Theoretical Foundations for Sound's Use in Multimedia Instruction to Enhance Learning

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Recent technological advances now make possible the full integration of sound in instructional software. Sounds may gain and focus learner attention, reduce distracting stimuli, and make learning more engaging. In addition, they may help learners condense, elaborate on, and organize details, highlighting interconnections among new pieces of information and making connections to preexisting knowledge. Thus, sound may hold great promise for moderating acquisition, processing, and retrieval "noise" in instructional software. Unfortunately, interface and instructional design guides almost completely ignore sound, and research suggests many promising instructional uses remain largely unexplored. This paper explores information-processing and communication theoretical foundations for sound's systematic use in the instructional communication system and proposes a framework for a program of research on instructional software's use of sound.

☐ Technological and cost barriers to full integration of sound in instructional software have recently disappeared. Conceptual and preconceptual barriers, however, still appear to prevent software designers from using sound effectively in their instructional products. Interface books seldom discuss the use of sound, and when they do, the use most often discussed is simple verbatim narration of on-screen text (see Bickford, 1997; Cooper, 1995; Galitz, 1997; Mandel, 1997). Because most "classics" of instructional interface design were written before sound was a viable design component, sound is seldom well discussed (see Alessi & Trollip, 1985, 1991; Hannafin & Peck, 1988; Jonassen, 1988; Keller, 1987). In general, interface design guidelines identify three main uses of sound in instructional software: (a) to alert learners to errors; (b) to provide stand-alone examples (such as musical passages or digitized versions of speeches); or (c) to narrate text on the screen (for multimodal presentation, for nonreaders, or for those with auditory limitations). Review of research on sound in instructional software reveals a focus on the third use cited above, digitized or computer-generated synthetic speech narration (see Barron & Atkins, 1994; Mann, 1995; Shih & Alessi, 1996). While some outside of the educational field have considered nonspeech interface sounds (Blattner, Sumikawa, & Greenberg, 1989; Gaver, 1986), many promising uses remain unexplored.

Reeves (1991, 1995) has advised those researching the impact of instructional software to improve their understanding "bit by bit," by first constructing theory-based models that preserve the technology's dimensional complexity, and then collecting and analyzing relevant data

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using methods that illuminate instructional decision making, thus avoiding the "empirical swamp" of media-comparison studies. Salomon (1994) argued that to devise technologies that truly make a difference, instructional designers must be supplied with development guidelines that are based on the unique ways various communication technologies and media presentations affect the learner. In agreement, Luskin (1997) argued that understanding the fundamental components of instructional media and the psychology behind them may be the only way to discover their pedagogical capabilities, particularly as it becomes increasingly difficult to separate multiple media from the computer technologies that allow students to interact with them. Further, without a strong theoretical cognitive foundation, the sounds used in instructional software may not only fail to enhance learning, they may actually detract from it. Such a strong theoretical foundation should address *information-processing theory* because it supplies a model for understanding how instructional messages are processed by learners and *communication theory* because it supplies a model for structuring optimally effective instructional messages. The following section suggests how these two theories might be combined to help describe the fundamental nature of the *instructional communication system*.

THE FUNDAMENTAL NATURE OF THE INSTRUCTIONAL COMMUNICATION SYSTEM

According to information-processing theory, learning emerges from processing interactions among information from the environment and the learner's knowledge and previous experiences. Most theorists have adopted at least the basic structure of the three-stage memory model first proposed by Atkinson and Shiffrin in 1968.

The Atkinson-Shiffrin Information-processing Model

In the Atkinson-Shiffrin model, environmental stimuli in their primitive form are first handled by a sensory information store, or *sensory register*. Signals held there are readily displaced by further signals in the same sensory channel. The sensory register filters and then routes the incoming signals to a second, *short-term,* store where information is held temporarily until it can be encoded for storage. *Encoding* is the process of building relationships and connections within new material or between new material and existing knowledge structures. Once encoded, the information is moved into *long-term* store. Long-term store is the place where we hold newly encoded information and from which we retrieve well-established memories. Recovering information from long-term store requires *cues* that may be supplied externally by the situation or internally by one's existing memories. Information-processing theorists maintain that learning occurs when information that has been transferred to and stored in long-term memory can be retrieved when needed.

Phye (1997) proposed that transforming incoming environmental stimuli into learned images and *schemata* (organized, propositional knowledge) involves three main operations: acquisition, processing, and retrieval. It appears, however, that limitations in each of these operations may restrict the amount of data one can consign to long-term storage.

Limiting factors in information processing

In order to *acquire* or make sense of the constant barrage of sensory information, an individual must decide, often unconsciously, which information to attend to and which to ignore. To explain this phenomenon, Broadbent (1958) posited that all information reaching the sensory register is subjected simultaneously, or in parallel, to a preliminary analysis based on prior knowledge. From this preperceptual analysis of the entire sensory scene, one chooses a smaller subset of stimuli to process successively, or in serial, through the rest of the cognitive system. The "bottleneck" created between parallel preperceptual and serial perceptual stages restricts the amount of information entering the cognitive system. Individuals remain essentially unaware of information not selected for attention.

