COMPONENTS OF COGNITIVE AGING IN VERBAL WORKING MEMORY REVEALED BY COMPUTATIONAL MODELING WITH THE EXECUTIVE-PROCESS INTERACTIVE-CONTROL (EPIC) ARCHITECTURE*

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Aging, Verbal Working Memory, and the Digit Span Task

- Age-related declines in verbal working memory (VWM) have been reported, but their magnitudes vary with task complexity.
- For the digit span task, a basic test of VWM (Miller, 1956; Baddeley, 1986), performance declines with age, but not at the same rate as it does for other VWM tasks. Digit span decreases gradually until about the age of 65, after which steeper declines occur (e.g. Orsini et al., 1986; Gregoire & Van der Linden, 1997; Ryan et al., 1996).
- Furthermore, Collette et al. (1997) found that the digit span correlates positively with resting metabolism in posterior brain regions, but not in prefrontal cortex. Some related research suggests that as the brain ages, frontal-lobe functioning declines disproportionately relative to functioning in posterior regions (Raz, 2000).
- This pattern of age effects has led some researchers to conclude that the digit span task involves primarily passive storage (Welford, 1980), and that the phonological loop is an “automatic mechanism”, whose operations require little if any executive control (Gregoire & Van der Linden, 1997). Others have reached a similar conclusion, based on neuropsychological studies of normal young adults and brain-damaged patients (D’Esposito & Postle, 2000).
- Taken together, these conclusions suggest that the digit span task is not crucial for assessing VWM and executive control in cognitive aging. Instead, it has been proposed that more complex VWM tasks should be used for such assessments.

New Claims About The Digit Span Task and VWM

Contrary to what previous cognitive-aging researchers have concluded, we claim that the digit-span task provides crucial information about how aging affects VWM and executive control processes. Our claims are based on recent discoveries from computational modeling of VWM by Meyer et al. (1999, 2000). Through modeling performance of the digit span task, Meyer et al (1999, 2000) showed that:

- The digit span task does not involve simply “pure storage”.
- The digit span task requires complex cognitive rehearsal and recall procedures.
- The phonological loop does not function like an automatic tape recorder.
- Flexible strategic executive processes manage operation of the phonological loop.
- Executive processes for performing the digit span task are implemented in the left inferior posterior parietal lobe, not prefrontal cortex.

These discoveries have major implications for cognitive-aging research. In order to understand how aging affects more complex VWM tasks, it is essential to study how aging affects the basic digit span. These effects could stem from several sources. Thus, we need to analyze exactly which sources contribute to declines in digit span with age.

Potential Sources of Age-Related Declines inVWM

Age-related declines in VWM can stem from several sources.

Processing speed may decrease with age, for example:

- Perceptual slowing may occur for stimulus encoding and identification;
- Cognitive slowing may occur for central retrieval and decision processes;
- Motor slowing may occur for movement production and/or response execution;
- Generalized slowing may occur for all peripheral and central processes.

Working memory may become less durable with age, for example:

- Verbal item information may decay faster;
- Serial-order information may decay faster.

Performance strategies may become less efficient with age, for example:

- Rehearsal rates may be lower;
- Error detection and correction may occur less frequently.

Executive processes may deteriorate and become less efficient with age.

Precise and Integrative Theories are Needed to Identify The Sources of Age-Related Declines in VWM

To identify which sources actually contribute to age-related declines in VWM, it is necessary to precisely predict how VWM is affected by each source.

Equally important, it is necessary to predict how these effects are combined in causing declines of VWM, because they may have complex unexpected interactions.

Theories that fail to make distinctions between different aspects of processing speed, memory durability, performance strategies, and executive control provide little or no guidance for obtaining the needed predictions.

However, these predictions can be obtained from one theoretical framework that is appropriate for present purposes. The Executive-Process Interactive Control (EPIC) architecture (Meyer & Kieras, 1997, 1999) can be used to build precise computational models of VWM and performance in the digit span task. On the basis of these models, age-related declines in digit span and other VWM measures can be analyzed to identify the sources from which they come.

The EPIC Architecture

Our computational models of VWM for the digit span task are based on modeling with the Executive-Process Interactive Control (EPIC) architecture shown here. EPIC implements algorithmic information processing in an interactive brain-like manner. EPIC has multiple types of working memory stores, with distinct modules for perceptual, cognitive, and motor operations. EPIC's cognitive processor uses the contents of WM to control perception and action through production rules that “fire” in parallel, enabling performance of many tasks to be modeled realistically. The distinct properties of each processor allow hypotheses about the sources of memory declines with aging to be tested precisely.

