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The Relationship between Implicit and Explicit Processing in Statistical Language Learning

Nicolette B. Noonan, *The University of Western Ontario*

Supervisor: Dr. Lisa Archibald, *The University of Western Ontario*

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THE RELATIONSHIP BETWEEN IMPLICIT AND EXPLICIT PROCESSING IN STATISTICAL LANGUAGE LEARNING

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by

Nicolette B. Noonan

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The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

Abstract

Statistical language learning is an implicit process wherein language learners track sequential statistics in fluent speech, and may it facilitate the learning of word boundaries. This process is well studied, however, the cognitive mechanisms supporting it remain poorly understood. The present thesis investigated whether domain-specific or cross-domain explicit working memory engagement would impair implicit statistical learning of word boundaries in fluent speech. Participants (n = 110) were exposed to an implicit statistical word segmentation paradigm while concurrently engaged in no other task (control), or an explicit domain-specific (verbal) or cross-domain (visuospatial) working memory task of either low- or high-demand. Participants in the control task and either visuospatial task (low- and high-demand) reliably segmented words from the artificial language, however those in either verbal working memory condition (low- and high-demand) did not. These findings suggest an interference effect on implicit verbal learning by explicit processing of material from the same domain.

Keywords

Statistical language learning, language learning, word segmentation, implicit learning, explicit processing, working memory

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Introduction

One of the hallmarks of human cognition is the ability to rapidly learn our complex system of language without instruction and seemingly, without much effort. It is proposed that the language learner undertakes this task via a process of *statistical language learning*, wherein learners implicitly track the statistically predictable regularities inherently present within language (Chun & Jiang, 2003; Conway & Christiansen, 2006; Fiser & Aslin, 2001; Thiessen, Kronstein, & Hufnagle, 2013; Turk-Browne, Jungé, & Scholl, 2005). Implicit statistical learning may be especially important in early word segmentation (Saffran, Aslin, & Newport, 1996). What remains poorly understood, however, are the cognitive mechanisms that support implicit statistical learning. One growing area of interest (Ludden & Gupta, 2000; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997; Toro, Sinnett, & Soto-Faraco 2005) requiring more systematic investigation is the extent to which implicit learning may be supported by explicit cognitive processes such as working memory, a resource suggested to be important in complex learning and word learning in particular (Baddeley, Gathercole, & Papagno, 1988; Gathercole, 2006). The question of domain-specific effects in statistical learning also requires further study. Findings of statistical learning of both phonological and nonphonological patterns have led to the suggestion that statistical learning is a domain-general mechanism (Evans, Saffran, & Robe-Torres 2009; Fiser & Aslin, 2001; Kirkham, Slemmer, & Johnson, 2002; Reber, 1967), although domain-specific interference effects may be possible depending on the stimuli. The purpose of the present thesis was to investigate the cognitive processes supporting statistical language learning by systematically imposing concurrent explicit working memory demands involving either same- (verbal) or cross-domain (visuospatial) stimuli.

Statistical learning of language

In the most general sense, statistical learning can be defined as the “discovery of patterns in the input” (Reber, 1967). Natural languages are composed of statistically reliable distributional patterns (Bloomfield, 1933; Harris, 1951). Indeed, some of the earliest investigations of implicit learning demonstrated that learners exposed to an artificial grammar string could learn the lawfulness of the stimuli without explicit awareness or instruction (Reber, 1967). More recent research has demonstrated that infant language learners are able to exploit statistical regularities of syllables within words in order to segment words from fluent speech (Saffran, Aslin, et al., 1996). It is not surprising then, that growing attention has been paid to the idea that language is supported by a statistical learning mechanism (Altmann, 2002; Conway & Christiansen, 2005; Conway & Pisoni, 2008; Gupta & Dell, 1999; Kirkham, Slemmer, Richardson, & Johnson, 2007; Kuhl, 2004; Pothos, 2007; Reber, 1967; Saffran, 2003; Turk-Browne et al., 2005; Ullman, 2004). Indeed, the evidence demonstrates that implicit statistical learning is important for word segmentation (Echols, Crowhurst, & Childers, 1997; Goodsitt, Morgan, & Kuhl, 1993; Johnson & Jusczyk, 2001; Saffran et al., 1996), word learning (Graf Estes, Evans, Alibali, & Saffran, 2007; Mirman, Magnuson, Graf Estes, & Dixon, 2008; Saffran, 2001), learning phonemic contrasts (Maye, Werker, & Gerken, 2002), learning phonological patterns (Saffran & Thiessen, 2003), the acquisition of syntax (Gómez & Gerken, 1999, 2000; Marcus, Vijayan, Bandi Rao, & Vishton, 1999;

Ullman, 2004), and simultaneous word segmentation and syntax acquisition (Saffran & Wilson, 2003).

