AN EPIC COMPUTATIONAL MODEL OF VERBAL WORKING MEMORY

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Introduction

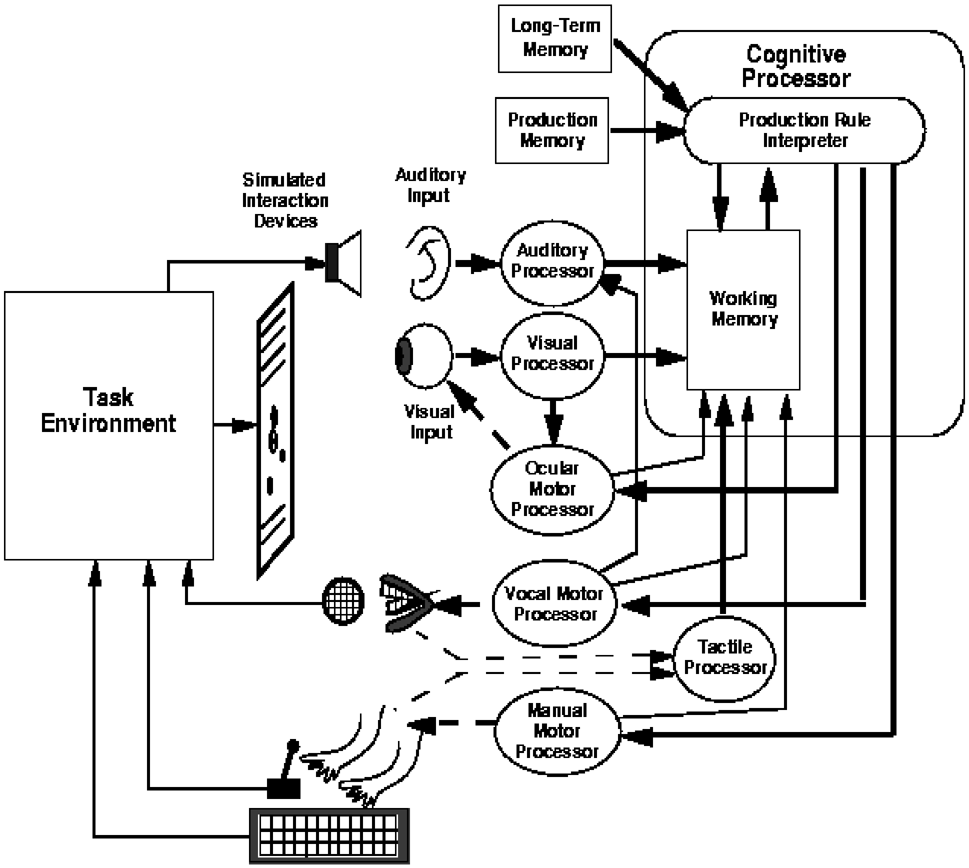
During the past several years, we have been developing the *Executive-Process/Interactive-Control (EPIC)* architecture, a comprehensive theoretical framework for symbolic computational modeling of skilled perceptual- motor and cognitive performance (Kieras & Meyer, 1997; Meyer & Kieras, 1997). Our initial research with EPIC has focused on tasks that place little strain on memory resources. Thus, the components that mediate working memory in our theoretical framework have not yet required extensive elaboration.

Nevertheless, it is clear that to model the performance of complex tasks like aircraft cockpit operation and air-traffic control, we must take the contributions and limitations of working memory more fully into account. Consequently, the goal of this poster is to introduce an EPIC computational model of verbal working memory that accounts for the major empirical findings, with the hope of later using insights from it for modeling the performance of more complex tasks. For more details about our model, see Kieras, Meyer, Mueller & Seymour (1999).

The EPIC Architecture

The Executive-Process/Interactive-Control (EPIC) architecture is devoted to constructing models of skilled human performance.
In developing EPIC, emphasis has been placed on characterizing the perceptual and motor, as well as cognitive, constraints on people's ability to perform various tasks. EPIC is thus one of the most precise general-purpose architectures for modeling human performance.

Within EPIC, information flows forward from peripheral sensors through perceptual processors to a cognitive processor (with a production-rule interpreter and working memory) whose outputs control motor processors that move peripheral effectors. The architecture also has multiple feedback pathways from the motor processors to working memory and the perceptual processors.



