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ATC/Pilot Voice Communications – A Survey of the Literature

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16. Abstract

The first radio-equipped control tower in the United States opened at the Cleveland Municipal Airport in 1930. From that time to the present, voice radio communications have played a primary role in air safety. Verbal communications in air traffic control (ATC) operations have been frequently cited as causal factors in operational errors and pilot deviations in the FAA Operational Error and Deviation System, the NASA Aviation Safety Reporting System (ASRS), and reports derived from government-sponsored research projects. Collectively, the data provided by these programs indicate that communications constitute a significant problem for pilots and controllers. Although the communications problem was well known the research literature was fragmented, making it difficult to appreciate the various types of verbal communications problems that existed and their unique influence on the quality of ATC/pilot communications.

This is a survey of the voice radio communications literature. The 43 reports in the review represent survey data, field studies, laboratory studies, narrative reports, and reviews. The survey topics pertain to communications taxonomies, acoustical correlates and cognitive/psycholinguistic perspectives. Communications taxonomies were used to identify the frequency and types of information that constitute routine communications, as well as those communications involved in operational errors, pilot deviations, and other safety-related events. Acoustical correlate methodologies identified some qualities of a speaker's voice, such as loudness, pitch, and speech rate, which might be used potentially to monitor stress, mental workload, and other forms of psychological or physiological factors that affect performance. Cognitive/psycho-linguistic research offered an information processing perspective for understanding how pilots' and controllers' memory and language comprehension processes affect their ability to communicate effectively with one another.

This analysis of the ATC/pilot voice radio communications literature was performed to provide an organized summary for the systematic study of interactive communications between controllers and pilots. Recommendations are given for new research initiatives, communications-based instructional materials, and human factors applications for new communications systems.

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ATC/PILOT VOICE COMMUNICATIONS — A SURVEY OF THE LITERATURE

"When I use a word," Humpty Dumpty said, "it means just what I choose it to mean neither more nor less."

— Lewis Carol

I. INTRODUCTION

Pilots and air traffic control specialists (ATCS)[1] operate as teams to ensure the safe and efficient use of the Nation's airspace so that passengers and cargo arrive safely at their destinations. The Airman's Information Manual (AIM) states that the pilot in command of an aircraft is directly responsible for and is the final authority as to the operation of that aircraft. The air traffic controller is responsible to 1) give first priority to the separation of aircraft and to the issuance of radar safety alerts, 2) second priority to other services that are required, but do not involve separation of aircraft, and 3) third priority to additional services to the extent possible (para 5-71). Efficient, accurate, and timely information transfer between pilots, their crew, and controllers is critical for these teams to operate effectively.

Air traffic control/pilot voice radio communications illustrate some of the redundancies that are built into the ATC system to compensate for potential emergencies and errors. The readback/hearback loop is a communications procedure developed for actively listening and confirming messages between pilots and controllers. A typical ATCS/pilot communication consists of 4 parts: (1) ATCS sends message, (2) Pilot actively listens to the message, (3) Pilot repeats the message back to the ATCS, and (4) ATCS actively listens for a correct readback for confirmation. Although either can initiate a transaction, the exchange of information between them begins once the controller accepts responsibility for an aircraft requesting permission to enter his/her assigned airspace. Aircraft call signs, altitudes, crossings, airspeeds, radio frequencies, and other pertinent information might be included in a readback by the recipient to ensure that the transmitted information was received and understood correctly. Unlike Humpty Dumpty, controllers and pilots do not have the luxury of assigning meanings to words. To do so could have catastrophic results. Pilots and controllers use a standard phraseology[2] to minimize the likelihood that a transmission is misinterpreted in order to achieve a mutual understanding of the pilot's intentions.

Problems in information transmission, reception, or comprehension can occur at any point in this communication chain. The role of the ATC specialist within this chain is to issue a correct clearance to the correct aircraft and then ensure that the pilot correctly reads back that clearance. If the occurrence of an incorrect pilot readback goes undetected, then the controller may be cited with a "systems deviation" (Monan, 1988, p. 5). If a loss in maintaining minimum separation between aircraft or obstructions should result, then the responsible controller could be cited with an operational error. Although misunderstandings and other forms of miscommunications occur, many are corrected through recipient requests for clarification, additional information, message repetition, or when faulty readbacks are detected; however, these extra communications increase radio frequency congestion and reduce the efficiency of information transfer.

Overview of the Information Transfer Problem

The literature presented and summarized in this document was obtained from survey data, field and laboratory studies, narrative reports, and reviews. A total of 43 reports are represented. Table 1 provides a

[1] ATCS and controller are interchangeable terms used to refer to an air traffic control specialist.

[2] These words and phrases can be found in the AIM or the 7110.65 Air Traffic Control Pilot/Controller Glossary.

Table 1

An overview to the ATC/pilot voice radio communications literature.

Data Source

Approaches	Survey	Field	Laboratory
Taxonomic Approach	Grayson & Billings (1981) -ASRS	Gellman Research Associates (1987) -ATC tapes	Kanki & Foushee (1989) -Simulation study
	Monan (1986) -ASRS	Golaszewski (1989) -ATC tapes	Human Technologies, Inc. (1991) -Simulation study -Audio/video ATC tapes
	Pope (1986) -ASRS	Morrow, Clark, Lee & Rodvold (1990) -ATC tapes	Foushee, Lauber, Baetge & Acomb (1989) -Simulation study
	Monan (1988) -ASRS	Morrow, Lee & Rodvold (1990) -ATC tapes	
	Morrison & Wright (1989) -ASRS	Clark, Morrow & Rodvold (1990) -ATC tapes	
	ASRS (1990)	Morrow, Rodvold & Lee (under review) -ATC tapes	
	Spence (1992) -ASRS	Morrow, Lee, & Rodvold (1991) -ATC tapes	
	Billings & Cheaney (1981) -ASRS	Cardosi & Boole (1991) -ATC tapes	
	Monan (1983) -ASRS	ATH Report on September Readback Survey (1989) -ATC tapes and survey data	
	Work Group on Human Factors Relating to Controller and Pilot Errors (1991) -ASRS		
Acoustical Approach	Ruiz, Legros & Guell (1991) -Literature survey	Williams & Stevens (1972) -Tapes of Hindenburg radio voice broadcast	Brenner, Shipp, Doherty & Morrisey (1985) -Lab study
	Tomilin & Pikovskiy (1979) -Personal accounts	Dornheim (1991) -LA tower tape	Brenner & Shipp (1987) -Lab study

Table 1 (cont)

An Overview to the ATC/Pilot Voice Radio Communications Literature.

	Data Source		
Approaches	**Survey**	**Field**	**Laboratory**
Acoustical Approach	Borden & Harris (1984) -Textbook	Brenner & Cash (1991) -Valdez radio voice transmissions	Hecker, Stevens, von Bismarck & Williams (1968) -Lab study
			Alpert & Schneider (1987) -Lab study
Cognitive Psycho-linguistic Approach	Navarro (1989) -Literature survey	Salt Lake City Study (1991) -Interviews, reports -ATC tapes	Bisseret (1971) -Lab study
	McCoy & Funk (1991) -NTIS	Morrow & Rodvold (1992) -ATC tapes	Loftus, Dark & Williams (1979) -Simulation study
	Adams & Hwoschinsky (1991) -ASRS	Clark & Schaefer (1987) -Telephone operator tapes	Schweickert & Hayt (1987) -Lab study
		Mitre Corporation (1990) -Observations	Morrow & Rodvold (1992) -Simulation study

summary of the reports and their derivation. Bold faced terms are defined in the Glossary. Italicized words and phrases reference corresponding terms presented in cited tables.

Information transfer between air traffic control specialists and pilots is the most frequently reported problem cited in the Aviation Safety Reporting System (ASRS). Controller and pilot communication techniques are qualitatively different. The ASRS data suggest that controllers often deliver information too rapidly, fail to detect erroneous pilot readbacks, or fail to verify pilot readbacks. Pilots tend to use non-standard phraseology, truncate their readbacks, fail to issue a readback, or do not ask for clarification when information is unclear. Although the ASRS is valuable in tracking problems, it fails to explain why such problems arise (Spence, 1992).

Based on the findings of the Work Group on Human Factors Relating to Controller and Pilot Errors, verbal miscommunications in (ATC) operations have been identified as *a causal factor in operational errors* and pilot deviations (Final Report, in preparation). For example, some ASRS database studies shed light on the severity of miscommunications in flight safety and identify procedural factors associated with miscommunications (Billings & Channey, 1981; Monan, 1983, 1986). A comprehensive analysis of survey reports that focused on controllers monitoring pilot readback procedural deviations led to the development of a readback taxonomy that included frequency of occurrence by type of readback error (commissioned by the Office of Air Traffic System Effectiveness (ATH), 1989). Cardosi (in process) is currently in the process of analyzing tapes to identify the frequency of occurrence of specific communication practices; whereas, other researchers have analyzed actual ATC/pilot voice tapes of routine operations to 1) identify and classify the frequency of occurrence of various types of information (i.e., speech acts) contained in a communication (Morrow, et al., 1990; Clark, et al., 1990), 2) record the frequency and type of communication error present in operational errors (Golaszewski, 1989), and 3) identify and report the frequency of occurrence of ATC communication task components during live and simulated environments (Human Technologies, Inc., 1991).

The draft of the Work Group's final report further states,

> A review of relevant research work and operational analyses on errors in pilot-controller communication by the Work Group indicated that current analyses have focused primarily on the counting and description of pilot-controller communication errors, with little systematic work on developing explanations or examining the causes of errors (Work Group on Human Factors Relating to Controller and Pilot Errors, draft of the Final Report, 1992 , p. 9).

Purpose of the Report

Although there are many potential uses for this report, it was initiated to address 3 basic questions: 1) What is known about ATC/pilot voice communications and the issues pertaining to miscommunications? 2) What approaches have been used to study miscommunications? 3) What research needs to be performed so that real solutions can be offered to the aviation community?

To answer the first question, a survey of the existing ATC/pilot communications literature was performed.

To answer the second question, the literature was organized according to the different methodological approaches employed. This allowed identification of research gaps relevant to understanding ATC/pilot communication problems.

Finally, once the problems were identified, then the third question could be addressed by providing recommendations and guidelines for considering these issues. This report provides an organized summary of the ATC/pilot voice communications literature and a framework for the systematic study of interactive ATC/pilot verbal communications.

II. LITERATURE REVIEW

This literature review addresses some of the human factors issues that may contribute to air traffic control/pilot verbal miscommunications. The materials are presented in a general, chronological progession in each of the 3 major sections. The Communications Taxonomic Approaches Section presents communications taxonomies developed from data obtained from the Aviation Safety Reporting System (ASRS), audiotaped voice radio communications, and laboratory-based studies. These taxonomies defined types, frequencies, and possible sources or catalysts of verbal miscommunications. The Acoustical Correlates Approaches Section presents several methodological approaches that examined changes in some acoustic-phonetic properties of the human voice under conditions associated with miscommunications. The Cognitive/Psycholinguistic Approaches Section provides an information processing perspective to air traffic control (ATC) communications, research on short-term memory and communications, and how interactive conversation strategies reduced voice-based communications problems.

