Insights about Verbal Working Memory and Serial Recall Enabled by Precise Quantitative Measurement of Phonological Dissimilarity

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Sponsored by the Office of Naval Research

Poster presented at the meeting of
the Society for Mathematical Psychology,
Providence, RI, July 2001.

Abstract

According to the phonological−loop model of short−term verbal working memory, serial−recall accuracy and memory span should increase directly with the phonological dissimilarity of the items being recalled. However, little is known about the conditions under which this prediction may hold. To characterize these conditions better, we have developed PSIMETRICA, a formal quantitative technique for measuring phonological dissimilarity (Mueller & Meyer, SMP 2000). Analyses based on PSIMETRICA suggest that even introspectively undetectable differences in phonological dissimilarity can affect recall accuracy significantly. Consequently, many past memory experiments may have been contaminated by unacknowledged differences in phonological dissimilarity. For example, Lovatt et al. (2000) conducted three serial recall experiments involving six sets of words. They found no consistent relationship between articulatory duration and recall accuracy across their word sets, which led them to reject the phonological−loop model. However, our analyses show that Lovatt et al.'s conclusions are unwarranted because their sets of words embodied subtle but potent differences in phonological dissimilarity. Furthermore, using Lovatt et al.'s word sets, we have conducted experiments whose results support the phonological−loop model. Our phonological−dissimilarity measurements based on PSIMETRICA have enabled us to predict the outcomes of these new experiments on an a priori basis. Given these outcomes, we consider several detailed hypotheses about how articulatory rehearsal and phonological dissimilarity interact in the context of short−term verbal serial recall.

The PSIMETRICA Technique

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

This technique yields a quantitive ratio−scale measure of the phonological dissimilarity between paired words.

This measure can be used to calculate the mean dissimilarity for an entire set of words.

Using PSIMETRICA involves four steps:

(1) Coding words into phonological−feature hierarchies.

(2) Aligning paired words.

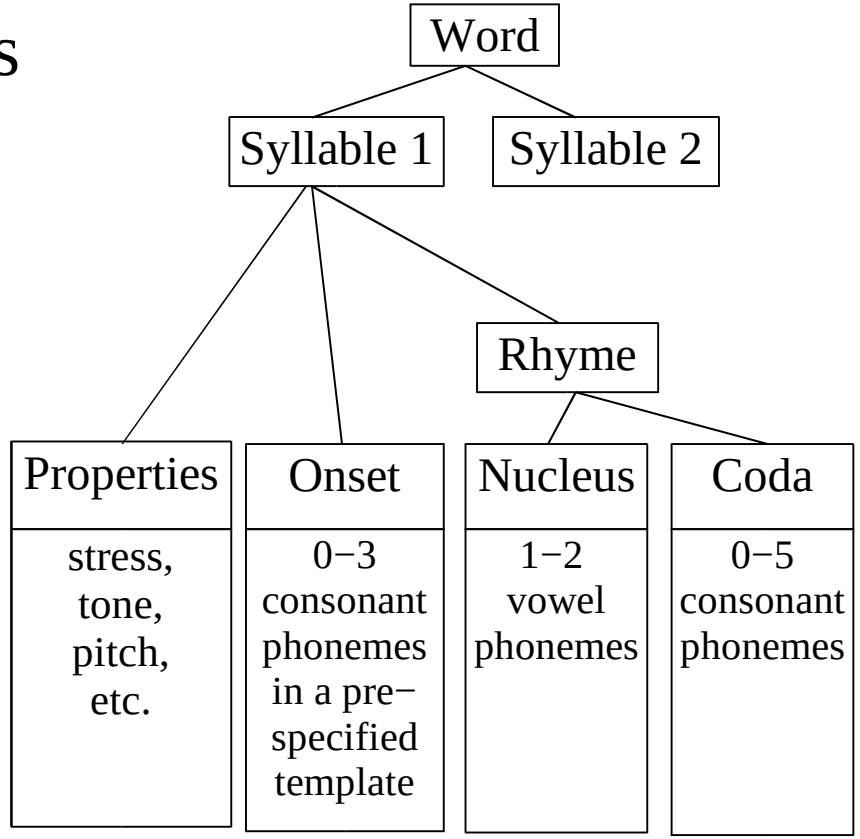
(3) Quantifying the phonological dissimilarity of paired words.

