Human Factors 35(2), pp. 28-43.

# COCKPIT CHECKLISTS: CONCEPTS, DESIGN, AND USE

Asaf Degani
San Jose State University Foundation
San Jose, CA

Earl L. Wiener
University of Mami
Coral Gables, FL

## ABSTRACT

Although the aircraft checklist has long been regarded as a foundation of pilot standardization and cockpit safety, it has escaped the scrutiny of the human factors profession. The improper use, or the non-use, of the normal checklist by flight crews is often cited as a major contributing factor to aircraft accidents. This paper reports the results of a field study of flight-deck checklists, and examines this seemingly mundane, yet critical device, from several perspectives: its functions, format, design, length, usage, and the limitations of the humans who must interact with it. Certain socio-technical factors, such as the airline "culture," cockpit resource management, and production pressures that influence the design and usage of this device are also discussed. Finally, a list of design guidelines for normal checklists is provided. While the focus of this paper is on the air transport industry, most of the principles discussed apply equally well to other high-risk industries such as maritime transportation, power production, weapons systems, space flight, and medical care.

## BACKGROUND

### Cockpit Check Procedure

(a) Each certificate holder shall provide an approved cockpit check procedure for each type of aircraft.

(b) The approved procedures must include each item necessary for flight crewmembers to check for safety before starting engines, taking off, or landing, and in engine and system emergencies. The procedure must be designed so that a flight crewmember will not need to rely upon his memory for items to be checked.

(c) The approved procedures must be readily usable in the cockpit of each aircraft and the flight crew shall follow them when operating the aircraft. (Federal Aviation Regulation 121.315)

Recently, within a 25-month period, there were three major airline accidents in which the misuse of a checklist was determined by the National Transportation Safety Board (NTSB) to be one of the probable causes of accident. In the first, Northwest Airlines Flight 255, an MD-80, crashed shortly after takeoff from Detroit Metro Airport following a no-flap/no-slat takeoff (NTSB, 1988b). In the second, Delta Air Lines Flight 1141, a B-727, crashed shortly after lifting off from Dallas-Fort Worth International Airport, following a no-flap/no-slat takeoff (NTSB, 1989). In the third, USAir Flight 5050, a B-737, ran off the runway at LaGuardia Airport and dropped into adjacent waters, following a mis-set rudder trim and several other problems (NTSB, 1990).

Testifying before the Safety Board's public hearing on the Northwest Airlines Flight 255 accident, the second author of this paper stated with respect to checklist presentation "that he did not know of any human factors research on how a checklist should be designed..." (NTSB, 1988b, p.62). This was confirmed when the authors performed an intensive search, through U.S. and Western European databases, for any literature about this topic.

The Safety Board had previously recognized the importance of checklist use and its critical role in the safety of flight operations in a 1969 recommendation following a Pan American World Airways B-707 crash after a no-flap takeoff. This recommendation called for "Air carrier cockpit checklists to be reviewed in an effort to ensure that each list provides a means of reminding the crew, immediately prior to takeoff, that all items critical for safe flight have been accomplished" (NTSB, 1969).

It took 18 years and a tragic accident before the Safety Board recognized the problems with the human factors aspects of checklist design, display, and procedure. Following the Northwest accident, the NTSB recommended that the Federal Aviation Administration (FAA) convene a human-performance research group to determine "...if there is any type or method of presenting a checklist which produces better performance on part of user personnel," and for the FAA to recommend checklist typography criteria for commercial operators (NTSB recommendations A-88-068 and A-88-072).

Checklist problems are not confined to aviation; they also prevail in other industries such as maritime transportation, weapons systems, space flight, and medical care. In the nuclear industry, operators use paper checklists for normal and abnormal procedures as well as for scheduled maintenance tasks; this use also leads to checklist errors and omissions (Swain and Guttman, 1983; H. P. Van Cott, personal communication, 1988). Traditionally these and other high-risk industries have looked to aviation for guidance in such common problems. Accordingly, while this paper addresses the cockpit checklist, we believe that our analysis, findings, and the list of guidelines presented at the end of this paper will apply to other endeavors as well.

## METHODS

The intent of this research was to study and document the role of the flight-deck checklist within the socio-technical matrix of procedures, operators, manufactures, cockpit systems, management, and the regulating agency, i.e., the Federal Aviation Administration (FAA). This study consisted of a combination of three approaches:

1. A field study in which we observed flight crews in actual operations.
2. Interviews with flight crews from seven major U.S. airlines.
3. Examination of three databases of aircraft accidents and incidents in which checklists were implicated.

Our purpose was to examine checklist design and usage from several perspectives. The study was not intended to provide statistical estimates.

**Field Study**

A field study of checklist usage was conducted at one major U.S. airline employing both short and medium range aircraft. We observed (from the cockpit observer seat) flight crews in their daily line operation. This method, direct and non-intrusive observation, has been previously used in several aviation human factors studies that focused on the operational environment (Curry, 1985; Lyall, 1990; Wiener, 1985, 1989). For a further commentary regarding the problems and limitations of collecting data in the airline cockpit environment, see Wiener (1985, pp: 74-75).

Forty-two crews were observed during 72 flights (legs) totaling about 140 flight hours. In order not to bias the data, the crews were not told about the specific purpose of the observations, nor were any notes taken or forms filled out by the observers during the flights.