Like many later researchers, Wundt (1896/1897) found that short-term store is also of limited capacity. There is a limit to the amount of information, or maximal *cognitive load*, an individual can *process* in short-term store at any given time. Information that exceeds cognitive processing capacity is dropped from short-term store without being processed. Further, unless information that enters the store is rehearsed, it decays within approximately 5 to 20 seconds. Short-term store limitations dictate that data not encoded and moved into long-term store must be overwritten to make room for new incoming stimuli (as when we forget a new phone number after hearing another series of numbers) or consciously rehearsed and then discarded immediately after use (as when we repeat a telephone number aloud until we have dialed it).

Forgetting is a failure to *retrieve* information from long-term store. There are three general hypotheses about the factors that cause forgetting, each of which probably contributes to overall retrieval problems. (a) The decay hypothesis asserts that the strength of a memory simply weakens over time and therefore is harder to retrieve (Wickelgren, 1976). (b) The interference hypothesis claims that competition among memories blocks the retrieval of a target memory (Postman, 1961). (c) The retrieval-cue hypothesis asserts that at the time of retrieval we lose access to the internal "indices" that point to the memory's location in long-term store (Norman, 1982). While there is some evidence to suggest that once information has been moved to long-term store it remains there forever (Nelson, 1971), it appears that individuals certainly can lose access to it.

Information-processing theory addresses human cognition. Communication theory, on the other hand, addresses human interaction. As was the case with information-processing theory, one model—Shannon and Weaver's *The Mathematical Theory of Communication* (1949/1969)—appears to have been particularly influential in shaping communication theory.

The Shannon-Weaver Communication Model

The Shannon-Weaver model proposes that all communication processes begin when a *source*, desiring to produce some outcome, chooses a message to be communicated. The message is encoded into an ordered set of perceptual elements, or cues, in order to produce a signal appropriate for transmission over the *channel* that will be used. After the message has been transmitted, a *receiver* then decodes the message from the signal transmitted. All channels have limited capacity. In humans, *channel capacity* generally refers to the physiological and psychological limitations on the number of symbols or stimuli that individuals can process. When more symbols are transmitted than a channel can handle, some information is lost.

According to Shannon and Weaver, communication is "perfect" when the information contained in a message affects the receiver in exactly the way intended by the source. Communication is rarely perfect, however; at any point things can get added to the signal that were not originally intended by the source. This spurious information, or *noise*, introduces errors that increase the uncertainty in the situation and make the signal harder for the receiver to reconstruct accurately.

Limiting factors in communication

Shannon and Weaver divided the analysis of communication problems into three levels. Level A deals with how accurately the signal is received. When competing external or internal stimuli exist in a communication channel, the resulting noise introduces technical errors that can overpower all or part of a signal transmission. This disruption prevents the receiver from being able to select the communicated signal for decoding. No matter how accurately a message is transmitted, however, if it cannot be decoded by the receiver it is not likely to convey the intended message. Level B, therefore, concerns how precisely the received signal conveys the intended message. Decoding requires the receiver to analyze an incoming signal based on his or her existing schemata. When no interpretive framework exists and none is supplied by the source, the resulting noise introduces semantic errors that prevent the signal from conveying the intended message. Even when a message is interpreted correctly, it still may not accomplish the source's goal. Thus, Level C involves whether the received message ultimately produces the outcome desired by the source. To effect an outcome, the elements and structure of the message that assign connotative meaning—such as aesthetic appeal, style, execution, and other psychological and emotional factors—must mesh with the receiver's own relevant beliefs, cultural values, and experiences. If this synthesis leads the receiver to make inferences about the message that are not intended by its source, the resulting noise introduces conceptual errors that can prevent the communication from producing the desired result.

Berlo (1960) suggested that the study of learning processes and the study of communication processes differ only in their point of view. While learning models generally begin with and focus on how messages are received and processed by learners, communication models most often begin with and focus on how messages are sent. Learning from instructional software, therefore, might be viewed as an instructional communication system with a set of interrelated parts working together to produce learning (Banathy, 1996).

The Instructional Communication System

In an ideal instructional communication system, an educator selects an instructional message to communicate for student learning. Anticipating communication problems at each of the technical, semantic, and conceptual levels, the instructor plans a lesson carefully by organizing and choosing the appropriate message cues based on the aptitudes and needs of the students. As the information to be learned is transmitted over the chosen channel, the student selects the lesson material from among the many competing internal and external environmental stimuli. The student then interprets the message signals in the way intended and analyzes the information selected, making the appropriate internal connections between related content points. Having committed the information to memory, the student then retrieves the constructs necessary for understanding, relates the message to those deeper meanings, and synthesizes the new material into existing knowledge. With these external connections established, the instructional message is then committed to the student's long-term memory, the effect desired by the educator.

Unfortunately, one need not visit many classes before discovering that instructional communication systems rarely work ideally. While it is tempting to blame the problems within these systems on noncurricular pressures such as divorce, drugs, teenage pregnancies, racism, and in-school violence, considerable theoretical work and research support the argument that students' difficulties are quite often due to failures in overcoming acquisition, processing, and retrieval "noise" in the instructional communication system (Glasser, 1969; Goodlad, 1984; Holt, 1969; Rutter, Maughan, Montimore, Ouston, & Smith, 1979; Silberman, 1970).

Limiting factors in the instructional communication system

Like other forms of communication, instructional communication systems can fail because of errors induced by excessive noise. Limitations within any of the three information-processing operations (acquisition, processing, and retrieval) can contribute to problems in instructional communication. Noise encountered within each operation is discussed below.

