

Preparation Modulation in Timing of Speech-Movement Sequences

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Preparation Modulation in Timing of Speech-Movement Sequences

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To Mom and Dad

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SUMMARY

When timing a fluent sequence of either movement or speech, evidence suggests that people consider the amount of time available during the production of a first unit to prepare a second unit, evident in a *reverse length effect* for response onset of the sequence (e.g., Griffin, 2003; Ketelaars, Garry, & Franks, 1997). The current study investigated whether such considerations extend to sequences composed of both speech and movement units. Participants named an object and manually traced a course to produce a fluent sequence. Duration of the first production was manipulated. If preparation modulation operates over speech and movement units within the same sequence, sequence onset will be earlier when the first unit is short in production duration as opposed to long. In general, participants began sequences later when production of first unit did not exceed preparation time of the second unit. This finding provides support for preparation.

INTRODUCTION

Everyday tasks require that we perform sequences of actions that demand precise timing. The coordination of key presses when typing or playing a musical instrument and even the words of a fluent sentence all require timing. Sometimes sequences require timing across seemingly unrelated tasks. In spontaneous language production, speech is often accompanied by gestures. This concurrent production of both speech and movement has a relatively consistent timing relationship (see McNeill, 1992). So how do we accurately time units of a fluent sequence? Investigation of the production of speech and goal-directed movement sequence could provide some insight to the answer. In the review to follow, I will first discuss what I mean by a “unit” within a sequence, and then I will discuss planning patterns of single modality sequences of speech and movement. Following this, I will present the hypothesis to be tested and discuss the assumptions of the hypothesis.

CHAPTER 2

LITERATURE REVIEW

What Constitutes a Unit?

For the present purpose, a sequence is considered a series of unit productions. But what exactly is a “unit”? A unit can be defined as a basic processing element that can interact and coordinate with other units to form more complex productions. Unit sizes are variable depending on the level of interest. In speech, for example, gestures, phonemes, syllables, words, or clauses could each be considered units depending on the level of interest. Generally, the coordination of units is not dependent on a constant association with another particular unit, but rather the larger production or sequence (Lashley, 1951) dictates their order.

In the reported study, speech tasks used the word as the basic unit of planning. Arguments that support the word as a basic unit of speech come from studies of hesitations (e.g., Lounsbury, 1954; Goldman-Eisler, 1958) where an increased amount of hesitation occurs before content words or more difficult words compared to simpler function words. These hesitation patterns suggest that speakers choose words as they are forming a sentence. However, opposition to the notion of words as basic units of speech comes from studies that show an increase in disfluencies at clause boundaries, suggesting that multiple words can be simultaneously planned or chunked into a single program constituting a clause (Boomer, 1965).

Within movement research, variables that independently influence the reaction time of a movement are considered directly related to movement units (Rosenbaum,

1985). By identifying those variables that directly influence reaction of a task, it is evident that they vary between task types (e.g., tapping, handwriting, pointing, goal-directed movement). Within rapid goal-directed movement, Meyer, Smith, and Wright (1982) argue that force and time are independently related variables that are in some direct way related to the underlying control parameters involved in basic motor units of such types of movements. In summary, the definition of a basic unit of movement is left relatively uncertain (Rosenbaum, 1985) and variable between movement task types. As word production is the level of interest in the present study, and a single word can take less than 500 ms (e.g., 1 syllable word) or longer (i.e., multisyllabic words) to produce, the movement task used in this study was designed to equal the production duration of a word while minimizing the complexity of the movement and the noise that may be come from such complicated movements. Therefore, the task used involved a single stroke goal-directed movement as opposed to other more dynamic types of movements (e.g., handwriting, tapping, etc).

Similarities in Single Modality Sequences of Speech and Movement

Both language and movement research demonstrate similarities in timing during the preparation of sequences. When producing a two-unit sequence of a single modality (e.g., consisting of speech production only), the execution of the first unit is modulated in response to the amount of time needed and available to prepare this second unit (e.g., Griffin, 2003; Ketelaars, Garry, & Franks, 1997; Garcia-Colera, & Semjen, 1988). That is, with insufficient time to prepare a subsequent unit during the production of earlier units, the onset of the entire sequence will be delayed to prepare enough of the second unit in advance and maintain fluency. For example, if a speaker is to produce the two-word sequence, “window-bear,” where the second word “bear” can be entirely prepared

during the long production duration of the word “window”, speech onset of the sequence should not be delayed (see Figure 1a). However, if the speaker is to produce the sequence “wig-bear” such that the second word cannot be completely prepared during the relatively shorter production duration of “wig”, speech onset should be delayed because more of the second word needs to be planned in advance of speech onset in order for a fluent sequence (see Figure 1b).

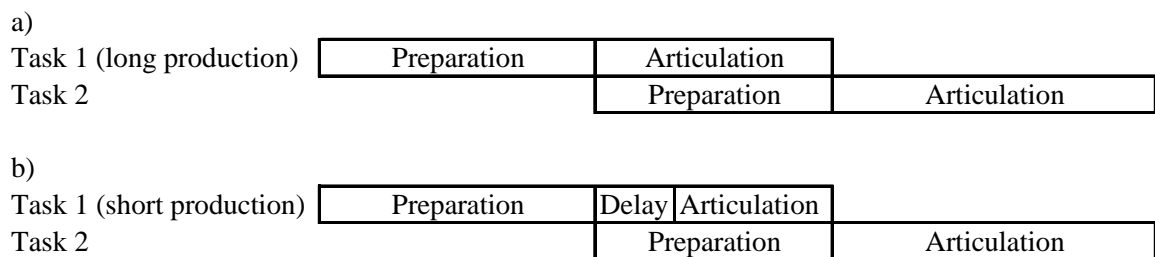


Figure 1 a) Timecourse for long first unit production b) Timecourse for short first unit production

This ability to modulate preparation suggests that: (a) there is sensitivity to the temporal information of units, specifically, the duration of execution and preparation time needed for a unit; (b) such information operates over multiple units and is used during the preparation of later units; (c) some processing occurs on-line rather than entirely in advance. However, these findings are currently restricted to the production of single modality sequences. The reported studies investigate timing involved in the production of a sequence composed of units from two modalities. One perspective is that planning of a two-modality sequence is similar to that of a single modality: the preparation of a later unit is modulated in response to the amount of time available and needed. This implies that preparation modulation is independent of modality and that the interactivity and use of temporal information between consecutive units is a property of timing in general. An

alternative perspective is that preparation modulation is specific to a modality, suggesting that temporal information is not shared across speech and movement units.

A significant amount of research exists that investigates the relationship between gesture and speech, as well as eye-hand coordination. However, there is a dearth of work directly addressing the factors of temporal coordination during simple sequence productions composed of different modalities that are arbitrarily related. By manipulating the execution duration of the first unit, I investigated whether people can modulate the preparation of speech and goal-directed movement to coordinate a fluent sequence. If such preparation modulation exists, perhaps the ability to share temporal information across units is not determined by the modality composition of the sequence, instead it could be specific to timing of units in general. Furthermore, the results could serve to elucidate the nature of speech and gesture timing during language production. More specifically, it may be possible to understand whether the tight temporal coupling of speech and gesture is dependent on a shared semantic message or if it can be replicated in arbitrarily paired speech and movement units. I will discuss studies from both language and movement literatures that suggest people can estimate the relative production and preparation duration of successive units to coordinate a sequence. However, these studies are limited to sequences of a single modality. The review will conclude with the hypothesis and assumptions of the reported experiments. The implications of the results to timing and preparation in general will be discussed.

Planning in Speech

Producing a fluent sentence requires precise timing to coordinate the end of the current unit (e.g., word or phrase) and the initiation of the next unit. When timing is not precise, the sentence may be disfluent. One explanation for the coordination of words in the production of a sentence is that all units are planned before the initiation of the utterance. In this case, production only requires phonological retrieval and execution (not, for example, semantic or syntactic retrieval). *Advanced planning models* are supported by studies that demonstrate a linear relationship between response delay and the number of units in the sequence. (e.g., Sternberg et al., 1978; Ferreira, 1991). However, this perspective fails to explain the occurrence of fluent sentences without intervening pauses assuming that no planning can occur during articulation. Preparation of a single content word takes about one second (e.g., Snodgrass & Yuditsky, 1996) while articulation time varies (e.g., one syllable word takes less time than a two syllable word). Consequently, complete advanced planning models predict that a series of utterances would be separated by pauses of up to several seconds long (i.e., the time required to prepare all units in advance). Yet, people can produce a series of sentences relatively rapidly, fluently, and absent of such long pauses.

The alternative to advanced planning is an *on-line planning view*. This view posits that sentence production and preparation of successive units occur concurrently; speech can begin before all units of the utterance have been prepared (e.g., Kempen & Hoenkamp, 1987; Levelt, 1989). According to this view, preparation of later units occurs during the production of earlier units. Unlike advanced planning, the distribution of preparation across time lowers the processing demands of working memory (Wheeldon,

Meyer, & Smith, 2003) and therefore is more efficient. If the articulation time of a first unit is equal to or exceeds the preparation time required of the second unit, fluent speech is expected. However, if articulation time is less than the preparation time required of the next unit, there is not enough time to prepare the following unit. Consequently, additional time would be necessary to complete preparation and this added time could be embodied in a disfluency (e.g., filler, pause, or stretching of word) to “buy” more time. In this situation, on-line processing models fail to explain the occurrence of fluent sentences, and assume the production of preceding units is independent of preparation information of subsequent units.

Both advanced and on-line planning models use planning and production units. Various units have been proposed (e.g., word, phrase, syntactic constituent) based on evidence from speech errors and disfluencies. However, to describe sentence production as a function of particular linguistic units does not completely explain the precise temporal coordination of fluent sentences (Griffin, 2003). Advanced planning models predict prolonged pauses before each utterance; on-line planning models breakdown when articulation time of the current unit is shorter than preparation time of the next unit. Alternatively, speakers may be using temporal information (i.e., estimated duration) of units to successfully time the components of a fluent sentence.