Schematic drawing of the EPIC architecture, Kieras et al., 1999

Major Features of EPIC

- Separate perceptual and motor processors that have distinct temporal properties.
- Separate permanent memory stores for procedural knowledge (production rules) and declarative knowledge (propositions) with no explicit capacity limitations.
- Multi-component working memory that contains all temporary information needed for and manipulated by a model's production rules, including control items such as task goals and sequencing indices, along with coded representations of received sensory inputs and selected motor outputs.
- Separate partitions for auditory working memory and visual working memory.
- No size-based capacity limitation within partitions of working memory.
- All-or-none stochastic decay from phonological WM stores.

Functions of Working Memory in EPIC

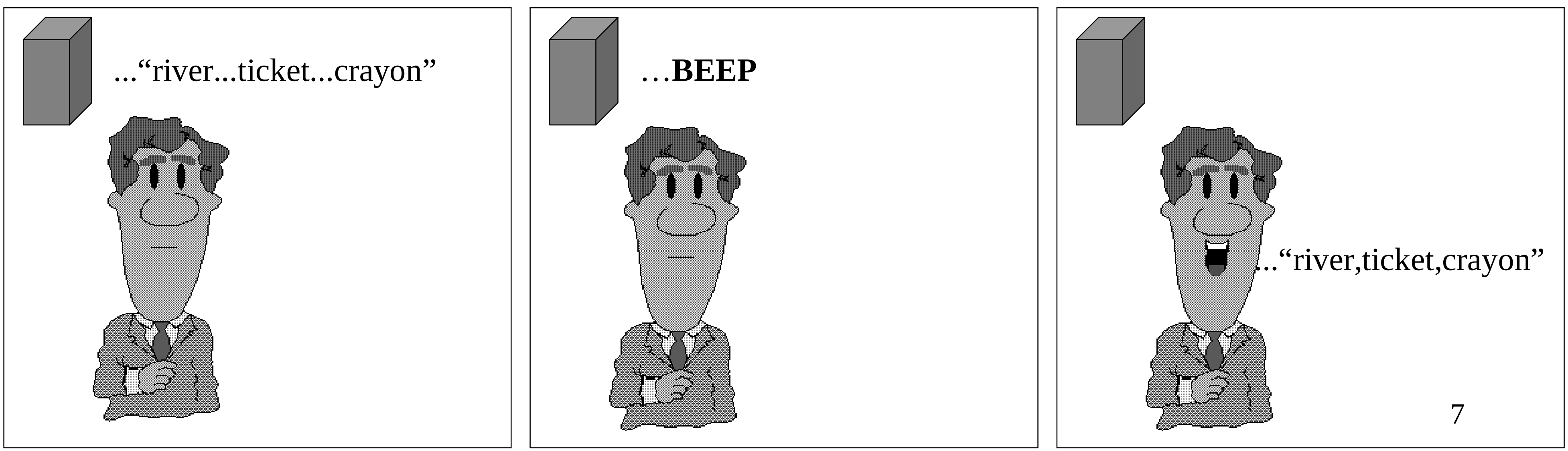
- Accommodate the entire ensemble of temporary stored codes, knowledge representations, and procedures whereby information is maintained, updated, and applied for performing perceptual-motor and cognitive tasks.
- Represent the internal and external world.
- Store and manipulate temporary and permanent information.
- Interpret external inputs and select appropriate responses.
- Keep track of goals and strategies relative to a particular task.
- Keep track of progress within tasks and sub-tasks.

An EPIC model for Verbal Working Memory

Using available components of the EPIC architecture, we have developed a precise computational model of verbal working memory that emulates a **phonological-loop mechanism** in detail (cf. Baddeley & Hitch, 1974; Schweickert & Boruff, 1986; Waugh & Norman, 1965), and that accounts quantitatively for performance of representative working memory tasks (Kieras, Meyer, Mueller & Seymour, 1999). For example, one prototypical case with which our model deals especially is the **serial memory-span task** (Miller, 1956). In what follows, a generic version of this task is considered more fully, and empirical results from it are fit with simulated outputs from our EPIC model. Given this purpose, the model includes sets of production rules that use components of the EPIC architecture to implement a performance strategy with two complementary functions: item rehearsal, and recall.

