots found the ASAR useful as a large amplitude pitch reference for locating the horizon or recovering from an unusual attitude. This symbology is very compelling and effective for simple, instant instruction. However, they questioned its utility as a precision instrument. The Theta symbology was found easy to interpret and was the preferred attitude reference. The globe provided a good analysis of the situation. However, its utility in complex scenarios remains to be determined.

In a more recent effort at the Air Force Research Laboratory, a "non-distributed flight reference symbology" was designed to supplement HMD target acquisition information with ownship status information, the latter particularly useful during high off-boresight targeting tasks [18]. The key challenge was to ensure the presented information is useful without any associated clutter or disorientation incurred by its presence. This non-distributed flight reference symbol set presents ownship aircraft reference information close together and positioned within the attitude symbology (see Figure 6.4). The primary flight information is spatially arranged so that the conventional basic "T" layout is maintained with airspeed to the left of altitude and heading between airspeed and altitude. The information is presented digitally inside an outline designed to mimic the shape of aircraft wings and tail. Collectively, this compact information montage can be located anywhere in the HMD field-of-view (e.g., near the bottom during air-to-air applications).

The aircraft symbol is fixed relative to the HMD field-of-view and the attitude symbology moves about it. The flight path angle and roll of the ownship montage is represented by its relation to a half circle arc (using the ASAR approach described earlier). Heading tags appear at extreme climb and dive angle to give additional indication of ownship roll. This functionality was found useful in previous evaluations of the Theta attitude reference symbology and helps provide orientation information throughout the full aircraft-maneuvering envelope. During rolling maneuvers, the arc and artificial horizon rotate about the ownship symbol.

It is only through systematic evaluation of candidate symbology sets for specific flight tasks that optimal HMD symbology can be identified. Unfortunately, a format found to quickly provide pilots with an overall situational awareness and orientation perspective, may not provide the information required to precisely control the aircraft through a commanded mission. Also, the ideal format may depend on environmental factors, ground detail, and the availability of an outside reference. For instance



Straight and level

45 degree climb

85 degree climb

89 degree dive

Straight and level

180 degree roll

45 degree right roll

135 degree left roll

Figure 6.4. Non-Distributed Flight Reference Candidate Symbol Set with modified ASAR Attitude Symbology during various Climb and Dive Angles and Roll Maneuvering [18].

the reference frame used to present attitude information to the pilot ("pilot perspective") needs to be determined. Two major display concepts are commonly referred to as inside-out or "pilot's view" versus outside-in or "God's view." Typically, inside-out displays are viewed more appropriate for precise flight control and outside-in displays more appropriate for navigation and landing tasks. However, some research has demonstrated that an outside-in format is superior for unusual-attitude recovery [19]. In fact, pilots have noted that traditional aircraft-referenced inside-out attitude displays are more difficult to interpret when the head is moved off-axis.

Multiple coordinate reference frames can also be used. For example, one complex format envisioned for a HMD has a large instantaneous field-of-view and multiple cueing symbols. One aiming symbol would be in the upper portion of the HMD for designating aiming points outside the aircraft and another aiming symbol would be in the lower portion of the display to designate space stabilized electronic cockpit switches and functions [2]. The position of the cockpit switches imaged on the HMD stays fixed with respect to the cockpit, while the lower reticle moves with changing head position. When the lower reticle is placed over the electronic cockpit switch, it's visual form changes to indicate it is active and is being designated by head position. The pilot must then give a consent response by activating a single standard switch located on one of the primary manual controllers (e.g., joystick) or by issuing a standardized verbal command. Meanwhile, the upper aiming reticle remains active for designating outside world targets through other electronic control loops. Although it appears that this envisioned format would provide pilots with enormous display and control capabilities, there are numerous ergonomics issues that need to be examined before these anticipated advantages can be realized.

6.3.1.4 Pictorial Portrayal of Information in HMD/T Systems

Symbols and alphanumerics presented in display formats depicting status of aircraft systems can be viewed as individual chunks of information that must be perceived and cognitively integrated by the pilot. Humans are limited as to the number of information chunks that can be managed at a time. Advances in the generation of display graphics enable pictorial portrayal of information that groups individual pieces of information into fewer chunks. Theoretically, this reduces the pilot's workload because the processing required to chunk the information has already been accomplished [20]. The pilot can more rapidly acquire the message (assuming the pictorial is easy to interpret) and then devote time executing a response.

For HMD formats, the most popular pictorial presentation entertained is a three-dimensional perspective path to assist the pilot in flight control (see below). Pictorial formats occupy more display area than conventional formats. Given the limited field-of-view of the HMD and a desire to minimize the extent to which symbology interferes with the pilot's outside view, the added value of pictorial formats for HMDs needs to be verified.

6.3.1.5 Stereopsis Cues in HMD/T Systems

The introduction of true depth cues via stereopsis techniques in HMDs offers a means of further enhancing pictorial displays, particularly in improving the perception of pictorial layouts. For example, in one format a range marker element (waterline symbol) provides a non-stereo cue in that when the lead aircraft is at the desired range, the wingspan of the aircraft symbol is the same width as the ownship symbol (the desired range marker). Inclusion of stereo depth cues with this symbology was found to improve performance by 18% in a simulation evaluation [21].

Probably the most entertained cockpit application of this technology, is to provide the pilot with a three-dimensional "pathway-in-the-sky" which integrates all relevant information into a single display and the pilot's task is reduced to simply following the path (Figure 6.5). With the current accuracy afforded by

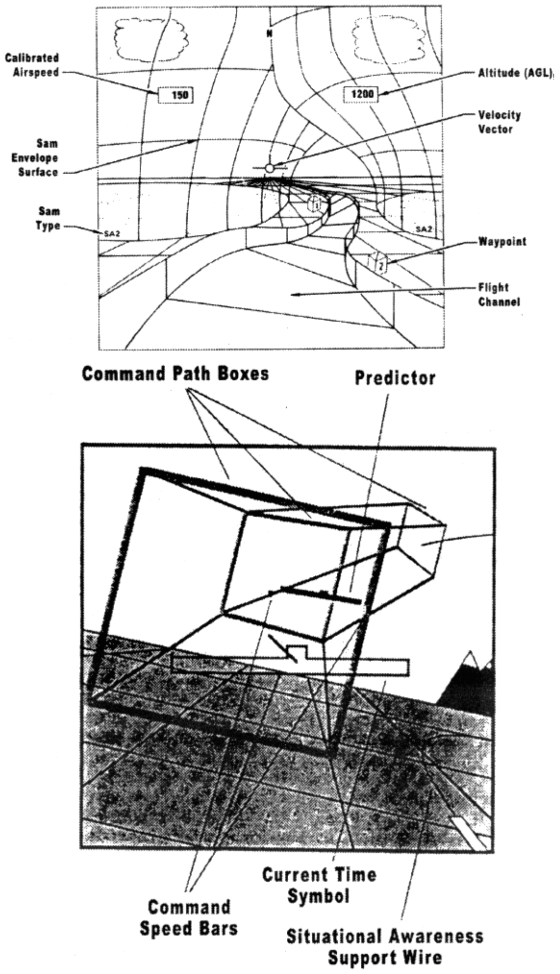


Figure 6.5. Examples of Pictorial Pathway-in-the-Sky Flight Display Formats [22,23].

Global Positioning and vast digital terrain data bases, the pathway-in-the-sky visualization concept is even more obtainable. In the example flight path display formats depicted in Figure 6.5, the pilot's task requires guiding the aircraft through the center of the channel to accurately stay on course. Each of the channels extends into the distance so the upcoming changes in the path can be anticipated. In the channel depicted at the bottom of Figure 6.5, the aircraft is a stationary symbol and the channel moves about it with changes in lateral and vertical direction. This channel configuration depicts the aircraft to be slightly to the right of command path, but flying the command altitude.

Of course during combat, the dynamics of the maneuvers make using a path-type format as a command display less appropriate. However, such a display could be very useful for: 1) providing predictive information to the pilot – illustrating the endpoint if the aircraft continues in its current flight path, and 2) providing short term command information to execute a pilot-selected stereotypical maneuver (e.g., scissors maneuver). In considering these channel displays for agile aircraft, there is a body of relevant research. Researchers have found that three-dimensional tunnels where the viewpoint of the display corresponds to the position of the pilot (i.e., fully egocentric) are superior for flight path control, particularly for flying curved paths [13, 23]. Subjects found the channel display intuitive and to provide quick and simple orientation. Integrating information pertaining to the aircraft's vertical situation, horizontal situation and profile situation also relieves the pilot from scanning multiple displays to acquire the same information. However, such a display reduces situational awareness due to its narrow field-of-view, making it difficult for the pilot to be aware of hazards in the surrounding airspace. If the field-of-view is increased, however, valuable display real estate is consumed or a distortion occurs as real space is compressed. This, in turn, also disrupts situational awareness, increasing the ambiguity of where things are in space. The resolution of predictor information in the display is already less, since the perspective presentation means a reduction of size for objects far away. Moreover, it is difficult to get sufficient quantitative information, unless additional scaled reference markers and readouts are added. These items, though, lessen the natural impression of flying through the channel [13]. In an experiment evaluating a three-dimensional perspective flight display compared to multiple two-dimensional planar displays, measures for flight performance and situational awareness were worse for the perspective display. The subjects commented that the key problem was the ambiguity in depth judgement along the line-of-sight that the perspective display caused when the aircraft was approaching landmarks [24].

A more near term application of stereopsis cueing for agile aircraft is to present different categories or classes of information at different levels in depth [25]. With this application, only a few levels in depth are needed and there is no requirement that they accurately represent a certain dimension in depth. Use of three-dimensional presentations on HMDs helps declutter information and enables the pilot to more efficiently switch attention between different information classes. For instance, the altitude, heading and airspeed indicators could appear on a different plane from the aircraft symbol [25]. As one pilot interviewed by the Working Group commented, if information can be positioned at different depth levels, much more information can be presented on the HMD. Of course, research would be required to determine the optimal assignment of information to depth levels – whether by information class (flight, weapon status, threat status, etc.), priority, flight segment, or some other combination. Another possibility is to have the coding pilot selectable.

6.3.1.6 Use of Color in HMD/T Systems

Assuming that the image source for a HMD is such to make colors visible under high ambient illumination conditions, use of color in display formats with discrete elements can make information uptake easier and faster. A likely near term application of color is in the pitch ladder symbology. Monochrome coding has already been applied in conventional formats to help reduce ambiguity between the positive and negative pitch bars and facilitate recovery from unusual attitudes. This has included using different shape coding for negative (bendy) and positive (tapered) bars. Color coding the pitch ladder (positive bars blue, negative bars brown) has been found to be beneficial in simulations, especially when used in conjunction with shape coding [26].