Acquisition noise. In order to learn, students must first receive an instructional message accurately (Ormrod, 1990). When competing external or internal stimuli exist in the channel, the resulting acquisition noise may disrupt instructional signal selection. These technical errors often cause the learner to fail to attend to the communicated instructional material.

Processing noise. Unless a learner can decode an instructional signal, the signal is not likely to convey its message. That is, learning is more securely established when an instructional signal, the material of learning, can be broken down into its constituent parts, relationships between those parts made explicit, and the organizational principles and structures of the combined parts recognized (Bloom, 1956). However, when learners have no way to interpret a signal, the resulting processing noise may distort instructional message analysis. These semantic errors can cause the learner to misinterpret the communicated instructional material.

Retrieval noise. If the elements and structure of an instructional message do not mesh artfully with the receiver's constructs and personal experiences, the message is unlikely to produce the desired outcome. That is, learning is accomplished most effectively when an instructional message triggers links to existing knowledge (Resnick, 1989). When messages fail to evoke the correct framework for understanding and schema building, the resulting retrieval noise may discourage instructional message synthesis. These conceptual errors can cause learners to misunderstand the broader, connotative meaning of instructional material.

Like the three levels of communication problems (technical, semantic, and conceptual), the nature of an instructional communication problem varies depending on the level or phase of learning—selection, analysis, and synthesis. The works of a number of authors apply here (see Anderson, 1995a,b; Gagné, 1985; Gagné & Driscoll, 1988; Glass, Holyoak, & Santa, 1979; Grabe, 1986; Harris, 1982; Thomson & Tulving, 1970; Tulving, 1972; Tulving & Thomson, 1973). Synthesizing their works, one might hypothesize difficulties in each of the learning phases.

During *selection* the learner receives the instructional signal. Technical difficulties at this phase arise when the signal cannot overpower competing external and internal stimuli in the channel. The disruption causes message-transmission problems. Defeating selection-phase instructional communication problems requires that the learner direct attention to the signal, isolate and disambiguate the signal from the surrounding stimuli, and relate the incoming signal to some existing schema in memory. In other words, the learner must be sufficiently interested in the message and be physically able to select it for further processing.

In the *analysis* phase, learners decode the received signal based on their existing schemata and any clues provided from within the signal itself. Semantic difficulties in the analysis phase stem from the noise created by missing interpretive frameworks, which causes message-interpretation problems. Overcoming analysis-phase problems calls for the learner to focus attention on the message, organize and categorize the information contained in the message, and use the information contained in the message to build upon existing knowledge. Stated differently, in order to decode and encode the material under study for long-term memory storage, the learner must be actively curious about the material and possess the interpretive framework necessary for appropriate analysis.

During *synthesis* the learner internalizes and reacts to the decoded message in the way intended by the source. Conceptual difficulties in this learning phase occur when prompts in the message do not match the learner's existing schema and cause misunderstandings. Defeating synthesis-phase problems requires that the learner sustain attention over time, elaborate on the information contained in the instructional message, and use the information contained therein to construct transferable knowledge structures. That is, in order to process the material more deeply, learners must be engaged in the instructional message and appropriately synthesize the concepts conveyed with their existing schemata.

A Framework for Understanding the Fundamental Nature of the Instructional Communication System

Acquisition, processing, and retrieval operations are all applied—in varying amounts—during each phase of learning. During selection, learning calls on acquisition heavily; in contrast, only the most salient memories are retrieved during selection. During analysis, processing is central—although acquisition and retrieval are also relatively active. During synthesis, learning calls on retrieval most heavily, while only the most salient new stimuli are acquired. Table 1 depicts the orthogonal relationship between the selection, analysis, and synthesis phases of learning and the acquisition, processing, and retrieval information-processing operations.

Table 1 ☐ The fundamental nature of the instructional communication system.

	Acquisition	*Processing*	*Retrieval*	
	Acquisition Noise Level A. Technical difficulties. Competing internal and external stimuli cause message-transmission problems.	*Processing Noise Level B. Semantic difficulties. Missing interpretive frameworks cause message-interpretation problems.*	*Retrieval Noise Level C. Conceptual difficulties. Prompt or schema mismatches cause message-understanding problems.*	
Selection	Learner has trouble directing attention to the instructional message.	Learner cannot isolate and disambiguate relevant information contained in the instructional message.	Learner's existing schemata are not activated by the instructional message.	*Not Interested*
Analysis	Learner has trouble focusing attention on the instructional message.	Learner cannot organize the information contained in the instructional message.	Learner does not use the information contained in the instructional message to build on existing knowledge.	*Not Curious*
Synthesis	Learner has trouble sustaining attention to the instructional message.	Learner cannot elaborate on the information contained in the instructional message.	Learner does not use the information contained in the instructional message to construct transferable knowledge structures.	*Not Engaged*

The rows in Table 1 (running horizontally from left to right) represent the learner's selection, analysis, and synthesis learning phases, while the columns (running from top to bottom) represent the learner's acquisition, processing, and retrieval information-processing operations. The subheadings across the top of the table indicate the general nature of the channel noise that might be produced. The intersections of the learning phases and information-processing operations detail the specific nature of the acquisition, processing, or retrieval noise that a message is likely to encounter at that juncture.