Planning in Speech Sequences

Perhaps fluent sentences result from the modulation of preparation relative to production duration by speakers (Griffin, 2003). If speakers can anticipate the amount of time they have available during production of the current unit to prepare the next unit,

they can delay the onset of the earlier unit to accommodate the time required for preparing consecutive units and produce a fluent sequence.

Griffin (2003) found evidence that speakers can adjust the distribution of preparation in the production of a two-word sequence. Participants named two displayed objects from left to right fluently, minimizing the time between the offset of the first word and the onset of the second word. The length of the first object's name was manipulated. If the articulation duration of the first name was long (i.e., more than one syllable) speakers had more time during the production of the first word to plan the second word and still remain fluent. However, if the first name was short (i.e., one syllable), there was less time to plan the second word so delaying the onset of speech may have "bought" more planning time. Consistent with the predictions of adjusting preparation distribution, participants began their speech earlier if the first word was long, and later if the first word was short. The effect disappeared when extra time was added to the end of the first word (i.e., participants produced "next to" after the first word) and speech began significantly earlier. Speakers in this condition had more time after the production of the first short word to finish the preparation of the consecutive word. The results suggest that speakers can anticipate the amount of time available to plan successive units, and prepare more of the second unit in advance as a response to the estimated available time. However, Meyer, Roelofs, and Levelt (2003) and Meyer, Belke, Häcker, and Mortensen (under review) propose an alternative explanation for the reverse length effect. They suggest that instead of preparation modulation, the reverse length effect is due to the temporal coordination of articulation and phonetic programming of words.

Preparation modulation implies that speakers have access to execution and preparation duration information before production begins. This information can be used to precisely time the sequence of units, as evidenced in speech onset differences. From this, it follows that sequence processing occurs on-line (e.g. preparation of second unit during execution of first unit). But, is this ability to estimate and use execution and preparation duration of consecutive words limited to linguistic units (e.g., word length)? Or does this time estimate represent the general anticipated time available, independent of its composition (e.g., word, pause, other non-linguistic task)? Similar modulation patterns in movement studies provide some clues to answer this question.

Planning in Movement

Unlike speech production, goal-directed movement is not linguistic, and does not (at least in the studies to be described) have a communicative role. Goal-directed movements begin at a designated start position and end at a target position. Research on such movement involves different effectors than speech production (see Peters, 1990). These apparent differences characterize them as quite different processes. However, there are similarities between timing sequences of either speech or movement production. The similarities in planning of these single modality sequences implies that the accessibility and use of timing information (i.e., duration estimation of execution and preparation of units) is not restricted to planning sequences of a single modality. Instead, such duration estimation maybe utilized in sequences composed of multiple modalities.

Advanced Planning of Movement

An underlying assumption in the present study is that advanced planning is possible for a movement task. Gueye, Viallet, Legallet, and Trouche (1998) show that advanced cueing of a future movement (e.g., positional information of the target)

decreases reaction time of the movement compared to trials where no informational cue was given. A reduction in movement onset suggests that participants can indeed plan more of the movement in advance with advanced information about the movement. It follows that participants should then have the opportunity and ability to prepare at least part of their movement in advance as direction and distance of the movement was provided during the entire duration of the imperative stimulus.

Preparation Modulation in Movement Sequences

Parallel results to Griffin (2003), who identified preparation modulation in the timing of speech production, have been found in movement production studies. In Ketelaars, Garry, and Franks (1997), participants performed a movement consisting of two units: arm extension, pause, and flexion back to the original start position. The authors varied the duration of the pause between the two movement units from 50 to 200 ms, and kept the number of units in the sequence constant. Sequence execution began earlier in trials where the pause duration was 200 ms as opposed to 50 ms. These results resemble speech onset differences found in word production: when participants anticipate less time to plan a second response, the execution of the first response was delayed so that a sufficient amount of the second response can be prepared in advance. Though conceptually similar (i.e., both add more available planning time prior to the second unit), Ketelaars et al. (1997) varied the pause duration between sequence units to increase the available time before the second unit, not the duration of the first movement unlike Griffin (2003). Together, results of these two studies, suggest that production and preparation duration is estimated in advance and can be used to adjust the distribution of preparation of successive units during a fluent sequence production. However, it is not clear if there are limitations for the generation of these estimations. In other words, are

they representative of the general anticipated time available, independent of the components of the duration (e.g. pauses, stress syllables, movement units)?

Rosenbaum, Hindroff, and Munro (1987) varied the number of repetitive, predictable movement units (i.e. same key press sequence) that occurred before a novel, critical unit (i.e. alternative key press). Consistent with Griffin (2003) and Ketelaars et al., (1997), the onset of the first movement unit in the sequence was modulated in response to the preparation time available for a unique key press. More units preceding the novel key represented more time available to prepare the novel movement, and consequently sequence onset began earlier. With fewer units preceding the novel key press, less time was available for the preparation of upcoming units and sequence onset was delayed to allow sufficient advanced preparation of the novel key to produce a fluent sequence. Both movement studies (see also Garcia-Colera & Semjen, 1988) suggest that the general anticipated time available modulates fluent movement sequence production; estimations of duration are not constrained to a particular composition (i.e., pauses or movements).

In summary, the literature suggests that production of fluent simple sequences within a single modality (i.e. speech or movement) is sensitive to the amount of time needed and available to prepare later units. This information is available before the onset of production, as evidenced in differences in the onset of the sequence in response to the amount of time available to prepare later units. In addition, this preparation modulation demonstrates some level of on-line planning: preparation of later units occurs during the production of earlier units. The present experiments investigated whether this modulation extends to sequences composed of different modality units.

The Present Study

A series of experiments were conducted to test whether such modulation occurs during the production of fluent sequences composed of different modalities (i.e., speech and goal-directed movement). Participants produced a simple two-unit sequence consisting of one movement unit and one speech unit, presented either as speech first or movement first. The production duration of the first unit (i.e., word length for speech production, distance for movement production) was manipulated. Participants were asked to produce the sequence fluently (i.e., no stretched words, filled and silent pauses, stutters and false starts). Speech onset measures and kinematic variables of the movement production were measured and served as dependent variables.

The study tested whether people will modulate the preparation of sequential units across speech and movement modalities. If the first unit has a short duration (e.g., a short word such as “pig” or a short start to target movement distance), there will not be enough time to prepare the second unit and maintain fluency (i.e., no noticeable pauses between the offset of the first task and the onset of the second or disfluent production of either task). However, by preparing more of the second response before the initiation of the first unit in the sequence, the transition between units can be fluent. If such modulation existed, it was expected that mean onset of the first unit will be delayed when the first unit has a short production duration relative to the preparation time needed for the second unit.

For sequences where the first unit has a long duration, there should be enough time to prepare the second unit during the production of the first unit. In this case, the mean onset of trials with long first units should not be delayed. Overall, when producing

a fluent sequence (minimizing the delay between both units), a difference between the mean onset for short and long first units is expected if preparation modulation exists, a “reversed length effect” (Griffin, 2003). If additional time is provided between the end of the first unit and the onset of the second unit (e.g., more word units which do not need to be prepared) so that there is more opportunity to prepare the second unit, then the reverse length effect should disappear.

The alternative hypothesis is that participants cannot modulate the preparation of units across modalities. Three possible scenarios exist: 1) participants may prepare all units in advance, which would result in a much longer response onset, 2) preparation of two tasks occur concurrently so no modulation is required, or 3) participants may prepare the second unit after the production of the first unit (i.e., during the interresponse interval), which would result in an increase in the interresponse interval and no difference between the mean onset of short and long first units should be observed.

The expectation of a reverse length effect is based on the following assumptions: 1) Estimated preparation and production time of sequential units is an estimation of general time (not, for example, restricted to a count of particular production units such as stress syllables, movement segments), 2) speech and movement timing information is commensurate, therefore timing of one modality unit can be compared relative to the other modality unit, and 3) a central bottleneck between speech and movement tasks exists at the preparation stage of both tasks. According to the third assumption, if a reverse length effect is expected then speech and movement cannot be prepared simultaneously (a central processing bottleneck should be present) but preparation and production of different modalities can occur simultaneously.

Assumption of a Processing Bottleneck

The hypothesis that a reverse length effect will occur in sequences of two different modalities assumes a processing bottleneck at the preparation stages of the two tasks. According to bottleneck models of dual-task performance, certain processing stages of two tasks cannot be performed simultaneously, and therefore they must occur serially (Posner, 1978; Welford, 1981). For the present purpose, if a reverse length effect is predicted in sequences composed of two different tasks; a processing bottleneck at the preparation stage must be assumed as the reverse length effect reflects a modulation in the scheduling of preparation for two tasks.

Support for such a processing bottleneck across different modalities is evident in Holender (1980) who investigated interference of a vocal and a manual response to a single stimulus. When participants produced a keypress and a vocal response to a stimulus when either a synchronized or no timing constraint was placed, speech onset was delayed significantly while movement onset remained the same compared to their baseline reaction time. These results support the notion of a bottleneck at the preparation stage for both tasks (as reaction time was effected) and therefore the assumption of serial preparation between tasks is supported.

However, contra to Holender (1980) and the processing bottleneck models, Schumacher, Lauber, Glass, Zubriggden, Gmiendl, Kieras, and Meyer (1999) proposed that concurrent processing of two tasks of different modalities is possible. In Experiment 4 of their study, they observed that when participants performed a motor and vocal response, the effect of the second task difficulty on response time of the first task was reduced as SOA decreased. This underadditivity is counterintuitive from the predictions

of a processing bottleneck. Schumacher et al. (1999) proposed that an absolute processing bottleneck does not exist, rather participants can modulate the scheduling of processing stages for both tasks depending on the constraints put on the participant (Meyer and Kieras, 1997). For example, under time-pressured trials where SOA is 0ms, participants may begin earlier than expected because they choose a more “daring” schedule, such that stages in both tasks are initiated concurrently. At a longer SOA or when the performance of a first task is emphasized, participants may adopt a more cautious schedule, completing all of task 1 stages before initiating any processing of task 2. According to this theory, it would be possible for participants in the present study to prepare both speech and movement tasks concurrently and therefore no reverse length effect would be expected.