One of the first puzzles facing the language learner is uncovering the boundaries between words in fluent speech. Unlike written language, spoken language does not contain neat "white space" in between words to help learners segment words. Segmenting words from fluent speech is a complicated task as there are multiple opposing cues within spoken language that may demarcate word boundaries such as prosodic cues (Christophe, Dupoux, Bertoncini, & Mehler, 1994; Cutler, 1994; Cutler & Norris, 1988), stress patterns (Echols, 1993; Echols & Newport, 1992, Jusczyk, Houston, & Newsome, 1999), and speakers' tendency to rarely pause between words (Cole & Jakamik, 1980). However, one cue that has been proposed to be reliable in segmenting words from fluent speech are the statistically predictable relationships of syllables within words. The idea of using statistical relationships between syllables to uncover words dates back to Harris (1955), who proposed word units could be identified by uncovering correlational relationships between individual phonemes. Later, Hayes and Clark (1970) proposed that words could be segmented using a clustering mechanism based on correlations between syllables.

Following this, Saffran and colleagues (Saffran, Newport, & Aslin 1996) sought to clarify the clustering mechanism of Hayes and Clark (1970). The clustering mechanism formalized probabilities of co-occurrence between syllables *as transitional probabilities*. A transitional probability can be understood as the probability of *Y* given *X* (Miller & Selfridge, 1950), and can be computed as:

$$Y|X\colon \frac{frequency\ of\ pair\ XY}{frequency\ of\ X}$$

A high transitional probability value indicates that the presence of *X* reliably predicts the presence of *Y*. A low transitional probability value indicates that the presence of *X* does not reliably predict the presence of *Y*. Using the example of the phase "*pretty baby"* (/prɪti beɪbi/) as it occurs within a natural language corpus, the within-word transitional probability of syllables could be computed as:

$$\text{bi}|\text{beɪ}: \frac{frequency\ of\ pair\ /\text{beɪ}/./\text{bi}/}{frequency\ of\ /\text{beɪ}/}$$

Using the same example, the between-word transitional probability of syllables could be computed as

$$\text{beɪ}|\text{ti}: \frac{frequency\ of\ pair\ /\text{ti}/\ ./\text{beɪ}/}{frequency\ of\ /\text{ti}/}$$

In this example, the value of the within-word transitional probability is higher than the value of the between-word transitional probability. That is, the presence of /beɪ/ followed by /bi/ is a more reliable relationship than /-ti/ predicting /beɪ/; /-ti/ as the word-final syllable of *pretty* could be followed by an initial syllable for any number of subsequent words, but /beɪ-/ as a word-initial syllable is followed by a limited number of syllables (e.g.: ba*by*, ba*sil*, ba*con*). Thus, the words *pretty* and *baby* could be segmented at this between-word boundary based on transitional probabilities.

Although this approach appears computationally complex, research has demonstrated with considerable consistency that language learners utilize transitional probabilities to segment words from fluent speech. In one of the demonstrations of this finding, Saffran, Newport, and Aslin (1996) examined whether participants could segment words from an artificial language using *only* the transitional probabilities of syllables within and between words. Their language was rendered from an inventory of