When tracing the cells horizontally across the learning phases, one finds that if an instructional message fails to gain attention, is not sufficiently salient for the learner to isolate it from among the many stimuli encountered, and does not evoke the existing schemata from memory, the learner is not likely to be interested. Similarly, if an instructional message fails to focus attention, neglects to help organize the information it contains, and does not help build upon existing knowledge, the learner is not likely to be curious. Lastly, if an instructional message does not hold attention over time, help elaborate on the information it contains, or support efforts to construct transferable knowledge structures, the learner is not likely to be engaged.

Following the cells vertically down the information-processing operations, it appears that the relative strength of potential noise increases and the ultimate consequences of that noise become more serious at each deeper (top to bottom) phase of learning. Thus, instructional-message transmission problems at each phase are constituted by the learner's deepening attentional difficulties. Message-interpretation problems at each phase consist of the learner's intensifying trouble with information manipulation. And message-understanding problems at each phase are compounded by the learner's advancing problems in connecting the new information to existing schemata.

The reader may observe that this framework for understanding the fundamental nature of the instructional communication system could more broadly inform the use of any class of medium in instructional software. However, we will focus here only on how adding sound to instructional messages may help to optimize communication by helping learners overcome the varying amounts of information-processing noise encountered at the selection, analysis, and synthesis phases of instructional communication. Once again, information-processing and communication theories might shed light on the role sound can play. The next section builds on these two theories to lay a framework for sound's potential role in the instructional communication system.

HOW SOUND MIGHT HELP TO OPTIMIZE THE INSTRUCTIONAL COMMUNICATION SYSTEM

McAdams and Bigand (1993) argued that sound is uniquely suited to assist learning for those who are not hearing impaired. It appears that sounds can support the acquisition, processing, and retrieval of new information in a variety of ways.

The Role of Sound in Information Processing

We know from our experience with loud, sudden alarms that sounds can be particularly demanding of our attention. Wickens (1984) observed that sounds are especially intrusive on our consciousness because, unlike eyes, ears can never be averted or shut with "earlids." In fact, research by Kohfeld (1971) and Posner, Nissen, and Klein (1976) has confirmed that sounds generally are more effective than images for gaining attention. But sounds evidently need not be alarming or startling to attract us. Some sounds—such as a far-away baby's cry or a flat tire's faint thumping—so immediately activate existing images and schemata that they can be particularly effective in focusing our attention (Bernstein, Clark, & Edelstein, 1969a,b; Bernstein & Edelstein, 1971). Other sounds—such as waves hitting the shore or an inspirational Sousa march—can hold our attention by making our environment more tangible or by arousing our emotions (Thomas & Johnston, 1984). Thus, sounds not only gain attention, but also can help focus attention on appropriate information and keep distractions of competing stimuli at bay, engaging an individual's interest over time.

Sounds supply us with volumes of complex information that we easily interpret in order to extrapolate important details about the world around us. Sounds can communicate information when visual attention is focused elsewhere, when tasks do not require constant visual monitoring, or when the visual channel is overburdened. In these ways, sounds can consolidate the information we might otherwise obtain visually to help us determine when to cross busy streets, to stop pouring liquids, and the like (McAdams, 1993). Further, sounds can elaborate on visual stimuli by providing information about invisible structures, dynamic change, and abstract concepts almost impossible to communicate visually. Perkins (1983) noted, for example, that many drivers of manual transmission cars rely on the sound of the car engine, not visual cues from a speedometer or tachometer, to decide when to shift gears. And Harmon (1988) suggested that without even having seen the performance, we know from thunderous applause a show was well received. Winn (1993) proposed that sounds form hierarchical clusters just as sights do; the difference is that sounds are organized in time, whereas images are organized in space. Take, for example, a situation in which five sound sources—(a) a factory operating, (b) a person speaking, (c) a helicopter flying, (d) a truck idling, and (e) a motorcycle running—are producing sound simultaneously. Yost (1993) observed that organizational temporal clues within this composite of sounds allow most people almost instantly to ascertain that five sound sources are present, to determine each source's identity, and to locate the sources spatially. Thus, sounds provide a context within which individuals can think actively about connections between new information.

Gaver (1993) asserted that when we hear the sound of a car while we are walking along a road at night, we are not likely to focus on the sound itself at all. Instead, we compare what we are hearing to our memories for the objects that make that sound, drawing from and linking to existing constructs and schemata in order to support our understanding of what is happening—and we step out of the car's path. If, however, the same automobile sound were used in a cartoon to accompany a character's nonautomotive hasty retreat, we might instead build upon our understanding of the action by metaphorically depicting one event in terms of our existing knowledge of another event. The language we later use to describe these sounds provides us with the means to discuss the experience with others and to transfer this knowledge to new situations where we can develop even deeper understandings. (Consider, for example, "The baby wailed like a siren"; "the mindless bureaucrat squawked like a parrot"; and "the coward squealed like a pig.") Thus, sounds can tie into, build upon, and expand existing constructs in order to help relate new information to a larger system of conceptual knowledge.

While there has been some debate among learning and memory theorists over the way knowledge is represented in memory, most acknowledge the importance of employing multiple sensory modalities for deeper processing and better retention (for example, see Paivio, 1971, 1986; Tulving, 1983). So, seeing a telephone and hearing it ring should result in better memory performance than only seeing it or hearing it (Engelkamp & Zimmer, 1994). Shannon and Weaver (1969) suggested that anticipating communication difficulties and front loading messages with this sort of redundancy might help to squelch noise even before it occurs.

