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Investigation of Air Traffic Controllers' Response Strategies in a Free Recall Task: What Makes Auditory Recall Superior to Visual Recall?

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This study investigated the response strategies displayed by air traffic controllers (ATCs) recalling visually and auditory presented verbal material in a free recall task. The end-of-list advantage for auditory compared to visually presented item lists (modality effect) was explored by using the procedure described by Beaman and Morton (2000). Results revealed that ATCs' response sequences frequently included ordered end subsequences of 2 to 6 items. These end subsequences were recalled as an initial run at a similar rate in both modalities, although they occurred more frequently in positions other than initial recall positions in the auditory modality. These results replicate and extend those reported in controlled laboratory studies, and this is despite ATCs' extended experience with processing visual information. The results are discussed in terms of the functional limitations of visual and auditory item processing and their relevance to air traffic control activities, training, and selection.

Processing and recall of information are directly involved in most air traffic control operations, including monitoring traffic, controlling aircraft movements, managing aircraft sequences, and resolving conflicts (Gronlund, Ohrt, Dougherty, Perry, & Manning, 1998). These operations can concern a large number of aircrafts and involve the processing of a considerable amount of information relative to directions of approach, speed, altitudes, and destinations. The information corresponding to each aircraft, such as instantaneous level, attitude (stable, climbing,

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descending), and speed group, is provided by strips containing a variable number of instructions per strip and a variable number of words per instruction. ATCs' recall performance has been shown to depend on a number of variables, including the amount of information to be remembered (Mélan, Galy, & Cariou, 2007; Schneider, Healy, & Barshi, 2004; Wickens & Hollands, 2000), the type of information to be processed (position on the sector map vs. details regarding an aircraft; Means et al., 1988), and the status of the aircraft (conflicting vs. nonconflicting aircraft; Gronlund, Dougherty, Durso, Canning, & Mills, 2005).

Recall performance of navigational messages has also been shown to vary according to the sensory presentation modality, with superior recall following auditory presentation compared to visual presentation (Barshi & Healy, 2002; Schneider et al., 2004). Immediate superior recall for spoken, as opposed to written, word or digit lists has come to be known as the modality effect. Laboratory studies demonstrated that the modality effect is very robust and holds true for a wide variety of memory test procedures (for a review, see Penney, 1989). Modality effects were most often investigated within the context of immediate serial recall, requiring individuals to recall all list items in the order of their presentation. Typically, serial recall results in a U-shaped serial position curve indicating superior recall for the first list item (primacy effect) and for the last list items (recency effect) compared to intermediary items. In regard to presentation modality, serial position functions have been shown to differ mainly for the end of the list, with a much larger recency effect for recall of spoken word lists than for written word lists (Jahnke, 1963; Madigan, 1971; Cowan, Saults, Elliott, & Moreno, 2002).

Theoretical speculation for the end-of-list advantage for auditory presentation has run mainly along the lines established by Crowder and Morton (1969). These authors proposed that a precategorial acoustic store, available for a few seconds, would favor end-of-list auditory items compared to visual items, and make a direct contribution to subsequent recall of auditory material from short-term memory. More recently, Penney (1989) suggested that auditory presentation provides acoustic-sensory information that is available over several end items of a list of unrelated words, whereas the visual-sensory code generated following visual presentation of information is only available for a very short period of time. In addition, whereas auditory presentation automatically generates a phonological code, visually presented words require phonological recoding. Recoding of visual items would disadvantage the last items of a list during subsequent recall (Baddeley, 1986; Penney, 1989). These theoretical accounts emphasize the existence of qualitatively different processing channels during short-term retention for written and heard material. Practical implications of the auditory advantage were shown, for instance, in the field of education. Thus, learning was shown to be enhanced if textual information was presented in an auditory, rather than the usual visual, format, but only when that information is accompanied by related visual information, such as a graph, diagram, or animation (for a review, see Ginns, 2005). This advantage was attributed to an increase in available working memory capacity when presenting information in both the visual mode (graphics, diagrams, etc.) and the auditory mode (verbal material).

