Implications of Articulatory Duration and Phonological Similarity Effects in Working Memory

Shane T. Mueller, Travis Seymour, Adam Krawitz, David E. Kieras, and David E. Meyer

University of Michigan

Sponsored by the Office of Naval Research

Poster presented at the 42nd
Annual Meeting of
the Psychonomic Society;
Orlando, FL; November 17, 2001.

Abstract

During the past decade, persistent controversies arose about which independent variables are especially good predictors of serial recall from verbal working memory. According to some theorists, recall accuracy and memory span are predicted well by the articulatory durations but not the phonological complexity of stored items, whereas other theorists have claimed the opposite. This disagreement has stemmed at least partly from inconsistent and inappropriate methods for measuring articulatory durations and related variables such as phonological similarity. However, when they are measured through more appropriate methods that we have developed, articulatory durations and phonological similarity together can account for as much as 99% of the variance in memory-span data, but phonological complexity is not such a good predictor. Our claims are supported by several new experiments whose results conform well with Baddeley's (1986) articulatory-loop model of verbal working memory.

The Articulatory Duration Effect in Verbal WM

- Baddeley, Thomson, and Buchanan (1975) claimed that serial recall accuracy depends on the articulatory duration of the to-be-recalled words.
- Caplan, Rochon, and Waters (1992) claimed instead that "word-length" effects arise from rehearsal based on speech-based planning, and consequently are affected by phonological complexity rather than articulatory duration.
- Baddeley and Andrade (1994) disagreed with Caplan et al. (1992), but evidence remains equivocal (cf. Caplan & Waters, 1994).
- Subsequently, other experiments (Cowan et al., 1997; Service, 1998; Lovatt et al., 2000) have yielded conflicting evidence about the effects of articulatory duration and phonological complexity on serial recall accuracy.

Resolution of Conflicts about Verbal WM

- Resolution of these conflicts has been difficult because previous experiments have used (1) many different methods to measure articulatory duration, and (2) stimuli that were contaminated by haphazard variability in phonological similarity.
- To help resolve prevailing controversies about verbal working memory, we have developed new quantititive methods for measuring phonological dissimilarity and articulatory duration.
- In our studies, phonological dissimilarity between words is measured with the PSIMETRICA technique (Mueller & Meyer, 2000).
- Articulatory durations are measured with a list-based rehearsal procedure.

The PSIMETRICA Technique

PSIMETRICA stands for **P**honological **Si**milarity **Metric** **A**nalysis.

- This technique yields a multi-dimensional quantitive ratio-scale measure of the phonological dissimilarity between paired words.
- The obtained measure can be used to calculate the mean phonological dissimilarity for an entire set of words.
- Using PSIMETRICA involves four steps:

(1) Coding words into phonological-feature hierarchies.

(2) Aligning paired words.

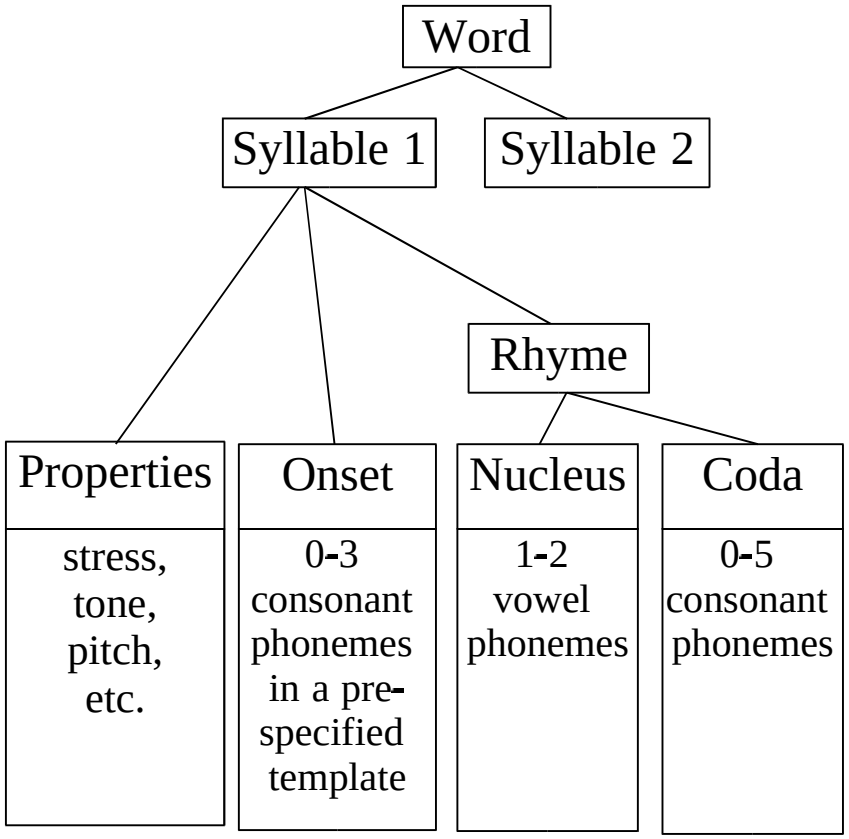
(3) Quantifying the phonological dissimilarity of paired words.