12 consonant-vowel (CV) syllables combined to create six trisyllabic words: *babupu, bypada, dutaba, patubi, pidabu,* and *tutibu*. Because some syllables from the inventory were reused in different words in the corpus, within-word transitional probabilities ranged from 0.31 to 1.0. Between-word transitional probabilities were low, ranging from 0.1 to 0.2. Words were combined in random order within the language, with the stipulation that no word was repeated. The auditory language stimuli were produced via a speech synthesizer, and contained no other cues to word boundary such as syllable stress, pauses, or contours. No instructions regarding the length or structure of words within the language were given to participants. Participants listened to the language for 21 minutes. Immediately following language exposure, participants were tested on their knowledge of words from the language. At test, a word from the language was paired with a word foil from the language and participants had to indicate "which of the two strings sounds more like something you heard from the language". Accuracy was judged as total items correctly identified. Word foils were either *part words* or *nonwords.* Part words were constructed by pairing a syllable pair from a word within the language, plus an additional syllable from another word. For example, the first syllable of the word *dutaba* was altered to create the part-word *bitaba*. Nonwords were constructed by combining three syllables from the language that did not occur together within a word or across word boundaries, such as in the test nonword *padubu*. Note that for the listener, the transitional probabilities within *padubu* would be zero. Results indicated that participants performed above chance, with a mean score of 27.2 out of a possible 36 (76% correct). This finding is important as it demonstrates that adults are able to discover word units rapidly, and

simply by using the transitional probabilities of syllables with no additional cues to segment words.

In a further study, Saffran and her colleagues (Saffran, Aslin et al. 1996) examined this process in 8-month-old infants. Infants were exposed to an artificial language produced by a speech synthesizer containing four trisyllabic words for two minutes. The language contained no cues to word boundaries except for the transitional probabilities of syllables within and between words. Using a novelty preference test, infants demonstrated they could discriminate between words from the language and nonwords. These results are particularly impressive as infants as young as 8 months with only a brief familiarization phase were able to extract words from the speech stream based on sequential statistics. Aslin and colleagues (Aslin, Saffran, & Newport, 1998) later demonstrated that this discrimination was not based on frequency information (i.e., words did occur more frequently than test-item part words in the Saffran, Aslin et al., 1996 study). Instead, infants discriminated on the basis of transitional probabilities above and beyond frequency information. It is evident from these findings that language learners have access to a powerful statistical learning mechanism responsive to the statistical properties of language input.

Researchers have sought to examine when statistical learning of word boundaries comes on line for infants. Jusczyk and Aslin (1995) demonstrated that 7.5-month-olds were able to segment words from fluent speech, but 6-month-olds were not. After demonstrating this ability in 6.5- to 7-month olds, Thiessen and Saffran (2003) suggested that the ability to segment words by computing transitional probabilities might emerge around 6 to 6.5 months of age. Thiessen and Saffran also found that 9-month-old infants appeared to use syllable stress to segment words, while ignoring transitional probability cues. It may be that the different strategies infants use to successfully segment words emerge over the early stages of language acquisition, and that segmenting words using computations of transitional probabilities may be of primary importance in the earliest stages of language learning.

Further studies investigated whether infants grant lexical status to segmented words. Saffran (2001) embedded newly segmented words or part-word foils in English sentences to examine if infants demonstrated a preference for materials consistent with their prior knowledge. Following artificial language exposure, infants preferred test sentences containing words from the familiarized artificial language to part-word foils. This demonstrated that the newly segmented words were more readily integrated into the infant's language of English. Graf Estes and collaborators (Graf Estes et al., 2007) presented similar findings, supporting the hypothesis that infants treat newly segmented words as lexical candidates. Here, infants were exposed to the statistical word segmentation paradigm (Aslin et al., 1998; Saffran, Aslin, et al., 1996). The infants then participated in a label-object association task, in which labels were words from the speech stream or foil words. The authors found that infants preferred word labels to nonword and part word labels, further supporting the notion that there is a connection between word segmentation and linking words to meaning. Saffran's (2001) and Graf Estes' and collaborators' findings suggest that infants are not just learning the statistical properties of sound sequences, but acquiring linguistic knowledge and integrating this with native language understanding.

It is clear from the preceding review that there is mounting evidence that statistical learning plays a role in language learning. Given this relationship, growing interest has been focused on understanding the cognitive processes supporting statistical learning. In particular, questions regarding possible interactions between implicit and explicit processes, and domain-specificity have been raised.

What cognitive processes support statistical learning?