**Interviews**

Interviews with pilots from seven major U.S. airlines were conducted in coordination with the Air Line Pilots Association. This sample consisted of ten captains and five first officers. The participants were asked several questions regarding use of checklists at their current airline and other organizations they had flown for in the past (military, corporate, commuter airlines, etc.).

**Incident/Accident Reports**

Three aviation databases were searched by the authors in order to obtain checklist related incident/accident reports:

1. NTSB accident/incident database (NTSB, 1988a, 1988c).
2. International Civil Aviation Organization (ICAO) accident database (ICAO, 1988).
3. NASA's Aviation Safety Reporting System (ASRS) incident database (ASRS, 1987, 1989).

The NTSB and ICAO databases reports are the result of formal investigations. The ASRS, however, is a voluntary reporting system in which pilots, controllers, and others can submit subjective accounts about safety-related aviation incidents. The information derived from this database, since reporting is voluntary, may reflect reporting biases.

Nevertheless, the power of the ASRS lies in the report narrative. The reporters detail incidents and situations; they explain what happened, why it happened, and sometimes add suggestions for improvements.

The reports obtained from the three databases were later classified according to phase of flight and source of error, in an attempt to determine the factors that influence checklist incidents/accidents. The narratives provided in this paper do not represent a statistical sampling; they were included to be illustrative.

## WHAT IS A CHECKLIST?

The major function of the flight deck checklist is to ensure that the crew will properly configure the airplane for any given segment of flight. It forms the basis of procedural standardization in the cockpit. The complete flight checklist is sub-divided into specific task-checklists for almost all segment of the flight, i.e., PREFLIGHT, TAXI, BEFORE LANDING, etc.; and in particular before the critical segments: TAKEOFF, APPROACH, and LANDING. Two other checklists are also used on the flight-deck: the abnormal and emergency checklist. This paper will address only the normal checklist.

We believe that normal checklists are intended to achieve the following objectives:

1. Provide a standard foundation for verifying aircraft configuration that will attempt to defeat any reduction in the flight crew's psychological and physical condition.
2. Provide a sequential framework to meet internal and external cockpit operational requirements.
3. Allow mutual supervision (cross checking) among crew members.
4. Dictate the duties of each crew member in order to facilitate optimum crew coordination as well as logical distribution of cockpit workload.
5. Enhance a team concept for configuring the plane by keeping all crew members “in the loop.”
6. Serve as a quality control tool by flight management and government regulators over the flight crews.

Another objective of an effective checklist, often overlooked, is the promotion of a positive “attitude” toward the use of this procedure. For this to occur, the checklist must be well grounded within the “present day” operational environment, so that the flight crews will have a sound realization of its importance, and not regard it as a nuisance task (Nagano, 1975).

## CHECKLIST PHILOSOPHY AND OPERATING CONCEPTS

The various ways of conducting a checklist are influenced not only by the checklist device and the method of using it, but also by its “philosophy of use.” This philosophy varies among airframe manufacturers, officials of regulatory agencies, and airlines. In most cases, the checklist philosophy of use is the outgrowth of the company’s *corporate culture*. This term includes many factors that contribute to the overall operational concept of the organization, including traditional methods of operation, predefined work policies, management style, delegation of responsibilities in the chain of command, and punitive actions. The airline's culture is an important factor because it is mirrored in the manner in which flight management and training departments establish, direct, and oversee flight operations and related procedures (Degani and Wiener, 1991). The checklist philosophy of use is also an important factor in the complex FAA certification process. The same is true for any modification done to the checklist during line operations (for more details on this issue, see Degani and Wiener, 1990).

### The Device

It is obvious that the type of device in use is a factor in the checklist philosophy of use. Various types of checklist devices have evolved over the years. Among them are the scroll, mechanical, and vocal checklist (Degani and Wiener, 1990; Turner and Huntley, 1991). More modern ones involve computer-based text displayed on a CRT and electronic checklist devices that sense sub-system's state (Rouse, Rouse, and Hammer, 1982; Palmer and Degani, 1991).

The paper checklist is the most common checklist device used today in commercial operation. It has a list of items written on a paper card (see Figure 1). Usually, the card is held in the pilot's hand. Because of the wide prevalence of this device, it will be the focus of this paper.

Sanders and McCormick (1987) state that "because humans are often the weak link in the system, it is common to see human-machine systems designed to provide parallel redundancy" (p. 18). A similar principle of backup and redundancy is applied in the checklist procedure. There are two types of redundancies embedded in this procedure. The first is the redundancy between configuring the aircraft from memory and only then using the checklist procedure to verify that all items have been accomplished properly (set-up redundancy). The second is the redundancy between the two or three pilots monitoring each another while conducting the checklist procedure (mutual redundancy).

### The Method

There are two dominant methods of conducting ("running") a checklist—the *do-list* and the *challenge-response*. Each is the product of a different operational philosophy.

*Do-list*. This method can be better termed "call-do-response." The checklist itself is used to lead and direct the pilot in configuring the aircraft, using a step-by-step "cookbook" approach. The setup redundancy is eliminated here, and therefore, a skipped item can easily pass unnoticed once the sequence is interrupted.