(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 consist of phonemes.
- Phonemes consist of phonological−feature vectors.



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 − − − −)	not applicable	
		l =	(+ + − − − + + x x + + − −)	ə =	(+ − − + − − − − − x x x x)
		e =	(+ − − − − − − − + x x x x)	not applicable	
		s =	(− + − − − + + x x − + − +)	m =	(− + − − − + − x x + − + −)
		m =	(− + − − − + − x x + − + −)	a =	(+ − − + + − − − + x x x x)
		æ =	(+ − − − + − − − + x x x x)	ʊ =	(+ − + + − − − + − x x x x)
		t =	(− + − − − + + x x − − − −)	n =	(− + − − − + + x x + − + −)
		s =	(− + − − − + + x x − + − +)	t =	(− + − − − + + x x − − − −)

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.

The following table illustrates this alignment for the words "placemats" and "amount".

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/

Step 3: Quantifying Phonological Dissimilarity for a 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 onsets, nuclei, and codas for the paired words' syllables.
- 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	0.225
Nuclei	(e)	(ə)	0.22	0.22	
Codas	(s)	(Ø)	0.37	0.37	0.25
	Second Syllables				
Onsets	(m)	(m)	0	0	
Nuclei	(æ)	(a ʊ)	0.11, 0.44	0.28	
Codas	(t s)	(n t)	0.37, 0, 0.37	0.25	0.31

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 $p_{ji}, i \in \{1....13\}$

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

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

Step 4: Calculating Phonological Dissimilarity for a Set of Words

- For a set of words, a dissimilarity profile matrix is calculated, as shown below.
- This matrix is symmetric with entries (0 0 0) on the diagonal, producing $n\ (n-1)\ /\ 2$ unique dissimilarity profiles for word pairs in an n−word set.
- An overall mean dissimilarity profile for a set of words 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

Initial Background Experiments

Two initial experiments were conducted using the serial memory−span task (Mueller et al., submitted).

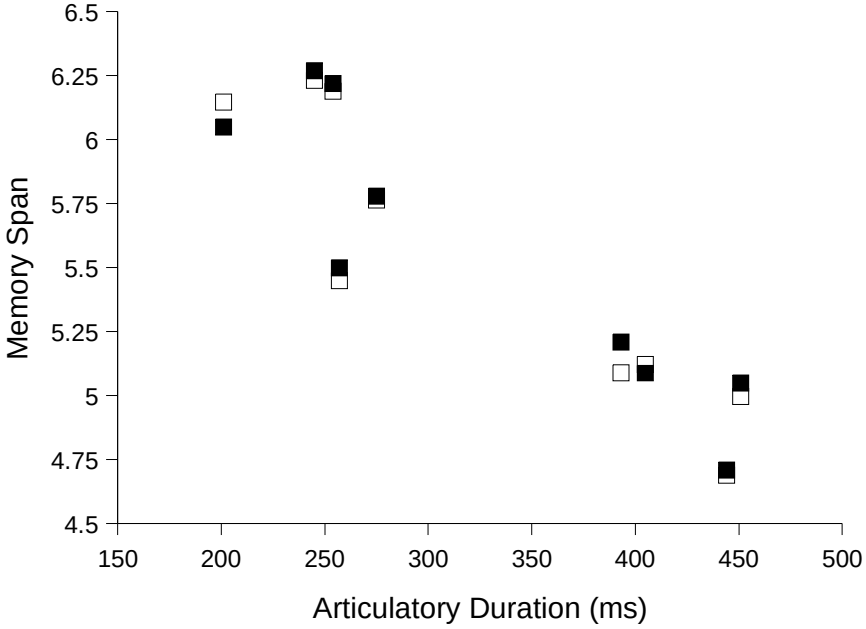
- Articulatory duration, phonological dissimilarity, and memory span were measured for nine word sets.
- The word sets differed in both their mean articulatory durations and phonological dissimilarities
- Obtained results appear in the following table.