The Role of Redundancy in Communication

Redundancy is the information that message cues share: the parts that overlap. While the word *redundancy* is commonly defined as something that is superfluous or unnecessary (Hawkins & Allen, 1991), in communication systems the surplus may not necessarily be uncalled for.

For example, a source might attempt to correct technical problems in the system (Level A, Shannon & Weaver, 1969) by retransmitting or amplifying the signal ("What I asked was, *can you pick up some things at the store on your way home*?"). This *content redundancy* often can help overcome transmission errors by completing obstructed signals or by preventing the interference in the first place (Berlyne, 1957a,b,c, 1958; Miller, Heise, & Lichten, 1951). A source anticipating semantic problems in the system (Level B, Shannon & Weaver) might attempt to correct them by supplying the framework to make relevant connections among related message signals ("No, *I'm baking a pie*, I need *flour* not *flower*.") This *context redundancy* often can help overcome misinterpretations by furnishing denotative meanings for signals (Aborn & Rubenstein, 1952; Bateson, 1978; Berger, 1987; Hewes, 1995; Rubenstein & Aborn, 1954). A source might attempt to correct conceptual problems in the system (Level C, Shannon & Weaver) by carefully choosing signals that make appropriate links to receivers' preexisting concepts in memory, such as immediacy ("I'm baking a pie for *tonight's* dessert"). This *construct redundancy* clarifies the connotative meanings behind message signals and reduces misunderstandings (Heit, 1997; Pask, 1975).

Various types of redundancy, therefore, may help to overcome the noise that can raise barriers at each level of communication. Redundancy that helps a receiver separate transmitted information from system noise increases understanding and is, therefore, desirable. However, redundancy that is not needed by the receiver or that fails to increase understanding can be a burden on the system. Because of channel limits, unnecessary redundancy may actually impede the flow of new information and, consequently, decrease communication effectiveness (Leonard, 1955). When redundancy exists at the expense of new information, it can introduce its own sort of noise—boredom and fatigue induced by repetitiveness—into the system. Thus, while highly redundant messages can overcome noise in communications effectively, they are not very efficient (Reza, 1994). When a source anticipates noise at the various levels of communication, the trick may be in knowing how much and which sort of between-cue message redundancy to include in order to counteract noise. Striking the right balance between redundant and informative message cues appears to be the key to successful communication (Krendl, Ware, Reid, & Warren, 1996).

The Role of Multi-Cue Messages in Instructional Communication Systems

For some time it has been thought that simply adding cues to messages might improve the effectiveness of instructional communication. Hoban (1949) and others hypothesized that the more cues used, whether within or across sensory channels, the greater the amount of information communicated and the more learning gained (see also, Clark, 1932; Einbecker, 1933; Hansen, 1936; Miller, 1957; Westfall, 1934). Unfortunately, the results of these cue summation studies have been contradictory—at least on the surface. Severin (1967a) maintained the differences might be explained by the degree of redundancy among cues used in the treatments. Severin noted that studies that found no difference between multiple-cue and single-cue communication used cues that were almost totally redundant, such as text coupled with word-for-word narration. In these studies the "wedded" cues apparently neither competed with each other nor supplied new information (see MacKay, 1973; Severin, 1967b; Travers, 1964a,b; Van Mondfrans & Travers, 1964). In contrast, studies that found multiple-cue communications to be less effective than single-cue communications used cues with no redundancy between them, such as text coupled with unrelated speech. In these studies, the "dueling" cues probably exceeded channel capacity, producing noise that decreased communication efficiency (see Boring, 1950; Carpenter, 1953; Cherry & Taylor, 1953; Hernandez-Peon, 1961; Spaulding, 1956). Severin concluded that studies that found multicue communications to be more effective than single-cue communications used cues that were partially redundant, such as pictures coupled with related narration. In these studies, primary and secondary cues appear offset just enough for the secondary cue to supply the right balance of redundancy and new information (see Hartman, 1961a,b; Ketcham & Heath, 1962; Kramer & Lewis, 1951; Lumsdaine & Gladstone, 1958).

Severin (1967a) contended that multicue messages can be designed to help improve instructional communication. The question is not just whether the message contains multiple cues, but how useful the secondary cues are to the receiver. Harrison (1972) proposed that in order for a secondary cue to be useful in communication, it really must be a *sign* that can be used to represent other potential stimuli or concepts, the way a flag stands for patriotism. Further, this sign must be part of a larger *code* or set of signs with procedures for combining the signs (or *syntax*) and meanings common to the members of some group. Thus, secondary cues appear to be interpretable only within the context of a primary cue (Emmert & Donaghy, 1981). These views match well with those of Fiske (1990), who suggested that in the absence of a primary cue, the receiver may supply a derived cue based on information acquired from other environmental stimuli or retrieved from existing schemata. For example, a waving, raised hand is a secondary cue that often accompanies a friendly verbal greeting primary cue. When no words are exchanged, understanding the message requires the receiver to infer the primary cue from the context of the situation and from previous experience. If the raised hand came from an old friend, the receiver might supply a *hello* primary cue. If it came from a uniformed police officer, however, the receiver might instead supply a *stop* primary cue.