*Challenge-response*. In this method, which can be more accurately termed "challenge-verification-response," the checklist is a backup procedure. First, the pilots configure the plane according to memory. Only then, the pilots use the checklist to verify that all the items listed on the checklist have been correctly accomplished. This is the most common checklist method used today by commercial operators.

**The Items on the List**

The fundamental decision regarding which items should be presented on the checklist is a cardinal question in checklist philosophy. Some will argue that most of the configuration items required in operating the aircraft must be presented in the checklist. Others will argue that since the checklist is a redundant task, only the most important items should be presented. An example of the conflict would be the “shoulder harness” check. Some consider this a critical item and feel it should be listed on the appropriate checklist. Others hold that the chances of an accident propagating directly from such an omission are very slim, that the use of the shoulder harness is second nature to the pilot, and therefore there is no need to include this non-critical item on the checklist.

Taking a system engineering approach, the first argument appears correct. If the checklist procedure is supposed to verify that the plane is configured correctly, then all items involved should be checked. Opponents of the above approach argue that a long and detailed checklist is no guarantee of absolute safety. Indeed, it carries the risk that some pilots might choose not to use the checklist or may conduct the procedure poorly because of its length. From a human performance approach, the second argument seems more appropriate. Since the procedure is to be used by humans in the cockpit, the checklist should accommodate “human nature”—its capabilities as well as its limitations. Nevertheless, this approach may also subsequently produce problems. The aircraft may not be configured correctly in the setup phase, and the checklist procedure will not alert the flight crews for such items.

**Level of Automation**

The use of computers on the flight deck allows for automated monitoring of flight status (Wiener, 1989). On-board computers can alert the crew when certain configuration items have not been accomplished and display the actual status of the plane. The computer can be used to verify that certain items have been accomplished and thereby substantially reduce the number of items on the checklist.

This capability has led airplane manufacturers and airlines to alter their checklist philosophies to coincide with the capability of system monitoring computers. Boeing’s B-757 normal checklist philosophy states that,

> Normal checklists are used to verify that certain critical procedural steps have been accomplished. Only procedural steps which, if omitted, would have a direct and adverse impact on normal operation are included. Items annunciated by the Crew Alerting System (EICAS) [an automated monitoring system] are not included. (Boeing B-757 flight manual, 1985)

Not all airlines employing the B-757 agree with the above philosophy, and some require their flight crews to check items even though system status is displayed by the on-board computer. The concern here is the level of reliance on automation.

The advocates of complete use of computer capabilities argue that the computer reduces workload, is far more reliable than the human in monitoring, minimizes time to perform the procedure, and thereby decreases the likelihood of checklist distractions. Opponents argue that despite software and hardware redundancies, computers do fail, and such reliance on automation might lead to an incident or accident. As examples, they point to the failures of the takeoff warning system of Northwest Flight 255 (NTSB, 1988b), and the takeoff configuration warning of Delta Air Lines Flight 1141 (NTSB, 1989). These automated systems were designed to warn the pilots of improper takeoff configuration. However, for reasons unknown in the case of the Northwest Flight 255, and due to component malfunction in Delta Air Lines Flight 1141, these systems failed to warn the crew of an improper configuration.

## SUMMARY OF OBSERVATIONS

The purpose of the field observations was to study and comprehend the system in its purest form, i.e., during routine airline cockpit operations. Observations of 42 flight crews gave us an insight into the process, the techniques, and the potential problems associated with checklist usage in the operational setting.

The observational information is presented here according to the three steps by which flight crew perform any checklist procedures: [1] *initiation*, [2] the *routine of calls and responses*, and [3] *completion*.

### Initiation

Traditionally flight crews rotate the duties of pilot flying, i.e., responsibility for controlling and navigating the airplane, between the captain and the first officer. This routine is done for sake of workload distribution and training, yet does not diminish the role of the captain as the pilot in command. The initiation of the checklist requires the pilot flying to judge when to call for the checklist, and to recall whether previous task-checklists have been done and properly completed. This process, when coupled with high workload, stress, and schedule pressures, can lead to checklist initiation errors.

Many pilots use internal as well as external cockpit cues to aid them in initiating the checklist. For example, the BEFORE START checklist can be cued by closing of passenger doors; the TAXI checklist after receiving the taxi clearance; the BEFORE TAKEOFF checklist by reaching the hold line before the runway. Checklist cues are not part of the standard operating procedures (SOP) of the airline, they are personal techniques. There are some problems with these techniques: the cues are not always present or applicable, and if pilots are occupied with other tasks, cues can pass unnoticed.

### Routine of Calls and Responses

*Memory-guided checklist*. There is temptation, on the part of experienced pilots, to memorize a checklist and avoid the burden of reading it from the card. In several instances during night operation, we observed that the checklist card was drawn out of its slot (above the glare shield), but no light was turned on to allow reading. Consequently, the checklist was performed from memory. A similar habit was observed in both day and night operation: the pilot would stretch his hand out and touch the checklist card situated on the glare shield, but would not draw the checklist out of its slot. It is interesting to note here that pilots had a habit pattern of associating a motor action (reaching for the checklist card) with the checklist procedure.