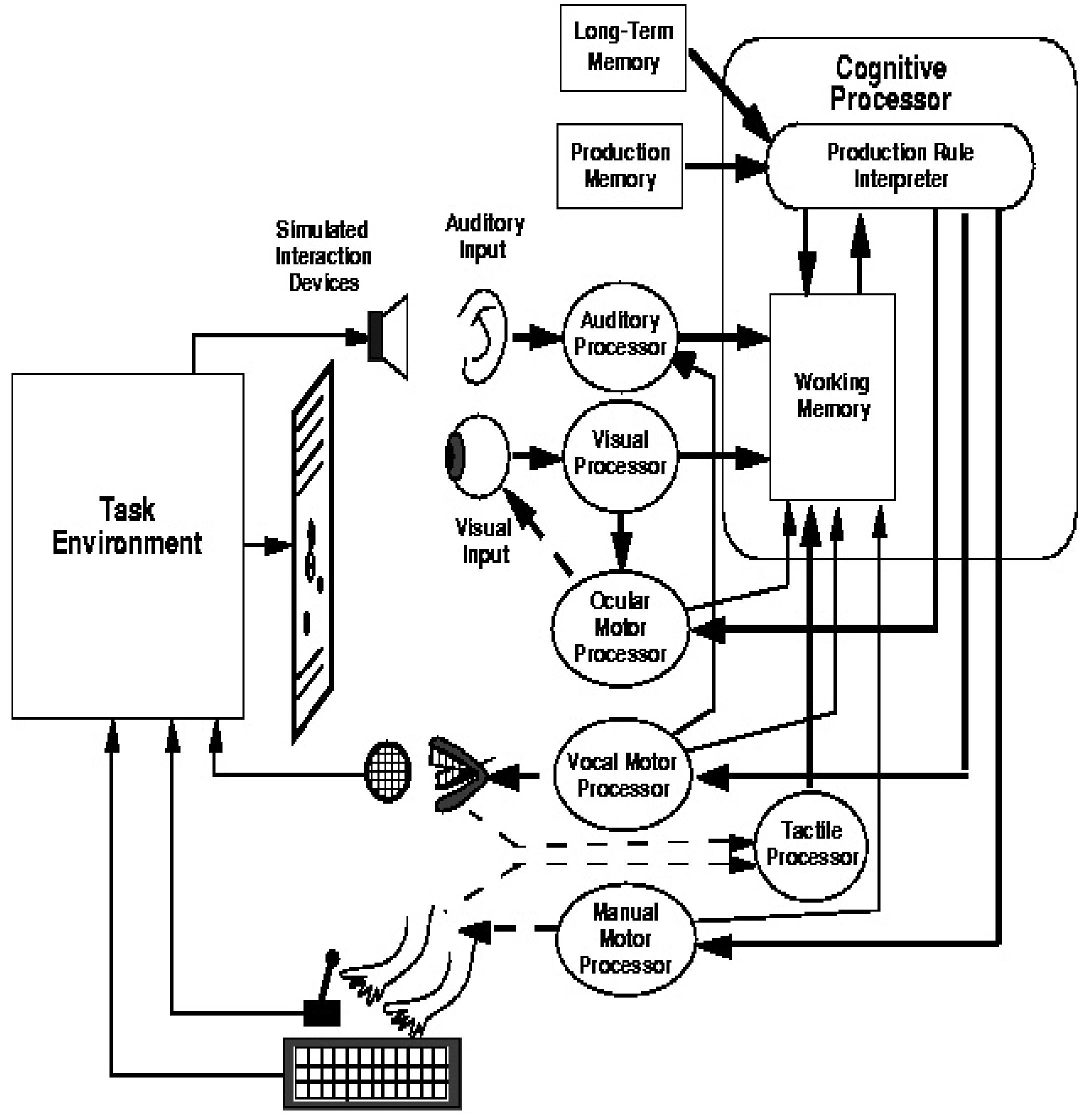


Figure 1: Schematic diagram of the EPIC architecture (Meyer & Kieras, 1999).

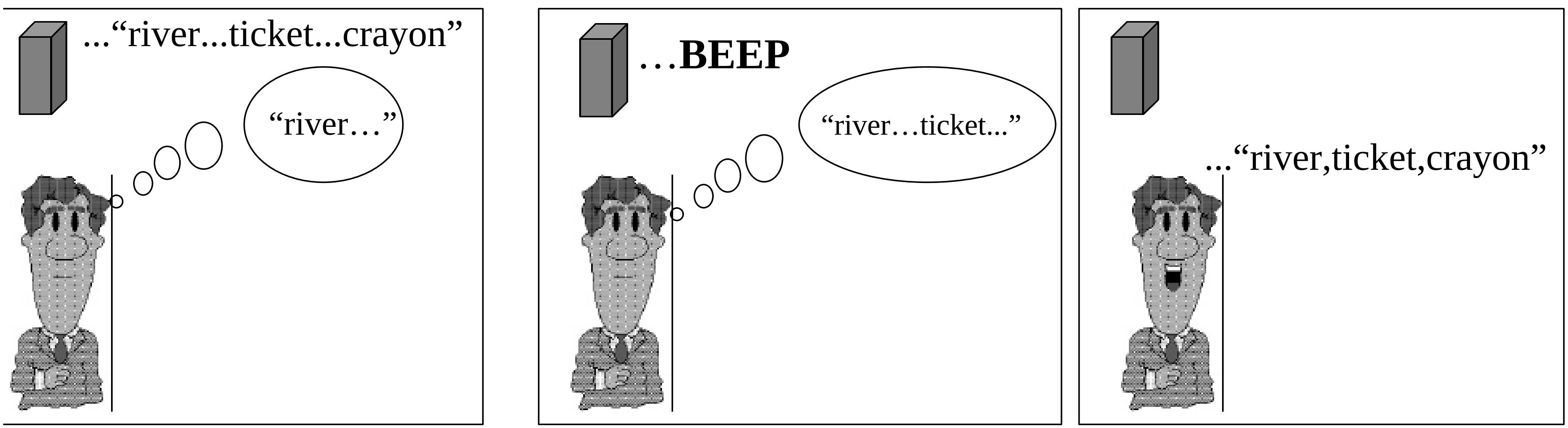
EPIC Model of Verbal WM in the Memory-Span Task