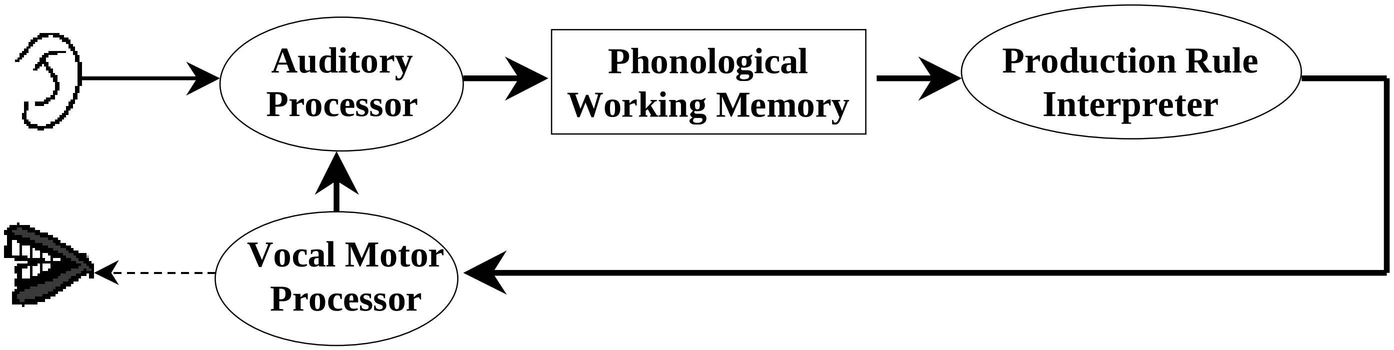
Generic Serial Memory-Span Task

- On each trial, 3 to 9 words are presented auditorily at a constant moderate rate.
- After the final word of a trial, participants hear a signal that prompts them to recall the presented sequence in its original order.
- Ample time is allowed for recall, after which a new trial starts.
- Word sequences are constructed randomly from a small pool, so no word is used more than once per trial, but the same word may occur frequently across trials.



Task Performance Strategy

- Consistent with EPIC, the stores and processes for performing the serial memory-span task are assumed to involve specific memory modalities and effectors.
- Auditorily perceived stimuli are held in a phonological storage buffer.
- Items haphazardly decay in an all-or-none fashion from this buffer, so covert articulation is used to reengage the auditory perceptual system, yielding fresh (covert) copies of the verbal information in the phonological buffer.
- Covert articulation and auditory perceptual processes constitute components of a programmable strategic phonological loop.
- The phonological loop is supervised by a set of production rules that use available articulatory mechanisms to aid in serial memory span task performance.