*Verification*. In some cockpits, the task of verification was left only to the pilot responding to the checklist. The pilot making the challenge calls read the checklist items but did not move his eyes away from the list to cross-check his partner. Therefore, the mutual redundancy embedded in the checklist procedure was not utilized. Often, the pilot flying would answer with the proper response immediately when he/she heard the challenge call from the pilot not flying, not verifying that the item called was set accordingly. This was evident in high workload phases of flight such as during the approach for landing. In this case, the pilot must rely on his memory to judge whether checklist items were set correctly. The setup redundancy embedded in the procedure was lost.

Several pilots who were interviewed stated that they have their own checklist procedure which they perform from memory just prior to takeoff to assure themselves that the plane is configured correctly. They viewed this as an additional safeguard against a poorly conducted checklist procedure. We found similar techniques during our observations. These memory techniques have some inherent hazards:

- They are dependent on the availability of time after the quick completion of the checklist.
- They are vulnerable to distractions such as air traffic control (ATC) communications, outside scan, starting an engine during TAXI segment, and more.
- They are based on memory, and not on a step-by-step challenge-and-response procedure.

*"Short-cutting" the checklist*. Several pilots deviated from the challenge-and-response method to a much faster routine, calling several challenge items together in one "chunk," while the other pilot would reply with a series of chunked responses. This technique undermines the concept behind the step-by-step challenge-and-response method. It is also dependent on the pilot's short-term and long-term memory as to the completion and order of checklist items. This dependency, in fact, is exactly what the checklist procedure is supposed to prevent. Interestingly, Swain and Guttman (1983) found the same routine employed by nuclear power plant operators. They defined this non-standard technique as "performing several steps and then checking them off all at once on the checklist" (chap. 16, p. 2).

When the normal checklists were lengthy, there was a tendency to perform the items while reading the checklist as a "do-list" in an effort to overcome a long and time-consuming procedure. However, by doing so, the crew sacrificed the setup redundancy embedded in the checklist. While this short-cutting technique pertained to non-critical configuration items, it can easily "migrate" to those items that are crucial to the safety of the flight.

### Completion

The lack of indication that a task-checklist is fully completed is one of the handicaps of the paper checklist. The only safeguard here is a completion call, such as "The BEFORE

START checklist is complete" made by the challenging pilot as he/she completes the checklist. Some airlines write the completion call as the last item in each task-checklist, making the call itself the final checklist item. Some choose not to list this call in the checklist, but still require the pilots to make the completion call. Other airlines disregard this call entirely.

The completion call is a redundant action. In most cases the other crew members already know the checklist is completed. However, if the pilot is distracted, the call may be the only reliable feedback available to indicate this. Furthermore, the statement that a specific checklist is complete provides a "cap" to the checklist process and enables all crew members to mentally move from the checklist to other areas of the operation with assurance of completion.

## FACTORS INFLUENCING CHECKLIST PERFORMANCE

### Perception

Several checklist-related incidents were the result of a situation in which a pilot thought he/she had set and checked a control properly, but actually had not. Perception changes constantly depending on the physical stimuli and on the way in which we blend incoming information with information already stored in memory (Foley and Moray, 1987). Therefore, the mere existence of a physical stimulus is not an absolute predictor of what the pilot will perceive and act upon while performing a task or checking the checklist items.

Many pilots interviewed by the authors stated that at one time or another they had seen a checklist item in the improper status, yet they perceived it as being in the correct status and replied accordingly. This phenomenon figured prominently in the investigation of the Delta Air Lines Flight 1141 accident in which the flight crew did not extend the airplane's flaps or slats for takeoff (NTSB, 1989). Yet, the proper checklist callouts for the takeoff flap handle position, flap indicator dial, and slat extension light were made (they were recorded on the cockpit voice recorder). During the analysis of this accident, the NTSB investigators measured the recorded time delay between the second officer's challenge ("flaps") and the first officer reply ("fifteen, fifteen, green light"). The investigators reported that "...the time between the checklist challenge and responses was less that one second, with little time to accomplish actions required to satisfy the proper response" (NTSB, 1989, p. 61).

### Cockpit Resource Management

Cockpit resource management (CRM) has been a topic of accelerating interest in the last decade, with concern being focused on the coordination, social processes, and combined performance of a multi-pilot flight crew (Foushee and Helmreich, 1988).

Checklist procedures are accomplished by coordinated actions and communication between the captain and the other pilot(s). In addition, the checklist procedure is designed in such a way as to assign very distinct role definitions. It also requires assertiveness from subordinates when the checklist is not initiated properly by the captain, as well as firm leadership by the captain when the subordinate officers are the culprits. These interactions between the CRM and the process of checklist usage makes CRM a valid area of interest in understanding checklist problems. Unfortunately, this vital area cannot be thoroughly covered here.

In a pioneering study on CRM concepts, the late H. P. Ruffell Smith noted that often crew performance suffers due to "the [captain's] failure to anticipate the overloading of a crew member by a certain combination of circumstances" (1979, p. 28). An ASRS report speaks to the same issue:

> The captain made the takeoff with total disregard of the flight engineer who was somewhat behind in his duties. The result was that the BEFORE TAKEOFF checklist was finished 10 knots prior to V1 [a critical takeoff speed]. This was not the flight engineer's fault, but the captain's. He could have waited 30 seconds for the flight engineer to properly perform his duties...(ASRS, 1987, Report No. 74174)

### Interruptions and Distractions

In a study of interruption and distractions of cockpit duties, Monan (1979) observed that "one of the frequently occurring causes of hazardous events in air carrier operation is the human susceptibility to distractions" (p. 3). He argues that due to distractions, one airman is removed from the operational loop and by that a vital cross-checking function is eliminated. The operation becomes vulnerable to any error committed during "the one-man show."