Application of color (red and green) to help code target location, tracking, and weapons deployment was examined in a simulation of off-boresight weapon aiming [27]. Overall, the pilots preferred the color-coded symbology to the monochrome baseline. Furthermore, a "red means shoot" color-coding strategy (involving a progression from green to red as an indication of shoot-criteria satisfaction) was preferred over a "green means go" strategy (progression from red to green). In a subsequent study, the "red means shoot" coding was systematically compared to a monochrome baseline HMD symbology in an air-to-air simulated weapon delivery scenario. Results showed the "red means shoot" symbology produced significantly faster shots without degrading the probability of kill [28].

Any application of color in agile aircraft should be aware of the results of an initial evaluation showing sequential changes in color perception during relaxed, gradual onset of Gz acceleration [29]. The effects occurred at 4 Gz and the first hue shift was a disappearance of light blue into white, indicating that use of light blue on a light background may be problematic during a high Gz turn. The second shift was green to yellow. Thus, use of green and yellow to code classes of threats on a display may be confusing. Such findings support formats that employ redundant (e.g., color and shape) coding.

6.3.2. EYE-BASED CONTROL

The next plausible extension of the capabilities of HMD/T systems is the integration of eye tracking to enable control of crew station functions using the pilot's eye line-of-sight [30]. In that the visual system is the primary channel for acquiring information and eye muscles are extremely fast and respond very quickly, it is advantageous to have the direction of eye gaze serve as a control input. In other words, if the pilot is looking at a target, it is more efficient to use the pilot's gaze to aim a weapon, rather than align the head or manually slew a displayed cursor over the target. In this manner, eye-based control can increase the envelope and speed of target acquisition with a HMD/T system. Line-of-sight cueing between pilots can also be facilitated by eye designation of points of interests. The pilots briefing the Working Group were very positive as to the increased capability that could be realized with eye-based control. Moreover, eye motion is more feasible under high acceleration conditions, compared to head or hand movement.

For eye-based control to be useful, however, it is important that the pilot's eye movements remain natural and not involve unusual blinking or lengthy fixations. Eye-based control is similar to operating a computer mouse in the sense that gaze position indicates the position or response option on a display, and some method analogous to a mouse button press is used to trigger the response. Without the additional consent response, a "Midas touch" problem could occur, with commands activating wherever the pilot looks. Different types of consent responses have been evaluated [31] and it is recommended that a dedicated, conveniently located button (e.g., on the joystick) be employed as a universal consent response. If the pilot's gaze is only being utilized to call up additional data for eye designated icons, then perhaps only a short fixation is sufficient, without a consent response. In this manner, the pilot's sequential review of a series of targets can be made more rapidly, with detailed information popping up, as the gaze briefly pauses on each target.

Although current eye tracking systems are not flight worthy for agile aircraft applications, numerous efforts are underway to explore how eye tracking optics might be integrated into HMD systems and how best to track the eye under varying illumination conditions. It is anticipated that eye-based control will eventually be feasible for agile aircraft and be used to designate display areas subtending approximately 1 degree of visual angle (by fixating 50-100 milliseconds) [32]. Designation of very small targets may be problematic; however, there are several techniques the designer can employ to aid in the gaze-based selection of densely packed targets [33]. Improvement in eye tracking technology will also be required to enable eye-based control at more extreme "look angles" (e.g., +40 degrees azimuth and elevation).

6.3.3. ELECTROMYOGRAPHIC (EMG)-BASED CONTROL

It is feasible to modify the hardware or helmet housing a HMD/T system, or the pilot's oxygen mask, to position electrodes on the surface of the skin which detect the asynchronous firing of hundreds of groups of muscle fibers. These electrical signals that accompany muscle contractions, rather than the movement produced by these contractions, can be used to provide EMG-based control. Most commonly, these electrical signals are compared to some threshold value to derive a binary control input – above threshold initiates one control action, below threshold initiates another [34]. Development is still required to optimize the signals employed, assess the stability of electrode contact over time, and minimize the effect of operator movement and external electrical activity on signal recordings. However, EMG-based control is a far-term candidate head up controller that enables the pilot to make discrete responses without using the hands. To implement EMG-based control, it is important to choose a body movement that does not interfere with the pilot's normal functions, is not likely to be made during normal activity or in response to acceleration loading, and can be implemented such that the system can discriminate a purposeful EMG input from an inadvertent one. To date, subtle/slight eyebrow lifts and jaw clenches have been successfully used in concept demonstrations as enter and tab functions on a computer task. However, these simulations targeted ground-based tasks and the results may not be applicable to agile aircraft controls.

6.3.4. ELECTROENCEPHALOGRAPHIC (EEG)-BASED CONTROL

Electrodes integrated into the pilot's headgear positioned over specific areas of the scalp can provide the necessary signals to implement EEG-based control [35]. This type of control translates the electrical activity of the brain into a control signal. In one approach, EEG patterns are brought under conscious voluntary control with training and biofeedback. A more applicable approach harnesses naturally occurring brain responses to modulated stimuli. These brain responses include components that modulate at the same frequency as the evoking stimuli. Selectable items of a display are modulated at different frequencies. The pilot's choice (gaze point) between selectable items can be identified by detecting which frequency pattern is dominant in the visual evoked brain activity. In effect, the advantages of eye gaze-based control can be realized with less expensive and obtrusive components with this mechanization.

Optimization of this head up control requires minimizing the time required for signal processing, developing easily donned electrodes, and minimizing the distraction produced by modulating (flashing) display items. Research is underway to investigate whether the brain responses produced by high-frequency modulated stimuli (that the pilot does not perceive as flashing) are adequate for implementing EEG-based control [36].

6.3.5. SPEECH-BASED CONTROL

Speech recognition technology allows the pilot's speech signals to be used to carry out preset activities (e.g., allocate missiles to targets, change navigation route and radio frequency, alter displays, control radar, etc.). Unless a high recognition reliability can be achieved (e.g., 95% correct recognition under 4 G), voice entries may need an additional validation step for many agile aircraft control functions. Design factors that influence the utility of speech recognizers include: acoustic similarity of commands, length of words, microphone placement, consistency of the speaker's speech, vocabulary size, and the extent to which the order of commands is restricted [1]. A key challenge to the application of speech-based control for agile aircraft is efficient dialogue design. The vocabulary and syntax must be manageable, without imposing a great memory load or interfering with communications. If the pilot has to look down into the cockpit to read command names off a menu, then the head up control advantage of speech-based control is compromised. Use of speech input also has the potential of rapidly accessing functions several levels down the hierarchical structure of a multifunction control. On the other hand, selection of a dedicated, frequently selected switch (e.g., HOTAS concept) may be more rapid than the mental processing involved in issuing a verbal command and the time required by the voice recognizer to process the signal.

There are several environmental factors, which can impact the performance of speech systems: high ambient noise, vibration, stress level of the pilot, and acceleration (although, "intelligible speech" can be produced up to 9 G). To compensate for these shifts in speech due to changes in the environment, adaptation algorithms are required in the speech processing, as well as noise canceling hardware [37].

6.3.6. GESTURE-BASED CONTROL

Besides using the electrical activity produced by slight facial gestures, other small sensors mounted in the oxygen mask can be used to track fine movements of the pilot's face or lips. Optical and ultrasonic sensing technologies, for instance, have been used to monitor an operator's mouth movement. In one implementation, a headset boom located in front of the speaker's lips contains an ultrasonic signal transmitter and receiver. A piezoelectric material and a 40 KHz oscillator are used to create a continuous wave ultrasonic signal [38]. The transmitted signal is reflected off the speaker's mouth, creating a standing wave that changes with movements in the speaker's lips. The magnitude of the received signal is processed to produce a low frequency output signal that can be analyzed to produce lip motion templates.

There are two candidate applications of lip motion measurement. In one, the pilot's lip movements are processed during speech inputs to provide "lip reading." An experiment using an ultrasonic lip motion detector in a speaker dependent, isolated word recognition task demonstrated that the combination of ultrasonic and acoustic recognizers enhances speech recognition in noisy environments [38]. Alternatively, symbolic lip gestures can be translated into communication tokens that are used as control inputs.

6.3.7. DISPLAYS IN THE PERIPHERAL VISUAL FIELD

Given the increased likelihood of spatial disorientation in agile aircraft, the "Malcolm Horizon" attitude display was reviewed [39]. This concept involves projecting an artificial bar of light across the instrument panel and having it move in a manner corresponding to the horizon outside the aircraft. Such a display enables supplemental attitude information to be acquired in the pilot's periphery. Although pilot response to demonstrations of this concept was generally positive, problems with upright-inverted ambiguity were noted.

The display of information in the pilot's periphery also takes advantage of the human's increased ability to detect movement in the periphery, compared to central vision. Thus changes in attitude may be more readily detected with a peripheral display. On the other hand, this phenomenon may make the frequent detections of attitude changes a source of distraction. Or the peripheral display may not be perceived at all, if the pilot is attending to the central field. To date, efforts to develop large-scale peripheral attitude displays have met with only mixed success and their value for agile aircraft can only be determined with additional evaluation. These evaluations should consider a more textured format that provides a "flow field" in the periphery and the likely utility of HMD/T systems. Other modalities (tactile and auditory) may also be useful for increasing attitude awareness.

6.3.8. TACTILE DISPLAYS

Tactile displays are another candidate device for agile aircraft applications. ("Tactile displays", herein, refer to devices that convey distributed sensations, rather than devices that provide vector force haptic feedback.) Tactile displays located on the human trunk have the potential of providing information without interfering with motor or any other sensory function. Also, they are "head up" displays since the perception does not require the pilot to glance into the cockpit. The human skin responds to several distributed physical quantities: vibrations, small-scale shape or pressure distributions, and thermal properties. Vibration based displays use frequencies ranging from a few Hertz (Hz) to a few hundred Hz. For aircraft applications, the distribution of skin stimulation is mapped to the state of some aircraft parameter or system. For instance, one university group [40] is examining microelectronic mechanical systems which, when integrated with a fabric suit, can provide a thumping or gentle pressure on a certain part of the pilot's abdomen to notify the pilot when the aircraft is listing to one side.

One tactile display has already been demonstrated for a helicopter application. The Tactile Situation Awareness System (TASS) is designed to provide an indication of velocity direction and velocity vector magnitude [41]. Specifically, 22 pneumatically driven tactors (1.25 in diameter) were integrated into an F-22 cooling vest worn on pilot's torso (Figure 6.6). By activating (vibrating the membrane at +/-2 PSI amplitude at 50 Hz) different tactor locations on the torso, the direction of helicopter drift (in 45 degree increments) was indicated and the tactor activation pulse pattern (rate of turning tactor on and off) was used to indicate the magnitude of drift. The preliminary results from four pilots completing hover maneuvers suggest that such a tactile display may improve pilot awareness of helicopter movement and reduce workload, especially under reduced visibility conditions. As one pilot commented: "I could feel the tactors before I could detect visual cues of movement." This promising technology may also have additional applications for altitude awareness (e.g., using a tactile display on the arm), position maintenance around a reference point, directional indication of threats, and non-verbal communication. The utility of tactile displays is determined in part by their limited resolution (discrete number of tactors), the limitations in the rate at which pilots' can effectively use incoming tactile data, and their utility under acceleration. In particular, evaluation is required to determine how pilots resolve any conflicts between visual and tactile information.