Communications Taxonomic Approaches

Overview

Various individuals, groups, and organizations have systematically arranged ATC/pilot voice communications into groups or categories according to some criteria; that is, they developed taxonomies. Two major groups of communications taxonomies are presented: ASRS-databased communications taxonomies and the speech act communications taxonomies. Reports were derived from survey (45%), field (41%), and laboratory (14%) data sources. The materials presented in this section made up approximately 51% of the 43 collected reports and are summarized in Table 2.

Early research in communications taxonomies focused on identifying the frequency of miscommunications between air traffic controllers and pilots. The NASA ASRS database was used in all the early studies; from this, the readback/hearback loop was developed. Early on, a taxonomy of miscommunications was developed, which basically divided miscommunications

Table 2

An overview to the taxonomic approach literature.

Data Source		
Aviation Safety Reporting System	**Audio Tape Analyses**	**Laboratory-Based Studies**
Grayson & Billings (1981) -Communication problems in flight operations	Gellman Research Associates (1987) -Pilot-controller readback errors	Kanki & Foushee (1989) -Communication as group process mediator of aircrew performance
Monan (1986) -The hearback problem	Golaszewski (1989) -Read-back errors	Human Technologies, Inc. (1991) -Controller communication in en route control
Pope (1986) -The hearback problem	Morrow, Clark, Lee & Rodvold (1990) -Collaboration in controller-pilot communication	Foushee, Lauber, Baetge, & Acomb (1989) --Crew factors in flight operations
Monan (1988) -The hearback problem	Morrow, Lee & Rodvold (1990) -Routine pilot-controller communication	
Morrison & Wright (1989) -Communication problems in ATC	Clark, Morrow & Rodvold (1990) -Routine communication in the ATC system	
ASRS (1990) -Human factors workshop briefing	Morrow, Rodvold & Lee (under review) -Nonroutine controller-pilot communication	
Spence (1992) -Communications problem	Morrow, Lee & Rodvold (1991) -Collaboration in controller-pilot communication	
Billings & Cheaney (1981) -Information transfer problem	Cardosi & Boole (1991) -Pilot response to control calls	
Monan (1983) -The callsign problem	ATH Report on September Readback Survey (1989) -Readbacks	
Work Group on Human Factors Relating to Controller and Pilot Errors -Controller and pilot errors		

into macro categories. Later, studies were conducted using audiotape analysis that developed better communications taxonomies. A speech act coding scheme was developed by Kanki and Foushee (1989) and modified by Morrow, et al. (1990) to catalogue routine and non-routine pilot-controller voice radio communications. Most of these audiotapes came from the TRACON[3] environment. Finally, beginning around 1990, simulation, survey, and field studies were performed that examined differences in communication patterns and controller task categories. One simulator study that examined controllers communications individually and as team performance, indicated that top-rated en route controller teams issued more reports and smaller units of information than lower-rated teams (Human Technologies, Inc., 1991).

(NASA) Aviation Safety Reporting System (ASRS)

Much of the early air traffic control voice radio communications research focused on determining the impact of ATC/pilot miscommunications on air safety. This was accomplished by tallying the frequency with which miscommunications were cited in filed reports to the ASRS. The ASRS is an independent third-party that receives and analyzes reports, as specified by the Aviation Safety Reporting Program. This program was developed by the FAA to "stimulate the free and unrestricted flow of information concerning deficiencies and discrepancies in the aviation system ... a program intended to ensure the safest possible system by identifying and correcting unsafe conditions before they lead to accidents" (P7-81, AIM). "Problems in the transfer of information within the aviation system were noted in over 70% of 28,000 reports submitted by pilots and air traffic controllers ... during a 5-year period 1976-1981. These problems are related primarily to voice communications ..." (p. 1, Billings and Cheaney, 1981). Grayson and Billings (1981) indicated that 70% of the reports submitted to ASRS between May 1, 1978 and August 31, 1979, involved some type of oral communications problem between flightcrews and air traffic controllers (p. 48). There were 6,527 reports in which 5,402 information transfer problems were found. Some of the reports contained more than 1 information transfer related problem. Using a coding scheme developed by the research team, these problems were classified into 10 generic types of communications problems, as shown in Table 3. From these and similar reports (Monan, 1983), it became apparent that miscommunications occurred with such frequency as to be considered a problem for air traffic safety. For example, Monan (1986) noted that out of 763 incidents reported to the ASRS during a 29-month time interval, 417 were due to misunderstandings, misinterpretations, mis-transmissions or unheard numbers in ground-to-air communications. From these pilot and controller-generated narrative reports, an analyst tabulated the frequency with which a misheard communication resulted in a hazardous incident. Four classifications emerged from the reports. As shown in Table 4, approximately 90% of the 417 hazardous incidents reported to the ASRS were classified as the result of ATC/pilot miscommunications stemming from misheard altitude/flight levels and headings. As shown in Table 5, active listening during information transfer was a major problem for both air traffic controllers and pilots. One clear pattern was identified as contributing to the mishearing of numeric content: 1 sentence clearance requiring 2 or more separate pilot actions (e.g., crossing, change in altitude, change in speed).

Pope (1986), citing Monan (1986), states "No other essential activity in aircraft operations is as vulnerable to failure through human error and performance limitations as spoken communication."

Morrison and Wright (1989) reviewed the narrative reports submitted to the ASRS database from January, 1986 to September, 1988. Variables of interest associated with ATC communication problems included controller workload, traffic volume, frequency congestion, ATC communications, and facility management policy. Forty-two percent of the 340 incident reports were filed by controllers. As shown in Table 6, errors were divided into 3 major groupings: *Controller Performance Errors*, *Communication Errors*, and *Environmental Factors*. Pilot errors were only briefly mentioned in

[3] TRACON is an acronym for Terminal Radar Approach Control

Table 3

Grayson and Billings (1981). Categorization of pilot/ATC oral communication problems.

Category	Number of Reports	Definition
Other inaccuracies in content	792	1) erroneous data (formulation errors) 2) errors in judgment 3) conflicting interpretation
Ambiguous phraseology	529	message composition, phraseology, or presentation could lead to a misinterpretation or misunderstanding by the recipient
Incomplete content	296	originator fails to provide all the necessary information to the recipient to understand the communication
Inaccurate (transposition)	85	misunderstanding due to the sequence of numerals within a message
Misinterpretable (phonetic similarity)	71	similar-sounding names or numerics led to confusion in meaning or in the identity of the intended recipient
Absent (not sent)	1,991	failure to originate or transmit a required or appropriate message
Untimely transmission	710	message not useful to the recipient because it arrived too early or too late
Garbled phraseology	171	content of the message lost or severely distorted to the point where the recipient could not understand the intended message
Absent (equipment failure)	153	equipment malfunction resulting in a complete loss of a message
Recipient not monitoring	553	failure to maintain listening watch, proper lookout, or read available correct information

Table 4

Monan (1986). Types of hazardous incidents resulting from misheard ATC/Pilot communications.

Types of Incidents	No. of Incidents
Deviations from Assigned Altitude/Flight Levels	232
Deviations in Headings	143
Failures to "Hold short" of the Active Runway and Similar on-the-ground Mishaps	34
Deviations in Airway Routings	8
Total	417

Table 5

Monan (1986). Link failures in the ATC/Pilot communications chain.

Failure Modes	Number of Citations
ATC message numerics transmitted correctly but heard incorrectly, and hearback failed	328
• Misheard ATC clearance/instruction numerics	174
• Cockpit mismanagement resulting in readback errors: complacency, fatigue, etc.	71
• Inadequate acknowledgements with subsequent flight deviations ("Roger", "So Long", "Okay")	46
• Apparent inattention to amendments to ATC clearances/instructions	38
ATC message numerics transmitted, heard, and read back correctly but followed by deviations due to cockpit mismanagement	71
• Misuses of altitude alerter display	46
• Other - - primarily "forgetting"	25
Acknowledged controller hearback failures	298
• Failure to hear error in pilot readback	174
• Source of numeric error unknown (either in transmission or receiving - - insufficient detail in report), but not heard in readback	86
• Clearance amendment not acknowledged by pilot and not challenged by controller	38

this paper. Factors that predisposed controller performance errors were mainly errors of omission; controllers failed to perform a function as expected or needed. The top 5 workload factors affecting controller performance were:

1) Large numbers of aircraft,
2) Frequency congestion,
3) Combined positions/sectors,
4) Conflict resolution, and
5) Inclement weather.

Frequency congestion included 1) stepped on transmissions due to large numbers of aircraft being worked on a frequency, 2) continuous controller transmission to a series of aircraft without a break for pilots to reply, 3) clipping, and 4) no breaks in communications between the controller and the aircraft being worked. *Combined positions/sectors* occur when a single controller is assigned to work all the positions making up a sector (generally 3 positions). For example, a facility may have 1 controller work all the positions due to staffing, traffic load, and time of day factors. Mid-shift (midnight to 8 A.M.) may only require a single controller to work the traffic making up the local, ground and clearance delivery positions. *Conflict resolution* involved an awareness of an impending conflict before it become one; not its resolution. For example, 2 aircraft are on a converging course, the controller becomes distracted, the CA symbol (conflict alert) present on the radar screen brings the controller back to the situation. The controller knew it was going to be a problem but did not act upon all the available information at the time. (Personal communication with R. H. Wright, March, 1993). Communications errors were primarily errors of commission that involved either ATC procedural or verbal mistakes. A further categorization of communications errors is presented in Table 7. Heavy traffic, resulting in controller overload and frequency congestion, was identified as the main factor associated with communications errors. No statistics were provided in this report.

The next major area of survey research developed macro categories of miscommunications. For example, 5 key communication problems present within the aviation environment were identified (ASRS, 1990):

1) Frequency congestion,
2) Similar sounding call signs,
3) Pilot frequency monitoring failures,
4) Controller monitoring failures, and
5) Pilot failures to verify doubtful communications.

Pilot and controller communications techniques included:

1) Problems during message composition,
2) Message production (i.e., transmission),
3) Message verification, and
4) Message comprehension.

According to the ASRS 1990 report, frequency congestion was "clearly the worst communication problem confronting the aviation system" (p. 1). Procedural shortcutting, phraseology truncation, and improper controller or pilot communication techniques were implicated with frequency congestion. A comparison of the 1988-1989 ASRS incidents presented in the 1990 ASRS Report indicated a 6% increase in the frequency with which communications techniques were cited as a contributing factor in the filed incident reports. There also was a 2% increase in the citation of a faulty **readback/hearback** during the same reporting period.