In 1983, a Republic Airlines MD-82 had both engines stop while cruising at 35,000 feet, 20 miles north of Bryce, Utah. During the emergency descent, the crew performed the appropriate emergency procedure and restarted both engines at 12,000 feet. The NTSB investigation revealed that the main fuel tank on each wing was empty while the center tank contained all the fuel needed to complete the flight.

The airline's MD-82 CLIMB checklist method required the pilot not flying to conduct this checklist by himself (no mutual redundancy). According to the procedure, center-tank fuel pumps were to be switched on shortly after takeoff. The first officer later wrote:

> ...during a turn, the captain called for the "CLIMB CHECK." Because of our weight and my being new in the plane, I thought he wanted to turn with flaps and slats extended.... I planned to go down the checklist to, but not including the hydraulic pumps [necessary for flap/slat retraction], and then wait for the flap/slat retraction command. During the checklist, as I completed the ignition off [item], he called for "flaps and slats retract." I then received a radio call to "change to departure" frequency. After flaps and slats were retracted and the radio frequency changed, I continued with the checklist as I had planned. In retrospect, it appears that I may have left the center boost pump switches off [this resulted in fuel being drawn only from the wing tanks]. (NTSB, 1983)

*Maintenance*. Maintenance duties, both inside and outside the cockpit, can also be a source of interruptions, distractions, and mis-configuration incidents. Frequently, maintenance personnel are under schedule pressures for on-time departure. While working on a malfunction, mechanics sometimes need to alter the configuration of the aircraft or disable certain systems in order to perform their duties. However, under pressure, maintenance crews may forget to reset these systems. The ASRS reports revealed several incidents in which maintenance crews pulled a circuit breaker and forgot to push it back, left the engine fuel injection levers in the idle (on) position, or unintentionally disabled an automated warning system (ASRS, 1987, 1989).

### Checklist Ambiguity

Ambiguous terms can be found even in such a verbally restricted procedure as the checklist. Many checklists examined by the authors employ the ambiguous responses "set," "checked," "completed," etc., to indicate that an item is accomplished. One ASRS report details this ambiguity and also provides the solution:

> ...I strongly feel that we need to back the response portion of our checklist with "what you see" responses [and] not just "checked and set," etc. For example "Altimeters—30.10" and not "checked"; "airspeed—125." It takes as much time to say it like it is as to say "checked and set." The problem is "checked" and "set" can be said too easily without any sound verification... (ASRS, 1987, Report No. 76798)

## DESIGNING A CHECKLIST

The following discussion will detail the considerations in designing a checklist. What follows is based on the findings from the field study and examination of the applicable human factors literature. This discussion is confined to aviation; however, the transfer to other domains should not be difficult.

### Defining the Task-Checklist

Checklists of older technology airplanes such as the L-1011, DC-9 series, and DC-10 usually have a long list of items on the BEFORE ENGINE START. Some aircraft have as many as 76 items on this task-checklist. Many pilots have complained about inadvertently skipping items in long checklists. Swain and Guttman (1983), in their study of nuclear power plant operations "recognized the fact that as the list of items grows, there may be a higher probability of overlooking any given item" (chap. 15, p. 13). A long checklist, therefore, can be sub-divided to smaller checklists. For example, the ground phase can be divided into five task-checklists: PREFLIGHT, BEFORE START, AFTER START, TAXI, BEFORE TAKEOFF. The above does not necessarily imply that every task-checklist should be divided into smaller lists. However, having a single task-checklist with 76 items may be somewhat extreme.

There are several principles that can be employed if the designer is constrained to use a long list of items. Wickens (1987) states that "...where printed information is read, stored and used (as in instructions, procedures, etc.), the retention process can be aided by [1] determining the logical chunks that are grouped together in memory, and [2] physically separating these chunks from others" (p. 82). The designer can apply these principles for checklist design by:

- Grouping the items corresponding to a system such as pressurization, hydraulic, electrical, etc., into chunks of checklist items.

- Physically (graphically) separating these chunks while designing the layout of the checklist card.

**The Order of Checklist Items**

The order of the items is the only indicator as to the pilot's point of progress in the checklist ("where are we on the checklist...?"). Therefore, it becomes an important structural format in an effort to reduce the potential for failure while conducting this procedure.

*Systems operational sequence*. In a complex system, it is clear that tasks must be sequenced according to the activation and operation of units and systems. For example, it would not be appropriate to check hydraulic pressure prior to activation of hydraulic pumps. This type of sequencing is most stringent in starting the engines and in activating related systems such as electrical, hydraulic, pneumatic, etc. Other duties such as checking altimeters, setting speed markers, brakes, lights, etc., are not so stringently coupled with prior activities. In such cases, the designer has flexibility to allocate these items in a sequence that will be most advantageous to his structured design.