The results of this experiment will be informative to the overall question of timing sequences. If people can adjust the distribution of preparation in response to an estimated amount of time they have available in a sequence composed of multiple modalities, the results suggest a common mechanism and measure for timing of sequences in general modality (see Kelso, 1984; Klapp, 1979; Klapp, 1981). The temporal information people use is a general representation of the amount of time they have, which is not restricted to a single.

The aim of the experiments was to comprehensively investigate the timing relationship between sequences of speech and movement by modifying the tasks involved and quantitatively analyzing movement behavior. In speech, disfluencies are observable (e.g. stretching of words, hesitations) and could be indicative of a breakdown in precise timing. Like speech, the movement task used in this experiment may also have

production patterns that reflect adjustments in preparation distribution imposed by the timing constraints of the task. Submovement patterns might be useful in analyzing the effect of anticipated time on the preparation of a movement that is not reflected in response latency of the movement. Before describing the proposed study further, a brief review of submovement patterns in goal-directed movement is presented.

Submovements in Goal-Directed Movement

Goal-directed movements can be parsed into primary and secondary submovements (Woodworth, 1979). The primary submovement is characterized as a fast, ballistic, and error prone movement. This movement is planned in advance of the entire movement execution. Because there is no on-line feedback, acceleration traces are relatively smooth and symmetrical (Crossman & Goodeve, 1983). Increase in the speed and distance of the primary submovement yields an increase in deviations from the desired end position (Meyer, Abrams, Kornblum, & Wright, 1988) and may call for more corrective movements to the target. The secondary corrective submovement is characterized by an increase in the number of zero line crossings, which are indications of change in the acceleration pattern of the movement (Carlton, 1981). Such deviations reflect on-line corrections in response to feedback (van Donkelaar & Franks, 1991). According to the stochastic optimized-submovement model (Meyer et al., 1988), goal-directed movements are composed of a primary submovement followed by an optional secondary corrective submovement. The mean duration of submovements and the frequency of occurrence for a second submovement are compromised to minimize the total movement duration. The model posits that if a primary submovement does not terminate at the desired target, a secondary corrective submovement will be initiated. Part

of this secondary submovement is planned during the production of the primary submovement and uses relative target position and feedback information (e.g. kinesthetic and visual) from the primary submovement during preparation. This model proposes that the on-line preparation of the secondary submovement allows for fluent production of the two successive submovements.

Analysis of the duration of primary (planned in advance) submovements in the movement component of sequences involving two modalities relative to movement in isolation could reflect adjustments in the distribution of preparation. These adjustments may not otherwise be evident in movement onset measures and therefore submovement analysis could be useful in understanding preparation modulation in timing.

As stated earlier, the principle issue addressed in the reported experiments concern whether or not preparation modulation is used to precisely time components of a sequence, regardless of the composition of the sequence. If people adjust the distribution of preparation in planning a sequence across modalities, a reverse length effect in sequences with a movement occurring first is expected during fluent production of the sequence. When time is added to the end of the movement, the word should be sufficiently prepared during the production of the movement, and consequently no length effect should be observed. Such a pattern is not expected when word production is followed by a movement because the production time of a single syllable word is greater than the preparation time of a single movement. Therefore, a movement could be adequately prepared entirely online, during execution of a preceding word.

CHAPTER 3

EXPERIMENT 1

Method

Participants

Twenty-eight Georgia Institute of Technology undergraduate students (between the ages of 18 and 22) participated. All participants were native English speakers or learned English before the age of six. Twenty-six students were right handed. Data from four participants were replaced because of equipment difficulties. Participants received extra credit in an introductory psychology course for their participation.

Apparatus

A Dell Dimension XPS Pentium II displayed the stimuli and recorded movement data. A headset microphone digitally recorded voice at a sampling rate of 22.1 kHz. Participants used a stylus to draw a straight line on a 6 x 8 inch Wacom Graphire 3 digitizer tablet. The tablet digitally recorded onset, offset, acceleration, velocity, and path measurements of the movement task with a sampling rate of 120 Hz.

Materials and Design

Nameable objects for the word production task came from a collection of normed photograph pictures (LaGrone & Spieler, submitted). Short and long named picture pairs were matched on spoken name agreement, naming times (LaGrone & Spieler, submitted) and first phoneme. The \log_{10} word frequency of the most common picture name (LaGrone & Spieler, submitted) was determined using the CELEX database. Table 1

provides a summary of the mean number of syllables, \log_{10} of noun lemma frequency per million, naming time and name agreement as a function of first word length (see Appendix A). Paired sample t-tests between long and short word properties show that there was no significant difference between name agreement ($t(30) = .06, p = .95$), and normed response time ($t(30) = .96, p = .36$), but a significant difference for \log_{10} frequency ($t(30) = 2.50, p < .05$).

Table 1. Mean (and standard error) properties as a function of left-object name

	Name Agreement	\log_{10} Frequency	Syllables	Response Time
Short	.94 (.01)	1.58 (.98)	1.00 (0)	880 (19)
Long	.95 (.01)	1.28 (.60)	2.54 (.09)	903 (14)

Each matched short-long word pair was paired with two right objects (see Table 2 for right object name properties) from the same picture collection, such that both left objects were presented with each right object equally across lists to control for any effects of right object names. Presence of a right object only occurred in the two-word production block. Each object subtended an approximate visual angle of 11.8° . The horizontal distance between the two objects subtended a visual angle of approximately 12.5° .

Table 2. Mean (and standard error) properties of right-object name

Name Agreement	\log_{10} Frequency	Syllables	Response Time
.94 (.01)	1.82 (1.14)	2.00 (.07)	908 (15)

Participants performed the motor task by drawing a straight line from a designated start position to a target position (presented on the computer screen) with the stylus on the digitizer tablet. The distance between the start and target position subtended a visual angle of 5.4° . The trajectory of the movement varied in two directions, 0° and 180° , to reduce effects of repetition. The start position, a filled circle, subtended a visual angle of $.36^{\circ}$ and was fixed across all trials. The target position subtended a visual angle of 2.5° which was initially filled green until participants entered the target after which it turned red.

Task types were blocked. There were a total of 90 long-short word pairs that were divided into three groups and counterbalanced across three blocks. Thus, each block had 30 long-short object-name pairs (left object in the two word condition), each presented once within the block and never repeated across blocks. The stimuli were presented in a fixed, random order within blocks.

For trials of word production followed by a movement, each stimulus display was divided in half. On the left half of screen, the object to be named was displayed. On the right half of the screen, a start and target position was displayed. The horizontal distance between the nameable object and the start position subtended a visual angle of 14.3° .

Each participant participated in all three sequence types, which were blocked with order counterbalanced across participants.

Procedure

The three different sequence types performed by each participant are described below:

1. Single word production: Participants named a single object presented in the center of the screen. I instructed them to name the object as quickly as

possible without compromising fluency or accuracy. A 500 ms fixation point preceded stimulus presentation. After the participant produced the name of the objects, I pressed the space bar to end recording for the current trial and initiate the next trial.

2. Two word production: Participants named two objects presented on the screen from left to right while minimizing the delay between the two words and maintaining fluency. A 500 ms fixation point preceded each trial. This block was intended to replicate the reverse length effect found in Griffin (2003) and to confirm that participants are able to adjust the distribution of preparation within a single modality. After the participant produced the name of the objects, I pressed the space bar to end recording for the current trial and initiate the next trial.
3. Single word production followed by movement production (Figure 2): Participants named the object on the left and coordinated the movement of the cursor from the start position to the end position while minimizing the delay between the end of the word and the onset of stylus movement (i.e., exit from the start position). A 500 ms fixation point preceded stimulus presentation. During this time, participants aligned their stylus on the designated start position, which was consistently located in the same position for each trial. After the 500 ms fixation point, a beep was presented for 200 ms indicating the onset of the stimulus (i.e., nameable object, start and target position). This beep was unique to this block because it was used for speech and movement alignment during data processing. The participant produced the name of the

object and then drew a line from the start position to the target. Trials iterated automatically at 5 second intervals.

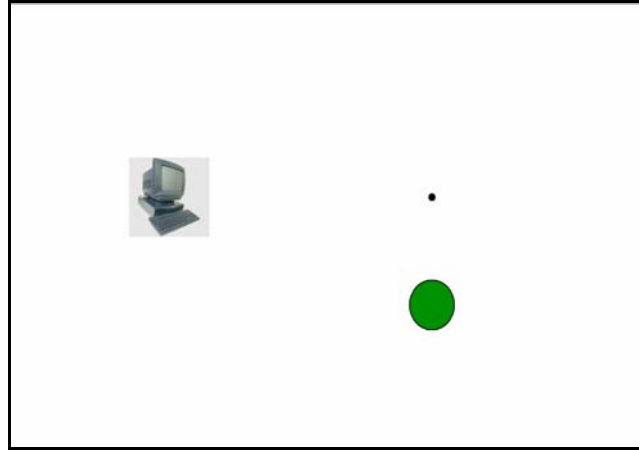


Figure 2. Example stimulus for word production followed by movement

For each block, participants were given 3 practice trials prior to the test trials. Participants were tested individually and the entire experiment took approximately 40 minutes.

Data Treatment

For the two sequence types containing only speech production, I recorded any unexpected words and disfluencies produced by the participant. SPHINX software determined the onset and offset of words produced in the two blocks containing only speech production. For speech occurring in the single word production followed by movement production, speech production was transcribed. Disfluent trials (i.e., stretched words, filled and silent pauses, stutters and false starts) as well as unintended names were noted for each trial in all sentence types. The onset and offset of each word was hand

measured using the sound editing software Audacity. Onset, offset, and submovement parsing of the movement production was determined by MovAlyzeR Version 3.0[©] software. The point at which velocity reached 5% of the peak velocity for the entire stroke determined the onset and offset of a movement. Offset of movement was similarly determined as the first point from the end during which 5 % of the total velocity was reached. The primary submovement was measured from the movement onset to the first negative-to-positive point (or second zero-crossing) of the acceleration profile after peak velocity. The secondary movement(s) was subsequent negative-to-positive points in the acceleration profile.