Fiske's broader concept has at least four implications here. First, it may be that one way to supply the redundancy needed to design useful multicue messages is to make sure that secondary cues are associated with some primary cue. The sound of an arrow being shot and hitting its target will be ambiguous until it has been deliberately associated with a definition of the concept of *accuracy*. Second, once a syntax and meaning have been clearly established, secondary cues may communicate information without the primary cue. Replaying the arrow-hitting-target sound on subsequent screens, for example, might elicit learners' memory for the accuracy definition without having to restate it. Third, with this primary-secondary code in place, it may be possible to build upon the primary cue by simply changing aspects of the secondary cue. For example, a subsequent screen accompanied by an arrow-missing-target sound might quite effectively illustrate the concept, *inaccuracy*. Fourth, there appears to be a body of well-established codes upon which a source can already draw. Using ambiguous musical notes, clicks, buzzes, and dings as secondary cues may not be as useful as sounds for which learners are likely already to have strong associations, such as the arrow-hitting-target sound.

It seems that once a syntax has been established, secondary cues can help make the message more effective. Stated differently, secondary cues may be able to supply the redundancy needed to overcome communication noise. Given the roles sound plays in information processing, it may be that multicue messages incorporating sounds can help achieve the optimal redundancy-information balance and offset noise in instructional communication systems. That is, there may be systematic ways to design sounds so that instructional messages supply the content, context, and construct redundancy necessary to optimize learning.

A Framework for Sound's Use in Multimedia Instruction

Table 2 reorganizes Table 1 slightly and fills in suggestions for how sound might be used in each cell; the aim is to use sound to enrich instructional messages with the redundancy necessary to overcome that cell's noise potential.

For example, a multimedia lesson equating information processing with a package-shipping center might introduce each member of the "staff" with an accompanying sound effect (Cates, Bishop, & Hung, 2000). The initial inspector of incoming packages, Tom (sensory register), would introduce himself—accompanied by the sound of a buzzing fly. The package sorter and router, Mary (short-term store), would introduce herself—accompanied by the sound of a spraying paint can. The warehouse manager, Fred (long-term store), would introduce himself—accompanied by the sound of a file cabinet drawer opening and closing. And the center supervisor, Tanika (executive function), would introduce herself—accompanied by sounds associated with the an intercom system. These and other similar auditory cues might be sufficiently novel, bizarre, or humorous to help learners direct their attention to the lesson (Table 2, cell 1). As packages traveled from station to station on the center's assembly line, a conveyer-belt sound would act as a divider between content groupings, helping learners to isolate and disambiguate instructional message stimuli (Table 2, cell 2). And, learners' past experience with flies, spray paint, file cabinets, and belt-driven devices means that the sounds are likely to evoke their existing schemata for these objects easily (Table 2, cell 3). Thus, when one traces the first row of cells horizontally across the learning phases, the framework suggests that learner interest may be captured by an instructional message that employs sound to increase novelty, to make the message salient, and to appeal to existing schemata.

As the same lesson progressed, Tanika might use her intercom to address each character on the shipping floor with a "Hey [character name]" accompanied by the intercom sounds. These sounds, combined with a simple animation of the character turning to face Tanika, might help to focus learner attention on particular content points (Table 2, cell 4). A fly might buzz around Tom's head to illustrate how the distractions of external stimuli affect information processing, Mary might spray-paint individual packages to encode them for long-term store, and Fred might open and close file drawers labeled "episodic" and "semantic" in order to insert the color-coded "packages" of information. As these concepts were introduced and discussed on subsequent screens, the lesson would repeat the appropriate sounds without providing the primary visual cues (fly, spray can, and file cabinet). In this way, sound might help learners differentiate among the components of the material under study and establish an auditory syntax that could be used throughout the lesson (Table 2, cell 5). Further, these sounds might help learners build on their existing schemata for them by now linking them to the newly learned material (Table 2, cell 6). Thus, learner curiosity might be aroused by an instructional message that uses sound to point out where to exert information-processing effort, when to differentiate between and systematize content points and main ideas, and how to help situate the material under study within real-life or metaphorical scenarios.

At the synthesis learning phase, the lesson might continue to build on its use of these sounds to help learners process the lesson content more deeply. For example, learners might hear the sound of a fly being swatted during a discussion of selective attention, the fizzle of an almost empty spray can during a discussion of

Table 2 ☐ The fundamental nature of the instructional communication system expanded with suggestions for sound's potential role in instructional software.

To overcome:				
	Acquisition Noise	*Processing Noise*	*Retrieval Noise*	
	Level A. Technical problems. Competing internal and external stimuli cause message-transmission problems.	*Level B. Semantic problems. Missing interpretive frameworks cause message-interpretation problems.*	*Level C. Effectiveness problems. Prompt/schema mismatches cause message-understanding problems.*	
The message should contain:				
	Content Redundancy	*Context Redundancy*	*Construct Redundancy*	
	"Amplifies" the content for message transmission (encourages noise-defeating learner acquisition states)	*Supplies the context for message interpretation (encourages noise-defeating learning processing strategies)*	*Cues appropriate constructs for message understanding (encourages noise-defeating learner retrieval schemes)*	
Selection	1. By using sound to help learners direct attention. Employs novel, bizarre, and humorous auditory stimuli.	2. By using sound to help learners isolate information. Groups or simplifies content information conveyed to help learners isolate and disambiguate message stimuli.	3. By using sound to help learners tie into previous knowledge. Appeals to learner's memories and evokes existing schemata.	*Interested*
Analysis	4. By using sound to help learners focus attention. Alerts learners to content points by showing them where to exert information-processing effort.	5. By using sound to help learners organize information. Helps learners differentiate among content points and creates a systematic auditory syntax for categorizing main ideas.	6. By using sound to help learners build on existing knowledge. Situates the learning within real-life or metaphorical scenarios.	*Curious*
Synthesis	7. By using sound to help learners hold attention. Immerses learners by making them feel the content is relevant, by helping to make it more tangible, and by bolstering learner confidence.	8. By using sound to help learners elaborate on information. Supplements the content by supplying auditory images and mental models.	9. By using sound to help learners prepare knowledge for later use. Helps learners transfer knowledge to new learning situations by building useful additions to overall knowledge structures.	*Engaged*