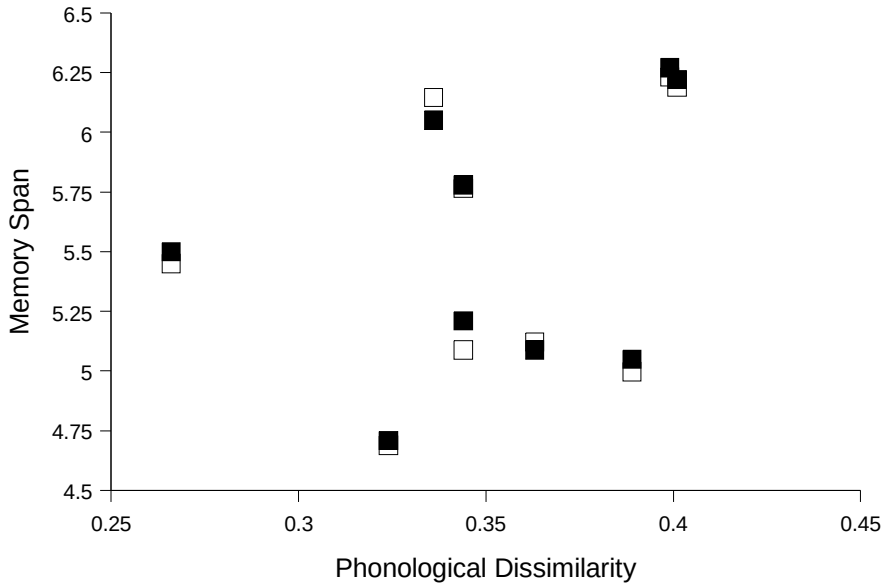
	Experiment 1 Word Sets						Experiment 2 Word Sets		
Measured Variable	1	2	3	4	5	6	7	8	9
Syllable numerosity	2	2	1	1	1	3	2	2	3
Mean phoneme numerosity	6.00	5.13	3.00	3.00	3.25	7.50	7.00	7.00	8.00
Mean onset phonological dissimilarity	0.401	0.344	0.266	0.336	0.399	0.363	0.344	0.389	0.324
Mean articulatory duration (ms)	254	275	257	201	245	405	393	451	444
Mean memory span (words)	6.22	5.78	5.50	6.05	6.27	5.09	5.21	5.05	4.71

Observed and Predicted Results

Results of Experiments 1 and 2 were fit with a 2−parameter linear model that used articulatory duration and phonological dissimilarity to predict memory span, based only on results from Experiment 1. Filled and empty squares indicate observed and predicted data, respectively.

Model Parameters	Linear Coefficients	Standard Error	Partial r	p(t)
Intercept	5.5	0.244		.0008
Articulatory Duration	−.00573	0.00045	−.991	.003
Onset Similarity	5.35	0.629	.980	.002

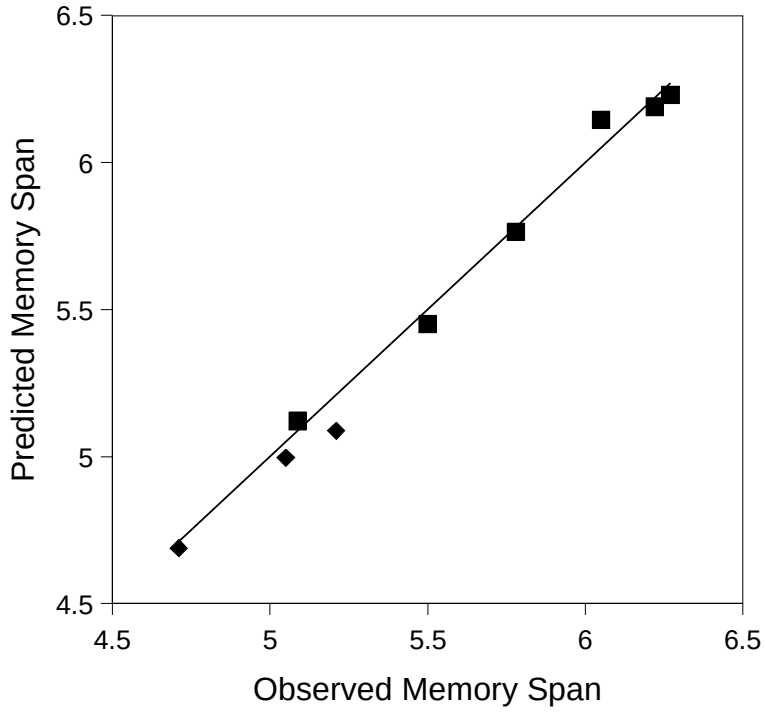




Summary of Initial Experiments

- Articulatory duration and phonological dissimilarity can explain and predict performance in the memory−span task (see right panel).
- This supports the phonological−loop model of verbal working memory (Baddeley, 1986), where subvocal rehearsal mediates an articulatory−duration effect, and a short−term memory buffer using a phonological representation mediates the dissimilarity effect.