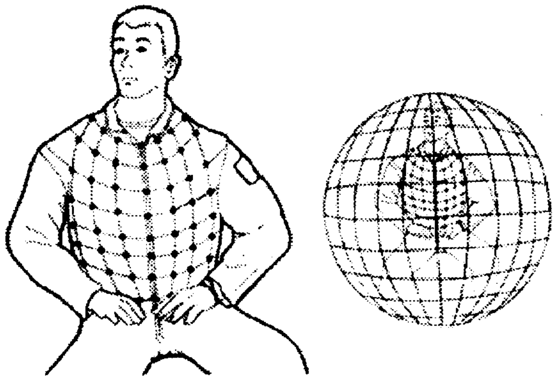


Figure 6.6. Schematic of Tactile Display Concept

6.3.9. AUDITORY DISPLAYS

Auditory displays are also a "head up" source of information for pilots. Although auditory signals have been used in crew station design for some time, to date they have been limited to single frequencies or voice communications, primarily presented monaurally. In one application, navigation deviations were indicated with a Morse code type auditory signal: a Morse code "A" for one direction and an "N" for the other. The two frequencies fused into a steady tone of 1,020 Hz when the aircraft was on course. Changes in both frequency and pulse rate of an auditory signal have been used to indicate key points in AOA (30, 40, and 70 degrees). Another approach "aurally" presents several flight parameters with an acoustic orientation instrument. The instrument displays airspeed as a sound frequency (repetition rate), vertical velocity by amplitude modulation rate (increase shown by increased pitch), and bank angle by right/left lateralization (louder signal in side that is same as direction of bank). This display was presented to pilots over earphones, after processing the auditory signal to map with the actual aircraft flight data. The results showed that acoustic signals can be useful indicators of the orientation of an aircraft, and interaural intensity differences, representing bank angle, are particularly effective in this regard [42].

Additional improvement in the acoustic orientation instrument might be realized by using three-dimensional localized signals, rather than lateralized signals. This is now possible due to recent advancements that have enabled the faithful reproduction of omnidirectional, complex auditory signals. This includes duplicating the interaural intensity difference, interaural time difference and the direction dependent spectral information that occurs when incoming sounds impinge the head and outer ear (pinnae). The latter are especially important to externalize the sound to appear "outside of the head." To reproduce the dynamic cue changes that occur with the pilot's head movement, some type of head tracker needs to be integrated with the audio display. Head tracking enables the headphone presented stimuli to be corrected in real-time so that they are perceived by the pilot to be at fixed positions in physical space.

For agile aircraft operation, the combination of three-dimensional auditory displays with a HMD/T may be especially useful. The auditory cues could improve situational awareness by informing the pilot that critical visual information lies outside of the current visual field. The spatial auditory cues may even indicate exactly where the information is located relative to the current position of the pilot's head (see Figure 6.7). In a study which compared different methods of directing attention to peripheral targets, target acquisition time with three-dimensional tones was less than other auditory signals (coded aural tone, speech cue, and three-dimensional speech cue) [43]. In another study, use of spatial information from the auditory channel reduced search latencies on the order of 100-200 milliseconds. This advantage increased as the eccentricity of the target increased beyond the limits of the central visual field [44]. The results of an evaluation on the effects of using localized auditory information to perform a target detection task using a HMD in a simulation study were similar. Subjects were able to detect targets with less overall head motion and reduced head velocity [45]. Under high acceleration environments, this may help reduce the risk of neck and shoulder fatigue and injury. In actual Harrier flight tests, a three-dimensional audio system was particularly effective for azimuth cueings. Aviators were able to discern targets separated by 12-20 degrees [46]. Three-dimensional elevation cues, however, did not provide similar precision, but were adequate in discriminating two spatial levels (low versus high).

Speech intelligibility and discrimination can also be improved by localizing speech inputs. Small angular separation of messages (45 degrees) has been found to greatly improve speech intelligibility. At 90 degrees of separation, the speech intelligibility levels were maximized [46]. A three-dimensional communication separation system also worked well in Harrier flight tests, aiding the copy of dual message traffic [46].

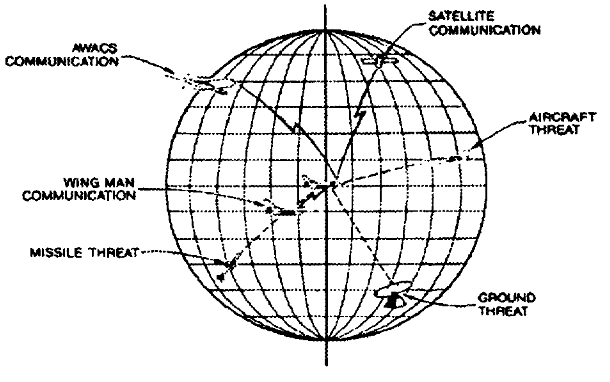


Figure 6.7. Schematic Illustrating Application of Three-dimensional Auditory Display for Three-dimensional Awareness of Threats and Communications.

Information from spatialized auditory cues can also help code system status information. For example, to aid the pilot in understanding a critical situation and add redundancy to the message, a left engine auditory fire alert message could be displayed such that it appears to emanate from the left. The auditory space can also be used to indicate the level of urgency of an auditory warning. The most urgent warnings would be presented so they are perceived inside the head, while less urgent warning are perceived to the sides [47].

In sum, three-dimensional auditory signals have the potential of being detected more quickly than visual signals, and, at the very least, relieving the pilot's already over burdened visual workload. Some candidate agile aircraft applications of three-dimensional auditory displays include: 1) alert pilots of ground or aerial threat location and facilitate target acquisition, 2) enhance situational awareness during air-to-air combat by localizing voice communications, 3) segregate multiple channels of communication so as to improve intelligibility, discrimination, and selective attention among audio sources, and 4) provide an additional cue for location or urgency of an aircraft system malfunction. Before these candidate applications can be implemented, further research is required to determine how best to exploit the capability to present spatial auditory signals and the best format for the information to be presented.

Given the flight envelope for agile aircraft, auditory localization accuracy under varying levels of sustained +Gz acceleration is of interest. The results from one centrifuge evaluation [48] showed that localization error did not significantly increase between 1 and 5.6 +Gz. Error did significantly increase at the 7.0 +Gz level, although, this performance decline can also be related to the difficulty making the manual response required in the experimental task. Localization performance in agile aircraft will more likely be influenced by factors already known to have an effect in ground-based simulations. First, auditory cues will need to be presented over headphones, as opposed to free-field localization, the latter providing more accurate localization. This is not foreseen as an insurmountable problem, since localization errors using headphone presentation has been reported as low as 4.4 to 5.9 degrees, depending on the type of stimulus [46]. Also, given the large field-of-view, a general indication of a target's position will greatly benefit the pilot. Second, errors in elevation are larger than for azimuth [46]. Once again, the pilot will benefit from any veridical directional information, whether it be solely azimuth or also include a coarse indication of elevation (e.g., high versus low). Third, and most important, it is likely that auditory localization will be accomplished with minimal movement of the head, since the pilot will most likely be attending to the forward field-of-view. This impacts performance because movement of the head helps disambiguate front/back reversals by tracking changes in the magnitude of the interaural cues over time influenced by the apparent source position. The most common type of reversals is when sounds simulated in the front hemisphere are heard at the mirror image position in the rear. The percentage of front/back reversals can be as high as 50% of the classifications. Until this confusion is controlled, application of three-dimensional auditory displays might best be limited to serving as a redundant cue. Also, further research is required to evaluate dynamic auditory resolution.

6.4. HEAD DOWN CONTROLS/DISPLAYS

In order for the agile aircraft pilot to keep the head up and out of the cockpit as much as possible, head down information needs to be easily acquired and head down control operations need to be quick to complete. This presents a difficult challenge to designers – *maximizing* the information conveyed or inputted by head down devices while *minimizing* the time required for head down viewing. The following addresses these implications and presents some candidate head down controls and displays.

6.4.1. HEAD DOWN CONTROL ISSUES

Head down controls need to be easily located, grasped, and manipulated. All the information and control devices needed for a particular set of activities should be in close proximity and available with less than two key presses. Proper and consistent formats, abbreviations, symbol meaning, control assignments, procedures and rapid (< 0.2 seconds) feedback need to be employed so the action required and status of control operation is intuitive to the pilot [9]. In addition to dedicated control devices, many control functions are activated by selecting a switch associated with a function presented on a display. The functions associated with each switch change depending on the flight segment or task to be performed. Human-engineered design of the required interactive sequences is key to the utility of these multifunction controls [49]. Function selection using touch activated displays (press display surface over appropriate label) has proven to be useful in ground-based applications, but operators must be more attentive to visual and audio feedback due to the lack of kinesthetic feedback [50]. Selection of small targets or closely spaced functions is also difficult, especially with flight gloves (one pilot described as "Fist on Glass").

6.4.2. HEAD DOWN DISPLAY ISSUES

The primary function of head down displays is to increase the pilot's situational awareness and provide additional systems information. If this information continues to be presented on numerous dials, indicators, and multiple small displays, it will be very difficult for pilots to rapidly fuse the information together to access the situation. One solution is to present this information on a single large (e.g., flat panel) display [3]. Merely moving all the information onto one surface will not facilitate pilot performance. Rather careful format design is required to identify an integrated format that makes it easy for the pilots to determine what actions are possible at any moment and evaluate the current state of aircraft systems. In other words, the right information in a useful format needs to be presented at the right time. Moreover the information needs to be presented in the right location – any critical information should appear at the same location all the time.

With programmable displays, there is virtually no limit as to how information can be presented. This is a mixed blessing because there is a natural tendency to provide the pilot with several options, not knowing the optimal approach in advance. This is counter-productive, adding to the pilot's visual workload and cognitive demands to filter out the required information. Display formats for head down displays (as well as head up displays) represents a research topic requiring significant attention. Specific design guidelines and useful metrics for managing the presentation of information in multipage displays are available in [51].