With the realistic components of EPIC, we have formulated precise computational models of verbal WM that emulate a phonological-loop mechanism (cf. Baddeley & Hitch, 1974; Schweickert & Boruff, 1986; Waugh & Norman, 1965). Our models account quantitatively for performance of representative WM tasks (Kieras, Meyer, Mueller, & Seymour, 1999). For example, one prototypical case with which we have dealt especially is the serial memory-span task (see next page). In what follows, a generic version of this task is considered more fully, and empirical results from it are fit with simulated outputs from one of our EPIC models. To achieve this fit, the present model includes sets of production rules that execute a performance strategy with three complementary functions: storage, rehearsal, and recall. We have discovered that for these functions to succeed, they must be coordinated by a highly elaborate executive control process. Without such control, it is impossible to perform the memory-span task properly. This realization, and the empirical good fit of our model, have important implications for identifying and describing sources of declines in verbal WM with age.

Generic Verbal Serial Memory-Span Task

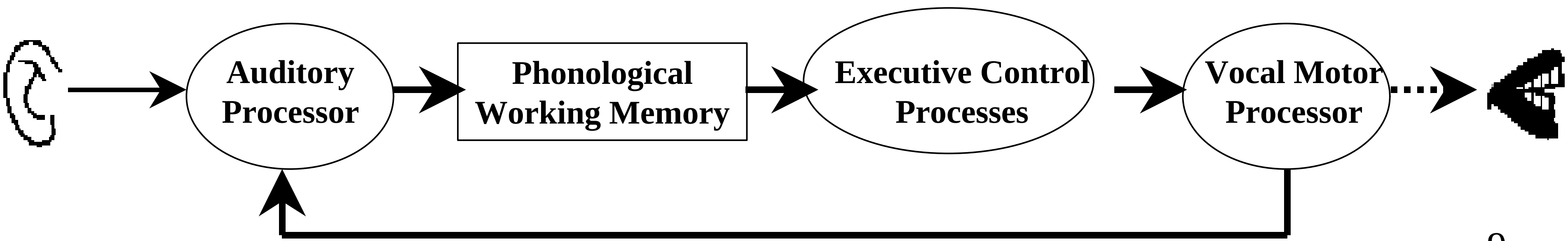
The verbal serial memory-span task modeled here has the following design:

- 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 (BEEP) that prompts them to recall the presented word sequence in its original serial order.
- Ample time is allowed for recall, after which a new trial starts.
- Word sequences are constructed randomly from a small pool of words.
- No word is used more than once per trial, but words occur repeatedly across trials.