(4) Calculating the mean dissimilarity for an entire set of words.

Hierarchical Representation of Words

The steps for using PSIMETRICA depend on several assumptions about the representation of words:

- Words are motor programs, represented in memory as hierarchical linguistic structures (as shown on the right).
- Words contain syllables, which consist of properties and phoneme clusters, including onsets, nuclei, and codas.
- Phoneme clusters contain phonemes.
- Phonemes consist of phonological-feature vectors.



PSIMETRICA Step 1: Phonological-Feature Coding

During the first step of using PSIMETRICA, a word is decomposed into a hierarchical feature-based representation through four procedural substeps, as shown in the table below for the words "placemats" and "amount".

Substep	Procedure	Representations for Illustrative Words: "Placemats"	"Amount"
a.	Determine constituent phonemes	/plesmæts/	/ə maʊnt/
b.	Decompose word into syllables	/(ples) (mæts)/	/(ə) (maʊnt)/
c.	Decompose syllables into phoneme clusters	/((pl)(e)(s)) ((m)(æ)(ts))/	/((Ø)(ə)(Ø)) ((m)(aʊ)(nt))/
d.	Decompose phonemes into binary features (Chomsky & Halle, 1968)	p = (- + - - - + - x x - - - -) l = (+ + - - - + + x x + + - -) e = (+ - - - - - - - + x x x x) s = (- + - - - + + x x - + - +) m = (- + - - - + - x x + - + -) æ = (+ - - - + - - - + x x x x) t = (- + - - - + + x x - - - -)	ə = (+ - - + - - - - - x x x x) m = (- + - - - + - x x + - + -) a = (+ - - + + - - - + x x x x) ʊ = (+ - + + - - - + - x x x x) n = (- + - - - + + x x + - + -) t = (- + - - - + + x x - - - -)

PSIMETRICA Step 2: Alignment of Paired Words

During the second step of using PSIMETRICA, paired words are aligned in terms of their hierarchical feature-based representations. For each of the paired words' syllables:

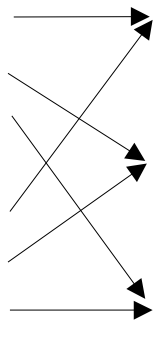
- Onsets are aligned according to a prespecified template.
- Nuclei are aligned by doubling shorter vowels.
- Codas are aligned to minimize dissimilarity.

Example Word	Phonemic Representation	First Syllables			Second Syllables		
		Onset	Nucleus	Coda	Onset	Nucleus	Coda
placemats	/((pl)(e)(s)) ((m)(æ)(ts))/	/Øpl/	/e/	/s/	/ØmØ/	/ææ/	/Øts/
amount	/((Ø)(ə)(Ø)) ((m)(aʊ)(nt))/	/ØØØ/	/ə/	/Ø/	/ØmØ/	/aʊ/	/ntØ/

PSIMETRICA Step 3: Quantifying Phonological Dissimilarity for Paired Words

- During the third step of PSIMETRICA, "**dissimilarity profiles**" are computed for corresponding syllables of paired words.
- These profiles describe the mean dissimilarity of the corresponding onsets, nuclei, and codas for the syllables of the paired words.
- The dissimilarity profiles for corresponding syllables of a word pair are averaged to produce a single dissimilarity profile, as shown in the following table.