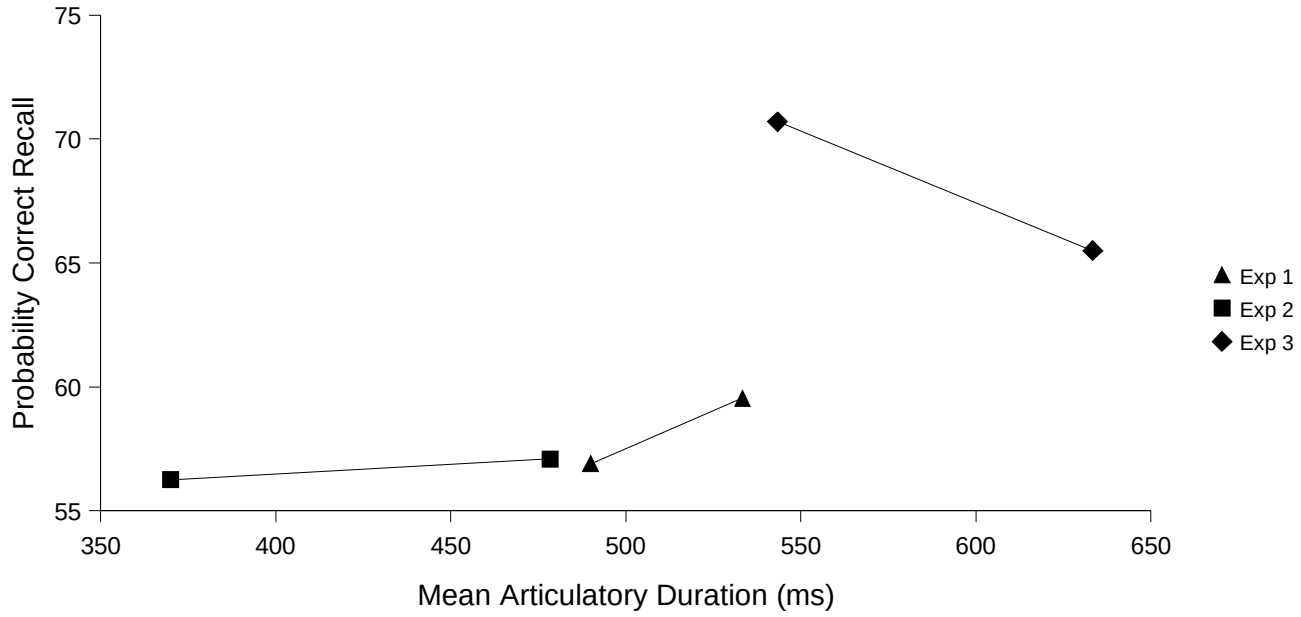
Results from Experiments 1 and 2



Lovatt, Avons, and Masterson (2000)

To test Baddeley's (1986) phonological−loop model, Lovatt et al. (2000) conducted three serial recall experiments with six different sets of 2−syllable words.

- Across word sets, phonological dissimilarity was "equated" on the basis of introspective judgments.
- There was no systematic relationship between mean articulatory durations and memory spans across word sets.
- Consequently, Lovatt et al. (2000) concluded that the phonological−loop model is insufficient for explaining verbal working memory.



Criticisms of Lovatt et al. (2000)

The results of Lovatt et al. (2000) are difficult to interpret because:

- They came from three different experiments.
- Articulatory duration was measured improperly.
- Word sets actually differed in their phonological dissimilarity.
- The reported dependent variable (percent correct recall) is inappropriate for evaluating phonological−dissimilarity effects with respect to our previous results.

Consequently, Lovatt et al.'s results may not provide any evidence against the phonological−loop model.