Results

The following analyses were conducted on a subset of items fulfilling the following criteria: 1) Long target words (e.g., the first word in the two-word production block) exceeded 2 syllables, 2) the expected word(s) was produced, 3) speech production and movement were fluent 4) onsets fell within 2 standard deviations of the participant or item mean onset, 5) movements began within 3 seconds and did not exceed 5 seconds to complete from the start of the trial, 6) movements did not exceed 3 strokes, 7) movements successfully reached the target, and 8) the time between two words was less than 200 ms; the time between a single word followed by a movement production was less than 300 ms. The latter 300 ms criteria was used because of the scarcity of trials which had a delay of less than 200 ms in the word production-movement block. Only item pairs where long words exceeded 2 syllables were included for analyses because on average long words tended to be shorter than those in Griffin (2003). Consequently, only 38 of 90 short-long pairs were included in the analyses presented below.

Fulfilling these inclusion criteria, the present analyses included 572 (40% of total)¹ trials of single word production, 317 (22% of total) trials of two-word production, and 495 (34% of total) trials of word production followed by movement. The analyses were conducted both by item means with word frequency as a covariate as it was not controlled for in the experimental design. Means and standard errors for speech onset are presented in Table 3 and Figure 3.

Participants differed in mean onset by sequence type, such that a single word was produced earlier than a word followed by either movement or a second word. During the two-word production sequence, sequences began earlier when the first target word was long as opposed to short. An ANCOVA by items was conducted on mean speech onset. There was an effect of sequence type (single word production, two-word production, word production followed by movement) ($F(2,182) = 17.36, p < .001$) and no significant effect of length ($F(1,182) = .83, p = .36$). There was no significant interaction of sequence type by length ($F(2,182) = 1.11, p = .33$).

Table 3. Mean (and standard error) of speech onset as a function of left-object name

	Single word production	Two-word production	Word production-movement
Short	733 (16)	951 (21)	1124 (26)
Long	744 (23)	831 (50)	1163 (44)

¹ The percentage of single word production trials included is lower than expected primarily because of the exclusion of all long word target items that were disyllabic.

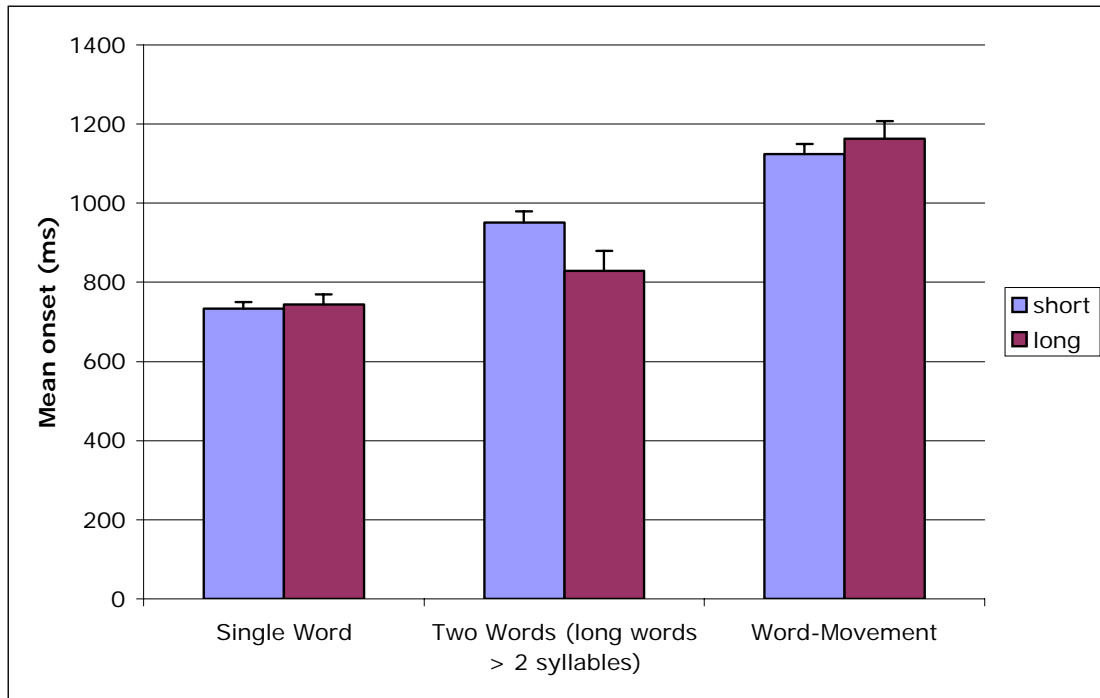


Figure 3. Mean speech onset (ms) as a function of first word length

To test the prediction that a reverse length effect occurred during the two-word production task (i.e., sequences with a long first word duration began earlier than those with a short first word), an ANCOVA by items was performed for this task alone, which supported the prediction with a main effect of length, $F(1,55) = 3.09, p < .10$. An additional ANCOVA on word production followed by movement reveals that participants did not differ in speech onset time contingent on the length of the target word when followed by a movement, $F(1,55) = .80, p = .37$.

Discussion

The pattern of speech onset for trials in the two-word production task replicates the reverse length found in Griffin (2003), showing that preparation modulation occurs within a single modality for this group of participants. Consistent with my prediction, the

lack of a significant length effect for trials in the word production followed by movement task provides initial evidence to extend preparation modulation to sequences composed of at least two modalities. Because word production duration was longer than preparation time of a subsequent movement, independent of the word length, movement preparation time could be completely absorbed during the production of the word and therefore be ready for execution immediately after the word offset, thus producing a fluent sequence. Perhaps then, speakers could anticipate that enough time was available to fully prepare a movement during the production of an earlier word. Interestingly, there was a general increase in sequence onset when a movement followed speech. This suggests that there is an effect of an upcoming movement in a sequence.

To further investigate the preparation relationship of two modality sequences, Experiment 2 tested the prediction of a reverse length effect in sequences where movement preceded speech. In such sequences, though the production of the first unit (movement) varied in duration (long vs. short), it was always less than the time needed for preparation of the second unit (speech). If two units cannot be simultaneously planned, the inadequate amount of time for the preparation of the second unit requires participants to modulate preparation in response to the relative time available during movement production in order to produce a fluent sequence.

CHAPTER 4

EXPERIMENT 2

Experiment 2 tested the prediction that participants modulate their movement initiation in a sequence of movement followed by speech production based on the amount of time they have available during movement production to adequately prepare the word and produce a fluent sequence. If a reverse length effect occurs, this would extend preparation modulation to sequences of different modalities.

Methods

Participants

The same participants from Experiment 1 participated.

Apparatus

The same equipment was used to record movement information and speech as that of Experiment 1.

Materials and Design

Movement duration was manipulated by varying the length and trajectory of the movement course. Start positions were consistent within blocks. Four movement trajectories were used, 0°, 45°, 180°, 235°. For trajectories of 0° and 180° the start and target distances and sizes were identical to that of Experiment 1. For the remaining trajectories, the distance between the start and target position subtended a visual angle of 3.6° or 10.7° which constituted a short or long movement respectively. Targets

subtended a visual angle of 2.1° and 2.9° for short and long distances respectively. Each movement distance was presented at both trajectories.

As in Experiment 1, nameable pictures from the normed database of photographs (LaGrone and Spieler, submitted) were used. A total of 30 picture pairs were selected to occupy the right position of the display (the same right object pairs for block 3 of Experiment 1, counterbalanced across lists such that each participant saw each right object only once across experiments. Distance between the movement start position and the nameable object was identical to of the word followed by a movement task from Experiment 1, as well as the size of the object. The experiment took approximately 20 minutes.

Two stimulus lists were composed such that each picture was paired with each movement distance and trajectory. Block order was counterbalanced across participants.

Procedure

1. Single movement production: Participants began each trial with a 500 ms centered fixation point (start position) during which they aligned their stylus on the fixation. The 500 ms fixation point was followed by a 200 ms beep indicating the onset of the remaining stimulus, the target position. Participants drew a straight line from the start position to the target position. Movement trajectory and distance (short or long) was manipulated. There were 20 trials of each movement trajectory and distance for a total of 120 trials.
2. Movement production followed by object naming (Figure 4): Participants began each trial with a 500 ms fixation point (start position) during which they aligned their stylus on the fixation. The 500 ms fixation point was followed by a 200 ms

beep indicating the onset of the remaining stimulus, the target position and the nameable object presented (presented on the right half of the screen). Participants drew a straight line from the start position to the target position. Once successfully entering the target, the target turned from green to red. Immediately after entering the target they began to name the object on the right. I instructed them to draw a straight line and coordinate their sequence such that there was no delay between the time entering the target and the onset of the word production. Movement direction and duration was manipulated. The trajectory of the movement varied in two directions, 45° and 235° . There was one short movement and one long movement for each trajectory for a total of four possible movements. The block consisted of thirty short-long movement pairs that were paired with a right object pair such that there were 15 trials of each movement trajectory and duration, for a total of 60 trials. Right object pairs were displayed with each movement trajectory and duration across participants, but never repeated within participants.

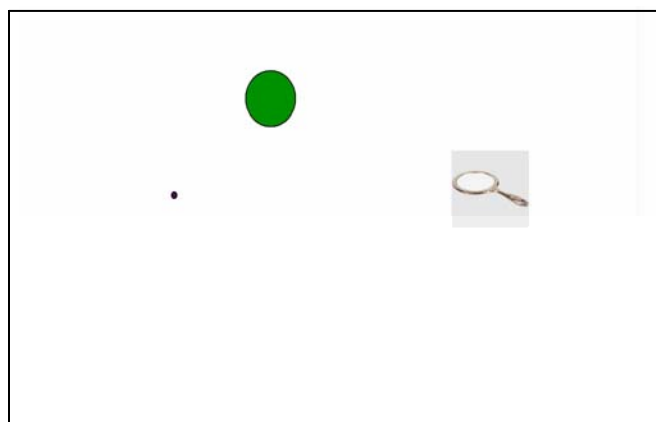


Figure 4. Example stimulus of movement followed by word production

Data Treatment

Speech and movement data were treated the same as that of Experiment 1.