Phoneme Cluster	Example Words: Placemats	Example Words: Amount	Mean Phonological Dissimilarity: Phonemes	Mean Phonological Dissimilarity: Phoneme Clusters	Dissimilarity Profile
	First Syllables				
Onsets	(p l)	(Ø Ø)	0.37, 0.53	0.45	Onset: 0.225
Nuclei	(e)	(ə)	0.22	0.22	Nucleus: 0.25
Codas	(s)	(Ø)	0.37	0.37	Coda: 0.31
	Second Syllables				
Onsets	(m)	(m)	0	0	
Nuclei	(æ)	(a ʊ)	0.11, 0.44	0.28	
Codas	(Ø t s)	(n t Ø)	0.37, 0, 0.37	0.25	



Calculation of Phonological Dissimilarity between Phonemes

The dissimilarity between paired phonemes is calculated through the following formula:

For phonemes p_1 and p_2, with features $p_{ji}, i \in \{1....13\}$

$$d_{feature}(p_{1i}, p_{2i}) = \begin{cases} 1 & \text{if } p_{1i} \neq p_{2i} \\ 0 & \text{if } p_{1i} = p_{2i} \end{cases} \quad \text{if } p_{1i} \text{ or } p_{2i} \in \{0,1\}$$

$$d_{phoneme}(p_1, p_2) = \frac{\sum_i d_{feature}(p_{1i}, p_{2i})}{\sum_i \#\left(d_{feature}(p_{1i}, p_{2i}) \in \{1,0\}\right)}$$

PSIMETRICA Step 4: Calculating Phonological Dissimilarity for a Set of Words

- A dissimilarity profile matrix is calculated for each word set (left).
- This matrix is symmetric with entries (0 0 0) on the diagonal, producing unique dissimilarity profiles for *n* (*n*-1) / 2 word pairs in an *n*-word set.
- An set's dissimilarity profile is calculated by finding the mean values of the *n* (*n*-1) / 2 word pairs' dissimilarity profiles.

Example Dissimilarity Profile Matrix

Word	1	2	3	4
1	(0 0 0)	**(.2 .3 .1)**	**(.1 .2 .1)**	**(.3 .25 .1)**
2	(.2 .3 .1)	(0 0 0)	**(.3 .21 .22)**	**(.4 .23 .12)**
3	(.1 .2 .1)	(.3 .21 .22)	(0 0 0)	**(.25 .31 .17)**
4	(.3 .25 .1)	(.4 .23 .12)	(.25 .31 .17)	(0 0 0)

Calculation of Mean Dissimilarity Profile

Word Pair	Onset	Nucleus	Coda
1-2	0.2	0.3	0.1
1-3	0.1	0.2	0.1
1-4	0.3	0.25	0.1
2-3	0.3	0.21	0.22
2-4	0.4	0.23	0.12
3-4	0.25	0.31	0.17
Mean:	0.26	0.25	0.135

The dissimilarity profile for a set of words is calculated by finding the average of all possible pairwise dissimilarity profiles in a set. For a set of four words, there are six pair-wise dissimilarity profiles.

Previous Measurement of Articulatory Duration

- The Phonological-Loop Model claims that since shorter words can be rehearsed more rapidly, they are less likely to decay before they need to be recalled.
- One of four methods is usually used to measure articulatory duration:
  - *Measurement of isolated word durations* (e.g., Baddeley, et al., 1975; Caplan et al., 1992; Lovatt et al., 2000);
  - *Measurement of durations for repeated short constant-length sequences* (e.g., Baddeley et al., 1975; Baddeley & Andrade, 1994; Lovatt et al., 2000);
  - *Measurement of durations for words read from lists* (e.g., Baddeley, et al., 1975; Caplan and Waters, 1994; Service, 1998; Lovatt et al., 2000);
  - *Measurement of durations for words during final serial recall* (e.g., Service, 1998; Cowan et al., 1997; Dosher & Ma, 1998).
- None of these methods provides a measure of articulatory duration that is relevant for testing the phonological-loop model.

Requirements for Measuring Articulatory Duration

To properly measure the aspect of articulatory duration that is relevant for testing phonological-loop model, measurements should be made in a context similar to verbal rehearsal for serial recall.