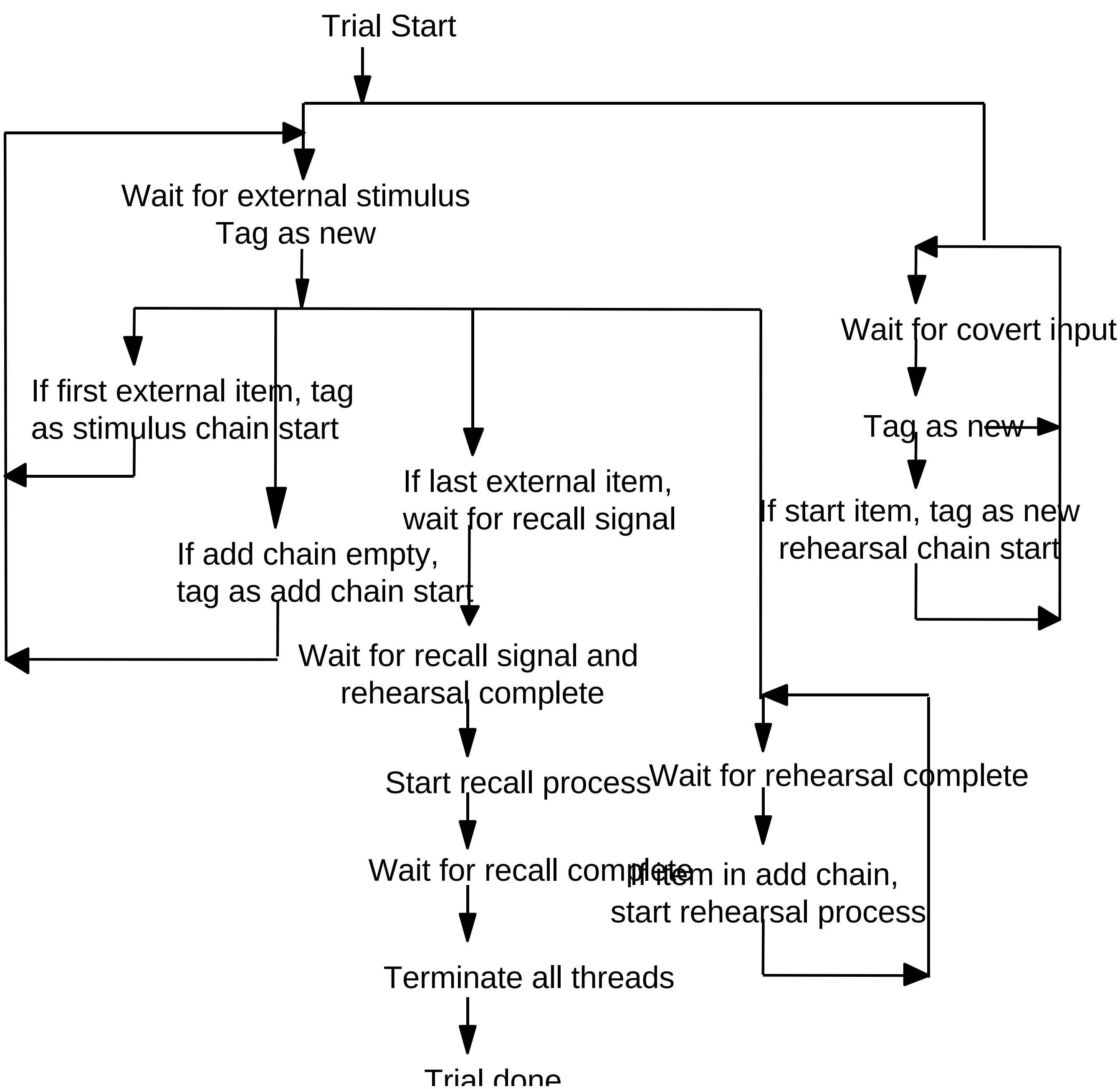


Memory-Span Performance Strategy

- Consistent with EPIC, storage and perceptual-motor processes for the memory-span task are assumed to involve auditory stimulus and articulatory response codes.
- Auditorily perceived stimuli are held in a phonological WM buffer.
- Individual phonological features of items decay randomly in an all-or-none fashion from this buffer, so subvocal articulation is used to reactivate the auditory perceptual processor, yielding fresh (covert) copies of the stored verbal information.
- For this purpose, EPIC's vocal motor and auditory perceptual processors serve as components of a strategic programmable phonological loop.
- Operation of the phonological loop is coordinated by an executive control process whose production rules use available auditory and articulatory mechanisms for storage, rehearsal, and recall of word sequences (see flowchart on next page).