short-term memory limitations, and a locked file drawer being jiggled during a discussion of forgetting. Changing one aspect of these sounds in this way might help to redirect learner attention so that it's held over time (Table 2, cell 7). Further, the images evoked by the slightly altered sounds could help learners to elaborate on the information supplied in the instructional message (Table 2, cell 8). Ultimately, the transferable knowledge structures constructed by these secondary auditory cues might help learners to make enduring connections between the sound effect and the concepts learned that could be referred to or built upon in subsequent lessons or assessments (Table 2, cell 9). In this way, a learner's level of engagement might be increased by an instructional message that utilizes sound to make the lesson more relevant, to supply elaborative auditory images and mental models, and to help learners transfer the material under study by building transferable structures that could be useful in subsequent learning.

As was the case with Table 1, Table 2 intensifies the nature of the auditory redundancy stimuli with each deeper learning phase. Thus, sound's content redundancy contributions to the instructional message address the learner's deepening attentional difficulties at each of the three learning phases. Similarly, sound's context redundancy contributions to the instructional message are intended to remediate the learner's intensifying trouble with information manipulation. Finally, sound's construct redundancy contributions to the instructional message are aimed at ameliorating the learner's advancing problems in connecting the new information to existing schemata.

Thus, sound's contribution to an optimized instructional communication system could be in the form of secondary cues. But if sound, like any design element, has a larger role to play in instructional software, its use should be grounded in helping students acquire, process, and retrieve the material under study. Systematically adding auditory cues to instructional messages in this way might enhance learning by anticipating learner difficulties and suppressing them before they occur. The framework presented above suggests a wide range of interesting research questions and establishes the boundaries of a fertile territory for empirical investigation.

AN AGENDA FOR FURTHER RESEARCH

The next step in a systematic inquiry into sound's optimal use involves exploring the effectiveness of sound cues in computerized instruction through an iterative process of software development and modification, data collection and analysis, theoretical refinement, and product revisions (Savenye & Robinson, 1996). The first author hopes to continue her systematic evaluation of sound's use in multimedia instruction to enhance learning by pursuing the following research questions.

Research Questions

It is important to gauge the positive residual that learners acquire from instructional messages containing sound cues and to determine the extent to which auditory redundancy "squelches" information-processing noise in the channel. What is the learner thinking? How is the learner thinking? Is the learner "thinking in sound?" Inquiries about sound's role in instructional software have three major goals: (a) overcoming channel noise, (b) staying within channel capacity, and (c) stimulating information-processing effort. These goals and the nature of the research questions to be explored in attaining each are discussed below.

Overcoming channel noise

The first area of inquiry concerns which sounds to use in instructional messages in order to overcome channel noise. The general assumption is that, in order for multicue messages to be effective, they must supply the amount of redundancy and redundancy quality appropriate for the learning phase in order to overcome the potential for channel noise. In this area, the following questions might be pursued:

- How might one determine the amount of content, context, and construct redundancy contained in a message?

- Similarly, how does one predict whether a message contains enough redundancy to overcome channel noise at each learning phase? Does a lesson's topic have any bearing on the redundancy levels necessary? If so, what effect does it have? Do differences among learners have any bearing on the redundancy levels necessary? If so, what effect do learner differences have?
- Can content-redundant auditory cues sufficiently amplify the material to help learners overcome acquisition noise caused by increasing attentional difficulties (Table 2, column 1)? Which sound cues are most effective in defeating acquisition noise at each learning phase?
- Might context-redundant auditory cues supply the internal connections needed to overcome processing noise emanating from intensifying interpretation problems (Table 2, column 2)? Which such cues are good to ameliorate processing noise at each learning phase?
- Will construct-redundant auditory cues supply the schema prompts necessary to help learners overcome retrieval noise caused by deepening misunderstandings (Table 2, column 3)? Are there sounds that are particularly good at overcoming retrieval noise at each learning phase?
- How might one determine the quality of the redundancy contained in a message cue in order to decide if it will be most useful for noise neutralization at the selection, analysis, or synthesis phase (Table 2, rows 1, 2, & 3, respectively)?
- Can learners supply their own primary cues when presented with a particular secondary sound cue? Are some learners better at this than others? If so, which learners?

Staying within channel capacity

The second area of interest involves how sound might be incorporated into instructional software without exceeding learners' channel capacity (cognitive load). The general assumption is that while it may be possible to use sounds to supply the right amount of redundancy, the parts of an instructional message outside channel capacity will be lost. Questions to answer in this area of inquiry might include:

- How "wide" is a learner's channel? Asked differently, how much redundancy in an instructional message is too much? For which learners?
- Similarly, how does one predict when the amount of content, context, and construct redundancy in a message might cause it to exceed learner channel capacity? Does the lesson topic have any bearing on whether the level of redundancy enhances or detracts from the lesson? Do differences among learners have any bearing on redundancy level effects?
- Comparatively, how much burden do content, context, and construct redundant sound cues place on the channel (Table 2, columns 1, 2, & 3, respectively)? Do construct redundant sounds place a higher burden on the channel than context redundant sounds? Than content redundant sounds?
- Comparatively, how much burden do sound cues of varying quality impose on channel capacity?
- Which aspects of sound cues—such as abstraction, symbolism, or imagery—seem to increase or decrease channel burden?