Results

Inclusion of All Trials

The following analyses were conducted on a subset of trials that fulfilled the following criteria: 1) Movements with a trajectory of either 45° or 235° (including both long and short movement distances), 2) the expected word was produced, 3) word production was fluent, and 4) onsets did not exceed 2 standard deviations from the participant's mean onset. The analyses included 2,866 (99%) trials of movement production in isolation and 1366 (95%) trials for tasks of movement followed by word production. Table 4 displays the mean onset time, total movement duration and primary submovement duration as a function of movement length.

Table 4. Mean (and standard error) as a function of first movement length (all trials)

	Movement in isolation		
	Onset	Movement Duration	Primary submovement duration
Short	288 (14)	267 (16)	278 (18)
Long	320 (15)	348 (28)	355 (23)
	Movement - word production		
	Onset	Movement duration	Primary submovement duration
Short	466 (44)	453 (24)	224 (10)
Long	476 (47)	528 (37)	319 (15)

In order to confirm that manipulation of movement length affected movement duration, mean movement duration was analyzed with a 2 x 2 (Movement length x sequence type) repeated measures ANOVA by participants. Movements were

consistently longer in production duration for movements of long distance compared to short, with a main effect of length, $F(1,23) = 192.70$, $p < .001$. Movements were longer in duration when they were followed by a word as opposed to performed in isolation, with a main effect of task type, $F(1, 23) = 13.64$, $p < .001$. No interaction was obtained.

Mean movement onset was analyzed with a 2 x 2 (Movement length x sequence type) repeated measures ANOVA. Movements took longer to initiate when they were long in production duration, with a main effect of length, $F(1,23) = 8.14$, $p < .001$. Participants took longer to begin movement when it was followed by a word production than if it was performed in isolation, evident in a main effect of sequence type (i.e., movement in isolation vs. movement followed by word production) $F(1,23) = 20.8$, $p < .001$. There was no interaction present.

ANCOVAs were conducted to test whether the frequency of the right object name (word production) affected movement onset or duration. Frequency was not significantly related to either production duration of movement or movement onset, $F(1,115) = .20$, $p = .20$ and $F(1,115) = .46$, $p = .50$ respectively.

To determine the amount of advanced planning for movement, mean primary submovement duration was analyzed with a 2 x 2 (Movement length x sequence type) repeated measures ANOVA. Long movements had a significantly longer primary submovement than short movements with a main effect of movement length, $F(1, 23) = 77.37$, $p < .001$. Movements followed by word production had a consistently longer primary submovement than those movements performed in isolation, with a main effect of task type, $F(1,23) = 11.02$, $p < .05$. There was a no significant interaction present.

Exclusion of Trials Based on Inter-Response Interval

The same analyses were conducted on a subset of these trials with an additional inclusion criterion such that the time between entering the target and word production did not exceed 300 ms. This subset represented sequence productions that successfully met the timing constraint of the tasks (no pause between production units).

The analyses included 2,866 (99%) trials of movement production in isolation and 204 (14.2%) trials for tasks of movement followed by word production. Table 5 displays the mean onset time, total movement duration and primary submovement duration as a function of movement length. The very small proportion of trials that were included (i.e., fulfilled the inclusion criteria) suggests that the demands of the task may be quite high.

Table 5. Mean (and standard error) as a function of first movement length (excluding trials)

	Movement in isolation		
	Onset	Movement Duration	Primary submovement duration
Short	295 (16)	274 (21)	226 (13)
Long	327 (16)	475 (32)	329 (19)
	Movement - word production		
	Onset	Movement duration	Primary submovement duration
Short	597 (62)	531 (80)	415 (65)
Long	575 (70)	759 (85)	498 (73)

In order to confirm that the manipulation in movement produced a manipulation in movement duration, mean movement duration was analyzed with a 2 x 2 (Movement length x sequence type) repeated measures ANOVA by participants. Movements were consistently longer in production duration for movements of long distance compared to short, with a main effect of length, $F(1,16)^2 = 112.36$, $p < .001$.

Movements were longer in duration when they were preceded by a word as opposed to performed in isolation, with a main effect of task type, $F(1, 16) = 17.90$, $p < .05$. No interaction was obtained.

Mean movement onset (see Figure 5) was analyzed with a 2 x 2 (Movement length x sequence type) repeated measures ANOVA. Participants took longer to begin movement when it was followed by a word production than if it was performed in isolation, evident in a main effect of sequence type (i.e., movement in isolation vs. movement followed by word production) $F(1,16) = 24.09$, $p < .001$. Movement onset did not differ contingent on its length when it was followed by a word, unlike movement in isolation, which began significantly earlier for short movements. This is evident in the presence of a marginally significant 2-way interaction $F(1, 16) = 4.08$, $p = .06$.

To test effects of right object name frequency movement duration and onset, ANCOVAs were conducted to control for frequency effects. Frequency was not significantly related to either production duration of movement or movement onset, $F(1,91) = .52$, $p = .27$ and $F(1,91) = .94$, $p = .33$ respectively.

²Because of the strict inclusion criteria, the degrees of freedom is equal to 16 instead of 23 because only 17 of 24 participants had results for all cells.

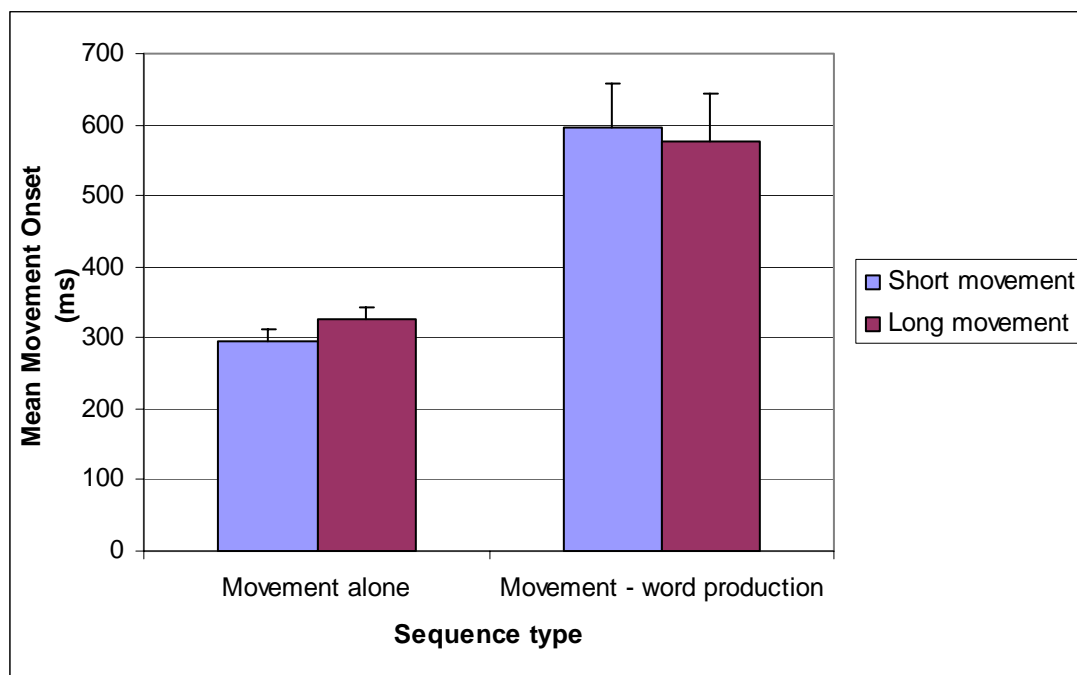


Figure 5. Mean onset (ms) as a function of movement length

To determine the amount of advanced planning for movement, mean primary submovement duration was analyzed (see Figure 6) with a 2 x 2 (Movement length x sequence type) repeated measures ANOVA. Long movements had a significantly longer primary submovement than short movements with a main effect of movement length, $F(1, 16) = 29.56, p < .001$. Movements followed by word production had a consistently longer primary submovement than those movements performed in isolation, with a main effect of task type, $F(1, 16) = 10.63, p < .05$. No interaction was obtained.

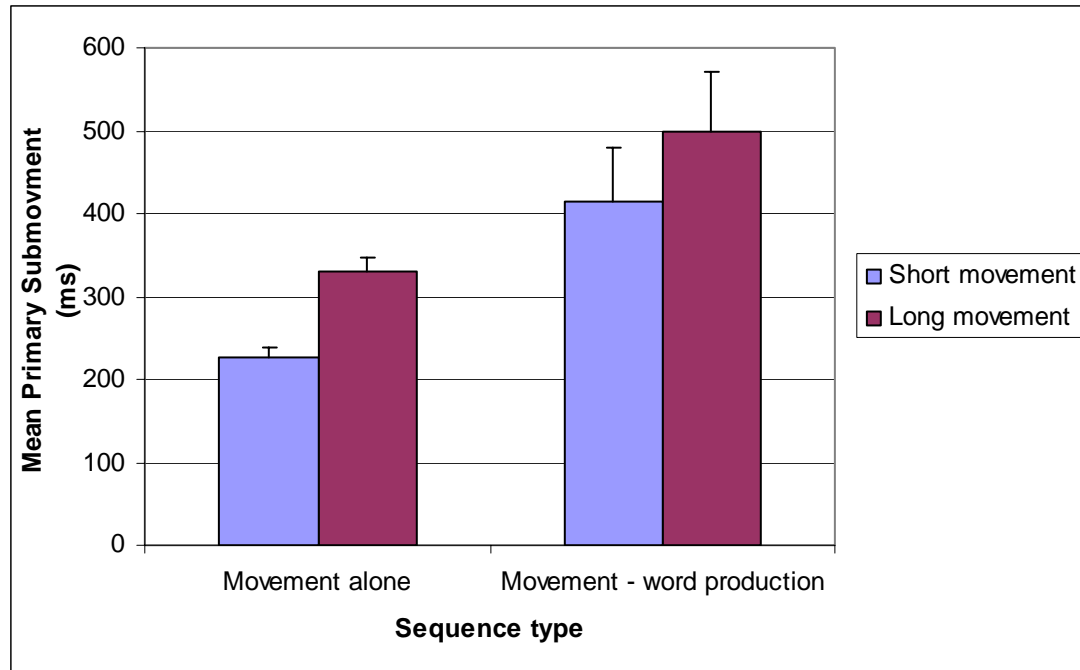


Figure 6. Mean primary submovement duration (ms) as a function of movement length

Discussion

The results of movement in isolation trials provide a baseline of the onset and structure for those movements used in the movement production followed by word production block. The results suggest that short movements have an initial advantage over long movements (i.e., less preparation time), evident in an earlier onset. However, consistent with the expectations of the manipulation of distance, long movement distances are longer in production duration than short movement distances. When movements were followed by a word production, total movement duration increased for both movement lengths. With this increase in total movement duration perhaps participants were “buying” time to prepare their subsequent word in order to meet the coordination demands of the task. Alternatively, the duration increase could reflect interference between producing a movement and planning a word. However, the increase

in primary submovement duration (which reflects advanced planning of movement) in movement preceded by a word suggests that participants planned more of the movement in advance with the anticipation of freeing up time to prepare the word during this ballistic component of the movement, perhaps explaining why onset was earlier.