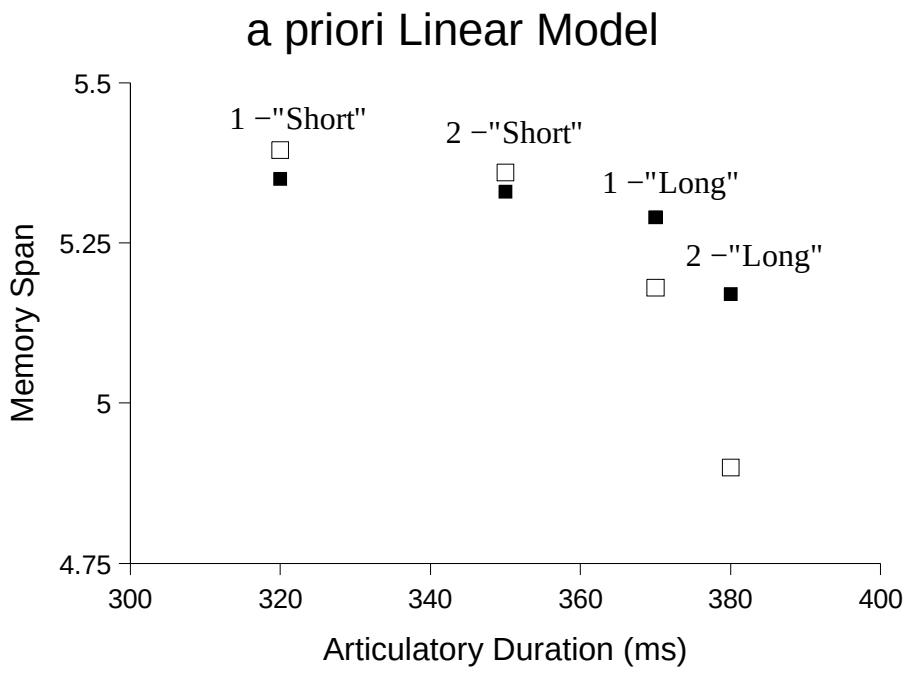
Replication of Lovatt et al. (2000)

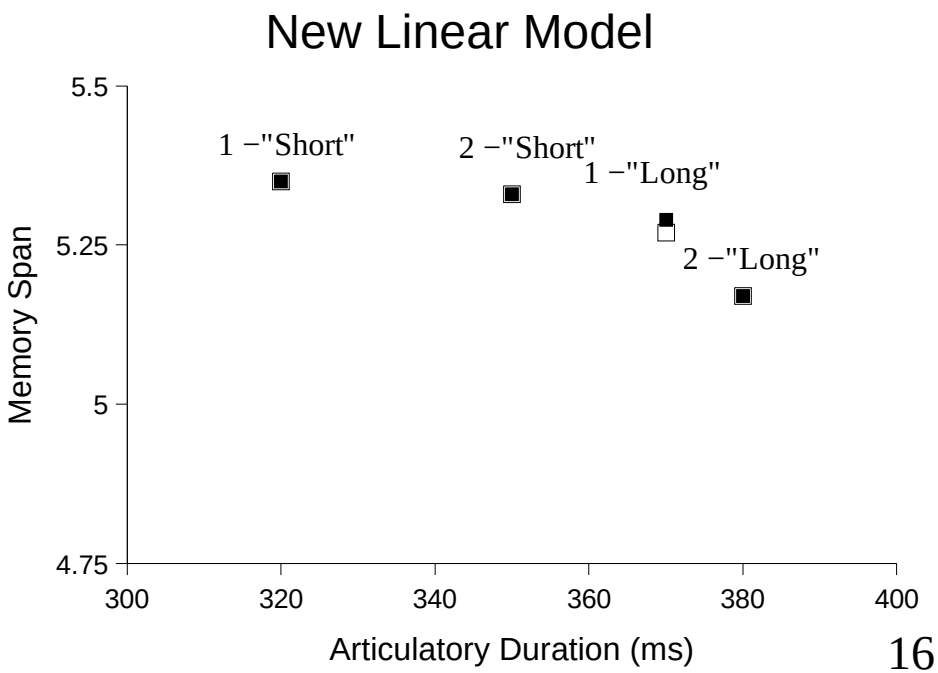
To determine whether Lovatt et al.'s (2000) results are problematic for the phonological−loop model, we conducted a new experiment:

- Four sets of words (from Lovatt et al., 2000, Exps. 1 and 2) were included.
- Articulatory duration was measured properly with a list recall procedure.
- Memory span was measured with an adaptive staircase method.
- Phonological dissimilarity was measured with PSIMETRICA.

Results of Replicating Lovatt et al.