Statistical learning is considered an implicit process. However, it may be that some minimal conscious awareness is necessary to support implicit learning. In contrast to implicit processes, explicit processes require conscious, active, and purposeful effort (Graf & Schacter, 1985; Reber, 1967, Schacter, 1987). For explicit learning, learners are generating and testing hypotheses in order to adapt to changes in the environment. Research has predominately focused on the separability of implicit and explicit learning (Gabrieli, Fleischman, Keane, Reminger, & Morrell, 1995; Rodeiger & McDermott, 1993; Rugg, Mark, Walla, Schloerscheidt, Birch, & Allan, 1998; Schacter, 1987), but some findings show that these two processes may interact. For example, in motor skill learning explicit and implicit knowledge can be learned in parallel (Willingham & Goedert-Eschmann, 1999). Furthermore, explicit knowledge becomes accessible following implicit learning in the learning of visual scenes (Goujon, Didierjean, & Poulet, 2013). As applied to language learning, infants' explicit knowledge of previously learned words can aid segmentation of subsequent words in a stream of speech (Lew-Williams, Pelucchi, & Saffran, 2011). All of these findings point to some interaction between implicit and explicit processes in learning.

One theory related to statistical word segmentation that incorporates both implicit and explicit processes is Thiessen, Kronstein and Hufnagle's (2013) *extraction and integration framework*. This is a memory-based framework of statistical learning offering a two-process account as to how conditional relations between discrete representations (such as words) can be learned. It is hypothesized that learners extract and store statistically coherent units (words) within long-term memory and integrate across these stored units within memory to identify a central tendency. The ability to extract patterns such as candidate word forms is considered to rely on implicit learning of conditional statistics such as transitional probabilities even before phonological cues to word boundaries are discovered (Thiessen & Saffran, 2003). Once stored within long-term memory, integration across word forms allows for the discovery of phonological regularities to extract newly encountered words, such as lexical stress in English (Thiessen & Saffran, 2007). It is possible that integration (and possibly extraction) relies on explicit processing resources as elements in the input are only chunked together when they are simultaneously held in attention (Perruchet, Tyler, Galland, & Peereman, 2004; Thiessen et al., 2013).

With regards to explicit processes that may support implicit learning, two potential candidates have been considered: Attention and working memory. Attention can be defined as mental effort (Johnston & Dark, 1986), limited by central resources that are shared amongst all concurrent tasks (Cowan, 1988). Attention is strongly linked to learning generally (Nissen & Bullemer, 1987) probably because attention facilitates processing of received stimuli. As such, at least minimal attentional focus may support the implicit extraction and integration of information (Thiessen et al., 2013). One way in which the role of attention can be investigated in implicit learning is to examine the negative impact on implicit learning of engaging attention in an attention-demanding secondary task. And indeed, engaging explicit processes using attention-demanding secondary tasks has been found to result in reduced implicit learning of artificial grammar learning (Diens, Altman, Kwan, & Goode, 1995) and sequence learning (Nissen & Bullemer, 1987).

Few studies have examined the relationship between implicit statistical language learning and explicit attentional processes. Thiessen, Hill, and Saffran (2005) examined whether infant-directed speech would help guide statistical word segmentation on the premise that infant directed speech is more likely than adult directed speech to hold an infant's attention (e.g.: Werker, Pegg, & McLeod, 1994) and lead to improved memory for segmented words (e.g.: Hertel & Rude, 1991; Rensink, O'Regan, & Clark, 2000). The authors found that infant-directed speech had a facilitative effect on word segmentation. One possibility is that increased attention to the stimuli improved memory for the segmented words during the learning phase. Attentional engagement, however, was not measured and so a possible role of attention in implicit learning is only speculative. Indeed, Saffran and colleagues (Saffran, et al., 1997) argued against a role of attention in implicit statistical learning based on findings that children and adults demonstrated learning of an artificial language after 21 minutes of exposure while engaged in drawing a picture. Nevertheless, the extent to which attention was captured by the drawing task is unknown. As well, the study did not include a control group, making the role of attention difficult to interpret. Results of a subsequent study by Ludden and Gupta (2000) shed light on these findings by including a control (no drawing) and drawing group. After 21 minutes of exposure to an artificial language, both groups exhibited learning of words from the language, with greater levels of learning for the control group. Although highly similar in design, the findings from the above studies conflict. Additionally, both face methodological limitations. Thus, they do not offer clear evidence as to the impact of explicit processing on implicit statistical language learning.