Though there was a marginally significant interaction between task type and length for mean onset times, there was no effect of length. To interpret the absence of a reverse length effect for movement followed by a target word, differences in preparation time between long and short movements produced in isolation must be considered. Short movements began earlier than long movements, suggesting that there is less preparation required to initiate a short movement. In order for a reverse length effect to occur (i.e., long movements began earlier than short for movement followed by word production), long movements must surpass the advantage of short movement production onset (found in single movement production). Given this, it is difficult to decisively conclude that a reverse length effect did not occur because the results are confounded by different amounts of time needed to prepare short versus long movements in isolation. The insignificant difference between short and long movement when followed by a word production suggests that there is a trend in the right direction (e.g., long movement onset are less delayed than short movement onset).

With a marginally significant interaction between sequence type and movement duration, it is unclear why participants delayed movement onset when it was followed by word production compared to movement in isolation. The interaction between task and length could be due to a subtle modulation of movement onset in response to the anticipated time they need and have available to prepare a word. This would suggest that

there is some level of modulation but not at the single unit level across modalities. Instead, perhaps there is a general notion that the production duration of the movement (independent of its length) will never exceed that required for a single word to be prepared. Alternatively, movement production may be more demanding and interfere with the simultaneous preparation of a word. In this latter case, a delay in movement onset may be due to general interference between the two modalities and not sensitivity to the time available during the duration of a movement. Experiment 3 tested the effects of adding more time between a movement and a word production to see if movement onset will begin earlier since participants had an adequate amount of time to fully prepare their word online.

CHAPTER 5

EXPERIMENT 3

The third experiment further investigated the reverse length effect in sequences of movement followed by word production by manipulating the duration between the two units. The critical difference between the movement production followed by word production in this experiment and Experiment 2 is the addition of a delay of 1 second between the units. This added time between units was intended to alleviate any length differences and any potential interference due to the second unit (i.e. word production).

Method

Participants

Thirty-two Georgia Institute of Technology undergraduate students (between the ages of 18 and 22) participated. All participants were native English speakers or learned English before the age of six. Participants received extra credit in an introductory psychology course for their participation.

Apparatus

The apparatus used was the same as that in the previous experiment.

Materials and Design

Stimuli designs were the same as those used in Experiment 1, and Experiment 2. However, short-long matched objects pairs and right objects were different than those in the previous experiments. Table 6 provides a summary of the mean number of syllables, frequency, naming time and name agreement as a function of first word length. There were 12 items per block for a total of 24 trials in each block. Each block was preceded by

3 practice trials. Block order was counterbalanced across participants. The experiment took approximately 40 minutes.

Table 6. Mean (and standard error) properties as a function of left-object name

	Name Agreement	Log Frequency	Syllables	Response Time
Short	.94 (.02)	1.39 (.71)	1 (0)	892 (21)
Long	.95 (.02)	1.18 (.42)	2.38 (.12)	922 (38)

Procedure

The critical blocks of this experiment are those that involve movement followed by word production. The delay between the movement production and the subsequent word production was manipulated such that there was no pause between units or a pause of approximately 1 second. The remaining blocks were the same as the two-word production and word followed by movement production sequence types of Experiment 1. The sequence types are described below:

1. Movement production followed immediately by word production: This sequence task is identical to that of the movement followed by word production sequence of Experiment 2.
2. Movement production, delay, followed by word production: This sequence task is identical to that of the movement followed by word production sequence of Experiment 2 with the exception that I asked participants to wait for a delay of approximately 1 second before naming the object.

3. Two-word production: This sequence task is identical to that of the two-word production in Experiment 1.
4. Word production followed by movement: This sequence task is identical to that of the word followed by movement sequence in Experiment 1.

Left objects in the two-word production and word followed by movement sequences were counterbalanced such that each object was presented in both blocks equally but presented to participants only once across blocks.

Results

The following analyses were conducted on a subset of trials which fulfilled the same criteria set by Experiments 1 and 2 (with exclusions based on IRI range) with the addition of the following: delay between the movement-delay-word production sequence was greater than 700 ms but did not exceed 1300 ms. The analyses were conducted on 535 (70%) trials of movement followed by a delay and word production, 438 (57%) trials of movement followed immediately by word production, 680 (89%) trials from the two-word, and 617 (80.3%) trials of word production followed by movement.

Table 7 and Figure 8 displays means onsets for sequences of movement followed by word production. A 2 x 2 (Delay x Movement length) repeated measures ANOVA was conducted on the movement production followed by word production blocks. Participants consistently began movements earlier when the movement was long versus short in duration with a main effect of length, $F(1,31) = 9.01, p = .005$. Participants began movements earlier when a movement was followed by a pause delay before the word production compared to movement immediately followed by a word production with a

main effect of delay (i.e., delay or no delay), $F(1,31) = 8.14, p = .008$. There was no interaction between length and task type, $F(1,31) = 1.26, p = .27$.

Table 7. Mean (and standard error) sequence onset as a function of first unit length

Word length	Movement Immediate	Movement Delay
Short	696 (43)	550 (27)
Long	647 (36)	524 (24)
Word length	Two-word Production	Word Production-Movement
Short	1129 (54)	1084 (42)
Long	1088 (33)	1080 (40)

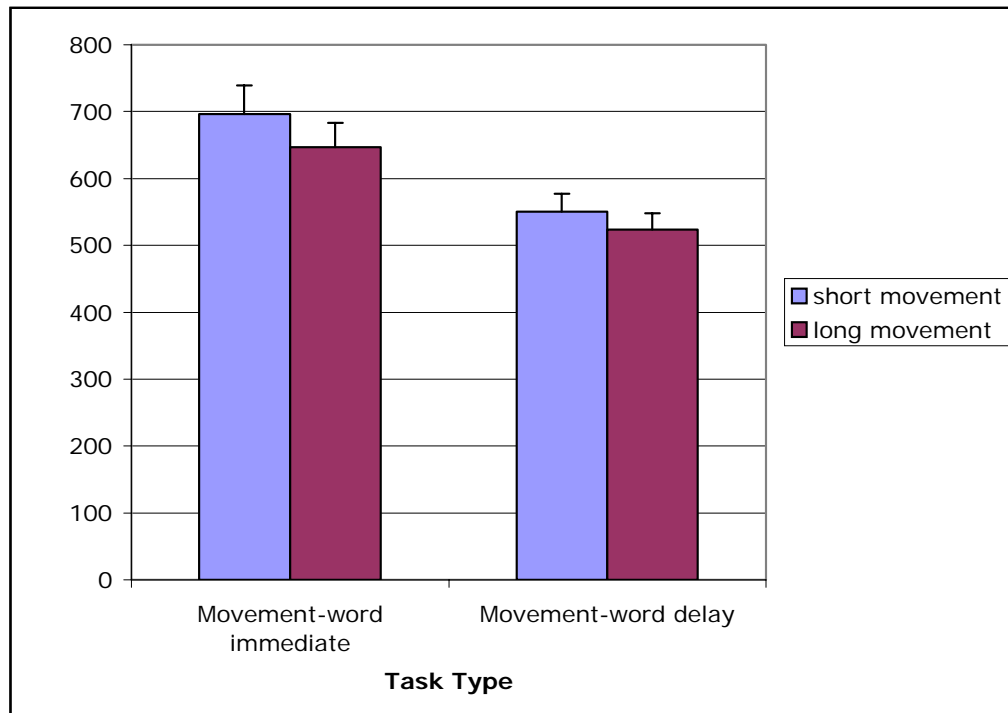


Figure 7. Mean onset of movement as a function of movement length

Paired sample t-tests were conducted to test the predictions made by the original hypothesis. When a movement was immediately followed by speech production, a reverse length effect was present, $t(31) = 2.69, p < .05$. However, when movement and

word production were separated by a delay, there was no significant difference between movement onset for short or long movements, $t(31) = 2.00, p > .05$.

A 2 x 2 (Task type x Length) repeated measures ANOVAs by items and participants on the mean onset of the first word produced suggests that participants did not modulate speech onset relative to the length of the first word with no main effect of word length, $F_i(1,11) = 1.29, p = .28$ and $F_p(1,31) = 1.24, p = .27$. Participants did not vary speech onset depending on the type of task they were performing with no main effect of task type, $F_i(1,31) = .18, p = .67$ and $F_p(1,11) = .003, p = .96$. There was no interaction present, $F_i(1,31) = 1.64, p = .21$ and $F_p(1,11) = .03, p = .87$.

Discussion

The main effect of task type for movement blocks such that movement in the delayed condition always began earlier than in the no pause condition, is consistent with the general prediction: more time available (i.e. during delay) to plan the second unit online will allow the sequence to begin earlier in anticipation of this extra time.