Executive Control Processes in EPIC Model of Verbal WM

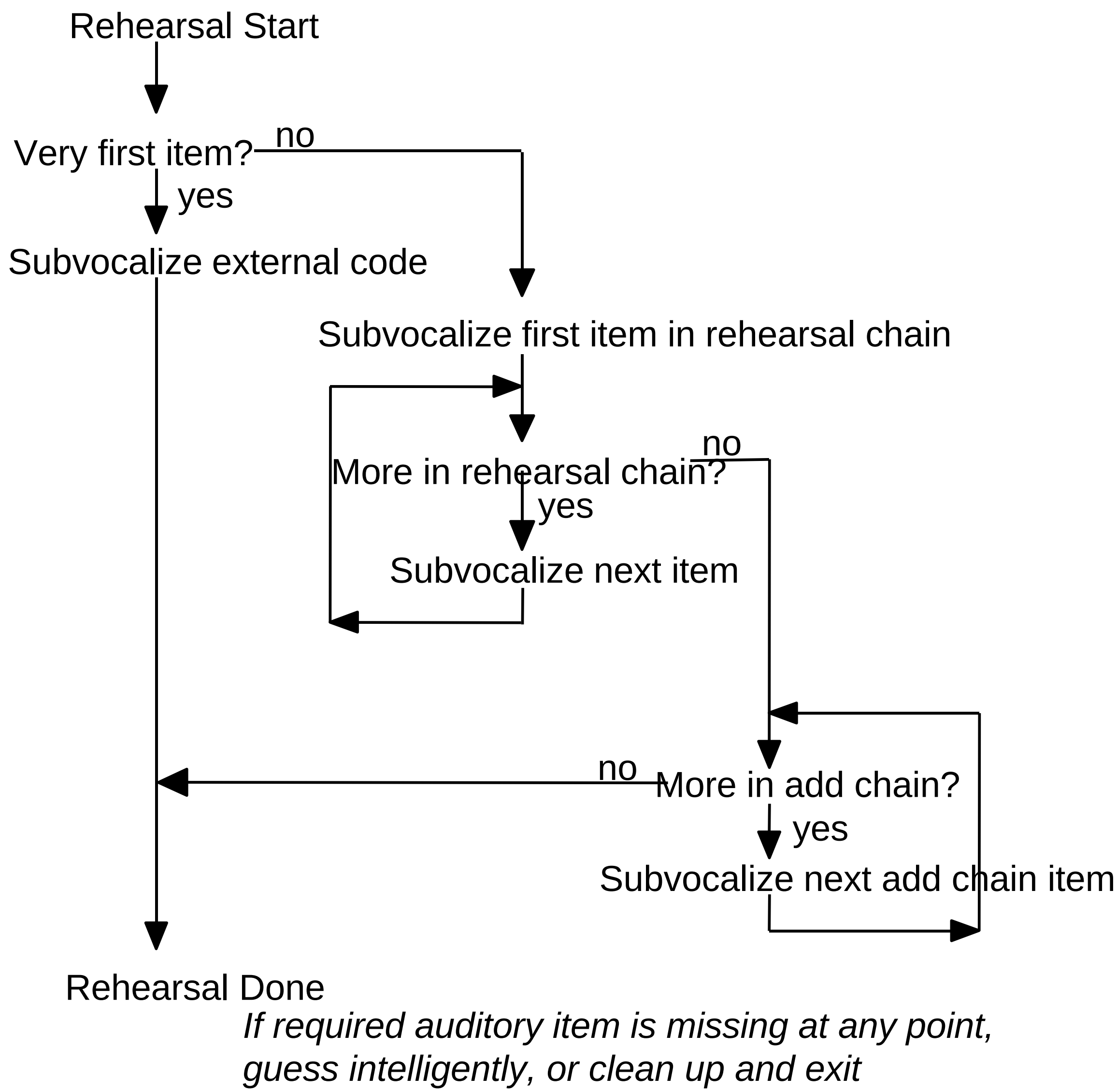


Flowchart of the executive control processes and overall task strategy used by the EPIC model of verbal WM for performing the serial memory-span task. The task strategy includes concurrent processes for rehearsal-chain and add-chain construction, subvocal rehearsal, and final recall.

Rehearsal Process in the EPIC Model

- Phonological codes for words are maintained in WM through rehearsal.
- Rehearsal is a cyclic process coordinated by executive control.
- The rehearsal process is implemented by a set of production rules that cause specific words to be articulated.
- The production rules for rehearsal keep track of two chains of items in phonological (auditory) WM: the **rehearsal-chain** and the **add-chain**.
- When a new stimulus item is perceived and stored, tags are generated that put a link to this item at the end of the add-chain (see flowchart on next page).
- Concurrently with construction of the add-chain, the rehearsal-chain is continuously cycled and rebuilt through covert articulation.
- A new rehearsal-chain is built by articulating the current rehearsal-chain followed by the current add-chain.