For map displays, the scale and frame of reference (track up or north up) should be pilot selectable. As a default, a track up view in which the map display rotates to match the momentary heading of the aircraft is better in that it eliminates the need for the pilot to do mental rotation [23]. A three-dimensional presentation may help provide information about the relative distances of objects from the ownship. To date, though, there has not been a consistent advantage with a three-dimensional approach [23]. Color-coding has been found useful for distinguishing boundaries and differentiating symbology sets. Rather than present sensor data on different formats, an attempt should be made to fuse the information into a single format or integrate and code the information so that the pilot knows the source of each datum.

Information presented on head down displays is the primarily source of weapon and aircraft systems status. The information needs to be limited to what is meaningful or more easily used by the pilot. Examples include fuel in available range format and threats as potential killers or not [1]. For some systems, a pictorial presentation of the information may be more intuitive and more quickly assimilated. Figure 6.8 shows examples that were generated in a study to examine use of pictorial formats for military cockpits [22]. Pictorial symbols can be used to describe the status of subsystems as well. For example, a pictorial representation of the four mechanical fuzing options (nose, tail, both, or none)

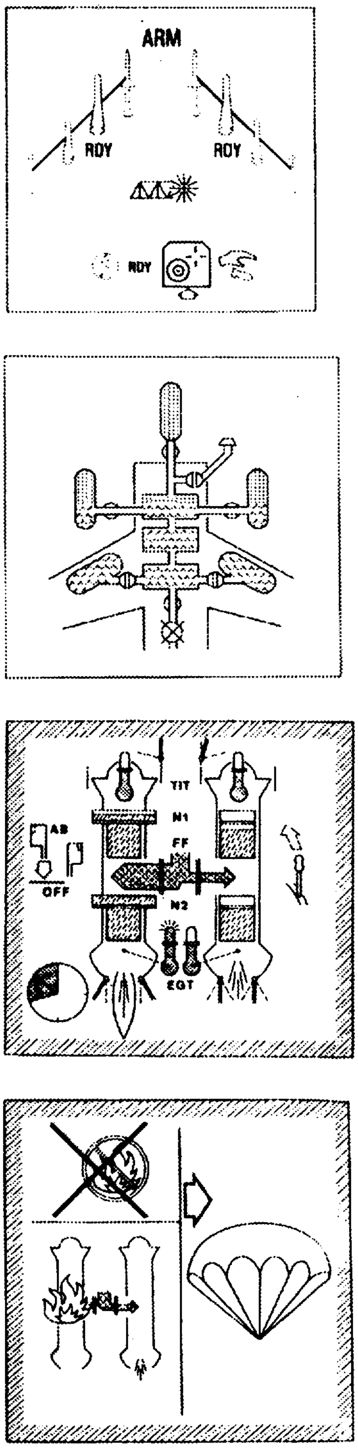


Figure 6.8. Example Pictorial Display Formats Showing Systems Status [22]. First two show weapons and fuel status. Last two are engine formats.

provides a more realistic impression of what is actually happing with the fuzing, compared to an alphanumerical readout. Color-coding can also be very useful to note operating ranges of a system parameter. Evaluations are required to determine whether additional costs to provide pictorial and color formats are merited in terms of aircrews' performance and preference. The results may differ depending on the particular display format [52].

The flight control stick can also convey information to the pilot. In the past, stall warning systems employed stick shakers or stick pushers to warn pilots of impending stall conditions. The pilot's attention can be easily acquired by altering the control stick's force gradient. More recently, the utility of the pilot's sense of touch was examined in a landing experiment that fed information concerning lateral deviations from a runway centerline into a force reflecting control stick. The results indicated a consistent advantage in performance and perceived workload for the force feedback system, particularly for landings conducted under heavy turbulence [53].

6.5. MULTI-MODAL CONTROLS/DISPLAYS

A *combination* of modalities can facilitate the information exchange between the agile aircraft cockpit and pilot. However, there is also a danger in imposing an additional load on the pilot to remember the steps used to employ different controllers or burdening the pilot with superfluous stimulation with multi-modal displays. It is only through research that the optimal control and display configurations can be identified for specific tasks/applications.

6.5.1. MULTI-MODAL CONTROL ISSUES

Just as operators with desktop computers can navigate with a variety of controls, it is possible to implement aircraft system such that several control modalities can be used for a single control action. This mapping approach provides the pilot with increased flexibility: a) the pilot may have individual preferences for specific controls, b) a temporary task or environmental condition may deem one controller more efficient than another (e.g., eye-based control when manual selection is difficult under high acceleration or positive pressure breathing interferes with speech-based commands), and d) should one control device malfunction, the pilot can use a different control.

A multi-modal approach is also useful when two or more controls are integrated such that they are used together to perform a task. In one integration approach, a control technology that cannot perform a particular function alone can be used to improve the performance of another control. For instance, eye line-of-sight data might be used to enhance speech processing by restricting the vocabulary search to the most probable verbal commands associated with the current gaze point. In another type of integration, two or more control devices operate in parallel to increase the accuracy or reliability of a control action (lip movement data when used together with acoustic signals can improve speech recognition compared to either one alone). In a third integration type, controls are mapped to different subcomponents of a task. For example, the pilot can use eye gaze to designate a waypoint on a map display and a voice command for a consent response, commanding the navigation system to update the mission plan. The use of both control devices capitalizes on the ability of eye gaze to rapidly designate a position on two-dimensional surfaces and voice commands to quickly initiate an action. In fact, eye and voice systems can replace or augment conventional controls for many interactions with aviation displays (e.g. configure displays, tailor displayed information, retrieve information, and input information) [54].

6.5.2. MULTI-MODAL DISPLAY ISSUES

Multi-modal displays may be more effective in warning the pilot of an aircraft system malfunction or an impending threat. In one experiment, visual icons and verbal warning messages were used singly and in combination and the results showed a significant decrease in response latencies when correlated bimodal information was provided, as compared to either unimodal alert [55]. In another experiment, both a three-dimensional tactical (visual) radar display and a three-dimensional auditory display were presented to provide the pilot with information about the target aircraft. The radar display showed the target's relative speed and whether it was above or below ownship. The auditory display showed the direction of the target to ownship. The displays also differed with respect to frame of reference. The radar display was outside-in, indicating the relative position of the target as seen from above and the auditory display was inside-out, indicating position relative to the subject's head. The results showed that both displays, when used individually, reduced search time [56]. However, when the two modalities, visual and auditory, were used simultaneously, search time was reduced more.

Multi-modal displays can also help overcome the inherent limitations of display technologies when used individually. For instance, target detection performance has been found to be poorer with a HMD compared to a full field-of-view visual condition [57]. The results of follow-on research suggest that a three-dimensional auditory display can be effective in mitigating the negative effects associated with performing a visual target detection task with a HMD [45]. Another example where two modalities could complement each other is three-dimensional auditory displays and tactile displays.

6.6. INTELLIGENT INTERFACES

6.6.1. ADAPTIVE INTERFACES

The use of computer-driven controls and displays in agile aircraft cockpits offers the opportunity to include intelligent interfaces which help the pilot acquire information and execute decisions. This would provide more time for the pilot to control the aircraft and think about decisions that must be made. To meet this objective, the displays must be configured to provide information salient to the specific situation being addressed by the pilot and the controls must facilitate the pilot's response. The use of tailoring has already been introduced – only information previously determined appropriate for the current flight phase is presented. This tailoring is a result of an explicit control input by the pilot (e.g., selection of a flight mode switch). However, it is likely that the pilot would benefit from variations in the control/display configuration for specific tasks within a single flight segment. Rather than have the pilot continually commanding the system to make such changes (and in cases where the pilot is over loaded or incapacitated), it is desirable to have dynamically adaptive interfaces that change the display and/or control characteristics in real time [58] (see Figure 6.9). These changes are initiated by predetermined triggers:

- external (changes in mission, tactical constraints, threats, and aircraft systems (hydraulic failure)),
- internal (physiological) indices (measurable aspects of the neurophysiology that index changes in the pilot's physical and cognitive states), and
- behavioral indices (overt behaviors executed by the pilot (eye gaze point, control activity, etc.).

Besides choosing and validating the triggers and decision rules that initiate the adaptations, the specific modifications to be made to displays and controls in each instance must be identified. Implementation of adaptive interfaces is also a challenge due to the real-time timing constraints and the need to analyze continuous parallel input streams from numerous sources. To ensure that the candidate adaptive interfaces are indeed a benefit to the pilot, evaluations are required. The goal is to provide the agile aircraft pilot with the right information, at the right time, and in the right location for optimal performance and mission success. On the other hand, there are potential problems with impeding the pilot's cognitive momentum and causing confusion by changing information. The lack of consistency could also interfere with the pilot's skilled-based behavior. However, the results of one simulation suggest that dynamic changes in displays or controls will not interfere with the development or execution of skilled behavior [59]. This experiment utilized three interface conditions: conventional, advanced (flight director display and force reflecting stick), and adaptive (which switched between the conventional and advanced, depending on pilot performance on a navigation task). The need for further evaluation was indicated, though, that utilizes a more demanding task environment and more complex mechanisms to trigger adaptive changes.

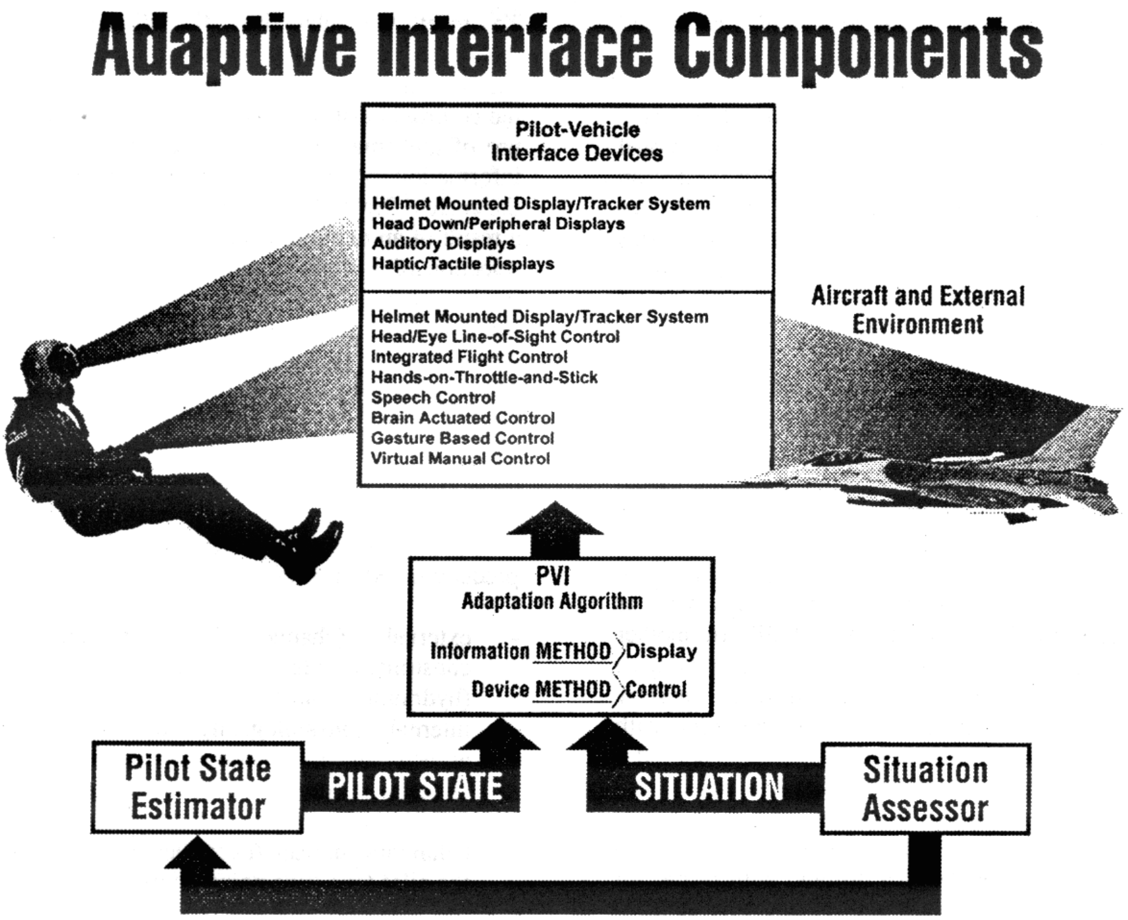


Figure 6.9. Illustration of Adaptive Interface Components in Crew Station Design.