To create a context similar to rehearsal:

- Typical **sequences of words** should be presented.
- Word sequences should be both **rehearsed** and **recalled**.
- Sequences should be **repeated**.
- **Multiple list lengths** should be measured.
- Sequences should be rehearsed **from memory**, rather than read.

Since this context will produce sequence production times composed of multiple components, proper **analysis** of these times is also necessary to isolate aspects of the measured durations that are relevant for serial recall tasks.

Procedure for Measuring Articulatory Duration

To measure articulatory duration, we used the following procedure:

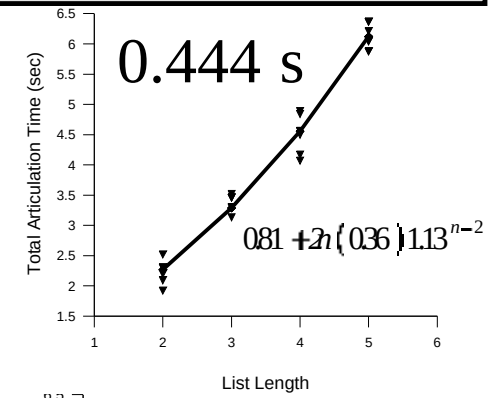
- During each trial, the participant is presented with a sequence of between 2 and 5 words.
- Initially, the sequence is presented on a computer monitor.
- The participant is allowed to study this sequence until he or she is prepared to rapidly articulate it.
- When prepared, the word sequence disappears and three tones are presented.
- At the third tone, the participant begins articulating the sequence of words two times, at a rapid clear pace, without pausing between subsequences.
- If an articulation error or a prolonged pause occurs, the trial is repeated.
- The time from the onset of the third beep until the offset of the final word is measured.

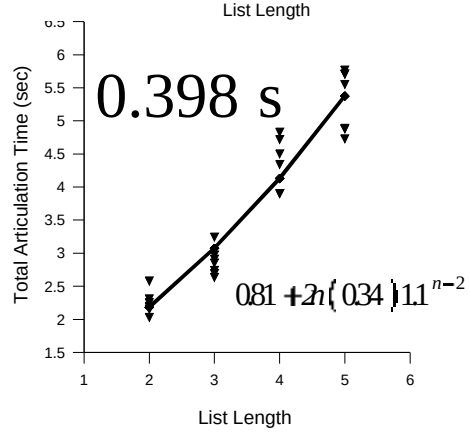
For each participant, all measured articulation times are analyzed with appropriate procedures (see next panel).

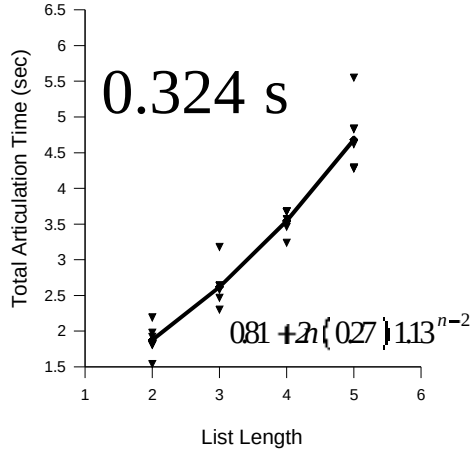
Formula for Estimating Articulatory Duration

Typically, speech production times are concave up with list length. To estimate articulatory duration:

- We assume that total articulation times for word set *j* and length *n* are described by $T = I + 2nd_j a_j^{n-2}$
  - *I* is a subject-based intercept.
  - d_j is a word-set based duration parameter.
  - a_j is a word-set based amplification parameter.
- Parameter values are found by minimizing mean squared deviations from predicted values.
- For word set *j*, we use the formula $d_j \sum_{i=0}^{3} d_j^i / 4$ to produce estimates for articulatory duration that factor out the intercept *I*.
- Typical data and analysis is shown on right.







Experiment 1

- Experiment 1 included six word sets in a verbal serial recall task.
- Word Sets 1-4 were the "Long", "Short", "Hard", and "Easy" sets from Caplan et al. (1992, Exps. 2-3).
- Word Sets 5 and 6 were one- and three-syllable words, respectively.
- Articulatory duration, phonological dissimilarity, and memory span were measured for each of the six word sets.
- The word sets differed in both their mean articulatory durations and phonological dissimilarities.