Rehearsal Process in EPIC Model of Verbal WM

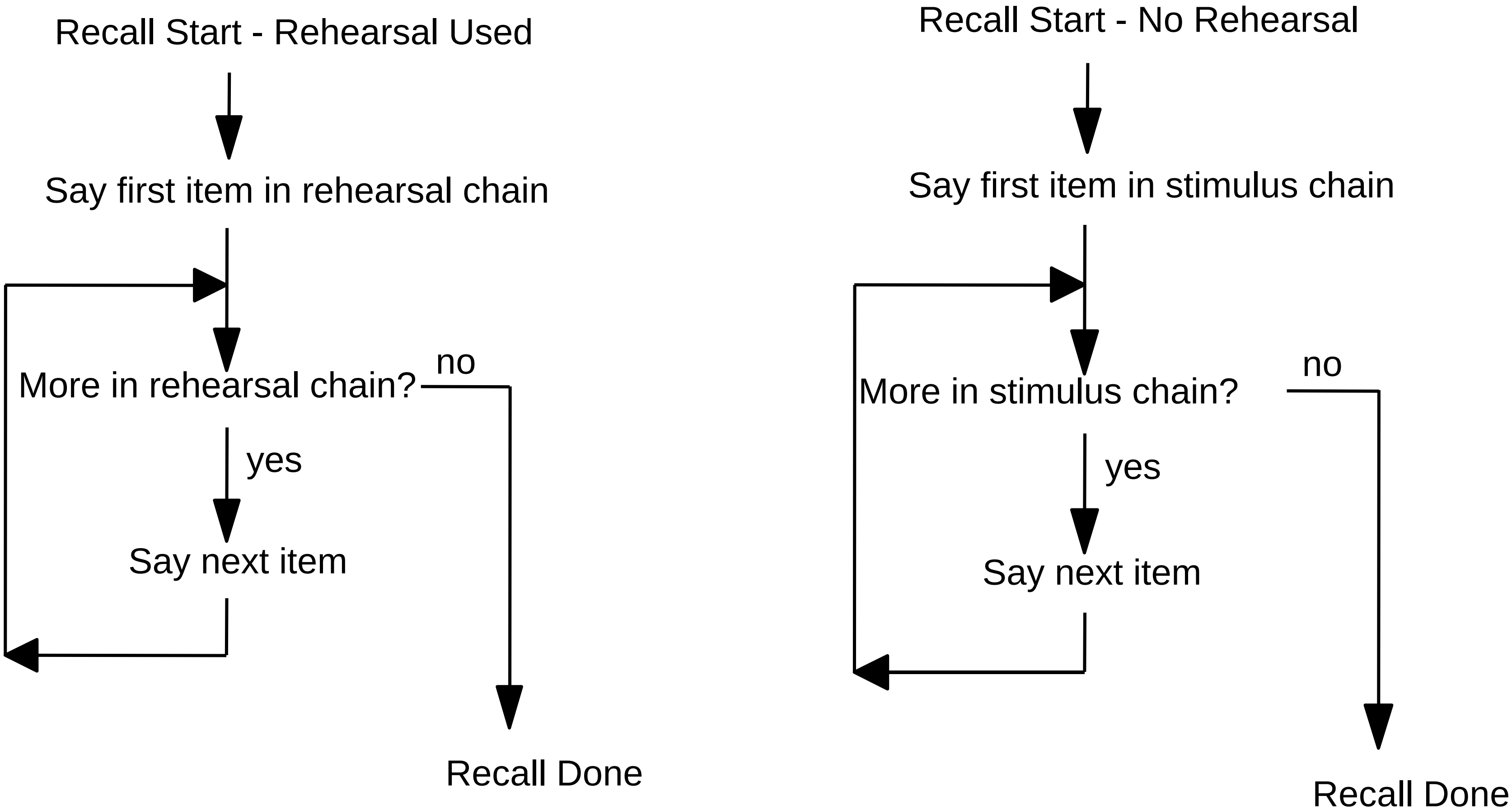


Flowchart of the rehearsal process used by the present EPIC model of verbal WM for performing the serial memory-span task. Represented here are the operations performed during one cycle of rehearsal. These operations include, when need be, subvocalizing the first stimulus item on a trial, subvocalizing each item of the current rehearsal-chain in auditory WM, and then subvocalizing each item in the current add-chain. On trials with articulatory suppression, no rehearsal process would occur.

Recall Process in the EPIC Model

- On each trial, after the recall cue has been perceived and the current rehearsal cycle has been completed, our EPIC model attempts to overtly recall the items in the rehearsal-chain.
- These items are transferred individually and serially from phonological WM to EPIC's vocal motor processor (see flowchart on next page).
- Recall errors occur when phonological features or serial-order tags of items decay from WM before they can be recalled.
- Under the current task strategy, the recall process makes "sophisticated" guesses when it attempts to recall an item whose phonological features or serial-order tags have already decayed from WM.
- The sophisticated guessing involves a "redintegration" of features based on phonological similarity.
- The identities of missing serial-order tags are guessed on the basis of remaining item subsequences in the rehearsal-chain.

Final Recall Process in EPIC Model of Verbal WM



If required auditory item is missing at any point, guess intelligently, or clean up and exit

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Flowchart of the final recall process used by the EPIC model of verbal WM for performing the serial memory-span task. The left panel shows steps in recall after prior rehearsal has occurred on a trial. The right panel shows steps in recall if there has been no prior rehearsal (e.g., if articulatory suppression has precluded rehearsal).

Other Parsimonious Assumptions Of The Model

- The serial order of items is represented by supplementary tags that form implicit *linked-list structures* in the rehearsal-chains and add-chains.
- Phonologically similar items have more features in common.
- No inherent fixed limit exists on the number of items stored in WM.
- Limitations in phonological WM capacity stem from time-based decay.
- Distinct codes are used for items from external (overt) and internal (covert) sources.
- The decays of distinct phonological features and serial-order tags from WM are independent, all-or-none stochastic processes.
- Decay times have a log-normal distribution with two parameters: *M*, the median, and *s*, the "spread".
- The values of *M* and *s* may differ for phonological features and serial-order tags, depending on their source (external presentation or internal articulation).

Simulation of Results from Past Memory-Span Studies

Using our EPIC model of VWM, we have simulated results from many representative memory-span studies (e.g., see Kieras et al., 1999). These simulations account well for effects of list length, serial position, word duration, and phonological similarity on performance by young adults, as shown below.