Reports generated from ASRS data have been helpful in developing broad classification communication taxonomies and for elucidating areas for further exploration. However, most ASRS analyses cannot be used to determine the causal factors related to an incident or operational error because of the subjective, post hoc nature of the reports. Pilots generally file reports to ASRS after they have been involved in a possible violation of a FAR. Their reports are filed after the fact and are based on private interpretations. It is not possible to verify the accuracy of their reports.

Audio Tape Analyses: Exploratory Studies Involving Real-time ATC/Pilot Radio Communication Tape Analysis

In the early part of 1990, new approaches for developing communication taxonomies began to emerge. Audio tape real-time recordings of pilot-controller communications supplied the data for analysis. Gellman Research Associates, Inc. (1987) developed a methodology and data reduction coding form for analyzing pilot-controller readback errors. Golaszewski

Table 6

Morrison and Wright (1989). Taxonomy of ATC errors.

Controller Errors	
Monitoring:	positions, altitudes, flight path
Timeliness:	delivery of frequency change, climb/descent clearance, crossing restriction, traffic advisory, correct pilot navigation error, altitude deviation, or clearance readback
Coordination:	handoffs, pointouts, approval requests
Communications Errors	
Clearance Composition:	order/sequence, content of a message (wrong heading or altitude assignment; faulty instructions)
Phraseology and Delivery Technique:	non-standard clearance terminology; too rapid speaking rate
Readback/Hearback:	failure to correct erroneous flight crew readbacks
Workload Performance Factors	
Large numbers of aircraft	
Frequency congestion	
Combined position/sectors	
Need to resolve a conflict	
Weather conditions	
Sector/corridor design	
Similar call signs	
Giving/receiving training	
Scope/data block clutter	
Long work hours	

Table 7

Morrison and Wright (1989). Categories of ATC communication errors.

Communications Errors	***Type of Error***	***Contributing Factors***
Clearance Composition	Sequencing/Content Heading Altitude Misleading instructions Inappropriate instructions Instructions to wrong aircraft Inconsistent instructions Non-standard vectors given	Heavy traffic causing controller overload *Similar call signs* Coordination difficulties
Phraseology and Delivery	Non-standard terminology	Frequency congestion Blocked transmissions Enunciation, speech rate Poor radio technique
Readback/Hearback	Failure to correct erroneous readbacks	Frequency congestion Blocked transmissions Controller overload

(1989) analyzed audio tapes containing readback errors using this coding scheme. Six general types of communication errors were identified:

1) Uncorrected pilot readback of an ATC clearance,
2) Uncorrected controller readback of a pilot communication,
3) Pilot readback of a clearance intended for another aircraft,
4) ATC instructions given to the wrong aircraft,
5) Pilot non-compliance with ATC instructions, and
6) Uncorrected controller readback of information from another controller.

Erroneous pilot readbacks not corrected by a controller (i.e., a hearback error) were involved in 50% of the 22 analyzed events. Pilot readback errors of clearances intended for another aircraft often resulted when aircraft with similar call signs were being worked on the same frequency without a controller alert to pilots. These 6 types of communications errors were classified as either environmental situations or "true" error situations. Environmental situations involved difficulties with the task environment and included:

1) ATC position/sector working aircraft with similar call signs,
2) VFR pop-ups for IFR clearance,
3) Garbled/inaudible transmission, and
4) Interphone communications distractions.

A speech act coding scheme developed by Kanki and Foushee (1989) to analyze flightcrew communications has been used and modified by several researchers to answer different types of questions involving voice communications. A speech act "Roughly corresponds to an utterance serving one discourse function" (Morrow, Clark, Lee, & Rodvold, 1990, p. 4). See Table 8 for the definitions of the various categories of speech communications.

Morrow, Lee, and Rodvold (1990) and Clark, Morrow, and Rodvold (1990) developed a method for cataloging **routine** and **nonroutine** pilot/ATC radio communications using a similar communications taxonomy to examine routine pilot/ATC radio communications (see Goguen, Linde, & Murphy, 1983). Their goals were to identify, understand, and explain why problems occurred in routine operations. In their preliminary study, the communications problems identified were inaccuracies (e.g., incorrect readback), procedural deviations (e.g., omission of readback or acknowledgment), and nonroutine transactions (e.g., detect and repair a misunderstanding). Focus was on identifying the possible causes of inaccuracies, procedural deviations, and nonroutine transactions. The possible causes included: 1) length of message, 2) procedural deviations, and 3) nonstandard language. Their paper describes the coding methodology.

In a related paper, Clark, Morrow, and Rodvold (1990) used the Morrow, et al. (1990) coding scheme to 1) describe the organization of routine communications between a single TRACON and air carriers, 2) identify the types and frequency of problems that interrupt routine information flow, and 3) identify factors associated with communication problems. They analyzed audio tape samples of approach and departure TRACON communications twice. The first pass focused on discourse organization, speech acts, aviation topics, problem transactions, and factors associated with problem transactions. The second pass focused on how controllers and pilots indicated and repaired communications problems. Once the audio tapes were transcribed, each communications sample was divided into coding units. Consider the transaction presented below:

Pilot:	Cactus 123 sir, request direct Charlotte
Controller:	Cactus 123 unable, contact Atlanta Center one-two-eight-point-seven-five
Pilot:	One-twenty-four-seven-five, switching
Controller:	That's one-two-eight, one-twenty-eight seventy-five, Cactus 123
Pilot:	One-twenty-eight point seventy-five, roger

This transaction involves 2 controller turns and 3 pilot turns. The transactions making up a communication occur sequentially. First, 1 person initiates a message to be received by the recipient. The speaker is responsible for delivering meaningful utterances. The recipient is supposed to actively listen to the speaker and indicate whether or not that message was understood. Thus, communications proceed 1 turn at a time. Each turn contains at least 1 speech act. Each speech act serves a specific communications function. The pilot's first turn contains 2 speech acts: a call sign

Table 8

Kanki and Foushee (1989). Speech act coding scheme.

Category	Definition
Command	A specific assignment of responsibility by one group member to another
Observation	Recognizing and/or noting a fact or occurrence relating to the task
Suggestion	Recommendation for a specific course of action
Statement of Intent	Announcement of an intended action by speaker; includes statements referring to present and future actions but not to previous actions
Inquiry	Request for factual, task-related information; not a request for action
Agreement	A response in concurrence with a previous speech act; a positive evaluation of a prior speech act
Disagreement	A response **not** in concurrence with a previous speech act; a negative evaluation of a speech act
Acknowledgement	(a) Makes known that a prior speech acct was heard; (b) does not supply additional information; (c) does not evaluate a previous speech act
Answer	Speech act supplying information beyond mere agreement, disagreement, or acknowledgement
Response Uncertainty	Statement indicating uncertainty or lack of information with which to respond to a speech act
Tension Release	Laughter or humorous remark
Frustration/Anger/Derisive Comment	Statement of displeasure with self, other persons, or some aspect of the task; or a ridiculing remark
Embarrassment	Any comment apologizing for an incorrect response
Repeat	Restatement of a previous speech act without prompting
Checklist	Prompts and replies to items on a checklist
Non-task Related	Any speech act referring to something other than the present task
Non-codable	Speech act which is unintelligible or unclassifiable with respect to the present coding scheme
ATC	Flight-crew radio communication with Air Traffic Control, dispatch, "the company," etc.
Total Communication	Sum of all the above

identifying the pilot and a request. The first controller turn contains 3 speech acts: a call sign identifying the pilot, and 2 commands. Each command can be further broken down into topics: denial of a request and a radio frequency change. Nested within this transaction is an incorrect readback of a frequency change. During the second turn the controller detected and provided the pilot with the correct frequency, followed by the call sign. This turn contained 2 speech acts.

The analysis examined the following 'typical' pilot-controller transactions: 1) duration of communication, 2) who talked the most, and 3) what types of actions were used most frequently to obtain the desired goal. Generally, in routine transactions, most of a controller's speech acts centered around presenting information to pilots. However, when understanding problems occurred, a controller's speech acts involved accepting of information from pilots (Morrow, Rodvold, & Lee, under review). As shown in Table 9, problems in communications were identified as disturbances that interrupted the flow of normal, routine information transfer. Morrow and co-authors pointed out that these problems did not necessarily lead to the occurrence of an operational error or incident; however, they did reduce the efficiency of information transfer.

Morrow, Lee, and Rodvold (1991) attempted to identify the types of problems that disrupted routine communications and determine how frequently each type of problem was likely to occur in ATC/pilot communications. The data from voice radio communications obtained from 4, level-5 TRACONs indicated that errors in routine communications were relatively infrequent; however, the majority of partial and incorrect readbacks were preceded by messages with multiple commands or messages that combined commands with requests or traffic reports. Apparently, pilots or controllers sometimes produced longer messages or abbreviated acknowledgments, but these strategies had the tendency to increase the probability of more nonroutine transactions.

Forty-six hours of ATC/Pilot Air Route Traffic Control Center (ARTCC)[4] communications obtained from 4 Centers were examined to determine the time required for a controller to transmit successfully time-critical messages to pilots (Cardosi & Boole, 1991). Communications were divided into those that required maneuvers for traffic, turns not for traffic [sic], and traffic advisories. As shown in Table 10, it took an average of 10 seconds for an en route controller to transmit accurately a message involving traffic information to a pilot. "The only controller second messages that were counted as such were ones in which the controller had to repeat or clarify some part of the original message" (p. 2-2). Approximately 14% of the transmissions involving traffic maneuvers were repeated, 13% of the time controllers had to repeat instructions involving turns not for traffic, and on 8% of the transmissions controllers had to repeat or clarify traffic advisory information. It is not possible to determine from this study why controllers needed to repeat their transmissions. Apparently, some of the frequency congestion problem may be attributable to controllers repeating previous transmissions, either fully or in part. Pilots may not be able to completely process the message because too much information was presented in a single transmission.

Simulation, Survey, and Field Studies Involving ATC/Pilot Communications

An analysis of controller communications obtained during live and simulated en route air traffic control environments was conducted by Human Technology, Inc. (HTI) (1991). The communications categories, modifications of the Foushee, Lauber, Baetge, and Acomb (1989) coding scheme, and speech acts were identified and tallied. The data analyses examined differences in communications patterns and controller task category (e.g., issue advisory, initiate handoff, manage arrivals; see Cognitive Task Analysis, Human Technology Inc., 1990, 1991). As shown in Table 11, more than half of the communications between en route radar controllers and pilots involved delivering *commands* to pilots and about 25% involved *acknowledgments*. Team ratings were made by FAA Academy subject matter experts' observations. The simulation data indicated that as workload increased, controllers in top-rated teams issued more *reports* to pilots than did lower-rated teams. Additionally, top-rated controllers tended to issue smaller message units

[4] Air Route Traffic Control Center or ARTCC also is synonomous with en route, and center.