Adaptive interfaces can also capitalize on the human's capability for parallel processing across sensory modalities. If a workload assessor determines that the pilot's visual channel is saturated, then a high-urgency display element that would nominally be presented on a visual display (e.g., approach of a G-limit) could be presented via the auditory system or via force feedback in the control stick. If it is determined that the pilot is heavily engaged in some activity (evading an enemy) and does not have the resources to attend to another task (activate electronic counter measures), intelligent systems could automatically perform the task and inform the pilot of its completion. In this case, the intelligent system is not only changing the interfaces but also accomplishing a task for the pilot. This role of automation in crew system design raises additional issues, which are discussed below.

6.6.2. AUTOMATION

Automation of some crew station tasks can certainly help reduce the workload facing the agile aircraft pilot. However, problems with automation can arise due to "clumsy" use of this technology. If the entire pilot/system operation is not considered, there is a likelihood of automation being activated at a time when it is least needed and hindering performance in situations where it is greatly needed. Even more common is the failure to provide the pilot with adequate feedback on the status and behavior of the automated system or task, which affects the pilot's ability to maintain situational awareness. The pilot needs to be able to maintain a mental model of both the monitored process and the status of the intelligent system, especially when multiple dynamic systems are in operation as is the case in aviation. Special attention should be given to the level of feedback. The complexity of modern systems makes it impossible and undesirable to display every data item, but a minimum level of information is desirable to keep the pilot on line, so that decisions can be made when needed. Also, the level of information provided to the pilot may be context-dependent. Lastly, there are instances where automating a task is not in the best interests of the pilot. For example, having the pilot a passive occupant during automatic guns aiming or automated missile avoidance can increase the pilot's disorientation and sickness during abrupt maneuver changes.

Some of these problems arise because the environment and workload characteristics of the cockpit are so complex and dynamic. What may be an optimal automation scheme for one flight segment/task may be totally inappropriate for another. Therefore, automation also needs to be dynamic or adaptive, with the goal of maintaining an optimal division of labor between the pilot and the aircraft [60]. In other words, the automation needs to be flexible and responsive to pilot and task demands and the same triggers used in adaptive interfaces are also useful for adaptive automation. With this pilot centered approach, there should be fewer difficulties with automation induced difficulties in monitoring and maintaining situational awareness because the pilot is kept more involved. Tasks requiring judgement, multi-sensory information gathering, hypothetical reasoning, and contingency reaction are best suited with the pilot in the loop. There are, however, some ongoing "housekeeping" tasks that can be automated; tasks that require accurate responses, fastidious and repetitive actions, and exhaustive calculations are good candidates for automation. The following are example candidate applications of automation:

- if an engine failure is detected, perform correction and concurrently notify the pilot
- manage fuel and hydraulic systems, but give high level information to pilot (range, malfunctions, etc.)
- perform appropriate actions for battle damages and inform pilot if operational capabilities or flight performance affected
- manage navigation systems, but store data for call up by the pilot
- assess situation, manage sensors and attach confidence indicators to fused and correlated outputs
- analyze target to provide identification, performance capabilities and optimum engagement parameters
- deploy aircraft defensive measures when pilot is busy accomplishing a popup weapon delivery sequence [61].

Besides adapting automation to the pilot and task demands, a human centered approach calls for obtaining the consent of the pilot (or requiring a command from the pilot) before initiating an automated action. This pilot preferred approach is referred to as "management by consent" – automation cannot take action unless and until explicit pilot consent has been received [62]. Since there are numerous instances where automation could play a role, requiring a consent response for every automated action is also unreasonable. It is recommended that the pilot input a nominal set of rules to be used by the automation system for the majority of tasks. For each task, the pilot should indicate preferences on whether the automation system should: always perform the task, sometimes perform the task, perform the task and notify the pilot, or ask for permission to perform the task. Having the pilot tailor the automation system before the mission helps minimize the chance of interfering with workload on other simultaneous tasks.

The term "management by exception" refers to instances where the system takes over *sometimes*. For instance, automation systems can perform less critical tasks on their own when it is detected that the pilot is suffering from demanding time pressures and workload. Of course, the pilot maintains an option to override this automation. There are also instance where pilot consent may not be practical (e.g., pilot injured) and function changes may need to be implemented directly by the adaptive system.

Given the number of aircraft systems and corresponding procedures and tasks involved, research is needed to decide how tasks should be shared between the pilot and aircraft, how much autonomy and authority should be given to each, and how agreements and commitments to actions can be negotiated between the two. Certainly, the degree to which automation is successful in agile aircraft is a function of the degree to which there is coordination between the pilot and the automation system [61].

6.7. SUMMARY

The issues raised in this lecture pertaining to controls, displays, and intelligent interfaces illustrate opportunities for enhancing the cooperative interaction between the pilot and the aircraft, with the ultimate goal of achieving pilot-cockpit symbiosis. Moreover, the importance of the pilot-cockpit interface to the successful exploitation of agile airframes, agile weapons, and agile systems has been demonstrated. It is clear that considering ergonomics in crew station design is key to the success of agile aircraft.

6.7.1. THE GOOD NEWS

The results of the pilot interviews and the reviews of this Working Group show that *drastic changes in the crew station design hardware are not needed for agile aircraft*. For the most part, near term control and display suites (Figure 6.10), current systems along with the advances that are nearing transition (e.g, HMD/T), are adequate. Even though modifications in formatting and configuration are required to address specific agile aircraft issues (e.g., presenting flight path information when at a high AOA), most are easy to implement since so much of the hardware is computer driven. A recent simulated air combat study demonstrated: 1) the feasibility of implementing many of these advanced concepts, and 2) these advanced concepts can result in statistically significant advantages, despite the fact that the subjects (pilots from three NATO countries) were more experienced with conventional crew stations [63]. This evaluation assessed both a conventional cockpit (F-16/F-15 type cockpit displays) and a virtually augmented cockpit (HMD/T, pictorial formats, color coding, three-dimensional audio

NEAR TERM
Head Mounted Tracker/Display System
Integrated Flight Control System
Hands-on-Throttle-and-Stick
Voice Control for secondary tasks
Improved Display Formats: color, pictorial, and sensor fusion

FAR TERM
Visual Peripheral & 3-D Displays
Tactile Displays
Auditory 3-D Displays
Eye Control
Gesture Control
Bio-potential Control
Multi-modal Displays/Controls
Adaptive Displays/Controls

Figure 6.10. Candidate Near and Far Term Displays and Controls for Agile Aircraft.

cueing for the radar warning receiver, and a ground collision avoidance system) using objective and subjective measures. The findings indicated that the new design not only resulted in superior mission performance, but also did so with less workload and enhanced situational awareness. In general, those aspects of the mission that relied on target identification and maintenance of tactical position relative to the target appeared to be the most positively affected by the advanced crew station design.

Therefore, there is good news that significant investments in control and display hardware development are not required to meet the pilot-vehicle interface requirements of agile aircraft. Far term developments (Figure 6.10) that provide the pilot with *new* capabilities are, though, certainly welcomed candidates for agile aircraft application.

6.7.2. THE BAD NEWS

The results of this effort showed that the mental workload involved with information management in crew station operation is a limiting factor for agile aircraft operation. In order to achieve full operational performance in agile aircraft, the pilot must be able to perform several simultaneous functions: fly the aircraft, maintain situational awareness of the total air battle scenario, communicate with friendly forces, plan attacks, fly complex attack maneuvers, control aiming and release of multiple weapons, manage onboard systems, organize self defense against arriving threats, and perform high acceleration escape maneuver for threat avoidance. Given the increasing number of systems involved in completing these tasks and the myriad of control options available, it is not difficult to understand how the pilot can be overwhelmed. Rather than helping the pilot with these added capabilities, the design may in fact be hindering the pilot's ability to execute and survive the mission.

The bad news is that the *current approaches for pilot-vehicle interfaces do not support fast assimilation of information and control actuation.* Simply, the right information is not being provided at the right time in the right location. It is this inadequate information flow between the pilot and the aircraft that is the limiting factor in the performance of agile aircraft. Therefore, a significant investment is needed to conduct the human factors engineering, task analysis, design iteration, and evaluation needed to identify how the pilot-vehicle interface needs to be improved to support pilot/airframe/weapons/systems information exchange [9]. Compared to past aviation ergonomic studies, this needed research will be much more difficult to conduct. As the complexity and dynamics of the systems increase, so do the ergonomic challenges to consider new styles of interaction. New requirements are levied on user interface software and user communication dialogue in order to handle and describe complex and substantial input/output processing, simultaneous parallel inputs, continuous inputs and outputs, imprecise inputs, and timing constraints. Thus, designers are faced with both a great challenge and opportunity to realize crew station designs that will truly enhance the operation of agile aircraft. Hopefully, the concepts and technologies described in this lecture will assist in this creation of a pilot-cockpit symbiosis for agile aircraft applications.

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SELECTION, TRAINING and SIMULATION

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1. GENERAL BACKGROUND

1.1. THE SUPERAGILITY ARENA

Superagile aircraft systems are a new challenging era in aviation history. These aircraft systems will be able to operate within new limits. Some of the areas of the super agile concept have already been explored in flight. Vectored thrust flying has been practised in aircraft such as the X-31, SU 37 and F-18 HARV.