Results of Experiment 1 are shown in the table on the right. Phoneme and syllable numerosity are indices of phonological complexity. Onset dissimilarity was measured with the PSIMETRICA technique, and articulatory duration estimated with formula in the previous panel.

	Word Sets					
Measured Variable	1	2	3	4	5	6
Syllable numerosity	2	2	1	1	1	3
Mean phoneme numerosity	6.00	5.13	3.00	3.00	3.25	7.50
Mean onset phonological dissimilarity	0.401	0.344	0.266	0.336	0.399	0.363
Mean articulatory duration (ms)	254	275	257	201	245	405
Mean memory span (words)	6.22	5.78	5.50	6.05	6.27	5.09

Experiment 1: Linear Regression Analysis

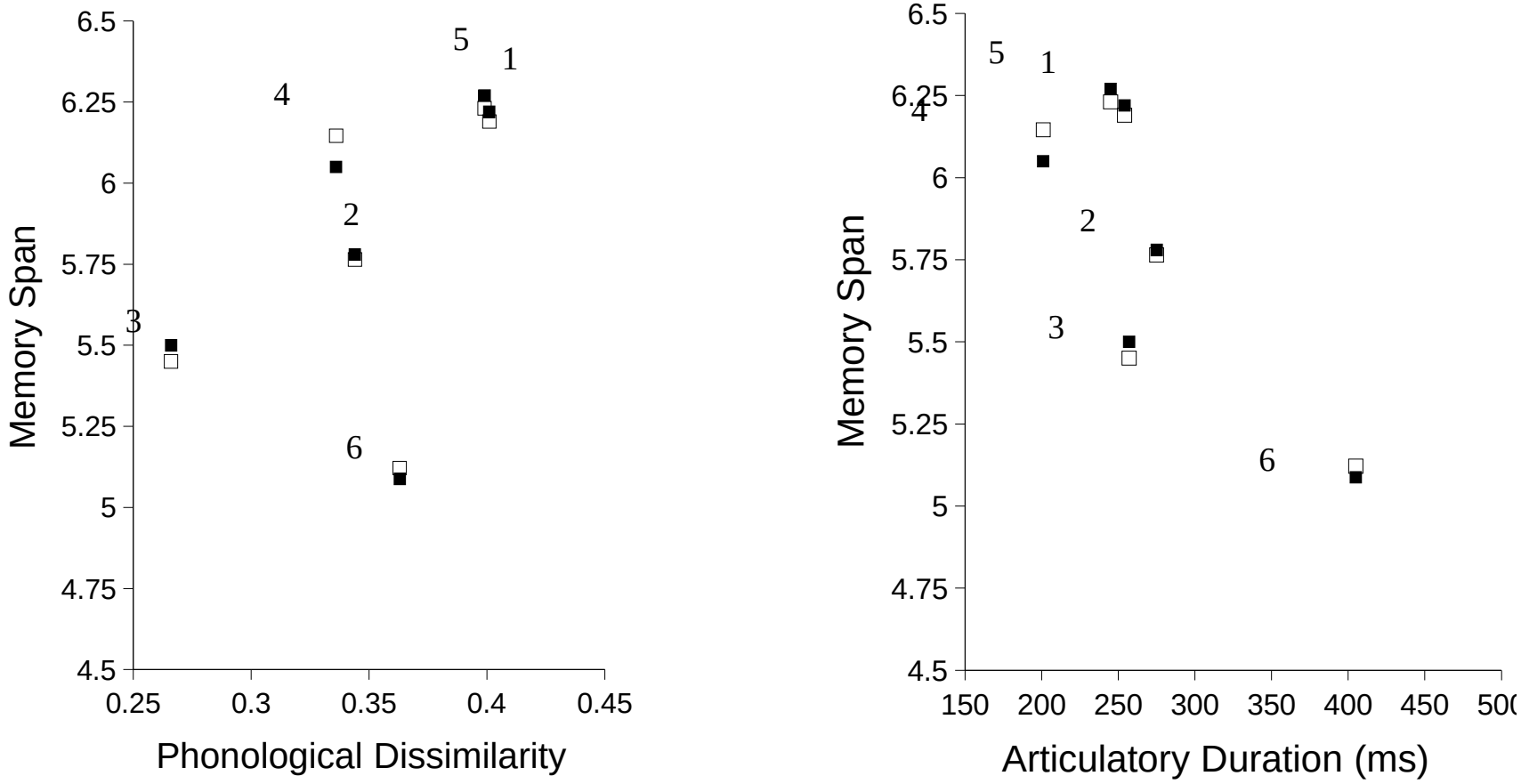
To assess the relative influence of articulatory duration, phonological similarity, and phonological complexity on memory span, a linear regression was performed. Results show that complexity adds no predictive power, but the overall goodness-of-fit gets significantly worse when articulatory duration is removed (Top table). Coefficient values for the regression with only articulatory duration and onset similarity are shown in bottom table.