Table 9

Morrow, Rodvold, and Lee (Discourse Processes, in press). Percentage of nonroutine transaction samples containing understanding and information problems (n = 163 and n = 120).

Type of Communication Problem	Percent	Contributing Factors (in understanding problems)	Percent	Result
Understanding Problems				
Addressee signals misunderstanding	60	[1]Radio-related factors frequency congestion		Repeat the message
Speaker repeats to get evidence of understanding	36	poor/blocked transmission	15	Query
		[1]Callsign recognition problems	9	Expand
Controller corrects erroneous pilot readback	4	[1]Other/nondeterminable	76	
Information Problems				
Self-correction	29	[2]Failure to acknowledge	60	
Addressee updates speaker message	19	[2]Partial acknowledgment	9	
Incomplete message (request for additional information)	19	[2]Noisy transmission	7	
		[2]*Communication stepped on*	16	
Speaker asks for other information (request for additional information)	11	[2]Other/nondeterminable	8	
Pilot has to ask for command (timing problem)	14			
Pilot challenges appropriateness of a command	8			

[1]Addressee problems [2] Speaker problems

Table 10

Cardosi and Boole (1991). Time components in ATC/Pilot verbal communications (seconds).

Source and Type of Communication	Mean	S.D.
Communication involving maneuvers for traffic (n = 80)		
Controller issues communication involving maneuvers for traffic	4.85	2.3
Lag time for pilot to respond to controller message	3.31	4.8
Pilot's initial reponse to controller's first transmission	2.61	1.83
Controller's second transmission to the same pilot	3.31	1.32
Duration of pilot's second reponse	1.37	0.92
Total communication duration	10.85	5.91
Communications involving turns **not** for traffic (n = 250)		
Controller issues communication involving turns	4.62	2.98
Lag time for pilot to respond to controller message	2.68	4.60
Pilot's initial reponse to controller's first transmission	2.66	1.58
Controller's second transmission to the same pilot	3.78	2.35
Duration of pilot's second reponse	2.65	2.00
Total communication duration	10.04	5.90
Communications involving traffic advisories (n = 178)		
Controller issues communication involving traffic advisory	6.47	2.41
Lag time for pilot to respond to controller message	2.67	6.25
Pilot's initial reponse to controller's first transmission	1.90	1.37
Controller's second transmission to the same pilot	3.00	2.83
Duration of pilot's second reponse	1.78	1.22
Total communication duration	10.96	7.26

Table 11

Human Technologies, Inc. (1991). Air route traffic control center (ARTCC) ground-air communications.

Category	Percent
Command	52.06
Observation	8.41
Suggestion	*
Statement of Intent	2.79
Inquiry	3.91
Agreement	*
Disagreement	*
Acknowledgment	25.06
Answer	*
Repetition	*
Correcting Response	*
Clarify Response	*
Courtesy	*

* The categories left blank occurred in less than 2% of the communications.

than lower-rated controllers to ensure accuracy during high workload conditions. HTI suggested that more experiments be performed to systematically control and manipulate message composition to verify their perceptions.

Acoustical Correlates in Radio Communications

Overview

As shown in Table 12, the research presented in this section is organized around laboratory studies that examined the acoustical-phonetic properties of human voice under conditions of laboratory-induced stress and acoustical-phonetic properties of human voice when environmental catastrophes occurred. Thirty percent of the literature on acoustical correlates in radio communications are resources, such as literature reviews, conference papers, or reference books; 30% are accident tapes, and 40% represent laboratory-based experiments.

Within aviation, analyses of voice transmissions stem from research data that focused upon pilot communications and workload. Three voice qualities appeared to vary systematically when workload (which again, is not consistently defined) was examined: pitch, loudness, and rate of speech. Under emotional stress or increased task complexity, pitch rose, the person talked louder, and the person talked faster (Griffin, 1987). Mental workload also appeared to produce similar effects on language production (Brenner, et al., 1985). However, Ruiz, Legros, and Guell (1990) argued that results obtained from laboratory and simulator environments are incomplete and may not be generalizable to actual real-life situations.

Differences also appeared in the variables selected by researchers for investigation. The measurement of voice qualities varies, depending on the acoustical property investigated and on the measurement scale used. For example, intensity can be measured in reference to power decibel levels when using watts or in decibels sound pressure level when using pressure as the reference (Borden & Harris, 1984). Notably investigated were male voice versus female voice, preferred rate of presentation, preferred frequency, voice to noise ratios, and intelligibility. Recently, qualitative and quantitative analyses on rate of speech were examined within the air traffic control environment. For example, Cardosi (in preparation), as part of a larger, preliminary study, used a general, subjective approach to speed of transmission (sounds slow, fast) and prosody (distinct accent present or absent) whereas Morrow, et al. (1991) reported the number of syllables spoken per second.

Laboratory Studies: Emotions, Stress, and Workload

Changes in **pitch perturbations** or "jitter," along with changes in **fundamental frequency** as a function of workload stress were properties of the human voice investigated by Brenner, Shipp, Doherty, and Morrissey (1985). Workload was defined by the number of digits subjects had to listen to, hold in **working memory**, and repeat following a 2-second pause. The numbers "one" and "nine" were presented in either a 2-digit number condition (defined as an easy task) or embedded within a 7-digit number condition (defined as a difficult task). The number of digits that subjects repeated placed different demands upon working memory, thereby changing anxiety and stress levels due to the variability in memory load (Miller, 1956; Beatty, 1982). The results indicated that lower mean jitter scores were associated with repeating back the numbers "one" or "nine" embedded in a 7-digit string.

Brenner and Shipp (1987) identified and tested 8 different voice measures, thought to be indicative of psychological stress, using an aviation-based tracking task developed by Jex, McDonnell, and Phatak (1966). The Jex, et al. tracking task required the subject to keep a computer-generated triangle centered on a computer screen. The triangle moved in unpredictable left and right horizontal patterns. Subjects also counted aloud from 90 to 100 so that acoustic patterns could be analyzed in terms of fundamental frequency, amplitude, speech rate, jitter, and **shimmer**. Frequency jitter was defined as minute variability that occurred in the spacing of the fundamental frequency periods when measured on a cycle-by-cycle basis (Brenner & Shipp, p. 365). Amplitude shimmer is the cycle-by-cycle variability in the amplitude pattern (Brenner & Shipp,

Table 12

An overview to the acoustical correlates approach literature.

	Data Source	
Overview of Acoustical Approaches	**Accident Audio Tape Analyses**	**Laboratory Studies**
Ruiz, Legros & Guell (1991) -Voice analysis to predict the psychological or physical state	Williams & Stevens (1972) -Acoustical correlates of emotions and speech	Brenner, Shipp, Doherty, & Morrissey (1985) -Voice measures of psychological stress
Tomilin & Pikovskiy (1979) -Forensic expert testimony in airplane crashes	Dornheim (1991) -LAX tapes show controller unaware of aircraft holding on runway - USAir/Skywest Metro accident	Brenner & Shipp (1987) -Voice stress analysis; mental state estimation
Borden & Harris (1984) -Speech science primer	Brenner & Cash (1991) -Speech analysis as an index of intoxication - The Exxon Valdez accident	Hecker, Stevens, von Bismarck & Williams (1968) -Acoustic speech signal and task-induced stress
		Alpert & Schneider (1987) -Voice-stress measures of mental workload

p. 365). The average fundamental frequency, amplitude, and rate of speech increased when task difficulty increased from easy to difficult.

Hecker, Stevens, von Bismarch, and Williams (1968) attempted to determine whether stress was detectable in a speaker's voice by examining the respiratory function, the operation of the larynx, and articulation under varying levels of experimentally-induced stress. Subject stress level was measured by changes in facial expressions, body movement (strain gauges), respiration (strain gauge respirometer), and galvanic skin response (electrodes placed on the surface of the skin). Graphic-level tracings were used to measure speech level (dB) changes and narrow-band spectrograms were used to measure changes in fundamental frequency (pitch). Two peaks of each test phrase were selected for level measurements. Thirty percent of the subjects spoke lower than average when stressed, and 10% displayed higher levels than when relaxed. Individual differences in fundamental frequency, indicated that for some subjects, stress was associated with increases in fundamental frequency, whereas for other subjects, stress was associated with a decrease in fundamental frequency. This study demonstrated that laboratory-induced stress could be detected by changes in the acoustical properties of human speech. Although individual differences occur, systematic changes within the individual appeared to be consistent for the individual, when compared to baseline measures.

Alpert and Schneider (1987) described a methodology for identifying some properties of mental workload by examining hypothesized changes in voice properties. The microtremor in human voice signals changes in emphasis, rhythm, and voice inflection of the speaker and often can help the listener understand the intended meaning of a communicated message. Suppression of the 8 - 12 Hertz microtremor has been used as a measure for the presence of stress. Alpert and Schneider argued that emotions (e.g., fear) differ from mood (e.g., sadness) and affect (e.g., excitement). Emotions manifested themselves through physiological changes in respiration, muscle tone of the vocal folds; moods by changes in temporal patterns of utterances, such as pause length and length of utterance; and affect by changes in voice amplitude and the number of multipeak utterances.

Ruiz, Legros, and Gueli (1990) summarized the major research efforts over the past 50 years that measured the acoustic modifications of the human voice as it was influenced by workload. Psychological or emotional stress and physical fatigue can be identified by examining the acoustic properties of a speaker's voice. One-, two-, and three-dimensional acoustic characteristics were evaluated. Their primary conclusion was that the fundamental frequency of the human voice rises in a stressful situation. The frequency of the first formants also are modified by emotional stress or workload. Energy level (volts or decibels) is less stable a measure. Although a speaker's total speaking time increases with stress, the speaker tends to decrease the number of syllables spoken per second. The two-dimensional spectral analysis indicated that the time contours of the fundamental frequency became more irregular and discontinuous under high stress. Three-dimensional sonagrams indicated that workload modified frequencies above 2,000 Hz. Although a relationship exists between stress, fundamental frequency, energy level, or speech rate, causality cannot be inferred from these correlations; that is, they should not be taken as estimators of individual reactions to workload. Empirically derived research is needed to determine whether a causal relationship of practical and statistical significance exists.

Field Studies: Accident Audio Tape Analyses

Williams and Stevens (1972) analyzed the voice characteristics of radio announcer Herb Manson of radio station WLS describing the approach of the *Hindenburg*, the famous Zeppelin that suddenly burst into flame, while landing at Lakehurst, New Jersey, May 6, 1937. Three narrow-band spectrograms of his voice were made, in which the phrase "ladies and gentlemen" was present prior to, during, and immediately following the disaster. Following the incident, the announcer's average fundamental frequency (f_0) was noticeably higher. A comparative analysis made of an actor reading the transcripts and acting the role of the radio announcer showed striking similarities. Various actors were asked to act out anger, fear, sorrow, or neutral situations. The general conclusion was that the normal contour of the fundamental frequency, as a function of time, was characterized by smooth, slow, and continuous changes occurring in syllables. Generally, sorrow lowered baseline f_0 and decreased f_0 range while anger or fear brought about an increase in both measures over baseline performance.