- Memory spans were predicted in two ways: (1) on an a priori basis with the linear model for results from our earlier experiments, and (2) with a new linear model that re−estimated the effects of articulatory duration and phonological dissimilarity.
- Observed (solid squares) and predicted (open squares) memory spans are shown below.





More Experimental Results

More results and model coefficents from our replication of Lovatt et al. (2000) are shown below:

Measured Variable	Word Set			
	1−"Short"	1−"Long"	2−"Short"	2−"Long"
Phonological Dissimilarity	0.318	0.337	0.348	0.297
Articulatory Duration (ms)	315	370	349	381
Observed Memory Span	5.35	5.29	5.32	5.16
Predicted Memory Span (a priori model)	5.39	5.18	5.36	4.9
Predicted Memory Span (new model)	5.35	5.27	5.33	5.17

Parameter	Linear Coefficients	
	a priori Model	New Model
Intercept	5.5	5.33
Articulatory Duration	−.00573	−.00199
Onset Similarity	5.35	2.02

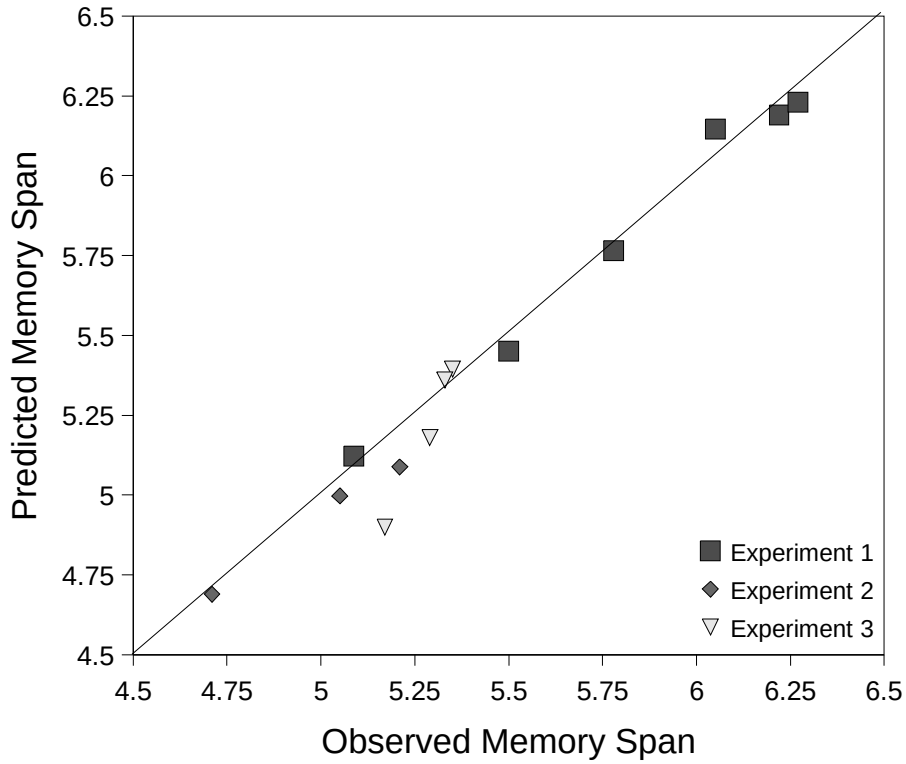
Discussion of Results from Replication

Our results that differed from those of Lovatt et al. (2000).

- Our estimates of articulatory duration differed from Lovatt et al.'s (2000) in *rank order* and *magnitude*.
- Our measurements of memory span did not correlate highly with the percentages of correct recall reported by Lovatt et al. (2000).
- Our results can be understood through an analysis of phonological dissimilarity, whereas Lovatt et al.'s (2000) results remain unexplained.
- Our replication of Lovatt et al. (2000) produced smaller effects of both articulatory duration and phonological dissimilarity than did our earlier experiments.

Conclusions

- Across three different experiments, we have accurately predicted performance in the memory span task based on phonological dissimilarity and articulatory duration (right panel).
- Articulatory duration and phono−logical dissimilarity have different magnitudes of effects in different experiments.
- If phonological dissimilarity is not taken properly into account, effects of other factors (e.g., articulatory duration) can not be evaluated accurately.
- PSIMETRICA is a useful technique for measuring phonological dissimilarity.



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