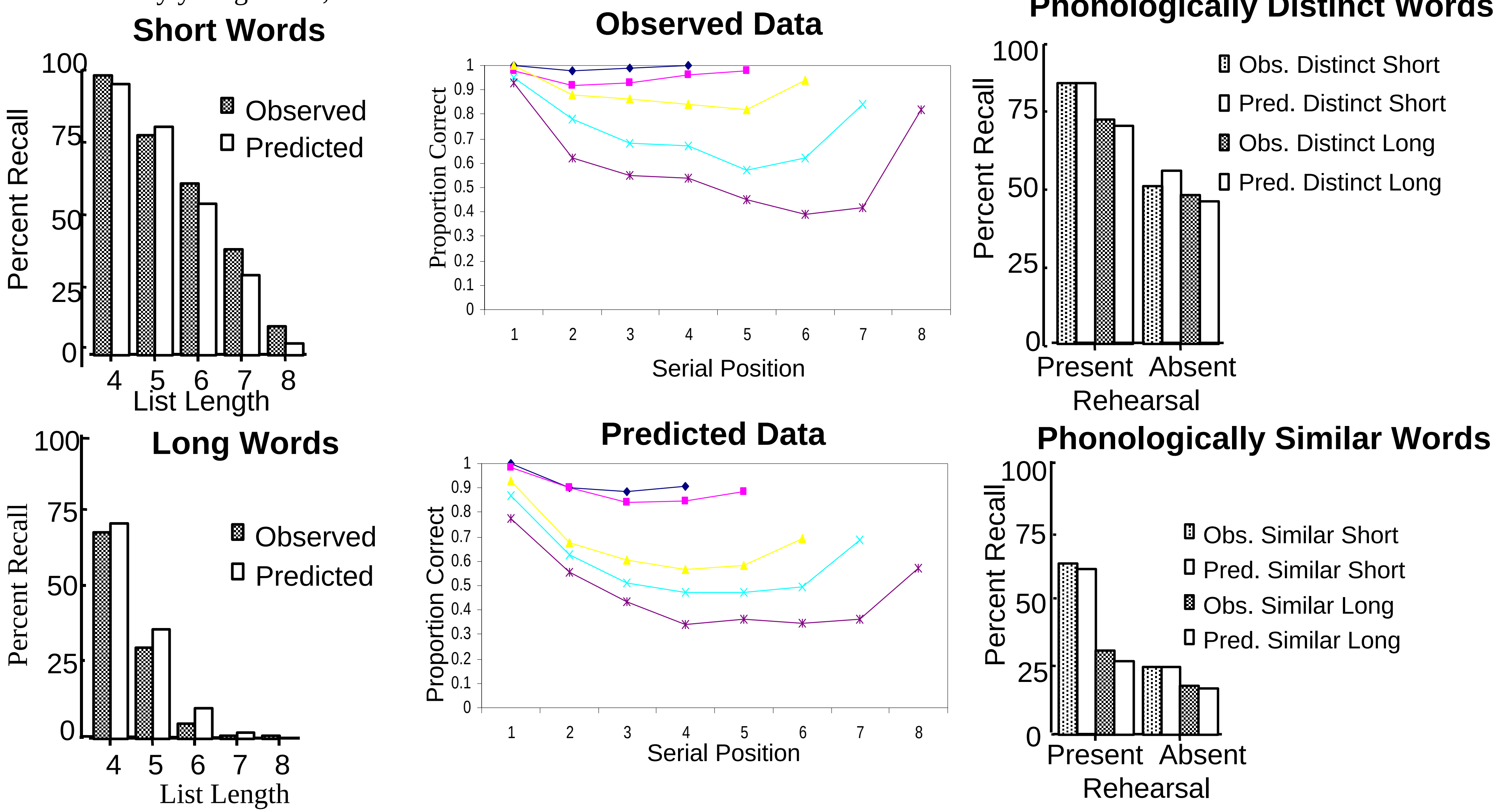

Figure 2. Left Panel: Probability of correct list recall across list lengths for short and long words. Data from Baddeley et al. (1975). Middle Panel: Probability of correct recall versus serial position for (Top) data from Drewnowski (1980) and (Bottom) EPIC model. Right Panel: Probability of correct list recall for short and long phonologically similar and distinct words under rehearsal-present and rehearsal-absent conditions. Data from Longoni et al. (1993).

Assessing Age-Related Declines in VWM with EPIC

To assess age-related declines in VWM and to identify their specific sources, we have made further assumptions that elaborate our EPIC models in two ways:

EPIC Model 1 with Central Cognitive Slowing--Basic Assumptions

- Both older and young adults perform the digit span task through active rehearsal and recall managed by executive control processes.
- The perceptual and motor processes of older adults function virtually as well as those of young adults.
- Phonological and serial-order information in verbal WM is equally durable for older and young adults.
- As adults age from 20 to 70 years old, the mean cycle time of their cognitive processors increases by about 12.5%, going from 50 to 56.5 msec.

EPIC Model 2 with Other Ancillary Deficiencies--Basic Assumptions

- For older adults, central cognitive slowing is accompanied by ancillary declines in perceptual-motor mechanisms, memory-trace durations, and/or executive control processes.

Rationale for Assumptions about VWM and Aging

The assumptions by our two EPIC models of age-related declines in verbal WM for the digit span task are based on the following rationale:

- Previous EPIC models of choice reaction times in dual-task performance indicate that across the life span from 20 to 70 years old, cognitive-processor cycle times increase by an average of about 12.5% (Glass et al., in press).
- Corresponding to this increase in the mean cognitive-processor cycle time with age, an increase of about 12.5% occurs in the mean period of adults' alpha rhythms (Woodruff, 1975).
- The forward digit span in adults declines gradually as they age from 20 to 70 years, suggesting that except for the modest increase of their cognitive-processor cycle times, their information processing mechanisms and executive control processes remain essentially intact.
- After 70 years of age, much steeper declines in both forward and backward digit spans occur, suggesting that other mechanisms and component processes eventually become less efficient.
- Based on evidence about neurophysiological changes with age, these further deficiencies probably involve perceptual, motor, memorial, and executive control components.

Aging and Predicted Vs. Observed Digit-Span Data

With Models 1 and 2, respectively, we have obtained accurate predictions for gradual and steeper declines of forward and backward digit spans in the 20 to 65 year and 70 to 80 year age ranges, respectively. Our success here reveals the differential contributions of several age-related sources to VWM.