Tomilin and Pikovskiy (1979) presented a psychophysiological method for studying oral and acoustic information following airplane crashes. Accident investigators who examined voice qualities generally looked for changes in the frequency spectrum and temporal amplitude of identical words or parts of words (i.e., phonemes) spoken by the same individual at different times. Generally, a frequency shift to the right was indicative of emotional stress whereas a frequency shift to the left indicated a reduction in stress. Pilots flying under complex conditions demonstrated similar changes in speech: Speech became more rapid, more frequent, longer pauses were present between words or phrases, and more slips of the tongue were present.

As part of the study involving the acoustical correlates of psychological stress, Brenner, et al. (1985) analyzed crew conversations recorded before and during emergency situations prior to aircraft crashes. Tapes were obtained from recordings at air traffic control facilities and from a cockpit voice recorder. Identical words or phonetic segments produced by the same speakers during routine and emergency communications were extracted and analyzed. In all of the tapes, both the mean and standard deviation of the fundamental frequency increased significantly in the emergency air to ground communications. Although preliminary, jitter scores decreased in emergency communications and may provide an additional acoustical component measure indicative of psychological stress.

Brenner and Cash (1991) completed an acoustic-phonetic analysis of selected voice radio communications by the master of the oil tanker *Exxon Valdez*. Speech analysis provided a technique for identifying secondary evidence of alcohol impairment. A total of 42 statements were analyzed at 5 different time periods: 1) 33 hours before the accident, 2) 1 hour before the accident, 3) immediately following the accident, 4) 1 hour after the accident occurred, and 5) 9 hours after the accident. Speaking rate was measured by the number of syllables spoken per second. Repeated measures analysis of the phrase "Exxon Valdez" during each time period indicated a slowing of speech prior to the accident. Misarticulations (e.g., slurring of speech) examined through phonetic transcription, plus power spectra displays of individual sounds, indicated changes in the sound [iz] to [is] in the word Valdez; [s] to [sh] in Exxon. Changes in voice quality measured by changes in fluency (e.g., speech rate, responsiveness, hesitation, grammar) indicated more word interjections, broken words, incomplete phrases, corrected errors, and increases in speaking time and hesitations.

Dornheim (1991) reported that approximately 1 minute before the US Air-Skywest aircraft collision at Los Angeles, "the local tower controller showed some surprise in her voice on the tape..." (p. 61).

These examples indicate that voice quality can be used to infer the psychological and physiological states of the speaker. Changes in a controller's voice qualities could signal changes in workload or stress levels that could contribute to the potential for error. Previously reviewed studies and reports indicated that workload was associated with increased incident reports and strategic changes such as procedural shortcuttings (cf. Morrison & Wright, 1989; HTI, 1991; Morrow, et al., 1991). Based on the acoustical correlates approaches reviewed, changes in fundamental frequency, amplitude, and frequency jitter may be important predictors of psychological and emotional stress levels. Changes in delivery technique, such as the presence of more hesitations, more misarticulations and dysfluencies, and rushed speech also may be indicative of heightened cognitive stress levels. When the literature on communications taxonomies is combined with the acoustical correlates literature, it would seem that as workload or stress increases, air traffic controllers and pilots alter their communications techniques to compensate for congested radio frequencies. These changes included shorter messages, message composition, message transmission speed, and voice properties.

Cognitive/Psycholinguistic Approaches

Overview

There are 3 major components in the cognitive/psycholinguistic approaches section. Several information processing models applied to ATC are presented. Next, research examining human short-term memory limitations and their relationship to ATC/pilot message content and delivery techniques are presented. Lastly, interactive ATC/pilot conversations are examined using the collaborative scheme. Thirty percent of the information in this section was obtained from survey materials, 40% was obtained from field studies, and 40% of the information was derived from laboratory-based reports. See Table 13 for a summary.

Early information processing models proposed that controllers' mental operations and thought processes centered around the performance of 2 primary functions: surveillance and correction. McCoy and Funk's ATC operational errors taxonomy (1991) is based on a functional model of human cognition that included: sensation, perception, working memory, long-term memory, central processing, and response execution. Some studies examined short-term memory as a human factors limitation in air traffic control information transfer. Studies on short-term memory mainly focused on the encoding process in order to identify strategies that would minimize perceptual errors. More recent studies are concerned with reducing encoding errors. "**Chunking,**" the process of combining several small units of information into larger units without disrupting their order, may prove to be effective in reducing some types of encoding errors. Alternative explanations re-introduce decay theory. Some studies assessed the time retention of chunks using the decay theory, while later studies suggested that using shorter units and allowing more time between those units would improve short-term memory performance and lower miscommunication errors. Studies in interactive conversations reexamined the traditional view of conversational speech, and replaced it with a **collaborative scheme** of conversational speech. Studies based on the collaborative scheme approach analyzed ATC-pilot audio tapes to identify how air traffic controllers and pilots detect and correct miscommunications. Some studies looked at **routine** communications to see what disruptions occurred, while other studies examined non-routine communications to identify the types of misunderstandings that were present.

Table 13

An overview to the cognitive/psycholinguistic approaches literature.

	Data Source	
Information Processing Models	***Short Term Memory***	***Interactive Conversations***
Bisseret (1971) -Mental processes in ATC	Loftus, Dark & Williams (1979) -Short-term memory in controller-pilot communication	Clark & Schaefer (1987) -Collaboration in conversation
Navarro (1989) -Errors in flight crew communication	Schweickert & Hayt (1987) -Memory load and pronunciation rate	Clark, Morrow, & Rodvold (1990) -Routine communication in ATC
McCoy & Funk (1991) -Taxonomy of ATC errors based on a model of information processing	Salt Lake City Study (1991) -Miscommunication errors	Morrow, Lee & Rodvold (1991) -Collaboration in controller-pilot communication
Adams & Hwoschinsky (1991) -Information transfer limitations in ATC	Morrow & Rodvold (1992) -Routine controller-pilot communications	

Table 14

Navarro's taxonomy of work situations with regard to types of error in communication and to types of adjustment.

	Type of Adjustment	
Type of Error	**Individual**	**Interactive**
Data Transmission (Uncertain or Erroneous)	Self-Correction	Exchange: discussion
Detection (No sign of detection)	Detection during message repetition	Crew member detects or reports the data
Identification (Data detected but not identified; message heard but not listened to)	Subject asks for a repetition	Crew member reports the type of data
Interpretation (Data identified but forgotten, distorted, or modified)	Subject asks for a verification of the values of the data	Crew member corrects or checks data
Action (Wrong actions being taken or already done)	Self-correction (verbalized)	Crew member halts or changes the action

Information Processing Approach

Bisseret (1971) proposed one of the first information processing approaches to understanding the mental processes involved in air traffic control. By gaining a better understanding of the thought processes and mental operations that a controller performs, he proposed that it might be possible to automate those processes and operations thereby improving upon air safety. Bisseret viewed the air traffic control system as serving two distinct functions: surveillance and correction. With the surveillance function, the air traffic controller, as a system, scanned for and detected the presence of air conflicts. With the correction function, the controller activated problem solving strategies and selected the best solution. The primary task that a controller performed was categorization. Categorization consisted of "dividing a set of objects into different classes in accordance with the given aim" (p. 566). Objects were classified in accordance with their attributes and to the values assigned to these attributes; that is, the importance the attributes had was determined by the situation (aim).

Within the air traffic control environment, maintaining aircraft separation was an important attribute whose value became increasingly important to the controller if the risk of minimal separation distance was threatened. Thus, Bisseret argued that controllers categorized aircraft not by type but into groups: potential conflicting pairs and all others. Information about aircraft attributes (type of aircraft, flight level, position, airspeed) weather condition attributes (clouds, wind, ice) and other relevant information was used in a working memory to monitor and categorize aircraft into groups and pairs. An experienced controller developed what Bisseret termed "operative memory." Operative memory consisted of all the relevant knowledge and information of the air traffic control position/sector that a controller had memorized, organized, and structured. Today, it may be called a "mental model" or acquired "situational awareness".

Navarro's (1989) method for studying flight crew communications errors that used an information processing taxonomy of communications is presented in Table 14. As with many information processing models, he proposed that information was processed sequentially. Information from the environment served as the input to the human information processing system, where it was detected, identified, interpreted, and output by the performance of some action. Using this model, Navarro believed that errors could be evaluated and corrections in communications applied to individuals or to groups. Although no data were presented, this model could be easily applied to the interactive communications between air traffic controllers and pilots. The necessity of ATC to repeat communications could be attributed to flight crews not detecting the message; "say agains" might have occurred during the identification process, and queries more likely to have occurred during the data interpretation when values were being verified (cf. Morrow, et al., 1991, 1992).

McCoy and Funk (1991) presented a taxonomy of ATC operational errors based on Wickens' (1984) functional model of human cognition. The major components in their model included *sensation, perception, working memory, long term memory, central processing,* and *response.* Table 15 presents definitions and limitations for each of the major components in their model. A simplified version of Wickens' model is presented in Figure 1. Information from the external world is sensed and some of the raw sensory input is acted upon by pattern recognition operations in working memory. Information and procedures from long-term memory in conjunction with central processes, such as attention and reasoning, contribute to the further processing of that content in working memory. The input is identified, interpreted, made meaningful, potentially stored, and so on, and could result in the execution of a selected response.

Based on this type of a model, McCoy and Funk categorized accidents involving the ATC System from 1973 through 1989. Abstracts were obtained from the Aircraft Accident Reports maintained by the National Technical Information Service Government Report Announcements and Index database. Of the 29 selected abstracts, 18 abstracts cited probable or contributing controller involvement in the accident. Approximately 5% of the accidents were attributable to attention, 10% to memory, and 20% to perception (situation awareness). The remaining accidents were

Table 15

McCoy and Funk (1991). Functional elements of human information processing model.