A key issue is whether modality effects can be attributed to the superior encoding of spoken items (input effects) or, instead, to the tendency of the representation of spoken lists to hold up better in the presence of a delay and interference from response output; that is, the degradation of memory representations as recall proceeds across output positions (output effects). Several studies supported the conclusion that "the basic modality effect occurs because auditory items are more resistant to output interference" (Neath & Surprenant, 2003, p. 38; see also Cowan et al., 2002; Madigan, 1971), although others suggested that "the primary locus of the modality effect is at input; . . . the effect of the delay and interference from the response output appears to be on the overall level of performance" (Cowan, Saults, & Brown, 2004, p. 644).

Recently, Harvey and Beaman (2007) showed that the size of the modality effect also depends on the modality of the response mode. They compared modality effects for written and vocal output and concluded that "both superior encoding and modality-specific output interference contribute to the classic auditory-visual modality effect" (Harvey & Beaman, 2007, p. 693). On the contrary, written output would leave the recency-linked auditory-sensory memory trace intact, whereas spoken output would partially overwrite auditory traces held in memory. Beaman and Morton (2000) investigated the modality effect by inspecting individuals' response strategies during recall in unconstrained free recall. They found that recall sequences (written key-press responses) starting with a subsequence from the end of a 16-item list (of the form 13–14–15–16, 14–15–16, 15–16) were almost as frequent for written lists as for spoken lists. However, if such visual subsequences from the end of the lists were not recalled right away at the opening run, they would generally not be recalled at all, whereas for spoken lists, later recall occurred on a number of trials. According to the authors, something about auditory presentation would prompt the participants to use some recall strategy more than they would do spontaneously with visual presentation. In light of their findings concerning output modality, Harvey and Beaman (2007) argued that the modality effect observed in that study would have been much smaller with vocal output.

We tested this hypothesis by investigating ATCs' oral output protocols in unconstrained free recall, by using the procedure described by Beaman and Morton (2000). More specifically, we determined whether end subsequences would be observed at a comparable magnitude in the visual and auditory modalities, both as an opening run and later during recall protocols, as has been predicted for vocal output by Harvey and Beaman (2007) in this test situation. This result would then extend the findings from a controlled laboratory study to a real-job situation, particularly concerning the substantial contribution of output modality to the auditory recall advantage. This would be of importance as air traffic control activities are centred on processing and recall of information presented largely in a visual modality (strip and radar information on airplanes). On the other hand, results obtained in a previous study suggest that a modality effect can be observed even for vocal output (Mélan et al., 2007). In that study, ATCs' free recall performance was decreased in the morning for visual compared to auditory lists, and more so when lists contained nine rather than six items. Moreover, when ATCs' alertness was low, free recall was systematically decreased, whereas probe recognition dropped only for visually presented nine-item lists. Hence, higher recall in a recognition task compared to a free recall task is generally accounted for by lower interference at output in the former (Cowan et al., 2002). Likewise, higher recall for short, as opposed to, long word lists is consensually attributed to decreased proactive interference in primary memory, which maintains up to four items, compared to retrieval from secondary memory (Broadbent, 1975; Cowan, 2001; Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005). If in this study auditory list presentation and recall results in a higher magnitude of end subsequences on the course of the recall protocols, as has been reported for written output (Beaman & Morton, 2000), the findings would be in line with the idea of fundamental processing differences between the visual and auditory modalities (Penney, 1989). This result would also indicate that the auditory advantage on short-term recall would be resistant to extensive experience in processing visual information.

METHOD

Participants

This study was carried out with volunteer ATCs from 12 working teams of an en route air traffic center in southern France. They were 13 men and 2 women, aged 31.3 (range = 27–42 years old), with an average of 7 years, 4 months experience in the control center (range = 3–18 years).

Procedure

The participants were tested in a quiet room, during duty pauses, four times on four different days by controlling for time of day. Four equivalent pools of 18 two- or three-syllable words were used, each comprised of a single category of objects (fruits, vegetables, house furniture, musical instruments, animals). On each of 24 trials, sequences of six or nine words were presented pseudorandomly either in the visual modality (center of a 14-in. computer screen) or in the auditory modality (neutral female voice, headphones) at the rate of one item per second. Immediately after presentation of the last item of a sequence, the participant was required to recall aloud all the words he or she could remember. Reports were recorded by using a microphone connected to the computer. After recall was completed, the participant pressed the spacebar on the keyboard to start the next trial.

Custom-made software was used to vary presentation modality (visual vs. auditory) and list length (six vs. nine items) according to a Latin Square design. In addition to the free recall task, participants performed a recognition task and completed a questionnaire (not reported here).