	Model Performance				Comparison to Full Model		
Model	R^2	F	d.f.	p	d.f.	F	Pr(F)
Full (Articulatory Duration & Similarity & Complexity)	.9858	48	3,2	.02			
Similarity & Articulatory Duration	.9767	106	2,3	.002	-1	.0412	.858
Similarity & Complexity	.6927	6.636	2,3	.08	-1	24.9	.0378

Model Parameters	Linear Coefficients	Standard Error	Partial r
Intercept	5.5	0.244	
Articulatory Duration	-.00573	0.00045	-.991
Onset Similarity	5.35	0.629	.980

Experiment 1: Observed and Predicted Results

Using the coefficients obtained in the previous panel, we plot both observed and predicted mean memory spans by articulatory duration (left) and phonological similarity (right).



Results of Experiment 1, with observed and predicted memory span for each list plotted by mean onset dissimilarity (left) and articulatory duration (right). Solid symbols represent observed memory spans; open symbols represent predictions of linear model using only articulatory duration and onset dissimilarity as predictors.

Experiment 1: Discussion

- Our results are consistent with earlier findings showing Set 1 was recalled better than Set 2, and Set 4 was recalled better than Set 3. (Caplan et al., 1992; Caplan & Waters, 1994).
- Our results confirm earlier findings (Caplan et al., 1992; Baddeley & Andrade, 1994; Caplan et al., 1994) that Set 3 (“Hard”) had longer mean articulatory durations than Set 4 (“Easy”), but suggest that Set 2 (“Short”) had longer mean articulatory durations than Set 1 (“Long”), contrary to earlier findings (Caplan et al., 1992; Caplan et al., 1994).
- Neither articulatory duration nor phonological dissimilarity alone can explain the entire pattern of obtained results.
- Together, articulatory duration and phonological dissimilarity account for the results with great accuracy, suggesting that phonological complexity is not an important predictor of serial recall accuracy.