In their examination of the role of attention in statistical word segmentation, Toro, and colleagues (2005) aimed to impose tasks that were more attention-demanding tasks than in the Saffran et al. (1997) or Ludden and Gupta (2000) studies. Participants in the Toro et al. study were exposed to an artificial language similar to the one used in Saffran et al. Performance on word segmentation was compared across controls and those who were engaged in a concurrent attention-demanding task, either in the auditory (Experiments 1 and 3) or visual (Experiment 2) domain. The authors speculated that the impact on the implicit learning task might differ based on the processing load of the secondary task. Specifically, it was hypothesized that task-irrelevant information (i.e., the artificial language) might undergo some processing if the demands of the secondary task were low (Lavie, 1995; Rees, Frith, & Lavie, 2001), whereas if the secondary task is sufficiently demanding, attentional resources may be depleted to a point where the learning of word boundaries does not occur (Rees, Frith, & Lavie, 1997).

In Experiment 1, participants had to attend to an auditory stream and listen for repeats in a familiar sound (e.g., car engine, door slamming, etc.). Sounds from the auditory stream were 400-500ms in length, with a 250ms inter-stimulus interval (ISI), giving a stimulus onset asynchrony (SOA) of 650-750ms. The authors titled this a high-attention load task. Performance for controls in Experiment 1 was above chance (78%), whereas performance for those in the high-attention load task was not significantly different from chance (58%). A noticeable limitation within this design is that the sound stream stimuli may have been a sensory mask for the speech stream. Thus, in Experiment 2, the authors used a high-attention load condition where participants attended to a visual stream of pictures while concurrently being exposed to the artificial language. Participants were to attend for and respond to repeating pictures. Pictures were presented for 250ms for half of the subjects, and 500ms for the other half of participants, with an ISI of 250ms. Thus, the SOA was either 500ms or 750ms with greater attention demands imposed by the shorter SOA condition. Controls (no concurrent task) and participants in the 750ms SOA group could successfully segment words from the speech stream above chance levels (69% and 63% correct, respectively), whereas those in the 500ms SOA group did not differ from chance (48% correct). In Experiment 3, the authors examined the effect of having the distractor task within the speech stream itself. Participants in the high-attention load group had to listen for and respond to a pitch change of 20Hz on pseudo-randomly selected syllables within the speech stream. Here, word recognition scores for control participants were above chance (64% correct), and the high-attention load did not differ from chance (55% correct). From these findings, the authors concluded that diverting attention with an attentionally demanding secondary task in either the visual or auditory domain compromises statistical learning, especially for tasks imposing a high processing load.

Toro et al.'s (2005) findings of reduced implicit learning when completing a concurrent attention-demanding task imposing a high processing load raised the possibility that another explicit process beyond attention may place a role in implicit learning, specifically, working memory. Working memory refers to both the storage and manipulation of information in the current focus of attention (Baddeley & Hitch, 1974; Cowan, 1999). According to the tripartite working memory model of Baddeley and Hitch (1974), working memory is comprised of a domain-general central executive resource responsible for the manipulation and processing of information necessary for the current cognitive task, as well as two domain-specific short-term memory resources responsible for the retention of phonological (phonological loop) or visuospatial information (visuospatial sketchpad). The storage and processing demands of a working memory task are thought to compete for required but limited attentional resources such that performance is constrained by the cognitive load of the task (Barrouillet & Camos, 2001). As a result, when cognitive load is high, fewer attentional resources can be shared for other purposes. A plethora of research has established links between working memory and complex cognitive tasks including learning across domains (Baddeley, Papagno, & Vallar, 1988; Cantor & Engle, 1993; Daneman & Carpenter, 1980; Smith & DeCoster, 2000; Unsworth & Engle, 2005).

In order to examine the potential role of working memory in implicit learning, Toro et al. (2005) examined statistical language learning after 21 minutes of exposure to an artificial language while participants were engaged in a 2-back task. The 2-back task is a variant of an *n*-back task widely considered to tap working memory (Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005; Kane & Engle, 2002). In an *n*-back task, the participant is required to monitor a series of stimuli and to respond when a presented stimulus is a match to the stimulus presented *n* trials previously. Subjects must continuously update their mental representation and storage of target items, while also continuously dropping now irrelevant items from consideration. Verbal versions of the task require monitoring of phonological information such as letter names whereas spatial versions requiring monitoring of locations. The *n*-back task requires on-line monitoring, updating, inhibiting, storage, and manipulation of information. Therefore, this task fits with the definitional aspects of working memory (Baddeley & Hitch, 1974; Cowan, 1999) as involving the storage and processing of information in the current focus of attention.