Statistics

Two-way analyses of variance (ANOVAs) were used to investigate the effects of presentation modality together with list length and serial position, respectively, on recall performance. Post-hoc analyses used Tukey's test. Primacy and recency effects were determined by performing paired-observation t tests on serial position data, separately for each modality and list length.

Participants' response sequences were investigated according to the procedure described by Beaman and Morton (2000). Wilcoxon tests were used to compare occurrences of subsequences (a) across serial positions, separately for each modality and list length; and (b) between modalities for a given serial position.

RESULTS

The mean numbers of correct recalls are summarized in Table 1, as a function of modality and list length. A two-way ANOVA of these data revealed a significant effect of presentation modality, $F(1, 30) = 41.99$, $p < .001$, and of list length, $F(1, 30) = 195.91$, $p < .001$, indicating superior recall following auditory compared to visual sequence presentation, and for six- compared to nine-word sequences. Analysis of presentation modality along with serial position (Figure 1) revealed an interaction between these factors for recall of six-item lists, $F(5, 168) = 2.66$, $p < .05$, and of nine-item lists, $F(8, 248) = 7.13$, $p < .001$. Post-hoc Tukey tests showed that recall for auditory items was higher in the terminal position for six-item lists compared to recall for visual items ($p < .01$).

TABLE 1
Mean Number of Correct Recalls as a Function
of List Length and Presentation Modality

List Length	*Presentation Modality*	*Recall*
Six-item lists	Auditory	4,930
	Visual	4,280
Nine-item lists	Auditory	3,672
	Visual	3,281

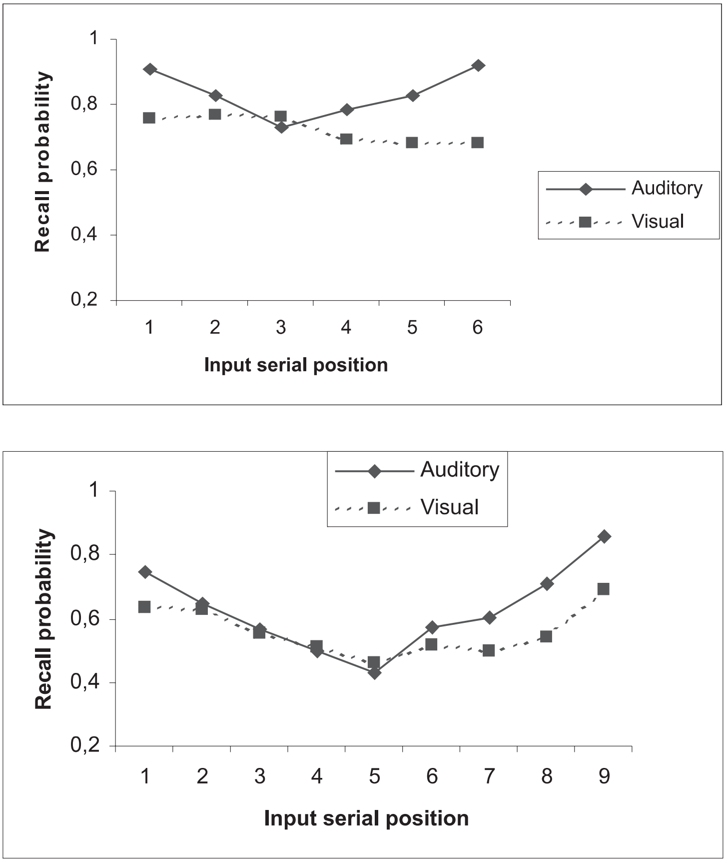

FIGURE 1 Serial position curve for free recall of (a) six-item lists and (b) nine-item lists as a function of presentation modality.

Paired-observation *t* tests on serial position data, performed separately for each modality and list length, revealed that for six-item lists presented in the auditory modality, recall was superior for items from serial position 6 compared to positions 3 ($p < .01$) and 4 ($p < .05$), and for items from serial position 1 compared to serial position 3 ($p < .05$). No such effects were observed following presentation of six-item sequences in the visual modality. For nine-item lists presented in the auditory modality, recall was superior for items from study position 9 compared to positions 5 ($p < .001$), 6 ($p < .001$), and 7 ($p < .001$), and from serial position 1 compared to positions 3 ($p < .05$), 4 ($p < .005$), 5 ($p < .001$), and 6 ($p < .01$). Following visual presentation, they recalled more items from study position 9 compared to study positions 5 ($p < .005$), 6 ($p < .05$), and 7 ($p < .05$), and from serial position 2 compared to serial positions 4 to 7 (respectively, $p < .005$, $p < .005$, $p < .01$, and $p < .005$).