New aircraft sensors, sensor-fusion and data-link techniques have made the battlefield much larger than before. The introduction of the night vision aids has also opened a whole new area.

Agile weapon systems make the scenario even more intriguing.

1.2.THE HUMAN CHALLENGE

How much of a limiting factor will the human become in super agile flight? Will he still have a place in this arena. And if he will operate on board super agile systems will he be able to do so without compromising his health?

We know since the introduction of first flight, that aviation does have an effect on aviators. Ever since Paul Bert studied the effects of high altitude, scientists and flight surgeons have been involved in studying the interactions between aviation, aviators and the aviation environment. The introduction of super agile aircraft systems will therefore most likely be an exciting chapter in the book of aviation medicine.

Flying these new generation fighter aircraft will be a new experience in a new threat environment. Improved engines will make it possible to fly at high altitude. To avoid adverse weapons from beyond visual range high linear and angular velocities and accelerations will be needed. In close combat situations vectored thrust gives high manoeuvrability at low speed and the super agile pilot will thereby have better possibilities to win and survive.

The flight environment will also hold new threats and players as super agile adversary aircraft with super agile weapons, unmanned aerial vehicles (UAV's) and powerful data links. This will certainly make the battlefield even larger. Although artificial intelligence and remote team members will help to diminish workload, the pilot on board will be a crucial part of the superagility complex.

In this highly complex flight environment the pilot will be submitted to different hazards. He has to be able to perform well under the given conditions. He will have to accomplish his mission and survive to allow him to fly a next one. All this has also to be done without compromising flight safety or the long-term effects on the pilot's health.

In this chapter an attempt will be made to approach the issues of how to select the right stuff and then how to train them to be efficient players in the superagility arena.

1.3. HUMAN CHARACTERISTICS

1.3.1.Limitations

In flying man's limitations become quite visible. Man has his information limits. He works cognitively more in a serial way, i.e. not too many bits of information at a time (**1**). Compared to most machines man is structurally fragile. And man is easy to fatigue.

In the context of a very multipotent aircraft system it is quite visible that man implies a restriction for the superagile system in some aspects. Yet technological systems without direct human participation have so far proved to be inferior compared to systems where man has his given role.

1.3.2.Strength factors

Adaptability when situations change. This means adaptation of both the cognition and of physiology. Adaptation usually takes some time and involves training. *Development of knowledge*. Man is a self-educating system where training again is an important factor. The ability to *communicate*. With intuition and creativity man normally also will outperform technical systems in pattern-recognition.

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1.4. FLIGHT SAFETY AND HEALTH RISKS

In order to find the criteria for selection and retention of super agile pilots one also has to identify and assess the risks of the super agile arena as well as the positive qualities that these pilots will have to have. In an occupational medical approach if these risks cannot be eliminated they have to be isolated. The next step is to give personal protection to those individuals who can meet the criteria of doing the job without compromising health and safety. Briefly some of the main concerns can be mentioned.

High altitude and radiation will stress the issue of oxygenation of human tissues, protective clothing for both body and eyes and survivability in case of ejection.

Acceleration will mean sustained high Gz, other G-vectors, push-pull effects and all these acceleration stresses will be combined with a lot of vestibular peculiarities. And beside the accelerative effects on the cardio-vascular system the spine, assisting muscles and joints will be strained.

Night-vision aids and helmet-mounted displays will both create a focus on flight safety issues and physiological factors. The visual system will also be at danger due to new laser and microwave weapons.

One issue that not by itself is related to the superagile flight is noise. But since there still are a lot of problems in today's flying, this issue must be remembered also in coming superagile systems.

Last but not least the whole spectrum of pilot workload must be remembered. This area can be predicted to be the issue of greatest concern.

1.5. HUMAN AGILITY

Superagility with its different aspects and reciprocal relationships is dealt with in other chapters of this work. Human agility is a key-factor, which in this context can be seen as an ability to interact with Aircraft agility, Systems agility and Weapons agility. This can be done if a well-developed Pilot-Vehicle-Interface (PVI) gives the right prerequisites. Real Human agility can be reached if selection has been performed optimally and training designed after expected scenarios (Figure 5.1.5-1).

When man is accepted as part of the Superagility system this must lead to a revolutionary attitude in how to develop new aircraft systems. These new systems have to be built for and adapted to man. The old attitude to build an aircraft and try to adapt man and make him fit into a technological experiment, is obsolete.

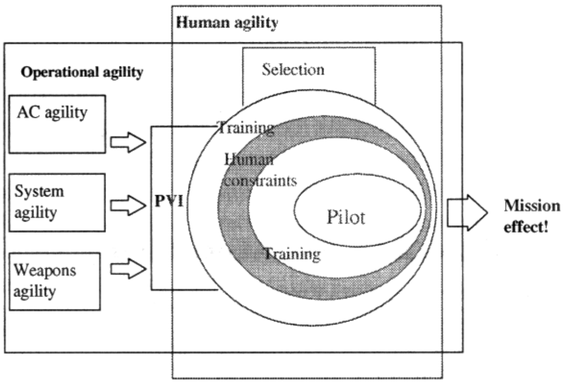

Figure 5.1.5-1 Human agility in the Superagility context

2. SELECTION

Selection should stand for the *best possible matching* between physiological and psychological resources versus the given operational requirements.

2.1. SELECTION- INTRODUCTION

With a classical definition selection refers to any process, whether natural or artificial by which certain organisms or characteristics are permitted or favoured to survive and reproduce in preference to others. It intents to pick out a number of individuals chosen from a group, by fitness or preference. In pilot selection the system tries to identify those individuals who will do best as a pilot in an operational setting.

The topic selection always starts a vivid discussion. Not only is it difficult to identify those individuals. It can also be debated if medical doctors or psychologists are best suited for such a task. In some countries experienced pilots take part in the selection by making interviews. This is a wise move since these experienced pilots are the criteria themselves.

Selection has in this time frame a negative connotation for many individuals and groups. The intention, some state, cannot be to exclude candidate pilots in order to create a whole new brand of super pilots. But, others reply, is a fighter pilot performing less than a top athlete?

On some of the arguments agreement is easily reached. We do need to identify those individuals that are able to fly, and accomplish their mission, without compromising flight safety. Therefore no foreseeable medical conditions should exist that creates a chance of sudden incapacitation. Also agreement can be reached on simple issues. The candidate should have two eyes, two hands and he should be able to hear. But it becomes more difficult if a specific quantity or quality of cognitive intelligence, sensory function or muscle strength, aerobic capacity etc., is asked for.

Part of the reluctance may lay in the fact that it is difficult to identify all these traits and abilities. And prediction becomes more difficult because most air forces select future pilots out of young adolescents that are high school or college students or graduates. At that stage it is difficult to predict future physical and psychological status and performance. Not only the body is not full grown yet, but also personality and character will mature. Moreover in adolescence motivation can still change easily. Fortunately these young men and women can still be trained and shaped well. If well organised, this training is in our own hands.

But even if everybody willingly agrees that selection of pilots is a dedicated task, there seem not to be any profound revaluation of the selection issues.

Essentially all the criteria, which have been used for decades, still are in use. The prediction of success according to these criteria does not hold for more than completion of the basic flying training. Furthermore most interest seem to focus on the development of automated tests and how to get sufficient numbers of applicants for the flying training.

2.2. CURRENT SELECTION

In all air forces psychological techniques are used to predict if applicants have the right stuff to become a pilot. Usually the success rate of pilot training is used as a criterion. It would be better to predict the success as a future fighter pilot. Not all people that do well in training end up as the aces at the squadrons. This apparently is difficult to do.

Much at this age has to do with motivation. But some abilities can fairly well be predicted. In the different air forces different selection procedures are used that for a part are due to the different recruiting strategies.

Mostly a selection battery is based on a strategy to waste out those individuals with little changes early with low budget techniques. These tests are still more or less paper and pencil like. They are sensitive. The possibility is high that also usable candidates are rejected, but as long as the number of applicants is high enough, that is not a major concern. Than sooner or later more specific and more expensive tests are introduced. Ranging from computer tests to simulators and actual flying. Some of the different test batteries are briefly discussed.

2.3. CURRENT METHODS

In Canada the "Canadian Automated Pilot Selection System (CAPSS)" is being used after the paper and pencil tests. It is a stand-alone selection device, which provides a measure of complex cognitive abilities and psychomotor co-ordination. The underlying constructs CAPSS is measuring are psychomotor co-ordination, learning rate, multi-task integration and performance under overload. It uses flight simulation technology and is comprised basically of two main elements, an aviation trainer and an analysis centre.

The United States Air Force uses a pre-screening before submitting candidate pilots to a selection board. They first have to pass the selection for officer commissioning. The selection decisions are based on leadership potential, educational achievement, physical fitness and ability based on paper and pencil or computer-based tests. There are no job sampling tests. Than there is a flight screening consisting of 23 hours of flight. The Air Force Academy policy is slightly different. They accept students not before they passed the flight screening. Since 1993 some experiments have been done with computer based aptitude tests. The selection research is focussed on learning ability. The goal is to develop a multiple test battery that predicts the different specific learning abilities. Analysis of the tests now used show that in predicting success in pilot training verbal abilities relate less than quantitative or spatial abilities.

The French Air Force

The Royal Netherlands Air Force

The German Air Force

The Swedish Air Force also uses pre-screening before applicants are subjected to the pilot selection. The conscript-time has to be finished with a rating as suitable for an officer's career. The tests are carried out over a two-day period, which on the first day include a general aptitude test to assess logical and spatial capacity and verbal ability. Those who progress through these stages proceed to the second day where they are given aptitude tests for co-ordination and simultaneous capacity. Applicants also undergo two interviews, one with a flight psychologist and one with a current line pilot. If successful so far the applicant will go on to two days of aeromedical tests. Thereafter the Selection Board will make a final decision.

The Royal Air Force uses the Pilot Aptitude Test Battery, consisting of five executives tests: Control Velocity Test (CVT, eye-hand co-ordination), Sensory Motor Apparatus (SMA, hand-food co-ordination), Instrument Comprehension (INSB, interpretation of instrument dials)), Vigilance (memory needing visual attention) and Digit Recall (short term memory). The test has a predictive validity of 0.52.

2.4. SUPERAGILE SELECTION

Introduction of super agile flight will not change the validity of old abilities and capacities. All principles that already are valid for current selection processes will also apply for that of super agile fighter pilots. One can also speculate that most of the selection criteria and variables of today might increase in importance. Yet there might be a need for something more or a different focus.

There are always scientific advances in the field of expertise and what are the extra demands of new technologies. For those reasons Nato's Aerospace Medical Panel (AMP), now Human Factors and Medicine Panel (HFM), held a conference in 1996 on Selection and Training Advances in Aviation (**2**). Some of the presentations already addressed the challenges of the super agile arena.