Planned comparisons between sequence onset of short and long movements within each task type supports the prediction that a reverse length effect will occur across movement and speech modalities. When movement was immediately followed by speech production a reverse length effect was present. The delay condition was designed to provide a generous amount of time to well prepare the second unit (word production) entirely on-line (during the 1 second pause between units) independent of the movement duration. The expected result was found, with the addition of time occurring before the word production, a reverse length effect diminished.

The results from the word production followed by movement block are consistent with the original predictions and the results from Experiment 1. However, there was a failure to replicate a reverse length effect in the two word-production block. One possible reason for this failure is the relatively small number of items in each block.

CHAPTER 5

GENERAL DISCUSSION

The reported experiments investigated the hypothesis that preparation modulation, apparent within single modality sequences of movement or speech, occurs in sequences of two different modalities. More specifically, I tested whether such modulation is a modality-independent estimation of time, such that temporal information can be communicated across different modalities.

Before summarizing the results of this study, it is important to mention two important issues with the data collected. First, for all but 1 participant (of useable data), participants utilized their right hand. This could be problematic because of findings of lateralized disruption in movement production while concurrently speaking (Hiscock and Chipuer, 1986; Dalby, 1980). This pattern of disruption is suggested to reflect lateralized cerebral representation of spoken language (Kinsbourne and Cook, 1971; Kimura, 1973) such that interference between speech and movement (with the right hand) is due to an increased processing demand in the left hemisphere. However, such evidence provides additional support for the assumption that a bottleneck exists between speech and movement.

The second issue to be addressed concerns the accuracy of identifying a primary submovement. The movement analysis software identified a primary submovement as all movement prior to the first zero line crossing of the acceleration profile occurring after the peak velocity. However, this criterion may erroneously characterize a segment as primary and “ballistic.” Examination of the velocity profiles of a sample of single trials

supports this. Figure 9 and 10 are examples of a velocity profile for two different trials of a participant's performance in the movement followed immediately by speech (Experiment 2). The smooth and positive velocity curve of Figure 8 within the primary submovement is consistent with the characterization of a "ballistic" movement. In contrast, the velocity curve for the primary submovement in Figure 9 includes two local minima, suggesting that perhaps movement in this segment is not "ballistic". Though only a small minority of trials has velocity patterns with non-smooth curves, submovement segmentation may not have been accurate and submovement analyses should be cautiously interpreted.

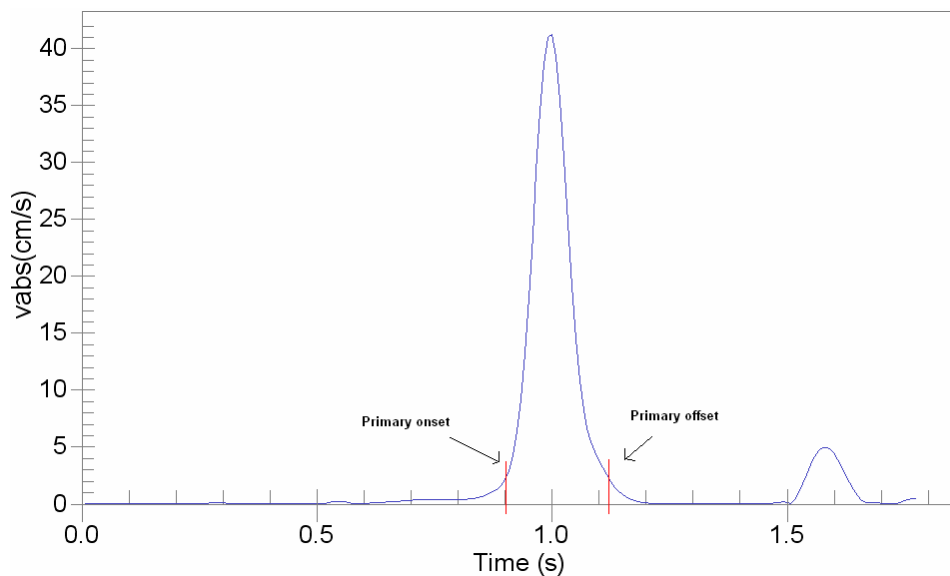


Figure 8. Example of ballistic submovement: Absolute velocity plotted over time relative to the onset of trial recording

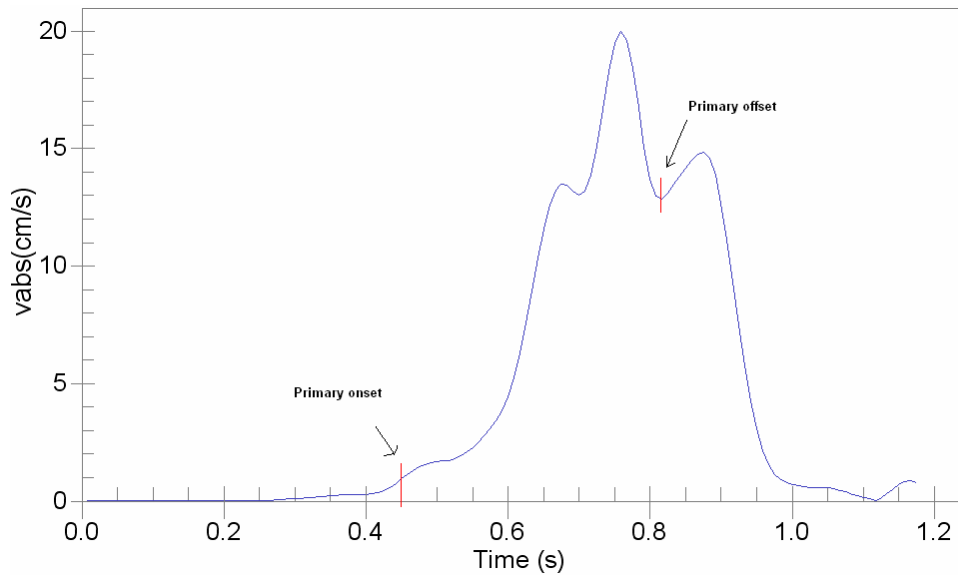


Figure 9. Example of a non-ballistic primary submovement: Absolute velocity plotted over time relative to the onset of trial recording

Summary of Results

Experiment 1 tested sequences with word production as a first unit in the sequence. The two-word production task replicated the reverse length effect found in Griffin (2003) and was used to support the assumption that such preparation modulation occurs within a single modality. Using the same word-eliciting items, there was no difference in speech onset between word lengths in the word production followed immediately by a movement. Production of a single short word took approximately 300 ms, which is equivalent to the time needed to prepare a movement -in isolation. Thus, movement could be prepared entirely during the production of the word, independent of word length. Consistent with the original prediction, there was no reverse length effect for word production followed by a movement, but a main effect of word length.

In Experiment 2, participants produced a movement followed by a word. In this case, movement production time varied between long (~800 ms) and short (~530 ms).

With a long movement duration, there should be significantly more time to prepare a subsequent word online as opposed to during a short movement. Participants took longer to begin a movement when it was followed by a word; however there was no reverse length effect that suggests that movement onset was not sensitive to the movement length. The main effect of sequence type could suggest that participants do generally anticipate more time needed to plan a subsequent word, therefore delaying movement onset, but this anticipation is not sensitive to differences in movement length, counter to predictions. Perhaps then, across modalities there is a general estimation of temporal information that can be used to modulate preparation.

In Experiment 3, participants produced a movement followed by a word however the target delay between the offset of the movement and the onset of the word was manipulated (i.e., no delay or 1 second delay). Participants generally began movement earlier when it was immediately followed by a delay as opposed to a word. This pattern is consistent with the general prediction of preparation modulation, that is with more time available to plan a second unit during the production of an earlier one (e.g., during the pause delay task) sequence onset can begin earlier. Furthermore, a reverse length effect was present during movement followed immediately by movement production and disappeared when adequate time was added between tasks, consistent with the predictions of the hypothesis.

Data Discrepancies between Experiment 2 and 3

It is apparent that, though both Experiment 2 and 3 involved identical sequence tasks (i.e., movement-speech immediate), there is a large discrepancy in the total proportion of “successful” (i.e., fulfilling the time constraints of the tasks) trials as well as a discrepancy in the presence of the expected reverse length effect. One possible explanation for this pattern is the effect of practice.

Extensive practice tends to diminish bottleneck effects, as there is a decrease any dual-task performance interference (e.g., Levy and Pashler, 2001, Ruthruff, Johnston, & Van Selst, 2001; Schumacher, Seymour, Glass, Kieras, & Meyer, 2001). Various explanations have been proposed for practice effects, such as the formation of new independent processing “paths” for each task (Johnston and Delgado, 1993), and the general reduction in processing demands (Norman and Shallice, 1986) for both tasks with experience. In the reported study, a difference in task experience between Experiments 2 and 3 may reflect a diminished bottleneck between movement and speech tasks.

Participants in Experiment 2 had substantially more experience in the movement-speech task compared to Experiment 3 (i.e., 60 trials vs. 24 trials respectively). Practice effects in Experiment 2 may have allowed participants to eventually carry out both tasks without a bottleneck at the preparation stage of both tasks, which as stated in the introduction is a necessary assumption for a reverse length effect to be present. In contrast, participants in Experiment 3 had relatively less exposure to both the movement alone and movement-speech tasks. With less experience, any shared processing stages between the tasks may have persisted, resulting in the expected reverse length effect.

If two independent processing paths formed with increased practice (e.g., Johnston and Delgado, 1993), the decoupling of shared processing stages may affect relative timing of the two tasks. When a processing stage of a second task (e.g., speech) is dependent on the successful completion of that shared stage of the first task, timing is necessarily more intimate between two tasks. However, the decoupling of the two tasks relieves any temporal dependence between the tasks. With this new processing independence, timing speech task to immediately follow a movement task may require increased volitional control. Ironically, it would follow that with more practice, timing a movement-speech sequence correctly becomes more difficult. This could explain the large discrepancy in successful trials between Experiment 2 and Experiment 3 (for the movement followed immediately by speech sequence type). In summary, perhaps with more practice in Experiment 2, any shared preparation stage of movement and speech becomes independent, timing then goes under conscious control and fulfilling the timing constraints becomes more difficult.