*Patterns of motor and eye movements*. In the cockpit of an airplane, the instruments, units, and systems panels are arranged in a certain "geographical" location according to frequency of use, criticality, and other human factors considerations (Sanders and McCormick, 1987). In order to facilitate a logical flow while initially configuring the plane, airline training departments require that this task be conducted in a particular sequence of motor and eye movements. They call this the cockpit's "flow-pattern."

Likewise, the use of a structured flow in conducting the actual (as opposed to initial) checking procedure can enhance the checklist task in the following ways:

- Making the checklist sequence parallel to the initial set up flow-patterns.
- Making the checklist actions logical and consistent (as opposed to intermittent) in the motor movement of the head, arms and hands.
- Providing greater accuracy by combining two processing channels: spatial (flow patterns) and verbal (challenge-response) (Booher, 1975).
- Providing an association between location and sequence, making it more difficult to skip an item.

Besides visual verification of the check item, motor movements such as touching controls and displays ("muscle memory" as some define it), are also an effective enhancement for the verification process. The use of the hand to guide the eye while conducting the check, can substantially aid the checklist procedure by combining the mental sequencing process with motor movements.

*The operational logic*. Certain tasks that are part of the checklist are dependent on agents external to the cockpit such as flight attendants, gate agents, fuelers, etc. When designing the chronological and logical sequence of the checklist, the influence of these "uncontrollable" entities must be addressed.

A task-checklist that includes items that do not run parallel to the activities occurring around the plane has an inherent disadvantage. Omission of checklist items sometimes occurs when an item that could not be completed in sequence (because of the above limitations) is deferred by the crew to be accomplished later on. Since the paper checklist has no means of prompting the pilot about such unaccomplished items, the pilot attempts to store any deferred items in memory. Yet due to the limitations of human memory, coupled with time constraints, and the vulnerability of the crew to distracting events, the likelihood of these items being omitted is somewhat high.

The following narrative illustrates how the crew deferred checking the fuel on the preflight checklist, and the ramifications.

> Prior to departure from Denver, as the preflight checklists were being accomplished, it was noted that the plane was not fueled yet. The crew continued [deferred the item for later completion] in accomplishing the rest of the checklist and related preflight duties. Approximately ten minutes after takeoff the second officer noted that the plane was not fueled. The flight returned to Denver for additional fuel. At company Denver facilities, experience dictates that dispatch fuel is not on board prior to completion of the pre-flight checklist in approximately 75% of departures... (ASRS, 1987, Report No. 2855)

*Sequencing of very critical items*. We previously stated that one of the important duties of the captain in managing checklist duties is to call for the task-checklist at the appropriate time. In a well managed crew, the pilot manipulating the controls will call for the task-checklist when the workload and the probability of interruption is low. For example, the captain will usually call for the TAXI checklist after the plane is clear of all obstacles on the ramp, all systems are working, instructions for taxiing are known, etc. At this instant, the probability of successfully accomplishing the first item on the TAXI checklist is the highest. However, the probability of accomplishing the subsequent items without an interruption diminishes as time progresses. For this reason we recommend that very critical items should be completed first on the task-checklist, and not last.

*Duplication of checklist items*. Few airlines have opted to repeat several checklist items for redundancy and therefore reduce the probability of skipping an important item by the flight crew. Although this additional redundancy in the checklist might prevent an item from being missed, overemphasis of many items can degrade the crew's overall checklist performance. Flight crews may degrade the importance of these items if they are being checked several times prior to takeoff.

On the other hand, some items such as flap/slat and stabilizer-trim setting may need to be re-set while taxiing because of runway changes or update of weight information. To prevent a delay in performing these items (while awaiting new information) and in order to check the updated setting, we believe that duplication of a very few highly critical items can be advantageous. In this respect, critical items are those whose omission can alone lead to an accident. Pilots call them "killer items."

We have now advocated conflicting principles: brevity of checklists and repetition of critical items. This is not the only case where conflicting principles will occur. In a complex operational issue such as flight-deck checklists, no absolute list of principles can be religiously adhered to by the designer. The application of such principles is so much affected by the type of aircraft (and its systems), the organization's modes of operation, and the organizational philosophy of operation (Degani and Wiener, 1991).

## THE CHECKLIST AS A SYSTEM

The manner in which checklists are designed, taught, and used can be examined by employing two concepts from systems analysis: *complex interactions* and *coupling*.

As high-risk systems grow in size and diversity, they tend to become more complex. These systems may include interactions that were not intended by the system designers. One of the reasons for a system failure in high-risk industries is the unpredictable interaction of several failed components (Perrow, 1984, 1986).

Coupling relates to the amount of slack or buffers between system components. Usually this factor is time dependent. In tightly coupled systems, such as nuclear power plant, there is only a small slack or buffer between system components. Time is a critical factor; the product cannot stand by until attended. It must be processed immediately and sequentially.

### Interactions and Coupling in the Checklist Procedure

The same characteristics that typify a large system apply also to the checklist procedure. Evidently, the checklist procedure does not have the characteristics of a system with complex interactions. The checklist process requires verifying configuration items in a linear and independent manner. One may argue that the checklist is a loosely coupled system: the checklist process can be stopped or delayed without affecting the outcome.

However, in daily line operations the reality is sometimes very different. The checklist can easily be transformed into a non-linear and tightly-coupled procedure. This transformation can be caused by [1] *operators*, [2] *checklist designers*, and [3] *management*.