To account for these results, participants' response sequences were investigated according to the procedure described by Beaman and Morton (2000). As shown by Table 2, the response protocols from recall of nine-item lists for instance, indicate that initial sequences of the kind "6, 7, 8, 9," "7, 8, 9" and "8, 9" were recalled at a comparable rate in both modalities. Figure 2 illustrates the results when recall of the end subsequences as the opening run was removed from the response protocols. It shows that in these conditions the recency effect was almost completely removed from the visual curve, but not from the auditory curve. Wilcoxon tests, comparing occurrences of the final three input serial positions of six-item lists, revealed a significant increase by participant between serial positions 4 and 6 in the auditory modality ($Z = -2.654$, $n = 16$, $p < .008$) and a significant decrease between these positions in the visual modality ($Z = -2.066$, $n = 16$, $p < .039$). Moreover, occurrences of items from serial position 6 differed between modalities ($Z = -2.365$, $n = 16$, $p < .018$). Likewise, for nine-item lists, participants recalled items in serial position 7 more frequently than those in position 9 following auditory presentation ($Z = -2.683$, $n = 16$, $p < .007$), whereas no such difference occurred following visual presentation.

TABLE 2
Number of Each of the Terminal Item Sequences as the Opening Run During Free Recall of Six- and Nine-Word Lists With Auditory and Visual Presentation

	Six-Word Lists	
Terminal Item Sequences	*Visual*	*Auditory*
6	13	7
5, 6	13	17
4, 5, 6	12	12
3, 4, 5, 6	3	2
2, 3, 4, 5, 6	7	2
1, 2, 3, 4, 5, 6	10	27
	Nine-Word Lists	
9	24	20
8, 9	22	18
7, 8, 9	7	14
6, 7, 8, 9	3	4
5, 6, 7, 8, 9	0	3
4, 5, 6, 7, 8, 9	1	1

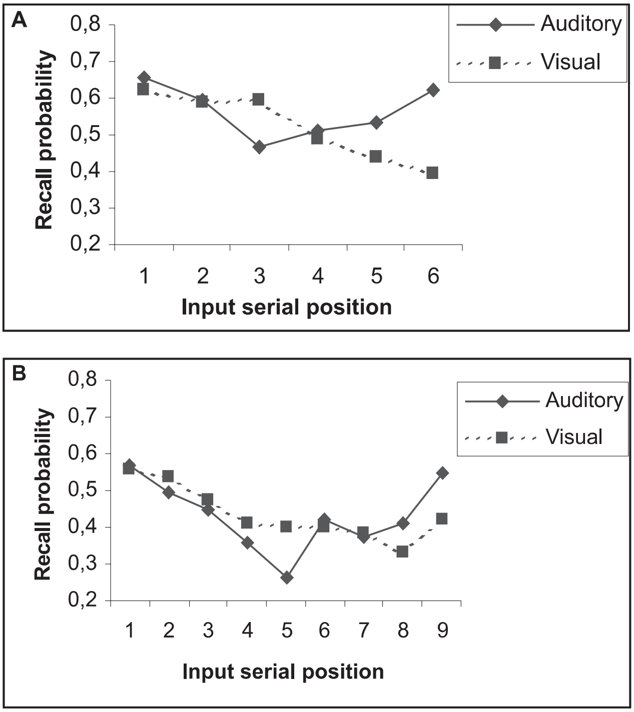

FIGURE 2 Free recall responses after removing those response sequences containing sequences of terminal items as the opening run: (a) six-item lists; (b) nine-item lists.