Stimulating information-processing effort

The third area explores whether sounds incorporated into instructional software will stimulate learner information-processing efforts. The general assumption is that by supplying the right amount of content, context, and construct redundancy within the constraints of learner channel capacity, sounds might help to stimulate learner interest, curiosity, and engagement. Among the questions of interest here:

- How might one determine sound's stimulation capacity at each learning phase?
- How might one predict whether the selection-level content, context, and construct redundancy in a message are sufficient to stimulate a learner's information-processing effort and slow the message? Does the lesson

topic have any bearing on whether auditory cues help or hinder learner information-processing efforts? If so, what effect does it have? Do differences among learners have any bearing on the ability of auditory cues to stimulate interest, curiosity, or engagement? If so, for which learners?

- Comparatively, do content-, context-, and construct-redundant sounds simulate learner interest, curiosity, and engagement in different ways (Table 2, rows 1, 2, & 3, respectively)?
- Comparatively, does the quality of sound cues have a bearing on the depth of information-processing effort that learners are willing to exert?
- Which sorts of sound cues (speech, environmental sounds, music) elicit the most acquisition effort, processing effort, and retrieval effort?

Truly understanding what is going on within the instructional communication system in order to observe the effect that adding content, context, and construct redundancy to messages has on learners will require research techniques that measure more than just content recall and retention.

Possible Methodologies and Data Measures

Getting "inside" the model, in order to assess the usefulness of the framework, calls for a research agenda that incorporates a mixed variety of triangulated quantitative and qualitative methodologies. Reeves (1993a,b) and Newman (1990) suggested an approach that includes:

Pilot studies to test initial sound choices. For example, do seventh-grade learners know the sound that a bulldozer makes? Can they determine when music "sounds right?" Answers to questions like these can help to guide secondary-sound-cue design choices, particularly when it is important for learners to supply their own primary cues.

Think-aloud studies to further hone design decisions. For example, designers would know they were creating transferable knowledge structures if students described out loud how hearing a particular sound used in a lesson helped them to "see" the screens that contained the related instructional content.

Formative experiments to polish the final product. These would be conducted in real instructional settings to accomplish meaningful instructional goals, and might seek to evaluate whether students are applying the information and strategies learned in the lesson to other content areas.

The data gathered from these evaluations should include:

Behavior observations. A teacher-observer, who knows what to look for and which questions to ask, might be able to spot some of the subtle changes occurring in learner instructional communication systems. For example, observers might be trained to look for specific sound-word analogies, particular word plays, and definite behaviors (such as singing the lesson's redundant tunes) that might indicate the lesson's lingering effects that are not easily measured by a questionnaire, survey, or test item.

Detailed information about learners' time in the software and where they spent more or less time. The analysis of these data might be structured around those portions of the lesson where the designer believes selection-, analysis-, and synthesis-level learning may occur. That way, one might determine where redundancy levels were insufficient to stimulate learner information-processing efforts.

Audit trails that provide information about valid and invalid clicks, drags, drops, and the like. This information is important not only for understanding where the learners might be having trouble with the interface, but also for spotting aimless clicking and advancing through the lesson.

Pre*treatment measures of independent variables thought to be relevant (previous schooling or experience, motivation, learning style, modality preferences, and the like).* This information, gathered through questionnaires and interviews, would supply information about the learner's existing potential for noise, channel capacity, and the like.

Post*treatment measures of learners' attitudes about the software and their experiences with it.* This information, gathered through questionnaires and interviews, would supply information about the residual positive affects of learning such as improved attitudes and feelings of success that serve as catalysts for continued learning.

Pretest–posttest comparisons. In some cases, well-written pretest–posttest instruments may yield information about the formation and quality of schemata formed at the synthesis phase.

According to system optimization theory, once the theoretical foundation has been laid and a framework for sound's use established, the next step in a systematic inquiry into sound's optimal use involves exploring sound's effectiveness through an iterative process of software development and modification, data collection and analysis, theoretical refinement, and product revisions (Wilde & Beightler, 1967). It is our hope that this paper lays the theoretical foundation and provides a framework for a program of research on instructional software's use of sound.

SUMMARY

While it appears that humans rely heavily on sound to learn about their environments, instructional designers often make little use of auditory information in their computerized lessons. The prevailing attitude seems to be that, after all of an instructional software product's visual requirements are satisfied, the designer might then consider adding a few sounds in order to gain the learner's attention from time to time. If instructional multimedia software were a train, sound would be its caboose—bringing up the rear, put in place last, and often serving no obvious purpose beyond bells and whistles. This neglect of the auditory sense appears to be less a matter of choice and more a matter of just not knowing how to "sonify" instructional designs to enhance learning. More extensive use of sound may someday lead to more effective computer-based learning materials; but only if designers understand the cognitive components of sound's use and the ways in which sound can contribute to appropriate levels of redundancy and information in instructional messages. ☐

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