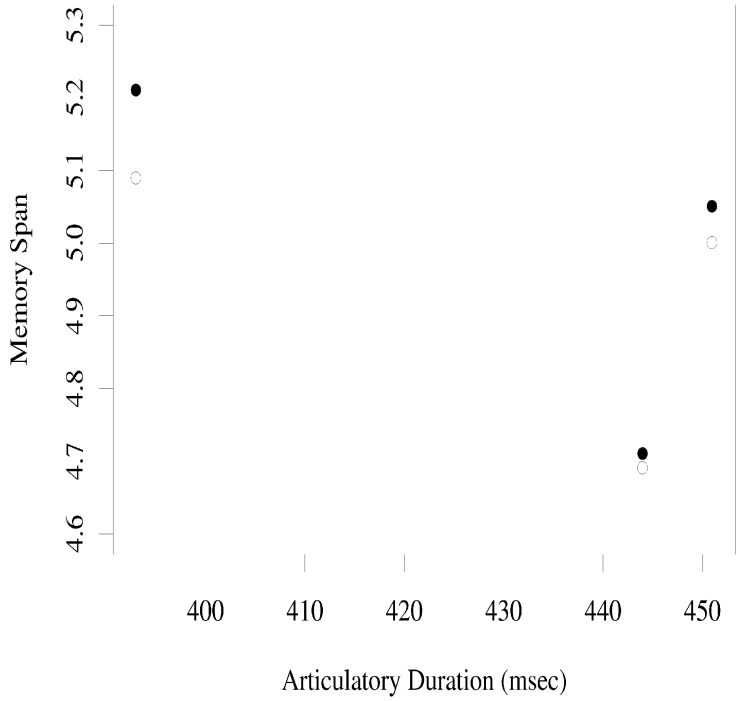
Experiment 2

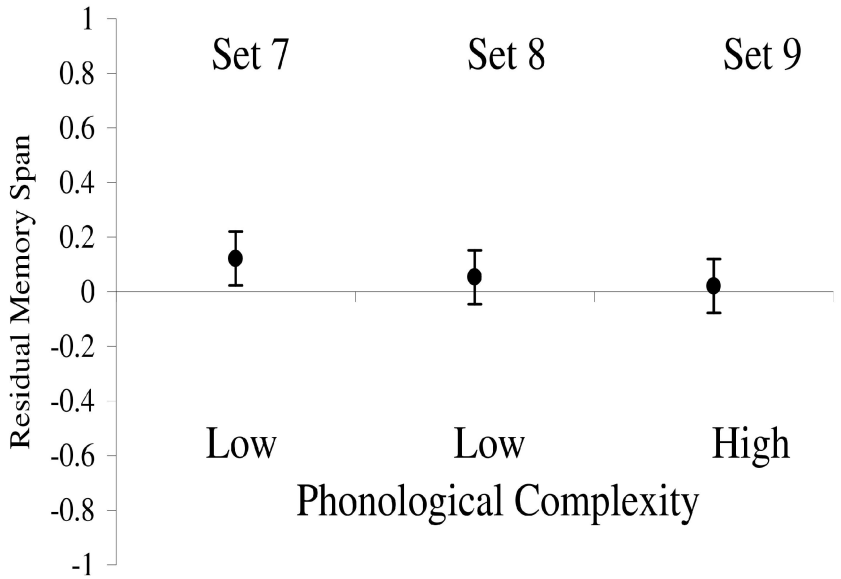
- In a second experiment, articulatory duration, phonological dissimi-larity, and memory span were measured for three new sets of words.
- In this experiment, one set was composed of words with “low” complexity and “short” mean durations; a second set was composed of words with “low” complexity and “long” mean durations; a third set was composed of words with “high” complexity and “long” mean durations.
- Data obtained in Experiment 2 are shown below.

	Word Sets		
Measured Variable	7	8	9
Syllable numerosity	2	2	3
Mean phoneme numerosity	7.00	7.00	8.00
Mean onset phonological dissimilarity	0.344	0.389	0.324
Mean articulatory duration (ms)	393	451	444
Mean memory span (words)	5.21	5.05	4.71

Experiment 2: Results

- Using the coefficients from the equation in Experiment 1, mean memory span was predicted by articulatory duration and phonological dissimilarity.
- Observed and predicted results are shown in lower left figure.
- Residual spans based on these predictions are shown in the lower right figure.





The coefficients of the linear regression in Experiment 1 were used to predict memory spans in Experiment 2, on an *a priori* basis. Left: Observed (filled circles) and predicted (open circles) memory spans plotted against measured articulatory duration. Right: Residual memory span and standard error shown for each set. There is no reliable relationship between residual memory span and phonological complexity.