A thorough analysis has to be done of the qualifications and resources a pilot need for the superagility arena. Since these new requirements have not been confirmed and agreed upon this section will bring up some ideas of possible new selection-criteria or suggest stronger emphasis on some old criteria.

2.4.1. The visual system

The *visual system* plays a most important role in flying. This is very natural since the eyes are the best correcting means. In the agile arena this will be even more important. Some of the new tests will certainly involve the way the visual system works.

How to select those capable of much more *cognitive work* while at the same time being able to react properly on *orientation cues*?

How to select those with a *true spatial ability*, bearing in mind that most tests of today could not differ between a high intellectual or spatial capacity (**3**).

2.4.2. The vestibular system and hearing

Rapidly changing G-vectors might have physiological implications speaking for an even more *perfectly balanced vestibulo-visual system.*

New dimensions in testing of the hearing since a good *3D-audio discrimination* might be crucial.

2.4.3. Respiratory system

Additional respiratory stress might be the result by positive pressure breathing under high-sustained G (**4**). New selection-tests for inspiratory muscle capacity, tests to stage the effects eventual tobacco smoking has had on applicants.

2.4.4. Cardiovascular system

It is also an important task to more in detail establish what exact *factors constitute a good G-tolerance.* Cardiac function during G-stress and pain-provoking factors in high-sustained G might also influence selection.

2.4.5. Musculoskeletal system

A more balanced view on the *muscular strength* where not only explosiveness and fast-twitch muscle fibres are rewarded. After all when long sorties have to be performed the endurance parameters of the muscular and cardio-vascular system have to be screened and evaluated more.

Specific factors of the *back and neck* have to be considered in the selection (**5**). Among these factors we can predict bone-mineralization, range of motion in relation to strength factors. Condition of vertebral discs and spinal canal.

2.4.6. Cognitive and nervous system

The cognitive ability is truly a question of selection for the superagile pilot. Especially the challenging task to select those with both capacity to work within the "higher" cognitive domain but also extremely "present" in the situation at hand.

Stress resistance will be even more important than in earlier systems. Ways to measure the status and reactivity of the autonomic nervous system will therefore be important. Selection tests where flight stress can be simulated will be appreciated tools.

Try to establish a common opinion whether *intuition and creativity* are desirable traits in the superagile world. One could argue for such an opinion since fights including BVR, rapidly changing scenarios, uncertainties of threats etc. indicate the value of these traits.

3. TRAINING

Training has to be both *basic and specific* to give the best prerequisites for the pilot to handle the superagile situation.

3.1. HUMAN RESOURCES AND CONSTRAINTS

These are their contrasts. In *selection we focus on human resources* while in *training* we often try to overcome or *reduce effects of human constraints* and reach or move human limits, which might be possible to reach.

3.2. SUPERAGILITY TRAINING STRUCTURE

Training for this superagile environment has to be performed for different reasons. Firstly man will more clearly than ever be the restricting factor. Secondly flying time will be so expensive that ordinary training sorties will have to be complemented with a variety of other training regiments. Thirdly the rivalry between spatial orientation and tactical awareness will make it necessary to train both specified single tasks and also combined mission-like tasks.

Training could be divided in training to reduce the human constraints (physiological and mental training) and training which in some respect goes with the right PVI-format. This latter training will give familiarity with cockpit instruments and facilitate "pattern-recognition" when it comes to real flying. The training will aim at strengthening the human capability to withstand mental and physiological threat in a superagility environment.

The superagility training could also be seen as a "training structure" which has to be worked through (Figure 5.3.3-1).

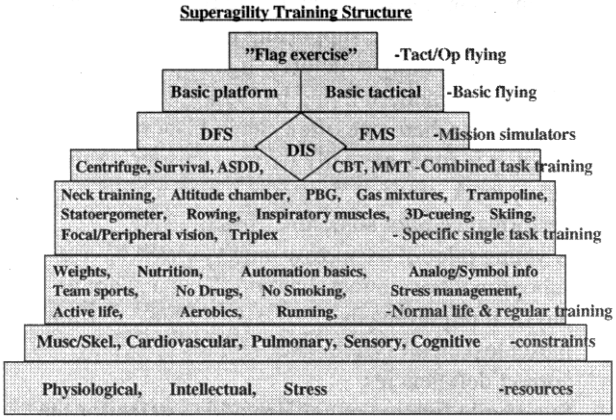

Fig 5.3.3-1 The Superagile Training Structure

In this superagility training structure we have earlier discussed the human resources who in this context are valid factors in the selection. In the following paragraphs of this section the human constraints and different parts of training are discussed.

3.3. HUMAN LIMITATIONS (INTERNAL CONSTRAINTS)

The human limitations in this scenario force us to focus on many training issues. Some of the factors, which could be considered to be human constraints in the superagile world, are mentioned below.

3.3.1.Cognitive function

The cognitive function of the pilot might not be a constraint in itself. But a lot of sensory information has to be processed in higher cognitive areas. And then we have an easy set-up for a conflict between the need not to lose the orientation in airspace and the need for effective use of higher cognitive functions according to the demands of the sortie. In addition physiological stress on the human system and perceived mental stress will reduce effectiveness. In conclusion one can state that there will be even more emphasis put on situational awareness (SA).

3.3.2. Sensory function

Signals to our 5 senses are crucial to orient ourselves in the agile world. Since flying is something so different from permanent residing on ground, which we are built for, man has to watchfully observe a lot of rather simple information. This information serves only the purpose of body orientation in the airspace

The *vestibular system* is sensible to different G-vectors, rotations, and translations. This system will be more stressed than ever before and it has to be adapted and if possible made less prone to react on unusual vestibular stimuli.

The *visual system* gives orientation cues but is also used for cognitive information. We need better and more intuitive information for spatial orientation, because the visual system is by far the most important sensory system and will also be the most important in flying. In years to come we will have a definite risk for overloading the visuals with "important" information on e.g. HMS/HMD: s, and VR-systems. The greater part of this information has to be percepted, interpreted, compared with elements in the long memory storage before any decisive action can be with taken. The conflict is given!

The *hearing system* gives orientation cues, informational load. An increasing importance is foreseen for the hearing system since e.g. 3D-audio cueing is to come thereby hopefully shortening the OODA-loop (observe, orient, decide, act) for this sensory system.

The *somatosensory system* is a simple sensory system in the context of flying. It gives some orientation cues and there are possibilities to artificially reinforce some of these cues.

3.3.3.Musculoskeletal function

High acceleration forces especially for back and neck, more if X-tra head worn equipment is used put a lot of stress to this system. In addition stress will be caused by static postures due to harness restraints and certain demanding mission profiles like low-level flying (**5**). Superagile flying will demand from both gross-muscular strength and fine-motorics function. It will also stress the need for a superb ergonomic cockpit.

3.3.4.Cardiovascular function

Cardiovascular function is sensitive to acceleration forces, mainly head to foot (Gz). The heart itself is a pressure generator and integrated electromechanical device sensitive to acceleration as well as is the vascular bed of the central nervous system. Peripheral vascular beds seem also to be heavily affected by acceleration forces and thereby prone to pain reactions, e.g. arm pain (**6**).

3.3.5.Respiratory function

Respiratory function is sensitive to atmospheric pressure changes and different gas mixtures. Additional oxygen supply at times with overpressure will be needed to match the superagile envelop. To secure CNS function and facilitate inspiration pressure breathing during G (PBG) will be used. This will reveal the deficiencies in the human respiratory function.

3.4. NORMAL LIFE AND REGULAR TRAINING

As individuals in a modern high technological society we need to broaden ourselves in relation to egg the information technology revolution. Yet this increasing competence has to be matched with a physically active life to stay healthy. This may contain an inherited contradiction since many youngsters who are good at computers do not like physical activity too much.

3.4.1 Cognitive training

It will be important to have an increased knowledge of and possibility to *handle mental stress*. Since automation will become part of every man's day *understanding of automation-principles* will be important. One specific area of concern for most high-tech professionals and especially for the superagile pilot will be to find the right way to work with *symbolic information* at the same time *analog information* is presented to the person or pilot. The saying "Right information in the right format" will be more and more important. Presentation principles have to be looked carefully upon.

3.4.2. Life style aspects

Every pilot has to consider his personal eating-habits, sleeping-patterns, drugs and so on. And he must be physically active with the right balance between endurance and strength training.

3.4.3. Cardiovascular training

Pilot selection criteria like body-type, heart-cerebral distance, vagal and sympathetic nerve tone will be more important. It has been emphasized that it is not acceptable to perform extreme marathon training when flying high performance fighters (**7**). Yet it must be pointed out that distances up to 5-7 miles x 2-3 per week will be of no harm if the training contains high intensity peaks.
A well-conditioned cardiovascular system has a great importance when considering multiple sorties and limited possibilities for rest as in a war situation. A variety of different sports can be performed to achieve needed goals.

3.4.4. Musculoskeletal training

In recent years it has been a focus on strength training. A sufficient muscular capacity will still be an important factor in superagile flying but one has also to focus on the supporting tissues like back and neck with its bony structures, ligaments and discs. The way of modern living including working conditions where one often sits in front of a desk or a laptop is fundamentally wrong considering the heavy work, static or dynamic, which a high performance pilot sometimes has to exert.
A young pilot of tomorrow might as well have a suboptimal bone mineralization (**8**). To adapt to physical requirements he or she will have to train the musculoskeletal system over months or even years to correct deficiencies.
Superagile fighters might also add systems for the pilot that will increase the load on the neck/back. Device integrated to the helmet will stress these structures. Already today there is evidence that the aging process of the neck of high performance pilots is accelerated compared to age matched controls (**9**). The clinical significance of this is unclear.

3.5. SPECIFIC SINGLE TASK TRAINING

This type of training will strengthen some specific abilities the pilot have to show in the superagile cockpit. Still this training will be performed outside the cockpit.

3.5.1. Cardiovascular and muscular training

To withstand high acceleration forces (normally Gz) is a primary goal. This will also include the area of negative Gz or the "push-pull" phenomenon (**10**). Factors important are actual G-experience, conditioned cardiovascular reflexes including both central adaptive mechanisms and local training effects on certain vascular areas such as the arms, to prevent arm pain. There are known device, which can be used for improvement in these areas like the statoergometer of Russian origin, rowing machines, downhill skiing.