Type	Function	Limitation
Sensing	Samples raw stimuli from environment and passes information to perception	Sensory thresholds and discrimination limits
Perception	Assigns information to perceptual categories	Suboptimal adjustment of critical detection thresholds, vigilance loss, and limits to perceptual attention
Working Memory	Bottleneck between sensing/perception, long-term memory, and the central processing function of reasoning and response selection	Capacity and duration
Long-Term Memory	Retains parameters used in perception, general factual knowledge, and has role in maintaining internal model of the world (including self)	No apparent limits on storage, but many factors limit retrieval
Central Processing	Decision-making and response selection, allocates mental resources to functions required to perform various competing, concurrent tasks	Confirmation bias and the interrelated limits to speed and accuracy of responses
Response	Transforms selected responses into mechanical energy	Speed and strength

classified as response selection errors involving issuing clearances, coordination, and a variety of non-specific situations

Adams and Hwoschinsky (1991) discussed some of the human factors limitations in ATC information transfer. They argued that the major limitations on the human information processing system included: *perception, how information is processed, capacity,* and *memory.* Perception was selective and determined, in part, by prior knowledge and experience (expectations). Processing of information was not simultaneous and instantaneous. "Processing is mainly done by parallel processing of several types of information in a sequential manner" (p. 492). During peak operations, time may become compressed whereby controllers may be forced to implement decisions based on partially processed information. Processing capacity is affected by the procedures and rules that people used to make mental comparisons, decisions, and so on. Using the rules appropriately could reduce mental effort. Adams and Hwoschinsky argued that people have limited memory capability. Memories were retrieved by associative recall and were reconstructions of prior life experiences. As such, memories were not perfect copies of actually experienced events. Although no empirical, study, or survey data were presented, the authors categorized communications errors using their model and specified causality. For example, they proposed that "readback errors, hearback errors, read forward errors, and transcription errors were caused by expectancy problems" (p. 494).

Short-term Memory

While many studies examined ways to encode information so as to minimize perception errors, few studies addressed the question of how to minimize encoding errors. Loftus, Dark, and Williams (1979) used the Brown-Peterson (1958, 1959) paradigm and designed an experiment to simulate a pilot's memory task in a controlled laboratory environment. A

Figure 1

A functional model of human information processing.

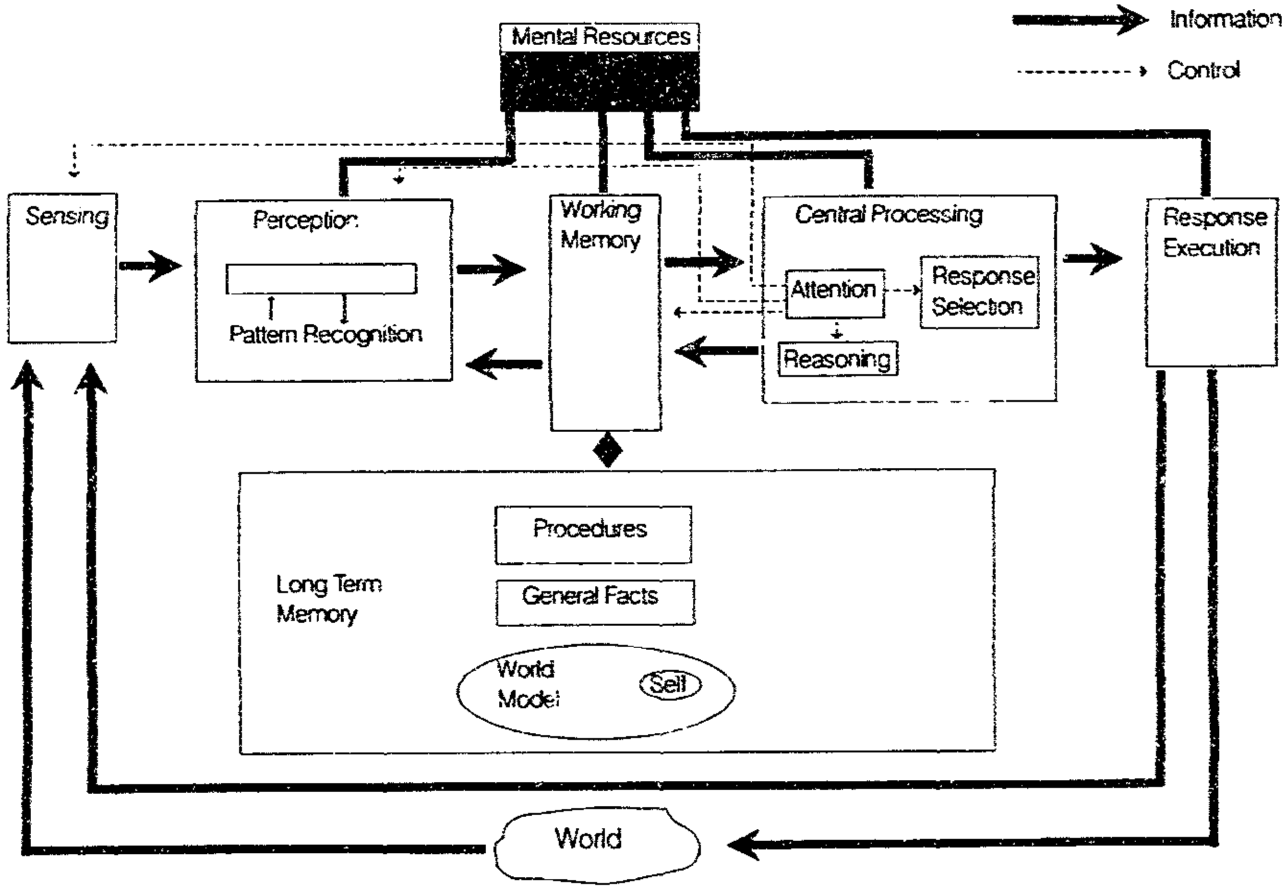

Table 16

A comparison between a typical trial in the Brown-Peterson paradigm and the Loftus, Dark, and Williams controller/pilot analogue.

Brown-Peterson Paradigm	Controller/Pilot Analogue
1. Present to-be-remembered information (BKG)	1. Transmit to-be-acted-on message (e. g. altimeter 2997)
2. Variable length retention interval in which subject performs distracting activity to prevent rehearsal of the to-be-remembered information (counting backward)	2. Variable length of time in which pilot must perform distracting activity that prevents rehearsal or acting on message
3. Recall signal: subject attempts to recall information	3. Pilot's attention freed and attempts to recall and act on message (e. g. dial 29.97 into altimeter)

comparison between the typical trial in the Brown-Peterson task and an experimental trial in the Loftus, et al. (1979) task is presented in Table 16. In the Brown-Peterson paradigm, subjects were presented with three consonants to remember followed by a brief retention interval in which the subject performed a non-related task to prevent rehearsal, and then recalled the 3 letters once a signal was presented. The amount of time given following the consonants and preceding recall varied from 0 to 30 seconds. Loftus, et al. replaced the components with numeric information commonly transmitted in ATC messages. The types of memory messages used were place/frequency (e.g., a place to contact with a 4-digit radio frequency) and transponder code message (e.g., a 4-digit radar transponder code). Four female college students were required to remember either a place/frequency, transponder code, or both. In addition to the types of memory messages, subjects either encoded the transponder code sequentially as 4 separate values or as 2, 2-digit values. For example, in sequential encoding the transponder code 2772 would be encoded as "two, seven, seven, two." In the chunked encoding, the transponder code would be encoded as "twenty-seven, seventy-two." Chunking is an encoding strategy that allows for more information to be processed in a limited capacity memory system.

The results showed high recall for place information, medium recall for transponder code information, and poor recall for radio frequency information at immediate, 5-, 10-, and 15-second retention intervals. Also, the number of pieces of information to be recalled had a large effect on the probability of correct recall, as did the time interval between presentation and recall. Radio frequency information was less likely to be recalled correctly, even with a 0-second retention interval and a small memory load. Chunking the transponder code seemed to increase correct recall of the radio frequency under a high memory load condition. Chunking did not improve correct recall of transponder codes. In general, the finding supported the idea that chunking some types of aviation-related information, that is, making the amount of information per message smaller with a larger interval between messages, may increase the probability of a pilot correctly reading back that message.

An alternative approach to counting the number of chunks (quantity constraint) that could be actively held in a short-term memory assumed that short-term memory was limited by the amount of time (time constraint) for which chunks could be retained (Schweickert & Hayt, 1987). That is, a chunk of information had to be actively engaged; otherwise, activation levels diminished, and the informational content of the chunk decayed and was forgotten. Some researchers reported that the number of items immediately recalled correctly 50 percent of the time (i.e., memory span) depended on the type of information that could be pronounced (read) in about 1.5 seconds (Mackworth, 1963; Baddeley, Thomson, & Buchanan, 1975; Schweickert & Boruff, 1986). Any information not retrieved after approximately 1.5 seconds was lost. Schweickert and Hayt's results showed that reading time was a better predictor of recall than the number of items presented for unpracticed subjects. Both reading time and number of items were equivalent predictors for practiced subjects. Longer word lists required more time to be read than shorter word lists, thereby increasing the chances for trace decay. However, longer word lists were more distinctive and increased the chances of correctly guessing the item. The applied suggestion was to make infrequently encountered messages shorter to pronounce (i.e., readback), but frequently heard messages distinctive, even if the messages had to be longer.

A study of ATC/pilot miscommunications was undertaken at the Salt Lake City terminal (McCandless, 1991). Random samplings of voice radio transmissions and behavioral observations of ground-to-air and air-to-ground communications were obtained. McCandless interpreted the preliminary findings to suggest that miscommunication errors were common and that miscommunications 1) led to operational errors, 2) caused operational inefficiencies, and 3) were committed most frequently by private pilots. The study suggested that ATC/pilot miscommunications were caused by several factors including: variability in equipment quality, poor speech-to-noise ratios, individual differences in communications ability, effects of excessively long transmission, and workload. There was a significant increase in controller speech rate and number of speech acts contained in a transmission during periods of heavy traffic. Pilots also accelerated their speech rate during heavy workload. More requests for repeated messages and corrections of incomplete readbacks were observed during moderate to heavy workloads Although not measured directly, subjective impressions lead McCandless to further suggest that this resulted in increased controller stress and anxiety (p. 8).

The McCandless study also offered specific recommendations to improve communications. McCandless suggested that controllers organize information into "chunks," that is, group-related information into a single transmission for clarity (e.g., topically related information, a main idea, or an idea unit) and increase the intelligibility of transmissions through good articulation, normal speech rate, and low background noise. Chunking has been used as a way to improve retention of information in working memory by combining individual pieces of information into a singular, meaningful unit (cf. Loftus, et al., 1979). The McCandless study suggested that pilots use brief, but essential, radio transmissions, request clarification when necessary, and increase the intelligibility of transmissions through improved delivery techniques.

Morrow and Rodvold (1992) reported the findings of 2 of their studies: a field study and a part-task simulation study. The field study examined ATC/pilot routine and non-routine communications sampled from each of 4 level-5 TRACONs. The results demonstrated that incorrect, partial, or missing readbacks were infrequent events when daily communications were considered. The results suggested that longer and more complex messages preceded incorrect and partial readbacks. Based on these findings, the part-task simulation study varied message length based on the number of commands contained in a message. The results of this study suggested that breaking longer messages up into shorter ones was generally better for communications if enough time were left between messages, so that a later arriving message did not interfere with memory for the first message.