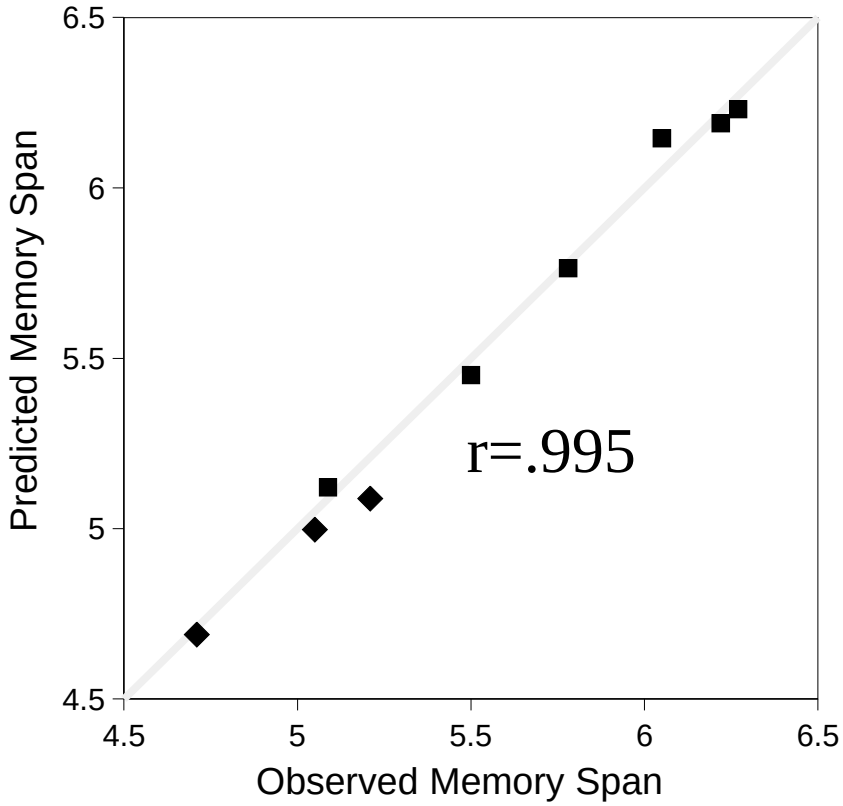
Experiment 2: Discussion

- Experiment 2 shows that when the effect of phonological dissimilarity is accounted for: (1) Differences in articulatory duration produce reliable differences in memory span for equal levels of phonological complexity; and (2) Differences in phonological complexity do not produce reliable differences in memory span for roughly equivalent articulatory durations.
- The results of Experiment 2 confirm the findings of Experiment 1.
- Memory spans in Experiment 2 were accurately predicted by the regression equation obtained from Experiment 1.
- Experiment 2 represents a successful generalization of the results of Experiment 1 to data obtained from new participants with new word sets whose articulatory durations were in a new range of values.

Summary of Experiments

- Across both experiments, articulatory duration and phonological dissimilarity together provided a good account of performance in the memory-span task.
- Phonological complexity did not predict memory span performance.
- The figure on the right shows observed and predicted memory spans across both experiments. Squares indicate word sets from Experiment 1, whereas diamonds indicate word sets from Experiment 2.

Results from Experiments 1 and 2



Conclusions

- Although previous results appeared to show that the Phonological-Loop model of verbal working memory is inaccurate or incomplete, our findings demonstrate that these earlier results are consistent with the phonological-loop model.

- Our conclusions rely on the accurate quantification of phonological dissimilarity and the appropriate measurement of articulatory duration.

- Our results confirm the predictions of the phonological-loop model (Baddeley, 1986), where subvocal rehearsal mediates the articulatory-duration effect, and a short-term memory buffer with phonological codes mediates the phonological dissimilarity effect.

References

Baddeley, A. D. (1986). *Working memory*. New York: Oxford University Press.

Baddeley, A. D., & Andrade, J. (1994). Reversing the word-length effect: A comment on Caplan, Rochon, and Waters. *Quarterly Journal of Experimental Psychology, 47A*, 1047-1054.

Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior, 14*, 575-589.

Caplan, D., Rochon, E., & Waters, G. S. (1992). Articulatory and phonological determinants of word length effects in span tasks. *Quarterly Journal of Experimental Psychology, 45A*, 177-192.

Caplan, D., & Waters, G. S. (1994). Articulatory length and phonological similarity in span tasks: A reply to Baddeley and Andrade. *Quarterly Journal of Experimental Psychology, 47A*, 1055-1062.

Cowan, N., Wood, N. L., Nugent, L. D., & Treisman, M. (1997). There are two word-length effects in verbal short-term memory: Opposed effects of duration and complexity. *Psychological Science, 8*, 290-295.

Dosher, B. A., & Ma, J. (1998). Output loss or rehearsal loop? Output-time versus pronunciation-time limits in immediate recall for forgetting matched materials. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*, 316-335.

Lovatt, P., Avons, S. E., & Masterson, J. (2000). The word-length effect and disyllabic words. *Quarterly Journal of Experimental Psychology*, 53A, 1-22.

Mueller, S. T., & Meyer, D. E. (2000). Psychophysical chemistry of phonological similarity: A formal similarity metric based on principled phonetic feature analysis. *Paper presented at the meeting of the Society for Mathematical Psychology*, Kingston, Ontario, Canada.

Mueller, S. T., Seymour, T. L., Kieras, D. E., & Meyer, D. E. (under revision). Theoretical implications of articulatory duration, phonological similarity, and phonological complexity effects in verbal working memory.