3.5.2. Sensory training

Of the 5 senses the human have for information, the visual system is by far the most important in flying. To be able to move in 3 dimensions unlike the situation on ground, the pilot in his AC has to overcome a lot of erroneous signals given from e.g. the vestibular and the somato-motor systems. A great deal of work has therefore to be focused on training for the visual apparatus. Orientation information simultaneously presented with a high flow of tactical information will or rather must be given in two different formats so the pilot can work in parallel with the information. This is very important since information overload of the pilot is an immediate threat in superagile flying.
The vestibular system has to be adapted to a variety of new movements in flying like yaw, side slipping, translations and unusual velocity-vector movements compared to regular flying.
In addition to the visual system there are now efforts to also include the hearing system into the informational inflow. Then we must have in mind that pilots in earlier stressed situations (e.g. Vietnam war) have had the tendency to shut off information they have considered to be annoying and distracting rather than helping.
With 3-D hearing information there will be a possibility to keep track of much more auditory information compared of today's situation. Yet the risk for informational overload of the pilot will always be critical.
The sensory training can contain formal sensory training outside the cockpit like the Triplex and Trampoline used in e.g. Germany and Sweden. Training of the spatial ability like 3D-cueing and exercise training focal and peripheral vision might be of specific value.

3.5.3.Respiratory training

Training has to include hypobaric exposition with possibilities to experience hypoxia and preferably also rapid decompression training.
With high performance AC in the inventory it has been shown that positive pressure breathing during G (PBG) gives a definitive advantage. Intrathoracal over pressurization of up to 70 mmHg has been tested. The overall consensus today seem to be around 50-60 mmHg at 9G(**11**). The ideal pressure schedule in relation to G is still under debate. The advantage of PBG seems to be an increase in G-endurance. One important factor for this might be the decreased load with PBG for the inspiratory muscles. These muscles are weak considering the normal physiology at 1 G. In this situation the lungs are almost passively filled with air as a function of the flattening diaphragm following the abdominal volume displacement acting in the same direction as the Gz-vector.
In the high-G situation there is an urgent need for the auxiliary respiratory muscles above the lungs to try to counteract the Gz-vector in the inspiratory phase and "lift" the lungs to get air. Activated G-suit will tend to counteract the filling process of the lungs by abdominal upward displacement during G. PBG seems to give a substantial help in this respect.
Device needed for the respiratory system will be altitude chamber, PBG-systems where especially the inspiratory phase of the cycle can be trained.

3.6. COMBINED TASK TRAINING

The type of training is much more functional and has a clear aim to be more directly useful for flying. This will also mean that there will be specific devices developed to be means to prepare the pilot for e.g. the cognitive work or to be able to withstand specific physiological stresses.

3.6.1. Cognitive training

Computer Based Training (CBT) and Multi Mission Trainers (MMT) are needed tools to give fundamentals of AC systems and of the superagile arena. Cockpit outlay, display arrangement and content as well as familiarization with buttons and switches make a good start for actual flying. Instructors can guide and interact with the trainee.
A broad knowledge of the AC, systems, weapons and the tactical and operational facts of the situation are crucial.
One of the biggest problems is the informational load on the pilot. Therefore information systems, which are more "intuitive", have to be developed. With increasing information to the pilot, decision support systems will come. Many of these systems will be automated to some extent. Still there will always be a need for the pilot to know the "actual state" of the automated process.

3.6.2. Sensory training

The visual and vestibular systems can be regarded as the most stressed sensory systems in the superagile world. Both adaptation to unusual stimuli and also suppression of unwanted side effects will be crucial.

Both simple gyro-simulators and advanced disorientation trainers are useful tools.

3.6.3. Cardiovascular and muscular training

High-sustained G and G-peaks of 9 or more are inevitable effects of the superagile world. The absolute need for an adapted cardiovascular system and muscular strength to be able to fight in this arena is already known with today's AC systems. High-speed BVR-scenarios stress this even more. The human centrifuge with sufficient G-onset rate is a basic tool for this. Different types of centrifuges from free-swinging single-gimballed centrifuges to modern dynamic flight simulators with both roll- and pitch-control will be used. With the more modern devices even push-pull training can be performed.

3.6.4. Survival

Pilots must also be prepared to leave their AC in case of a malfunction or an unwanted outcome of an engagement. Summer- and winter-survival training are ultimate combined training regimes where most everything from the Superagility Training structure can be applied.

3.7. SIMULATION

Integrated training, where most factors that have an implication in flight are used, is an intriguing task. And this is when *Simulation* comes into play. There is a justified need for *realism* and complexity in this form of training. The more realistic the simulation is the more will it bring forward actual stressors from real flying. In simulation both cognitive and physiological stressors are used.

In addition simulation can also be focused on decision-making and performance under all kinds of stress.

Coming to this part of the training, more complex device almost up to real flying have to be used. The best possible right format will then be given to produce all different factors including stress.

Due to the ever-increasing costs of flying-time simulators, though they often are very expensive, have to be used. And knowledge and experience might have to emanate more from simulator-experience in the superagility environment even though it is of outmost importance to fly.

Therefore also distributive interactive simulation (DIS) will be used more, where ACs "powered" and data-linked with each other and different simulator systems in a network will "play" together.

4.1. FLIGHT SIMULATION

Since the visual system by far is the most important in flying, much emphasis has been put on making visual realism in flight simulation. But in the superagile arena there is also a need for expressing the information loads and the physiological stress.

4.1.1. Visual simulation

The best visual simulators are domes or full-mission- simulators (FMS). They are static but they provide almost unlimited field-of-view (FOV). Domes usually are very big 20-40 ft in diameter and the image can be projected at an infinite distance. With head- and eye- trackers it is also possible to have an area of interest where the image-resolution is very good. The drawback can be motion sickness in inexperienced and individuals prone to this "visual overflow" of information (**12**).

The visual systems can be used in combination with so called "G-seats" where the tactile as well as the proprioceptive systems can be stimulated by e.g. shaker system, retractable harness and inflatable seat-cushion (**13**).

4.1.2. Motion based system

Though many civilian airlines have a need for a 6 degree-of-freedom (6DOF) device there is not so much need for that in the military applications. G-forces are not possible to create to a necessary degree. In addition most military simulators where motion bases were linked to each other have been disconnected since there were a lot of problems with visual and other sensory mismatching, causing a frequent tendency to motion-sickness.

4.1.3. Dynamic flight simulators

These gimballed centrifuges are a clear development from the centrifuges with a free-swinging gondola. Most of them have controllable pitch- and roll- axis. (The Dynamic Environmental Simulator at Wright-Pat AFB has also yaw-capacity, but only 1G/sec onset rate). Together with a G-onset capability of 6-10 G/sec the devices should be capable to give the superagile pilot most of the experienced G-vectors in a superagile AC. In addition there is hope that a very good visual system and a closed-loop control system could give the dynamic flight simulators "flying characteristics".

Yet there are some precautions to that. For vestibulary reasons the pilot could not move his head too much since he then will have heavy vertigo due to coriolis-effects. To minimize these problems most dynamic flight simulators have an arm-length of 25 ft or more.

Existing or oncoming facilities are situated in: US, Singapore, Germany, France, Japan, Sweden and UK (**14**).

4.1.4. The Combined Acceleration Flight Simulator (CAFS)

This is a concept from the early ´90s (USAF Armstrong Lab (**15**)). The concept involved a multi-gimballed cab suspended by electromagnets in a large circular loop with a radius of over 200 ft. Together with a wide-FOV visual system and man-in-the-loop control this simulator would have minimized Coriolis´ effects and given an outstanding possibility to simulate almost everything in the superagility arena.

5. PILOT-VEHICLE-INTERFACE (PVI)

The pilot vehicle interface (PVI) must in the future be a lot more adapted to man. That means the PVI have to be built according to a human centered design protocol. Some of these factors should be:

- Ergonomic cockpit
- Simple platform to fly (carefree manoeuvring)
- Clear distinction between displays for orientation purpose and displays for tactical awareness.
- The right information in the right format at the right time (no information-overload).
- Logic decision support.
- Pilot-monitoring system with situation feedback on the information-, decision- and control systems.
- The "right" degree of automation.
- Very good escape system and protective equipment.

The PVI has also to be placed as operational as possible in advanced simulators like FMS and DFS. These two very "much-alike" AC simulators should also ideally give a lot more physiological and mental stress compared to the more cognitive trainers like CBT and MMT.

SUMMARY

In this chapter a "superagility training structure" have been discussed and proposed for (Figure 5.3.3-1). The super agile pilot will in the new superagility arena be clearly dependent on both old training principles but also on training where some new interacting factors might come into play:

- At first *Selection* plays a major role with physiological, intellectual and stress management resources.
- Certain *human constraints* like musculoskeletal, cardiovascular, respiratory, sensory and mental are discussed.
- *Normal life and regular training* where almost everything the pilot does also have a definite implication also on flying.
- *Specific single task training* where a pilot trains crucial abilities like G-tolerance, back/neck-tolerance and so on. Today there is a lack in this area of specific training. There is also a need for training devices for pilots regarding the sensory system and the cognitive performance.
- *Specific combined tasks training* where the pilot have to train in a more complex way, e.g. survival training or mission scenarios in a Multi Mission Trainer (MMT).
- *Full ground mission task* where the pilot uses a Full Mission Simulator (FMS) or a Dynamic Flight Simulator (DFS).

Some parts of the Superagility Training Structure have not been a scope in this chapter. They are briefly mentioned below.
Basic flying consists in this context of platform training and tactical training and are the formal parts of flying. Due to the ever-increasing costs of flying, the real portion of a pilot's life in the air most probably will decrease. A different solution would be to get "cheap time" in the air e.g. with a modern propeller-AC.
Tactical/operational flying where "flag-like" exercises are as close to a real war-scenario pilots in general wish to come. As stated above actual flying will be even more expensive and therefore we most probably have to try to find measures to give more and more realistic training concepts. And when it comes to real flying it could not always be done at first with instructor pilots (IPs). This together with increasing complexity of all systems might in a superagile AC stress the need for air collision avoidance systems (ACAS), ground collision avoidance systems (GCAS), auto recovery or other "fix-it"-procedures.

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14. Abstract

This Lecture Series evaluates the human factors implications for pilots of "superagile flight", specifically with regard to agile airframes, agile weapons, and rapidly configurable systems. During interviews, experienced pilots have confirmed the operational need for military aircraft agility. Although pilots have noted that their experiences to date have not caused them any major concerns regarding the potential for physiological problems, significant gaps remain in our understanding of the effects of multi-axis accelerations. Human consequences are also anticipated in the area of situational awareness. Presentation of aircraft attitude and energy state in a helmet mounted display will be a design challenge. The minimal constraints on aircraft incidence angles and the expanded weapon launch envelopes anticipated with the forthcoming and next generations of air systems requires the provision of novel displays to enable pilots to effectively operate such air systems. Decision aids, intelligent interfaces and automated subsystems are required to enable pilots to maintain situational awareness whilst coping with dramatic increases in the tempo of the tactical situation and the 'data deluge'. Moreover, many of the current pilot protection systems will be inadequate for everyday use in such an unconstrained flight envelope and during ejection. Additional challenges in selection, simulation, and training are also anticipated.

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