*Operators*. The cockpit crew, in particular the captain, can tightly couple the checklist procedure to other tasks such as starting engines, takeoffs, landing, etc. This point was amplified previously.

*Checklist design*. The same concept of tightly coupling the checklist to other systems is sometimes carelessly “designed into” the checklist procedure. For example, several companies require that the TAKEOFF checklist should be accomplished on the active runway, or just prior to entry onto the runway. In this case, the TAKEOFF checklist is tightly coupled with other tasks such as receiving and monitoring ATC communication, sequencing with other aircraft on the final approach, engine and system monitoring, and with the pilots’ mental preparation for takeoff. Not foreseeing these interactions, the designer may provide the potential for tight coupling of these urgent and demanding tasks with critical checklist items. We recommend that these critical checklist items be completed earlier in the ground phase in order to decouple them from the takeoff segment as well as to allow enough time (buffers) for the crew to detect and recover from a configuration failure.

*Management*. One of the characteristics of any tightly coupled system is that it is efficient. However, this efficiency is purchased at a cost: a tightly coupled and extremely efficient system is more prone to failure (Perrow, 1986). The Airline Deregulation Act of 1978 has forced airline companies to confront the issue of efficiency as never before, or face the possibility of not surviving in a competitive environment.

Management pressure for "on-time performance" is one factor that yields high operating efficiency. Air transports fly in and out of hubs with fast turnarounds. The Department of Transportation monitors flight schedules in order to publish the highest and lowest ranking airlines in "on-time performance," placing another public relations burden on management. Such production pressures ultimately migrate into the cockpit, and consequently affect checklist management.

The checklist procedure is highly susceptible to production pressures. These pressures lay the foundation for errors by encouraging sub-standard performance when the crew is rushing to complete the checklist in order to depart on time. Furthermore, under production pressures, checklists are sometimes "...relegated to second place status in order to save time" (Majikas, 1989).

To conclude, flying an aircraft is a tightly coupled and a complex system by nature. However, when micro-systems such as checklists are practically made tightly coupled and non-linear, the result may be a checklist related incident or accident.

## GUIDELINES FOR CHECKLIST DESIGN AND USAGE

Based on this study we propose a list of guidelines for designing and using flight-deck checklists. These considerations are not specifications, and some, when applied individually, may conflict with others. Therefore, each should be carefully evaluated for its relevance to operational constraints. We feel, however, that these guidelines can also apply, with some adjustments, to other industries.

1. Checklist responses should portray the desired status or the value of the item being considered, not just "checked" or "set."
2. The use of hands and fingers to touch, or point to, appropriate controls, switches, and displays while conducting the checklist is recommended.
3. A long checklist should be subdivided to smaller task-checklists or chunks that can be associated with systems and functions within the cockpit.
4. Sequencing of checklist items should follow the "geographical" organization of the items in the cockpit, and be performed in a logical flow.
5. Checklist items should be sequenced in parallel with internal and external activities that require input from out-of-cockpit agents such as cabin crew, ground crew, fuelers, and gate agents. We note here that this guideline could conflict with No.4.
6. The most critical items on the task-checklist should be listed as close as possible to the beginning of the task-checklist, in order to increase the likelihood of

completing the item before interruptions may occur. We note that this guideline could conflict with Nos. 4 and 5 above. In most cases where this occurs, this guideline (No. 6) should take precedence.

7. Critical checklist items such as flaps/slats, trim setting, etc., that might need to be reset due to new information (arriving after their initial positioning), should be duplicated on the ground phase checklists.
8. The completion call of a task-checklist should be written as the last item on the checklist, allowing all crew members to move mentally from the checklist to other activities with the assurance that the task-checklist has been completed.
9. Critical checklists, such as the TAXI checklist, should be completed early in the ground phase in order to decouple them from the takeoff segment.
10. Checklists should be designed in such a way that their execution will not be tightly coupled with other tasks. Every effort should be made to provide buffers for recovery from failure and a way to “take up the slack” if checklist completion does not keep pace with the external and internal activities.
11. Flight crews should be made aware that the checklist procedure is highly susceptible to production pressures. These pressures set the stage for errors by possibly encouraging substandard performance, and may lead some to relegate checklist procedures to a second level of importance, or not use them at all.

## ACKNOWLEDGMENTS

This paper is based on NASA Contractor Report No. 177549 by the authors. The research was performed under grant NCC2-377 from NASA Ames Research Center to the University of Miami. The technical monitor was Everett Palmer. The cooperation of America West Airlines is deeply appreciated, as well as that of the following individuals: Michael Vandermark, James Carr, and Randall Kempf of America West Airlines; William Edmunds and Don Jefferson of the Air Line Pilots Association (ALPA). The authors thank Stephen Casner, Sheryl Chappell, Kevin Corker, Victor Lebacqz, and Leon Segal for providing helpful suggestions.

## REFERENCES

ASRS. (1987). Erroneous flap setting; checklist use (Special Request No. 1177/1182 [Database search]). ASRS office, Mountain View, CA: Battelle.

ASRS. (1989). Erroneous flap setting; checklist use (Special Request No. 1503 [Database search]. Update of special request No. 1177/1182). ASRS office, Mountain View, CA: Battelle.