A similar analysis was performed on the occurrences of ordered end items in other than in the initial recall position (Table 3). In these conditions, terminal subsequences were more frequent following auditory presentation than following visual presentation, for both six-item lists ($Z = -2.857$, $n = 17$, $p < .004$), and nine-item lists ($Z = -2.291$, $n = 17$, $p < .05$). Figure 3 illustrates the serial position curves obtained when the lists containing the end subsequences, in other than the opening run, were removed from the recall protocols. It shows that in this case the remaining modality effect was substantially reduced, and that the remaining recency effect was almost nonexistent for six-item lists but maintained for nine-item lists. Statistical analysis confirmed that a recency effect no longer occurred in either modality, and that the auditory presentation advantage persisted only on serial position 6 ($Z = -2.231$, $n = 16$, $p < .05$). For nine-item lists, recall following auditory presentation increased between positions 7 and 9 ($Z = -2.475$, $n = 16$, $p < .05$), and between positions 8 and 9 ($Z = -1.934$, $n = 16$, $p < .05$). Visual occurrences differed between serial positions 8 and 9 ($Z = -2.051$, $n = 16$, $p < .05$), indicating that for nine-item sequences the recency effect was spared in both modalities.

TABLE 3
Number of Occurrences of Terminal Sequences Recalled in Noninitial Response Positions During Recall of Six- and Nine-Word Lists

	Six-Word Lists	
Terminal Item Sequence	*Visual*	*Auditory*
5, 6	16	34
4, 5, 6	3	13
3, 4, 5, 6	1	2
	Nine-Word Lists	
8, 9	14	30
7, 8, 9	1	4
6, 7, 8, 9	1	2

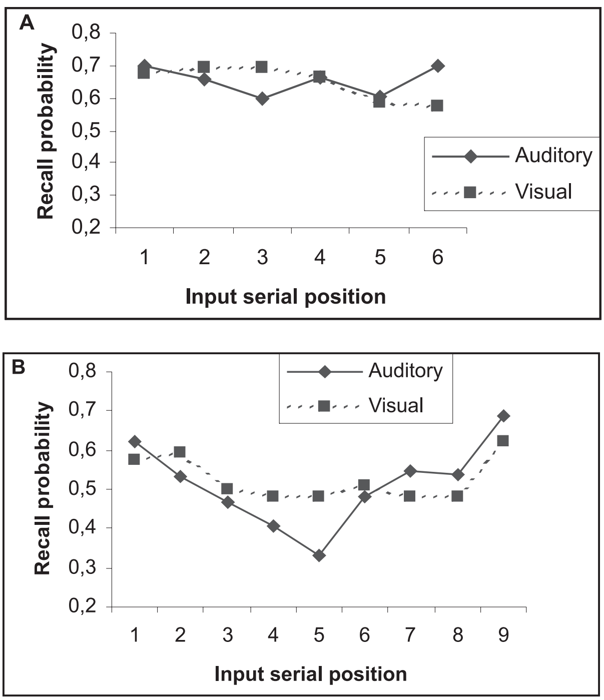

FIGURE 3 Free recall responses after removing those response sequences containing terminal item sequences in some position other than as the opening run: (a) six-item lists; (b) nine-item lists.

DISCUSSION

Investigation of ATCs' vocal recall protocols in a free recall task revealed superior recall in the auditory modality, both for six- and nine-item lists. Serial position curves revealed a large primacy effect and an even larger recency effect in both modalities. This finding supports those models suggesting that an item's underlying encoding salience is greater for the most recent items than for the first few items, with the least salience for intermediary items (Nairne, 1990). A greater distinctiveness of items at both ends of the list has also been attributed to the reduced confusability of these items, or to an enhanced temporal distinctiveness in the recency portion of the list (Baddeley & Hitch, 1993). The result is also in line with the more general idea that recall efficiency for end items is enhanced in tasks involving lower output interference, including free recall tasks when compared to serial recall tasks (Cowan et al., 2002).