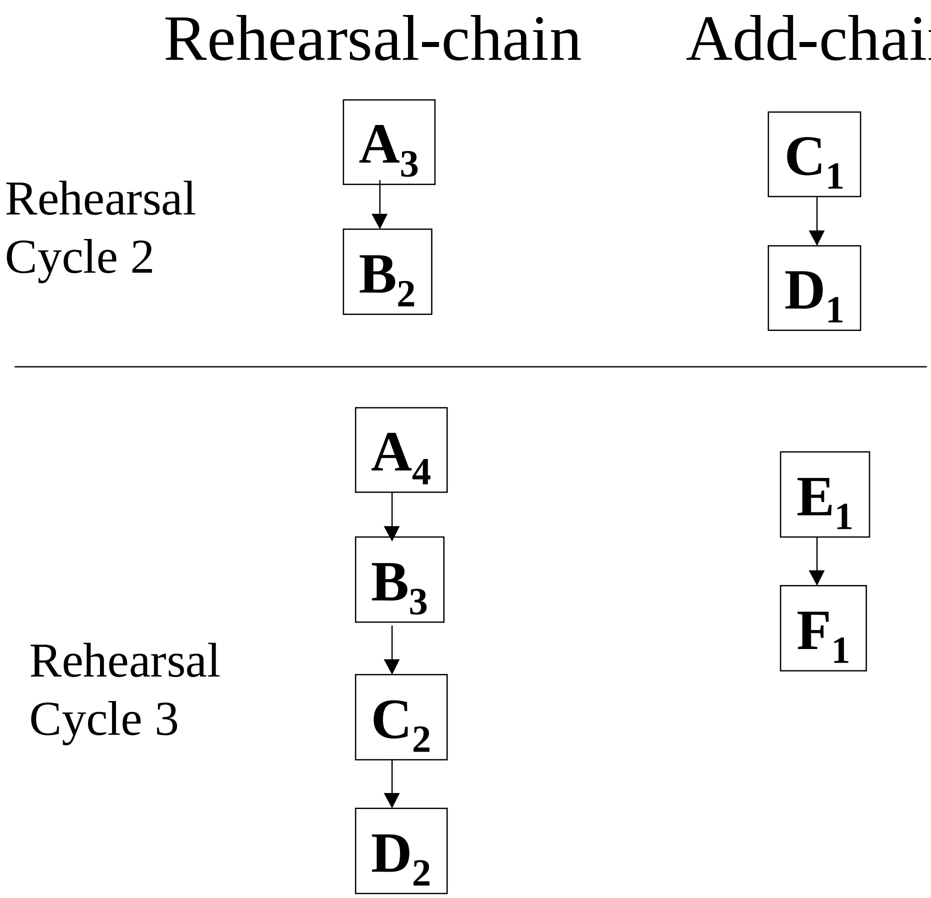
Rehearsal

- Phonological information is maintained in working memory through rehearsal.
- Rehearsal processes are represented by a set of production rules that embody the procedural knowledge for performing the task.
- Production rules cause specific words to be articulated, mark progress during the task, and achieve various subgoals required to complete performance.
- These rules form the overall strategy for performing the serial memory-span task.
- The rehearsal processes keep track of two chains of items in phonological (auditory) working memory: the **rehearsal-chain** and the **add-chain**.
- Maintenance of working memory involves updating and manipulating the contents of these chains.
- Computational modeling allows us to characterize both the Phonological Loop and the Central Executive more precisely than has been possible before with informal theorizing (cf. Baddeley et al., 1975).

Key Features of Rehearsal Process

- The detailed executive and memory processes for rehearsal are highly intertwined. The "simple" serial memory span task is actually quite complex!
- When a new stimulus item is perceived and stored, tags are generated that place a link to this item at the end of the add-chain.
- Concurrently and asynchronously with the creation of the add-chain, the rehearsal-chain is continually being reconstructed through covert articulation. A new rehearsal-chain is built by articulating the current rehearsal-chain, followed by the current add-chain.
- A new add-chain is generated after a new rehearsal-chain has been constructed.
- Multiple copies of words may exist in WM, but only the most recent copy is used in this strategy. Old copies disappear through stochastic all-or-none decay.
- Articulatory suppression requires activity of the vocal motor processor and thus precludes rehearsal. In this case, items remain in (and haphazardly decay from) a stimulus chain similar to the add-chain.

Rehearsal-chain and Add-chain Construction



During a single Rehearsal Cycle, EPIC generates a new rehearsal-chain by first rehearsing all items in the rehearsal chain.

Next, EPIC completes the new rehearsal chain by rehearsing the items in the add-chain.

Subscripts denote the "copy" of a word that is being used by this rehearsal strategy. For instance, during Rehearsal Cycle 3, "A" has been rehearsed or heard four times, while "E" has only been heard once.

Recall

- After the recall cue has been perceived and the current rehearsal cycle has been completed, EPIC attempts to overtly recall the items in the rehearsal-chain.
- These items are transferred individually from phonological WM to the vocal motor processor.
- Items are subject to haphazard decay, so recall errors occur when an item on the list disappears before it can be recalled.
- An item may disappear either during rehearsal or recall.
- With the current task strategy, the model aborts performance when it attempts to recall or rehearse an item that has disappeared.
- When the to-be-recalled item has disappeared, the current task strategy does not attempt to guess.

Other Key Assumptions Of The Model

- No limit exists on the number of items stored in phonological WM.
- Limitations in phonological working memory stem from time-based decay.
- The loss or decay of stored items from working memory is an all-or-none process.
- Individual stored items have stochastically independent decay times.
- Decay has a log-normal distribution with two parameters: M, the median, and s, the “spread”.
- The values of M and s are affected by the stored items’ phonological similarity and source (external presentation or internal articulation).
- Information about the serial order of items is stored as supplementary tags that form an implicit chain (linked list) structure.

Applications of the EPIC Working Memory Model

We have applied EPIC's verbal working memory model to account for the results of two representative studies that used the generic serial memory-span task. These studies provide informative data on the effects of articulatory suppression, phonological similarity, list length, and word duration, making them a good benchmark against which to test our model.