The results of these experiments support the hypothesis that people modulate the preparation of sequential units across speech and movement modalities when the sequence is relatively novel. However, with more practice, preparation modulation disappears.

Application to Gesture and Speech

Nevertheless, the results of these experiments provide some information into the relationship between arbitrarily related speech and movement units and perhaps some insight into the qualitatively different relationship between speech and gesture. Coupled speech and gesture evolve from the same idea or semantics to be expressed in both forms,

where gesture perhaps reflects the utterance in its “primitive form” (McNeill, 1992), as it tends to anticipate speech. A semantic relationship between gesture and speech may drive the tight synchronous coupling of the two distinct modality productions. In contrast, the movement and speech production units in the current experiments were arbitrarily paired, and the demands of the task determined how participants should synchronize the distinct units. The task demands imposed on the participants were high as they were asked for a very particular pattern of phasing between the two units. Perhaps then, the very precise and persistent synchrony between speech and gesture is entirely due to their shared meaning which supports the idea that speech and gesture are aspects of a single underlying process (McNeill, 1985).

APPENDIX

LONG AND SHORT LEFT OBJECT NAMES

Pair Number	Long Word	Log ₁₀ Frequency	Name Agreement	Syllables	
1	alligator	0.30	0.89	4	Included
2	baby	2.39	0.97	2	Excluded
3	balloon	.	.	2	Excluded
4	banana	0.78	1.00	3	Included
5	barrel	.	.	2	Excluded
6	basket	1.32	0.97	2	Excluded
7	battery	1.60	0.97	3	Included
8	binoculars	0.85	0.98	4	Included
9	bird cage	1.80	0.88	2	Excluded
10	boomerang	.	0.98	3	Included
11	briefcase	1.00	0.91	2	Excluded
12	bucket	1.20	0.91	2	Excluded
13	bullets	1.11	0.97	2	Excluded
14	butterfly	0.70	1.00	3	Included
15	camel	0.95	0.98	2	Excluded
16	camera	1.64	0.98	3	Included
17	candle	1.08	1.00	2	Excluded
18	carrot	0.60	1.00	2	Excluded
19	castle	.	.	2	Excluded
20	caterpillar	0.30	0.91	4	Included
21	celery	0.48	0.89	3	Included
22	chocolate	1.28	0.82	2	Excluded
23	chopsticks	0.48	0.86	2	Excluded
24	cigarette	1.85	0.98	3	Included
25	clipboard	.	0.97	2	Excluded
26	coconut	0.30	0.98	3	Included
27	computer	2.21	1.00	3	Included
28	croissant	0.00	0.97	2	Excluded
29	dictionary	1.18	0.82	4	Included
30	dishwasher	0.30	0.93	3	Included

31	dolphin	0.00	1.00	2	Excluded
32	dominos	.	.	3	Included
33	donkey	1.04	0.89	2	Excluded
34	dragon	1.04	0.98	2	Excluded
35	elephant	1.30	1.00	3	Included
36	faucet	0.30	0.98	2	Excluded
37	fireman	0.90	0.88	2	Excluded
38	flashlight	0.78	1.00	2	Excluded
39	flowers	1.94	0.91	2	Excluded
40	football	.	.	2	Excluded
41	glasses	1.82	0.89	2	Excluded
42	goggles	0.48	0.95	2	Excluded
43	guitar	.	1.00	2	Excluded
44	hamburger	0.48	0.84	3	Included
45	harmonica	.	0.95	4	Included
46	kangaroo	0.60	1.00	3	Included
47	lighter	1.43	0.98	2	Excluded
48	lion	1.48	1.00	2	Excluded
49	lipstick	0.95	1.00	2	Excluded
50	monkey	1.15	0.97	2	Excluded
51	mushroom	0.90	1.00	2	Excluded
52	nutcracker	0.00	0.82	3	Included
53	ostrich	0.30	1.00	2	Excluded
54	palm tree	1.36	0.88	2	Excluded
55	parrot	0.70	0.88	2	Excluded
56	peanut	0.48	1.00	2	Excluded
57	pencil sharpener	1.28	0.91	5	Included
58	pepper	0.95	0.84	2	Excluded
59	perfume	0.85	0.97	2	Excluded
60	piano	1.61	0.95	3	Included

61	pillow	1.26	0.95	2	Excluded
62	pineapple	0.78	1.00	3	Included
63	potato	1.15	0.97	3	Included
64	pyramid	0.85	0.98	3	Included
65	rabbit	1.15	0.86	2	Excluded
66	raccoon	.	0.98	2	Excluded
67	refrigerator	.	.	5	Included
68	rocking chair	.	0.95	3	Included
69	saddle	0.95	0.97	2	Excluded
70	scissors	0.85	0.98	2	Excluded
71	screwdriver	.	.	3	Included
72	skeleton	1.04	0.97	3	Included
73	slingshot	.	0.93	2	Excluded
74	slippers	1.00	0.86	2	Excluded
75	spaghetti	0.95	0.93	3	Included
76	speaker	.	.	2	Excluded
77	spider	0.78	0.95	2	Excluded
78	statue of liberty	1.26	0.98	6	Included
79	strawberry	0.48	1.00	3	Included
80	suitcase	.	.	2	Excluded
81	sunglasses	0.70	0.88	3	Included
82	thimble	.	0.91	2	Excluded
83	tiger	1.15	0.95	2	Excluded
84	toilet	1.58	0.97	2	Excluded
85	toilet paper	1.58	0.98	4	Included
86	toothbrush	0.30	0.97	2	Excluded
87	typewriter	1.20	1.00	3	Included
88	violin	1.11	1.00	3	Included
89	windmill	0.90	1.00	2	Excluded
90	windows	1.94	0.86	2	Excluded

Pair Number	Short Word	Log ₁₀ Frequency	Name Agreement	Syllables	
1	axe	.	.	1	Included
2	bed	2.53	1.00	1	Excluded
3	bow	1.30	0.75	1	Excluded
4	bear	1.97	0.98	1	Included
5	brick	.	.	1	Excluded
6	belt	1.48	1.00	1	Excluded
7	bowl	1.58	0.97	1	Included
8	broom	0.85	1.00	1	Included
9	bell	1.82	0.98	1	Excluded
10	boots	1.68	0.97	1	Included
11	blimp	.	0.93	1	Excluded
12	bee	1.26	0.88	1	Excluded
13	bench	.	.	1	Excluded
14	bat	1.15	1.00	1	Included
15	crown	1.60	0.97	1	Excluded
16	cake	1.43	0.98	1	Included
17	corn	.	.	1	Excluded
18	crab	0.70	0.95	1	Excluded
19	clock	.	.	1	Excluded
20	crutch	0.60	0.98	1	Included
21	saw	2.80	1.00	1	Included
22	cheese	1.53	0.86	1	Excluded
23	chick	0.60	0.77	1	Excluded
24	slide	1.76	0.98	1	Included
25	clown	0.48	1.00	1	Excluded
26	comb	0.85	0.98	1	Included
27	cat	1.72	0.89	1	Included
28	cross	.	.	1	Excluded
29	deer	1.15	0.84	1	Included
30	duck	1.15	1.00	1	Included

31	dart	0.48	0.98	1	Excluded
32	dice	0.30	0.93	1	Included
33	drill	1.23	0.88	1	Excluded
34	drum	1.11	0.75	1	Excluded
35	ear	1.00	0.86	1	Included
36	fan	1.34	0.97	1	Excluded
37	flask	0.78	0.86	1	Excluded
38	flag	1.51	1.00	1	Excluded
39	fork	1.23	1.00	1	Excluded
40	fish	.	.	1	Excluded
41	gloves	1.30	0.93	1	Excluded
42	globe	1.11	0.95	1	Excluded
43	grapes	0.95	1.00	1	Excluded
44	hose	0.60	0.82	1	Included
45	harp	0.60	0.97	1	Included
46	cane	1.32	0.98	1	Included
47	leaf	1.34	0.98	1	Excluded
48	lamp	1.43	1.00	1	Excluded
49	lock	1.56	0.98	1	Excluded
50	mask	1.23	1.00	1	Excluded
51	mouse	1.08	0.98	1	Excluded
52	nut	0.30	0.86	1	Included
53	owl	.	.	1	Excluded
54	paint	1.79	0.91	1	Excluded
55	plum	0.70	0.88	1	Excluded
56	peach	.	.	1	Excluded
57	plate	1.70	0.91	1	Included
58	peas	1.00	0.86	1	Excluded
59	pot	1.52	0.84	1	Excluded
60	pen	1.51	0.97	1	Included

61	pie	1.28	0.97	1	Excluded
62	purse	1.15	0.91	1	Included
63	pipe	1.63	0.95	1	Included
64	pear	0.60	0.98	1	Included
65	rug	1.15	0.91	1	Excluded
66	rose	.	.	1	Excluded
67	rope	.	.	1	Included
68	wrench	0.60	0.93	1	Included
69	safe	2.09	0.97	1	Excluded
70	socks	1.36	0.95	1	Excluded
71	seal	.	.	1	Included
72	screw	1.32	1.00	1	Included
73	sled	0.00	0.95	1	Excluded
74	swan	0.95	0.80	1	Excluded
75	sponge	0.85	1.00	1	Included
76	spring	.	.	1	Excluded
77	spoon	1.11	1.00	1	Excluded
78	snake	1.34	0.98	1	Included
79	stool	1.04	0.98	1	Included
80	skull	.	.	1	Excluded
81	skiis	.	.	1	Included
82	truck	1.54	0.86	1	Excluded
83	tire	.	.	1	Excluded
84	tie	1.72	0.97	1	Excluded
85	tent	1.59	0.98	1	Included
86	teeth	1.98	0.89	1	Excluded
87	tank	1.41	0.98	1	Included
88	vase	0.60	1.00	1	Included
89	wolf	1.00	0.97	1	Excluded
90	watch	2.26	0.98	1	Excluded

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