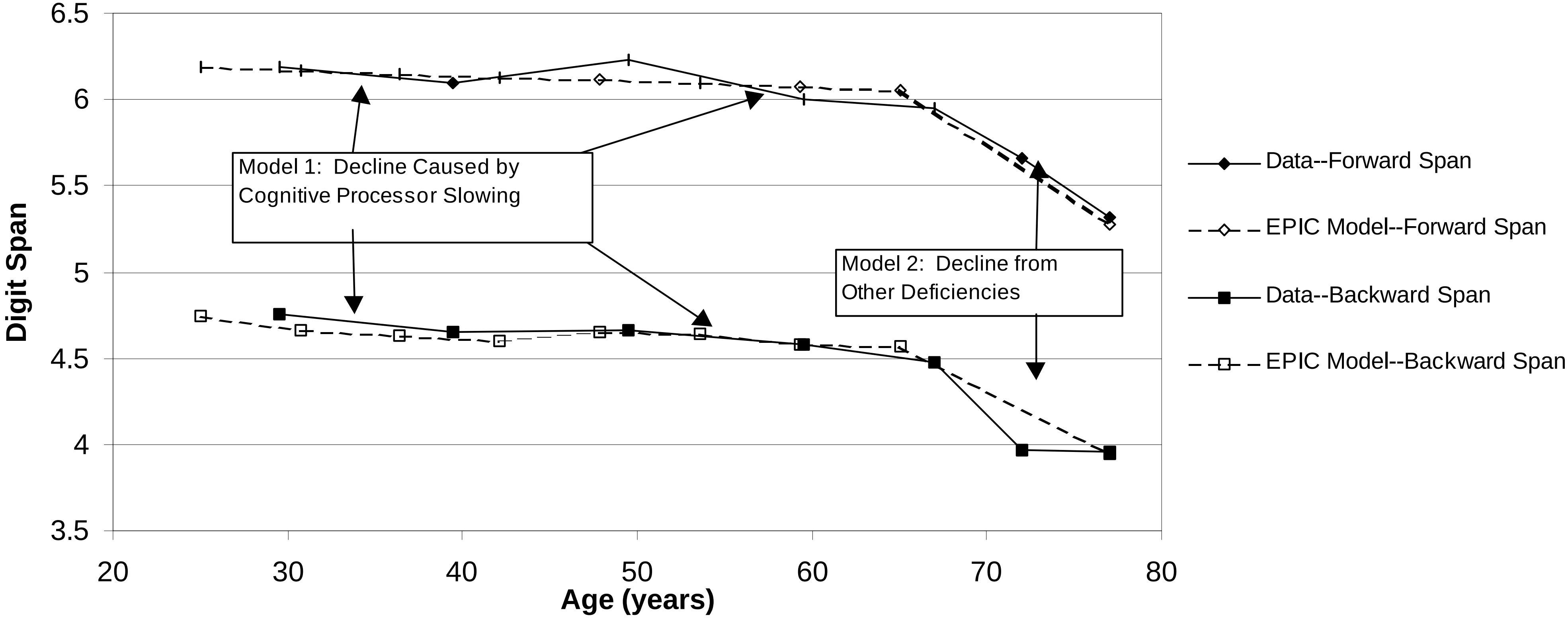

Figure 3. Observed and Predicted data from Forward and Backward digit span tasks. Declines from age 25 to 65 are accounted for by 12.5% slowing in the cognitive-processor cycle time. After age 70, steeper declines may be explained by four additional sources: Auditory perceptual degradation, verbal memory-code fragility, motor execution slowing, or executive control failure. Data from Gregoire and Van der Linden (1997).

Evaluation of Sources for Age-Related Declines in VWM

Each of several sources mentioned before may cause the observed steeper age-related declines of digit spans in older (>70) adults. Furthermore, these steeper declines each can be associated with specific changes in theoretical parameters and neural brain regions.

Locus of Decline	"Young" Parameter Value	"Old" Parameter Value	Old/Young Parameter Change	Physiological Locus of Decline (Brodmann's Areas)
Degradation of Auditory Perceptual Codes	Median Decay Time: **6500 msec**	Median Decay Time: **5600 msec**	-14%	Inner ear, Auditory Perceptual Cortices (B.A. 41,42)
Faster Decay of Verbal Memory Codes	Median Decay Time: **4800 msec**	Median Decay Time: **4050 msec**	-16%	Parietal Lobe (B.A. 40) for Serial Order; Temporal Lobe (B.A. 41) for Item Identities.
Slowed Motor Programming and Response Execution	Mean Articulation Time/Word: **250 msec**	Mean Articulation Time/Word: **360 msec**	+44%	Vocal Motor System (B.A. 4, 6, 44)
Disrupted Executive Processes	Success Rate: **100%**	Success Rate: **75%**	-25%	Inferior Posterior Parietal Lobe (B. A. 40)

Conclusions and Future Research Directions

Our EPIC models of age-related declines in verbal working memory for the digit-span task support several major conclusions:

- The small but significant decline in digit span between 20 and 65 years of age can be accounted for entirely through a slowing in rehearsal caused by a 12.5% increase in older adults' cognitive-processor cycle time.
- Declines in digit span after age 70 cannot be accounted for by just longer cycle times.
- The steeper declines in digit spans after age 70 may be accounted for by the following:
  - Slower motor programming and execution;
  - Auditory perceptual degradation;
  - Reduced duration of item or serial order information;
  - Deficient executive control associated with rehearsal and recall.
- These latter malfunctions may be associated with deterioration in posterior parietal and temporal regions of the brain, rather than in dorsolateral prefrontal regions.
- Further research to identify the sources of age-related declines in more complex VWM tasks should interpret results in terms of detailed computational modeling that incorporates our present findings at a fundamental level.

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