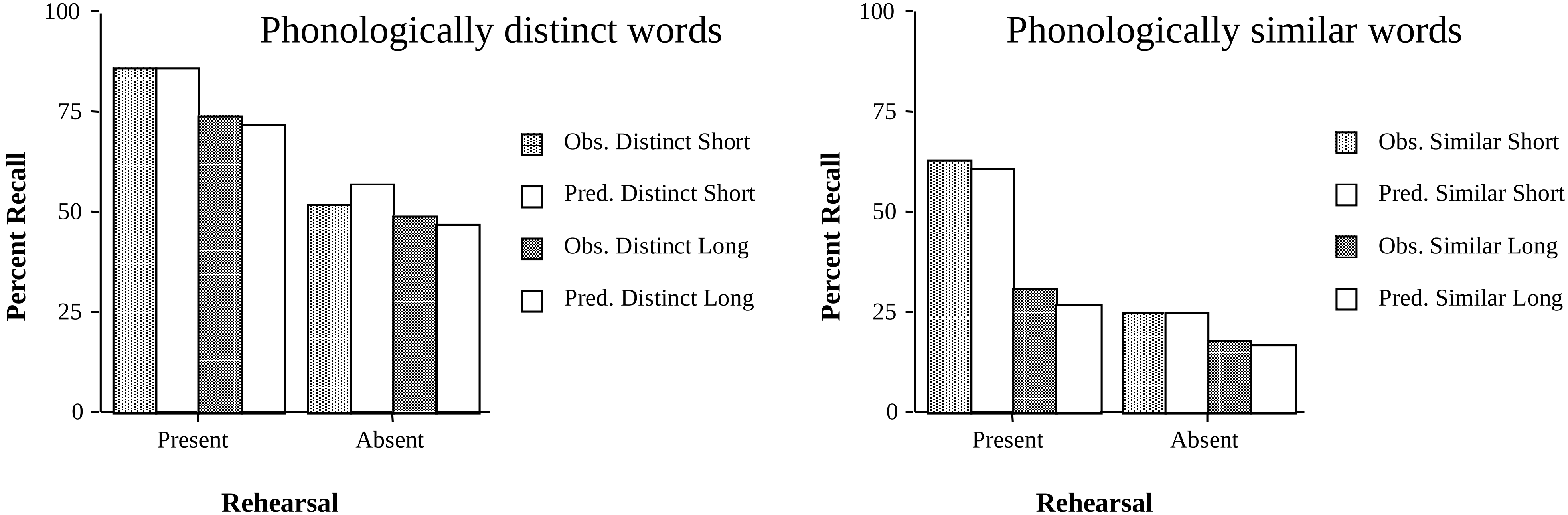
Longoni, Richardson & Aiello (1993)

- Lists of 4 Italian words (with Italian Participants)
- 2 (Rehearsal/Suppression) x 2 (Word Duration) x 2 (Similarity) design
- Results: Word Duration Effect due to Rehearsal
  Word Duration Effect independent of Similarity

Baddeley, Thomson & Buchanan (1975)

- 2 (Word Duration) x 5 (List Length) design
- Results: Memory Span decreases monotonically as word duration increases

EPIC Simulation for Longoni et al. (1993)



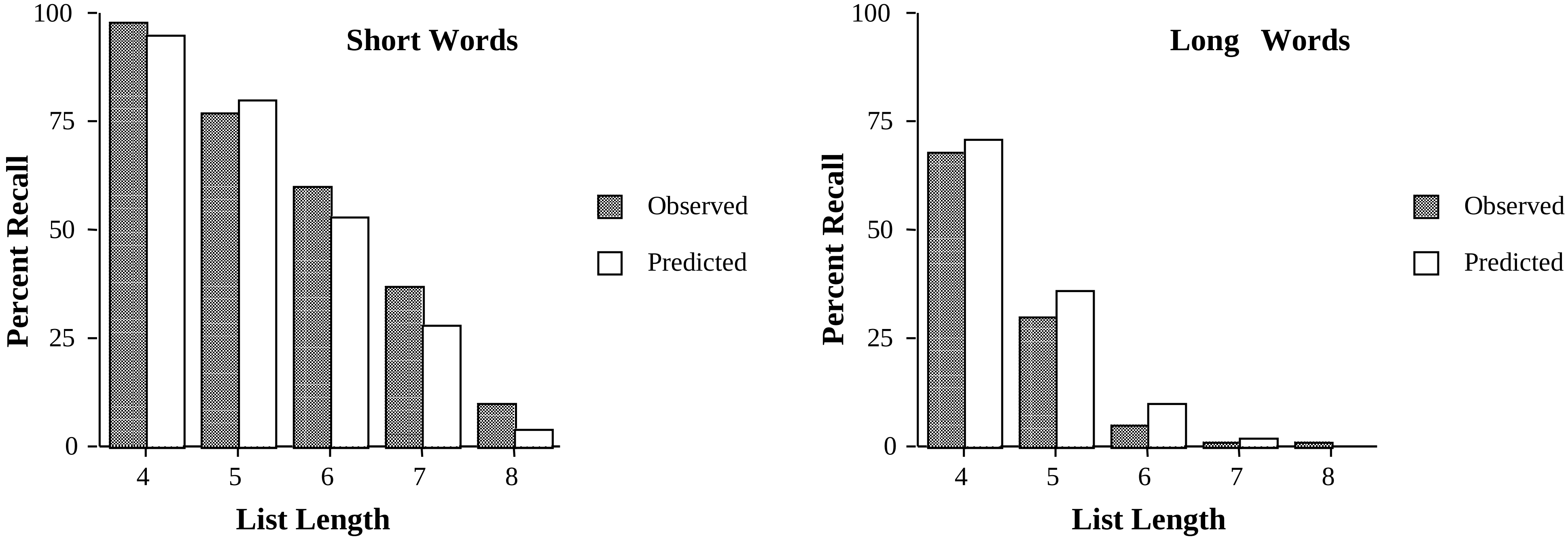
Empirical and simulation results for the study of Longoni et al. (1993, Exp. 1). Dark bars represent observed percentages of trials on which serial recall was perfectly correct as a function of sequence articulation time and articulatory suppression (rehearsal absent) versus non-suppression (rehearsal present). White bars adjacent to the right of the dark bars represent corresponding simulated percentages of correct-recall trials under the present EPIC model of verbal WM.