In Toro et al.'s (2005) study, participants simultaneously completing a visual 2-back task later identified words from an artificial language at a level significantly better than chance, and equivalent with controls. Taken together with their findings of reduced statistical language learning in the context of a attention-demanding secondary task from the same study (Toro et al., 2005), the evidence of statistical learning while engaged in a 2-back task was suggested to indicate that attention, but not working memory, supported implicit statistical learning.

It must be noted, however, that the attention-demanding secondary task employed by Toro et al. (2005) involved either picture-matching or sound-matching on consecutive stimuli. These tasks could be described as a 1-back task, where participants were required to detect a repetition on consecutive pairs, and a 1-back task may still place a load on working memory. Within the 1-back condition, maintenance processes are required to hold the information within the focus of attention while two stimuli are compared. Furthermore, there are updating processes involved with continually updating the to-be-matched stimulus. Stimulus decision, selection, inhibition, and interference are also involved in selecting correct responses, and rejecting incorrect responses. These processes are closely associated with working memory functions (Smith & Joindes, 1997). As well, 1-back tasks have been shown to elicit activation in areas of the prefrontal cortex commonly associated with working memory processes (Braver, Cohen, Nystrom, Joindes, Smith, & Noll, 1997). It may be that the picture- or sound-matching tasks employed in the Toro et al. study, in fact, measured the influence of working memory interference on implicit statistical language learning.

The possibility of the involvement of working memory in a statistical language learning paradigm was further suggested by findings from a study by Evans and colleagues (2009). Evans, Saffran, and Torres compared children with specific language impairment (SLI) and typically developing children on their ability to segment words using transitional probabilities of syllables from an artificial language. SLI is a relatively common developmental impairment in which a child fails to learn language at the typical rate, despite the absence of intelligence, hearing, or motor impairments, and with the presence of typical educational and experiential opportunities (Leonard, 1998). Implicit learning may be impaired in children with SLI, as made evident from learning deficits on serial reaction time tasks (Tomblin, Mainela-Arnold, & Zhang, 2007) and artificial grammar learning tasks (Plante, Gómez, & Gerken, 2002). Evans and colleagues examined whether children with SLI were impaired in the implicit learning of speech or sound information. After 21 minutes of exposure to an artificial language, children with SLI were significantly poorer than their typically developing peers at identifying words from the language, and that this was not correlated with age, nonverbal IQ, receptive vocabulary, or expressive vocabulary. However, after increasing exposure to the artificial language to 42 minutes, children with SLI and typically developing peers did not differ.

In a similar study design, both groups were exposed to an artificial tone "language" where tone sequences could be segmented based on transitional probabilities, similar to words in the artificial language. The authors found that children with SLI were impaired in this condition relative to typically developing peers after 21 and 42 minutes of exposure, demonstrating an implicit learning deficit for the SLI group on a non-linguistic task.

One possibility to explain the poor implicit word learning in children with SLI is that they may not possess the necessary memory resources to form appropriately specified phonological representations of newly learned words, whereas typically developing children could. Furthermore, there was evidence of individual variability in performance for children with SLI. It was suggested that individual differences in working memory could account for these findings (Evans et al., 2009). Children with SLI have been found to have a reduced working memory capacity relative to their peers, specifically in the domain of verbal working memory (Archibald & Gathercole, 2006; Ellis Weismer, Evans, & Hesketh, 1999; Montgomery 2000a, 2000b; Montgomery & Evans, 2009). It may be that when working memory resources are insufficient as may be the case in SLI, statistical language learning abilities are impaired.

It is clear from the preceding review that further examination of the role of explicit processing in supporting implicit learning is warranted. In particular, the potential role of working memory in statistical learning remains unclear. The present thesis sought to examine this relationship systematically by evaluating the impact on statistical language learning of working memory tasks with different cognitive loads across domains.