Booher, H. R. (1975). Relative comprehensibility of pictorial information and printed words in procedural instructions. *Human Factors, 17*, 266-277.

Curry, R. E. (1985). *The introduction of new cockpit technology: A human factors study.* (NASA Technical Memorandum 86659). Moffett Field, CA: NASA Ames Research Center.

Degani, A., and Wiener, E. L. (1990). *The human factors of flight deck checklists: The normal checklist* (NASA Contractor Report 177549). Moffett Field, CA: NASA Ames Research Center.

Degani, A. and Wiener E. L. (1991). Philosophy, Policies, and Procedures: The Three P's of Flight-Deck Operations. *Proceedings of the Sixth International Symposium on Aviation Psychology* (pp. 184-191). Columbus, OH: The Ohio State University.

Foley, P., and Moray, N. (1987). Sensation, perception, and system analysis. In G. Salvendy (Ed.), *Handbook of human factors* (pp. 45-71). New York: John Wiley & Sons.

Foushee, H. C., and Helmreich, R. L. (1988). Group interaction and flight crew performance. In E. L. Wiener and D. C. Nagel (Eds.), *Human factors in aviation* (pp. 189-227). San Diego: Academic Press.

ICAO. (1988). Occurrences related to checklists [Database search, ADREP request 121/88/USA]. Montreal, Quebec: Author.

Lyall, E. A. (1990). *The effects of mixed fleet flying of B-737-200 and B-737-300.* Unpublished doctoral dissertation. Arizona State University, Phoenix.

Majikas, M. L. (1989, May). Set and checked. *Air Line Pilot*, pp. 12-15.

Monan, W. P. (1979). *Distraction—A human factor in air carrier hazard events* (NASA Technical Memorandum 78608, pp. 2-23). Moffett Field, CA: NASA Ames Research Center.

Nagano, H. (1975). Report of Japan Air Lines (JAL) Human Factors Working Group. *Proceedings of the International Air Transport Association (IATA) Twentieth Technical Conference*. Montreal: International Air Transport Association.

National Transportation Safety Board. (1969). *Pan American World Airways. Boeing B-707 N799PA. Anchorage, Alaska. December 12, 1968*. Washington, DC.

National Transportation Safety Board. (1983). *Republic DC-9-82 N1004F. Flight 303, April 2, 1983* [Incident report]. Washington, DC.

National Transportation Safety Board. (1988a). Accident/incident regarding checklists [Database search]. Washington, DC.

National Transportation Safety Board. (1988b). *Northwest Airlines. DC-9-82 N312RC, Detroit Metropolitan Wayne County Airport. Romulus, Michigan. August 16, 1987* (Aircraft accident report, NTSB/AAR-88/05). Washington, DC.

National Transportation Safety Board. (1988c). Safety recommendations regarding checklists [Database search]. Washington, DC.

National Transportation Safety Board. (1989). *Delta Air Lines, Boeing 727-232, N473DA. Dallas-Fort Worth International Airport, Texas. August 31, 1988* (Aircraft accident report, NTSB/AAR-89/04). Washington, DC.

National Transportation Safety Board. (1990). *USAir, Inc., Boeing 737-400, N416US. LaGuardia Airport. Flushing, New York. September 20, 1989* (Aircraft accident report, NTSB/AAR-90/03). Washington, DC.

Palmer, E. A., and Degani, A. (1991). Electronic checklist: Evaluation of two levels of automation. *Proceedings of the Sixth International Symposium on Aviation Psychology* (pp.178-183). Columbus, OH: The Ohio State University.

Perrow, C. (1984). *Normal accidents*. New York: Basic Books.

Perrow, C. (1986). *Complex organizations* (3 ed.). New York: Random House.

Rouse, S. H., Rouse, W. B., and Hammer, J. M. (1982). Design and evaluation of an on-board computer based information system for aircraft. *IEEE Transactions on System, Man, and Cybernetics, 12*, 451-463.

Ruffell Smith, H. P. (1979). *A simulator study of the interaction of pilot workload with errors, vigilance, and decisions* (NASA Technical Memorandum 78482). Moffett Field, CA: NASA Ames Research Center.

Sanders, M. S., and McCormick, E. J. (1987). *Human factors in engineering and design* (6th ed.). New York: McGraw-Hill.

Swain, A. D., and Guttman, H. E. (1983). *Handbook of human reliability analysis with emphasis on nuclear power plant applications* (NUREG/CR-1278). Washington, DC: NRC.

Turner, J. W., and Huntley M. S. (1991). *The use and design of flight crew checklists and manuals* (DOT/FAA/AM-91/7). Cambridge, MA: National Transportation System Center.

Wickens, C. D. (1987). Information processing, decision making, and cognition. In G. Salvendy (Ed.), *Handbook of human factors* (pp. 126-127). New York: John Wiley & Sons.

Wiener, E. L. (1985). *Human factors of cockpit automation: A field study of flight crew transition* (NASA Contractor Report 177333). Moffett Field, CA: NASA Ames Research Center.

Wiener, E. L. (1989). *The human factors of advanced technology ("glass cockpit") transport aircraft* (NASA Contractor Report 177528). Moffett Field, CA: NASA Ames Research Center.