Parameter values in EPIC simulation of Longoni et al. (1993)

Item Source	Phonological Status	*M* (ms)	*s*
external	similar	6625	0.2
	distinct	7400	0.2
internal	similar	4875	0.5
	distinct	5500	0.5

Note: *M* is the median of the lognormal decay-time distribution for items in auditory WM; *s* is the distribution's spread parameter. The external source corresponds to overt auditory stimulation, and the internal source corresponds to covert vocal rehearsal. Although there are several other parameters in the EPIC architecture that can change, only the mean and variance of the decay distribution were adjusted to account for these data. All other parameters were held constant at predetermined values.

EPIC Simulation for Baddeley et al. (1975)



Empirical and simulation results for the study of Baddeley et al. (1975, Exp. 1). Dark bars represent observed percentages of trials on which serial recall was perfectly correct as a function of list length (i.e., the number of words per sequence). White bars adjacent to the right of the dark bars represent corresponding predicted percentages of trials on which serial recall was perfectly correct under the present EPIC model of verbal working memory.

Conclusions

To a close approximation, our EPIC model reproduces the major trends in the empirical data for the serial memory-span task, aptly describing the effects of articulatory suppression, phonological similarity, word duration, and list length. The use of a complete general-purpose architecture to account for these effects represents a significant advance from previous "toy" models of verbal working memory. We are able to explicitly characterize the non-trivial executive processes required to implement a phonological loop; we are able to specify precisely how rehearsal processes function; and we are able to gain insights into the nature of phonological codes in working memory. More specifically, detailed conclusions from our research may be reached about source-based coding, item decay times, and strategies of rehearsal.

Source-Based Coding

Our model reveals that distinct codes are used in auditory working memory for items from external (overt auditory stimuli) and internal (covert speech) sources. Specifically, codes for internal-source items appear to have shorter and more variable durations than do codes for external-source items.

Item Decay Time

According to our model, item decay times are substantially longer than previously theorized (cf. Baddeley et al., 1984; Schweickert & Boruff, 1986.) This must be so because executive processes can add non-trivial amounts of time to rehearsal and recall. Also, decay times must be relatively long because they vary randomly rather than having a fixed time limit. Because each item of a list must be recalled correctly in order to correctly reproduce a list, median decay times are presumably much longer than the time that it takes to articulate a list of words (as suggested by Baddeley et al., 1984).

Rehearsal

The present research demonstrates that even in apparently simple task domains, it is important to characterize task strategies in order to understand behavior. These strategies include both flexible rehearsal and executive control processes. Previous research has shown that articulatory mechanisms are an important aspect of verbal working memory performance (e.g. Standing et al., 1989; Logie et al., 1996), but our EPIC framework is the first attempt to explicitly model the role of rehearsal.

Directions for Future Research

EPIC provides a strong theoretical basis for future study of verbal working memory. Although its scope is currently limited, our model can readily be augmented to characterize other working memory phenomenon, such as the effects of acoustic similarity. By developing this model in EPIC, we have a tool for applying ideas about verbal working memory to a wide variety of tasks, many of which have previously proven difficult to study precisely from a theoretical perspective.

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