Elsewhere, the study demonstrates a large auditory advantage for vocal output. This result is at odds with the finding, in a serial recall task, of a negligible modality effect for vocal output, as opposed to a large modality effect for written output (Harvey & Beaman, 2007). According to these authors, written output would affect phonological or lexical memory traces but spare the auditory-sensory trace, whereas vocal output would affect both the phonological and auditory-sensory traces. Items encoded in the auditory modality would be overwritten in short-term memory by output in the same modality, whereas they would be preserved for output in a different modality (written output). In light of these results, the authors predicted a small or negligible auditory-visual difference for vocal output in the free recall task described by Beaman and Morton (2000). Hence, this study demonstrates a modality effect for vocal output in a free recall task that is of a comparable magnitude to the one reported for written output in a comparable task. There are, however, potentially important methodological differences between the free recall tasks described in this study and those described by Beaman and Morton, on the one hand, and the serial recall experiments described by Harvey and Beaman (2007), on the other. Harvey and Beaman's (2007) participants had to recall a new set of words from an "open" pool of common nouns on each trial, whereas in this study participants were required to recall item-lists of a "closed" set of 18 items all belonging to the same semantic category, yielding important intertrial interference. As a consequence of substantial intertrial interference, output interference might have been quite high in this study, despite the fact that order information did not have to be reconstructed. Given that the magnitude of the modality effect directly depends on the level of interference at output (Cowan et al., 2004), the results reported here suggest that different sources of output interference, rather than modality-specific output interference only, would contribute to the modality effect. However, this is not to imply that our results are inconsistent with the idea that the modality effect is primarily an encoding phenomenon. Indeed, investigation of ATCs' serial position curves showed that the modality effect is directly linked to serial input position. A recency effect and a primacy effect were observed in the auditory modality, for both six- and nine-item lists, but only for visual nine-item lists.

Moreover, examination of ATCs' recall strategies revealed that the main difference between recall of seen and heard six-item lists concerned those recall protocols that included recall of the entire list. Complete six-item lists were recalled three times more frequently following auditory (27) than following visual list (10) presentation, whereas recall protocols including all but the first list item (2, 3, 4, 5, 6) occurred at a comparable magnitude in both modalities (2 vs. 7, respectively). These results also indicate that occurrences for heard lists were tenfold more frequent for complete six-item lists than for five-item subsequences, whereas no such difference occurred for seen lists. Following presentation of nine-item lists, occurrences of equivalent end subsequences (5, 6, 7, 8, 9; 4, 5, 6, 7, 8, 9) ranged between zero and three, independently of presentation modality. Further analysis of nine-item lists revealed that the auditory recall advantage of these lists resulted from higher occurrences of ordered two- and three-item end subsequences in other than initial recall positions, as has also been reported for free recall of 16-item lists (Beaman & Morton, 2000). These results are in agreement with the proposal that "auditory presentation seems to protect the end of the list from output interference" (Cowan et al., 2002, p. 168). Moreover, they stress the hypothesis that there is something about the auditory modality that prompts participants to spontaneously adopt some output strategy more frequently following auditory compared to visual presentation of verbal material (Beaman & Morton, 2000), and this independently of output modality.

Taken together, the results reported here suggest that the modality-specific effect can be accounted for by an interaction between modality and temporal distinctiveness. "The temporal discriminability of auditory events is greater than that of visual events" (Gardiner, 1983, p. 717). Temporal information would be encoded more accurately in the auditory modality (Glenberg & Swanson, 1986), thereby favoring spontaneous temporal grouping of list items (Frankish, 1985). The results reported here strongly suggest that oral presentation of to-be-remembered word lists would not only favor spontaneous grouping of end items, but also chunking of entire sequences, but only when lists are comprised of a limited number of items. In the absence of perceptual markers, it could be argued that it was successive item presentation that favored both item grouping and chunking. This might then have further enhanced resistance to output interference for auditory verbal material in short-term memory (Baddeley, 1986; Penney, 1989).

These findings further indicate that overall ATCs' response strategies did not differ from those reported in laboratory experiments, despite control for a number of variables, including work content, workload, work organization, and individual differences, known to affect performance in operators. More specifically, ATCs participating in this study benefited from an extended experience in processing sequential information, and in particular visually presented information. The demonstration of a marked modality effect in this expert population supports the idea that some general properties characterize human performance in a given task, and that the auditory advantage would result from functional differences during immediate processing of auditory compared to visual material (Baddeley, 1986; Mélan et al., 2007; Penney, 1989).

Taken together, experimental paradigms like the one used in this study can be regarded as simplified models of real-life activities, and the results might be of interest for ATC activities. In particular, the findings suggest that short sequences of auditory information would tax controller's processing capacities less than longer sequences, visual material, or both. These findings might be useful particularly during conflict resolution, and they might also be useful for ATC selection and training, by using tests that manipulate, in addition to the more traditional quantitative aspects of memory, more qualitative parameters, such as presentation modality or information type and aircraft status (Gronlund et al., 2005; Means et al., 1988).

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