Taken as a whole, the studies presented here indicated that: 1) only a few speech acts should make up a single transmission; 2) the speech acts making up a transmitted message should be topically related; 3) a message should be brief; 4) a message should be meaningful; and 5) time factors should be considered.

Interactive Conversations

Clark and Schaefer's (1987) theoretical paper examined the traditional view of conversational speech. The traditional view holds that conversation is a single, sequential process of turn taking between a speaker and a recipient(s). That is, a speaker is tasked with delivering understandable utterances. The recipient is tasked with understanding those utterances. Within this simplistic model there are 2 turns, 1 turn is made by the speaker who initiates the conversation and the other turn is made by the recipient. In this way, conversations proceed 1 utterance at a time. Clark and Schaefer state that conversations are social exchanges that require cooperation and collaboration among those engaged in the act of conversing. Under such a framework, conversations occur concurrently at 2 levels. Level 1 (traditional view) consists of the conversation's topical focus; i.e., what the conversation is about (p. 20). Level 2 requires that the speaker and the recipient of the utterance share a common understanding (mutual belief) of the utterance. Both the speaker and the recipient are responsible for the recipient gaining a true understanding of what the speaker meant to say when an utterance was delivered.

In conversational speaking, collaborative effort is expended through the process of *presenting, correcting,* and *confirming* that the mutual understanding of an utterance has occurred before another utterance is delivered. Clark and Schaefer present their model using conversations that occurred between telephone operators and telephone users who requested directory assistance. Telephone communications often parallel air traffic control communications in that both have a structured grammar, both consist of minimal information exchanges, both contain message interruptions, and both are limited to 2 participants at a time who converse in a sequential order with minimal interruptions. The structure of information transfer can consist of either *continuous utterances* or as *installment utterances.* With *continuous utterances,* a telephone number has a sentential structure if the numbers are preceded by a subject and verb in the form "It's [prefix optional] 1234" or it has a phrasal structure if the subject and the verb are absent (e.g., [prefix optional] 1234). Installment utterances can be sentential or phrasal in form. They differ from continuous utterances in that the numbers are spoken in brief packets and may or may not contain confirmation acknowledgments trailing each of the packets. For example, "It's 01 [yes] 234 [yes]" is an example of a sentential *installment utterance with recipient confirmations.* Telephone operators generally use a phrasal structure (46.2%) over a sentence form (27.6%) when providing telephone numbers. Operators increased their use of installment utterances only when it became self-apparent that telephone users' displayed severe difficulties in understanding.

The *acceptance phase* in the collaborative model states that once an utterance has been received, the recipient's current state of understanding should be conveyed back to the speaker. It is at this point that any failures in understanding should be addressed and corrected. As shown in Table 17, Clark and Schaefer define 8 categories for recipient responses. The 8th category, side sequences and errors, although included, was not presented with sufficient explanation. Generally, *presuppositions* or *assert full hearing* occurred as a function of type of information (i.e., contribution) requested. More *presuppositions* or *assert full hearing* occurred for towns (39% of the time) or for addresses (33%) than for either names (15%), numbers (14%), or for combinations of towns, addresses, and names (19%). The apparent heuristic employed was "the easier the information was to grasp, or the less important it was, the more often the partner [in the conversation] presupposed or asserted full hearing" (p. 39).

Using the Clark and Schafer model of collaboration in conversations, Clark, Morrow, and Rodvold (1990) described the organization of routine communications between a single TRACON and air carriers using the Morrow, Clark, Lee, and Rodvold (1990) coding scheme. Audiotaped samples of approach and departure TRACON communications were analyzed to examine how controllers and pilots indicate and repair communication problems. Consider this transaction:

Table 17

Clark and Schaefer (1987). Categories of responses following message transmission.

Category	Example
Assert no hearing	I didn't hear you.
Presuppose no hearing	What did you say?
Presuppose incomplete hearing	12?
Presuppose fallible hearing	12345?
Display full hearing	12345
Assert full hearing	Right.
Presuppose full hearing	Thank you.
Other side sequences and errors	12345

Pilot:	Cactus 123 sir, request direct Charlotte
Controller:	Cactus 123 unable, contact Atlanta Center one-two-eight-point-seven-five
Pilot:	One-twenty-four-seven-five, switching
Controller:	That's one-two-eight, one-twenty-eight seventy-five, Cactus 123
Pilot:	One-twenty-eight point seventy-five, roger

During the pilot's first turn both phase 1 and phase 2 occurred. During phase 1, the pilot *initiates* the conversation and redirects the controller's attention to receive a transmission. During phase 2, information is *presented.* In this context, the new information is presented in the form of a request. Phase 3 is completed in the controller's first turn. During phase 3, the controller *accepts* the understanding of that message and denies the pilot's request. The controller *presents* new information in the form of a command to the pilot. During the pilot's second turn, the pilot *accepts* the new radio frequency information and complies by reading back the radio frequency. During turn 2, the controller indicates that there is a miscommunication by *not accepting* the pilot's message. Note that during the pilot's second turn, the pilot's readback of the radio frequency is incorrect, signifying an understanding problem (see Table 7). During the controller's second turn, the controller *repairs* the communication by repeating the radio frequency information twice. Collaborative effort to maintain a mutual understanding of the assigned radio frequency has occurred. The pilot displays *full hearing* (see Table 13) by correctly repeating the radio frequency and ending the transmission with the word "Roger," indicating a *confirmation* acknowledgment during pilot turn number 3. The controller and pilot, through collaborative effort, ensure that they both understand the transmitted information through the process of *presenting*, *correcting*, and *confirming* that a mutual understanding of the intended meaning has occurred. The radio frequency was presented, corrected, and then confirmed before a new topic was initiated.

In their analyses, Morrow, Rodvold, and Lee (1990) focused on nonroutine transactions with misunderstanding errors similar to the example presented above. They found that the most common type of problem disrupting routine communication consisted of difficulty understanding previously presented information. The other 2 types of misunderstanding errors were repeating unacknowledged commands and correcting an inaccurate pilot readback. Also during nonroutine transactions controllers spent more time accepting information and less time initiating transactions and presenting new information. Controllers repaired understanding problems by repeating, paraphrasing, or answering pilot questions, while pilots repaired by repeating or acknowledging messages. Nonroutine transactions were shown to have reduced efficiency since they were longer, yet presented little new information, and the organization of nonroutine transactions resembled "normal" speech more than standard ATC communications.

Morrow, Lee, and Rodvold's (1991) analysis of pilot/controller recorded TRACON communications identified different types of problems that disrupt routine communications. They found that problems were infrequent when counted as a percent of the total transactions; however, they suggest that identifying the communication factors that influence problems may provide insight into why they occur and how to eliminate them. There was a connection between communication problems and collaborative effort; that is, when 1 party produced long messages with several commands to decrease overall transaction time, the other party might have tried to abbreviate acknowledgments, thus increasing collaborative effort.

III. SUMMARY AND RECOMMENDATIONS

This section is a brief summary of the research contained in each of the previous sections, followed by some strengths and shortcomings of each approach. Several recommendations are presented.

Summary and Discussion

A review of the literature on communication taxonomies using the ASRS database and voice tapes was presented, followed by the acoustical correlates approaches and the cognitive/psycholinguistic approaches to voice radio communications between air traffic controllers and pilots.

The ASRS-based communications taxonomies identified problem areas in voice radio communications associated with operational errors/deviations. The communications taxonomy for voice tape-based speech acts described ATC/pilot communications, message content, differences in speech act use, and how problems in understanding were resolved. The communications taxonomies literature consistently found that miscommunications occurred more often when controllers experienced overload due to heavy traffic, frequency congestion, message length, etc. (cf. Morrison & Wright, 1989; Morrow, et al., 1990). Observational reports and ASRS reports consistently state that air traffic controllers speak too fast (cf. Mitre Report, 1990). However, retrospective voice tape analyses that examined ATC delivery techniques have not validated pilot and observer reports that speech rate is too rapid. (Morrow, Lee, & Rodvold, 1990; Cardosi, in preparation). Morrow and co-authors used the number of syllables spoken per second to measure speech rate on 49 message pairs; however, this was too small a number on which to base a conclusion.

ASRS-based communications taxonomies addressed basic, general issues involved in identifying factors in communications that compromised air safety. Grayson and Billings (1981) concluded that the preponderance of ATC/pilot oral communications problems involved human errors related to a failure to deliver timely, potentially important information, problems in message content and phraseology, and poor monitoring behaviors. Only a small number of communications problems were attributable to equipment failures, frequency saturation, or other system problems. Monan (1986,1988) identified the frequent absence of hearback as a major issue in ATC communications. That is, ATC failed to actively listen to a pilots' readbacks of ATC clearances containing numbers. Morrison and Wright (1989) separated environmental and task performance factors from communications problems. Controller overload, brought on in part by heavy traffic and radio frequency congestion, was cited as contributing to clearance composition, phraseology and delivery technique, and readback/hearback communications errors.

The ASRS database is a valuable resource that has been used to identify some of the communications problems in information transfer. It has provided direction for researchers. In communications-based questions, the ASRS can be used to: 1) distill information pertaining to the efficiency and effectiveness of maintaining air safety; 2) examine and compile narrative reports to get a sense of what's happening in daily flights; and 3) help researchers develop stimulus materials for experimental ATC/pilot communications studies.

There are several inherent weaknesses with using the ASRS that should be considered: 1) sampling is biased, in that reports are voluntary and are subjective interpretations of the circumstances that led to the event; 2) many more pilots than air traffic controllers submit reports, which could bias interpretations of the database; 3) the accuracy of the narrative descriptions of the event has not been established (memories are malleable and subject to distortion); 4) use of a standardized narrative to reformat the reports is subjective; 5) coding is subjective; 6) reliability in coding (inter-rater and intra-rater reliability and consistency) needs to be verified and periodically updated; 7) more objective operational definitions need to be established; and 8) base-line error rates pertaining to the incidence of specific problems are not available (Cardosi, personal communication, 1993).

Voice tape-based communications taxonomies addressed more specific issues in ATC/pilot communications derived from the ASRS based-communications taxonomies. Researchers developed speech act communications taxonomies that examined communication problems resulting from message composition, timeliness, or coordination in controller errors as part of the dynamics in information transfer. TRACON controllers used identification and commands most frequently and pilots used acknowledgments and identification most often. Headings and altitudes were the most frequently used topics in all transactions. Enroute radar controllers issued more commands and acknowledgments than reports or inquiries. Additionally, more expert enroute teams delivered more commands than less expert teams when they were under heavy workloads (HTI,1991). At TRACONs, longer messages were more likely to contribute to incorrect or partial readbacks. Some of the strategies and devices used in TRACON/pilot communications to achieve accurate and efficient information transfer included: ask for repeat (say again?), question (was that 240?), and paraphrases (signaled understand problem). Voice quality was an important signaling device that indicated a lack of understanding and that improved the accuracy of information transfer (Morrow, et al., 1991).

An advantage of using audio-taped communications databases is that they provide an objective, reliable, and verifiable real-time record of the information transferred between air traffic controllers and pilots. By developing and consistently using the same basic speech act categories, different researchers can examine different aspects of the same types of voice communications. Transcripts are valuable sources of data, but they have limitations. A complete analysis of voice radio communications would require that an evaluation of the information content of the speech signal be included with message content. The contributions of overlapping speech, as well as the role of pauses and hesitations in signaling understanding, would need to be determined. Speakers can lengthen words by drawing them out and alter the spacing between words, and use changes in intonation, as signaling devices. Generally a rising intonation at the end of a phrase indicates more information is forthcoming. A falling intonation indicates the end of a message. When people are the recipients of a message, this information aides the ease of interpretation of speech signals.

Audio tapes, like narrative reports, provide retrospective accounts of human factors, environmental factors, and task performance factors that may contribute to, act as catalysts for, or result in, miscommunications. These miscommunications may or may not result in operational errors or deviations. The context in which these communications occur must be considered before a complete understanding of the nature of interactive, dynamic, air traffic control/pilot voice communications and their involvement in air safety can be achieved and recommendations for change determined. An analysis of audio tapes alone is not sufficient to draw causal conclusions. Also, the amount of research that has been performed is limited to examining only a few TRACONs and even fewer en route centers. Thus, it is not appropriate to consider these limited results to be representative of the communications problems that occur at all ATC facilities making up the National Airspace System (NAS).

Audio tape recordings also were used to examine the relationship between the acoustical properties of the human voice when individuals directly experienced increased mental workload or experienced or witnessed emotionally charged events (cf. Brenner, et al., 1985, 1987, 1991; Williams & Stevens, 1972). Brenner and co-authors' laboratory study on mental workload, their evaluation of the Exxon Valdez audio tape, and analysis of cockpit recorders recovered from aircraft accidents revealed that voice quality changed as a function of cognitive, psychological, physiological or emotional stressors. Consistent and stable changes included an increase in pitch and a change in speech rate. Voice amplitude (speaking louder or softer), "jitter," and "shimmer" were less reliable measures. Overall, acoustical properties of human voice appeared to change as a function of change in mental workload or stress in many of the reported studies (cf. Griffin, 1987; Hecker, et al., 1968). Although the ASRS communications taxonomies and the speech act communications taxonomies included delivery technique as a miscommunications factor associated with operational errors/deviations, multivariate research investigating the influences of voice quality and speech rate on miscommunications has not been performed.

The major strength of acoustical forensic research is its methodology. That is, researchers compared the same syllable, word, or phrase spoken by the same person under normal conditions and when mental workload increased, emotional climate changed, or increased stress was experienced. With the introduction of technologically-advanced computer systems, acoustical and speech processing software, and digitized recording equipment, researchers have the capability to examine human voice properties with greater precision and accuracy. Changes in amplitude, jitter, or shimmer may be detected because of technological improvements in equipment. Often, changes in voice properties can be detected by the computer that are not detected by the human ear (Brenner, et al., 1987)

The primary weakness of performing an acoustical-phonetic analysis of voice tapes has been technologically based. Overused audio tapes with poor signal quality, unintelligible speech on audio tapes, poor recording equipment, and gain control settings that dampened voice amplitude are some of the problems researchers previously encountered when analyzing cockpit recordings and VHF audio tapes provided by air traffic control facilities.

Cognitive/psycholinguistic theories and models of human information processing have evolved significantly over the past 30 years. The cognitive/psycholinguistic approach views the human as an information processing system. Within this view, humans are thought to actively combine in a working memory environmental information with information obtained from permanent memory, store the contents, and perform a response. Human information processing, memory characteristics, and storage limitations place constraints on how much and how long information can be remembered. Established principles derived from research performed in academic settings have been applied to the aviation industry (cf. Morrow, et al., 1990, 1991, 1992; Salt Lake City Terminal Communications Terminal Staff Study, 1991; Loftus, et al., 1979). This research suggests that: 1) only a few speech acts should be presented within an ATC message; 2) speech acts embedded in the same message should be situation and time relevant; and 3) pauses between messages should be of sufficient duration so the message can be completely understood before more information is transmitted. Very few aviation-based cognitive/psycholinguistic studies examining voice radio communications exist (cf. Loftus, et al., 1979; Schweickert & Hayt, 1987). Loftus and co-authors' results, although consistent with the literature on working memory, used four female college students without aviation backgrounds as subjects. Whether the same results would occur using controllers or pilots is presently being determined in an experiment by Cardosi (in preparation).

Some problems associated with performing a cognitive/psycholinguistic analysis on the information presented on voice tapes acquired from centers or TRACONS include: 1) poor quality tapes that have unintelligible recordings are useless to researchers; 2) interpreting voice tapes without access to the context in which the communications occurred reduces the validity of the interpretation; 3) retrospective analyses of audio tapes do not allow for causal explanations; and 4) the tapes provide only a limited focus on the problem.

Much of the research presented in this survey involved the expenditure of effort in examining only a subset of miscommunications. For example, Golaszewski (1989) and Morrow, et al., (1990, 1991, 1992) examined incorrect, partial, and missing readbacks; Cardosi and Boole (1991) examined only messages containing traffic information; and Clark, et al., (1990) focused on strategies used to promote understanding between controllers and pilots. A complete picture of transactions or speech acts contained in daily communications has not been presented. A more comprehensive analysis would provide the community with a total picture of normal and problematic communications nested within an overall communications taxonomy. Only a few pieces of the communications puzzle have been presented without benefit of a complete picture on which to base accurate conclusions. Rather than try to derive a picture from the limited information, it might be better to start by defining the characteristics of daily communications and then extract the normal and miscommunications subsets. This way, a better understanding of how big of a problem miscommunications exert on daily ATC/pilot operations can be obtained.

There has been only a limited focus on individual differences among controllers and pilots in communicating information to each other. The ability to transmit information efficiently and effectively may vary with the ability to: 1) speak clearly, 2) speak at optimal rates, 3) compose messages, and 4) deliver messages with minimal interruptions or "say agains." Human Technologies, Inc. (1991) has provided some direction for further studies on individual differences and the Salt Lake City Terminal Communications Staff study (1991) has also made some suggestions.

Recommendations

Recommendations derived from this review of taxonomic, acoustical correlates, and the cognitive/psycholinguistic approaches include:

1. Determine whether a national database on voice communications, as part of the operational error/deviation database, should be constructed. As part of this database, the feasibility of having the speech act become the standard unit of measurement to examine voice communications should be determined.

2. Determine whether an evaluation of the ASRS data acquisition, coding, and entry system should be performed. As part of this evaluation, the reliability and validity of information coding procedures should be examined.

3. Sample more air traffic facilities to determine whether communications-based problems are of national proportion or site specific. A variety of data needs to be acquired including voice tapes of live communications and visual information so that the context within which voice communications occur can be determined.

4. Perform comprehensive experiments and correlational studies to examine the relationships between workload performance factors and communication errors. Variables of interest should include: a) number of aircraft being worked, b) radio frequency congestion, c) combined positions/sectors, d) conflict, and e) weather. Communication errors should include: clearance composition, phraseology, delivery technique, readback, and hearback.

5. Apply a cognitive/psycholinguistic approach to identify problems in ATC message composition, delivery techniques, and memory limitations. Experimental research and high fidelity simulation studies need to be performed to address these issues.

6. Undertake a coordinated research effort to investigate how acoustical approaches can be combined with the cognitive/psycholinguistic approach using communication taxonomies to improve our understanding of air traffic controller/pilot voice communications.

7. Examine current training program approaches for communications instruction so strengths and weaknesses can be identified and potential changes to the curriculum assessed prior to their implementation in the field. The implementation of suggested training initiatives should be evaluated to determine how they would change communication efficiency and accuracy. Untested changes in current practices might reduce some existing types of miscommunications, but could increase others and have the potential of creating new categories of communication problems.

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V. GLOSSARY OF ATC TERMS

ATC Instructions ------------------ Directives issued by air traffic control for the purpose of requiring a pilot to take specific actions; e.g., "Turn left heading two five zero," "Go around," "Clear the runway."

Communications error ---------- A causal factor associated with the exchange of information between two or more people (e.g., pilots and specialists). It refers to the failure of human communication not communication equipment, FAA Form 7210-3. Final operational error/deviation report, p. 15.

Collaborative scheme ----------- A hypothetical construct which serves to organize two-party communications into a meaningful shared mental model; consists of one or more transactions.

Formant ---------------------------- Vocal tract resonance; formants are displayed in a spectrogram as broad bands of energy

Fundamental frequency--------- The number of glottal openings per second. It is perceived by humans as the speaker's pitch.

Handoff ---------------------------- An action taken to transfer the radar identification of an aircraft from one controller to another if the aircraft will enter the receiving controller's airspace and radio communications with the aircraft will be transferred.

Hearback -------------------------- The act of a controller's actively listening to a pilot's readback of an ATC clearance.

Information problems----------- Problems in communications due to information which may be inaccurate, incomplete, or mistimed.

Instrument flight rules (IFR) ---- Rules governing the procedures for conducting instrument flight. Also a term used by controllers and pilots to indicate type of flight plan.

Level-five ------------------------- *Air traffic control facility conducting between 100.00 and 999.99* operations per hour.

Non-routine transaction -------- Purposeful interruption in the standard communication chain used to signal a problem in information transfer.

Operative memory --------------- All the relevant knowledge and information of the air traffic control position/sector that a controller had memorized, organized, and structured.

Phoneme -------------------------- Smallest unit of speech that distinguishes one utterance from another in all the variations that it displays in the speech of a single person or particular dialect as the result of modifying influences.

Pitch perturbations --------------- Minute variability that occurred in the spacing of fundamental frequency periods when measured on cycle-by-cycle variability in the amplitude pattern.

Plan View Display (PVD) ------- CRT and related computer hardware and software which displays on a screen radar-detected aircraft.

Pop-ups ---------------------------- A previously unidentified aircraft requesting IFR or VFR clearance.

Readback --------------------------- The act of a pilot repeating the information in a ATC clearance.

Shimmer --------------------------- Cycle-by-cycle variability in the amplitude pattern.

Speech act ------------------------- An utterance which serves one discourse function.

Transaction ------------------------ The delivery and receipt of a communication between a minimum of two people.

Understanding problems ------- Problem in understanding the intentions of a communication due to faulty mental model updating.

Visual flight rules (VFR) --------- Rules that govern the procedures for conducting flight under visual conditions. The term VFR is also used in the United States to indicate conditions that are equal to or greater than minimum VFR requirements. In addition, it is used by pilots and controllers to indicate type of flight plan.

Working memory ---------------- An active system of memory in which information is assembled and organized prior to recall.