Domain-specificity in statistical language learning

Implicit statistical learning is widely considered to be a domain-general learning mechanism (Reber, 1967). Researchers have demonstrated the learning of transitional probabilities between elements in sequence can be exhibited in multiple domains: Adults and infants use transitional probabilities to segment tone sequences (Creel, Newport, & Aslin, 2004; Evans et al., 2009; Saffran, Johnson, Aslin, & Newport, 1999; Saffran & Griepentrog, 2001), visual sequences (Fiser & Aslin, 2001, 2002; Kirkham, Slemmer & Johnson, 2002; Saffran, Pollak, Seibel, & Shkolnik, 2007; Turk-Browne et al., 2005), and manual response sequences (Nissen & Bullemer, 1987). This variety of findings suggests that statistical learning is a highly operational learning mechanism, and can be utilized for learning across domains.

If we are to view statistical learning as a domain-general learning mechanism, it could then be the case that learning is disrupted by cross-domain influences. The current thesis examined this hypothesis as it pertains to the potential support of the explicit processes of working memory on implicit learning. As mentioned previously, working memory is comprised of a domain-general central executive and two domain-specific short-term memory stores, the phonological loop and visuospatial sketchpad (Baddeley & Hitch, 1974). If statistical language learning is reduced while engaged in an explicit working memory task regardless of domain, then the most parsimonious explanation would be that the domain-general central executive component of working memory supports implicit learning. It should be noted, however, that the lack of a domain-general effect of an explicit task would not rule out an alternate domain-general mechanism operating implicitly.

It is important to note that the resulting knowledge from statistical learning is stimulus-specific (Conway & Christiansen, 2006; Saffran & Thiessen, 2007). For example, statistical language learning usually refers to the learning of phonological forms. Although domain-specific effects have not been examined in detail in studies of statistical language learning, domain-specific effects are documented widely for the explicit process potentially supporting implicit memory and investigated in the current thesis, working memory. Evidence for the domain-specificity of the short-term stores within the working memory model (i.e., the phonological loop and the visuospatial sketchpad) comes from tasks involving domain-specific interference effects. For example, the recall of primary verbal material in an articulatory suppression task is reduced when a secondary articulatory task interferes with the operations of the phonological loop, but not when a non-articulatory secondary task is completed (Baddeley, Lewis, & Vallar, 1984).

The phonological loop has been proposed to play a specific and important role in the early learning of phonological word forms (Gathercole, 2006). Gathercole proposed that initial encounters with phonological forms of novel words from verbal input are represented within the phonological loop. These phonological representations form the basis for a gradual process of abstracting a stable specification of the sound structure of the novel word across repeated exposures (Brown & Hulme, 1996). It is through this process of gradual extraction of relevant tokens that novel phonological forms become lexicalized. Conditions that compromise the formation of initial phonological representations (e.g., limited phonological short term memory resources) will necessarily compromise the quality of these phonological representations.

It is thought that information in the domain-specific phonological loop is entered and retained in an explicit fashion, where learners have conscious access to the stored information (Baddeley, 1986; Baddeley & Hitch, 1974). There is evidence, however, that phonological information can access phonological storage through an implicit channel. Consider the *cocktail party effect*: You are engaged in conversation in a crowded room, and all of the speech around you is nothing more than a buzz. However, when someone calls your name, your attention is immediately redirected (Cherry, 1953). This effect demonstrates that we are able to access phonological information without allocating conscious attention. Also, consider the *unattended speech effect*, where ignored phonological information (both words and nonsense words) disrupts digit recall, a phonological storage task (Salamé & Baddeley, 1982). Both of these effects illustrate that unattended phonological material can gain obligatory access to the phonological store. These findings leave open the possibility that phonological information is stored via a unitary phonological storage mechanism responsible for retaining attended and non-attended material. If this is the case, then engaging in any type of explicit phonological task that occupies the phonological loop's capacity may be expected to impair concurrent implicit encoding of phonological information.

The present study

In this study, participants were exposed to in an implicit statistical word segmentation task while concurrently engaged in an explicit working memory processing task in the form of a computer-administrated *n*-back task, or were not engaged in a concurrent task (control). The concurrent working memory task varied in whether the demands of the task imposed a high or low working memory load, and required monitoring of verbal or visuospatial stimuli. One goal of the study was to examine the effect of engaging in an explicit working memory process on statistical language learning. Reduced learning relative to the control group while engaged in any explicit working memory task would suggest that engaging attention in any way impairs implicit learning. On the other hand, performance dependent on the cognitive load of the task such that concurrent tasks with higher cognitive demands result in lower learning levels would specifically implicate working memory, and the central executive component in particular. A second purpose of the study was to examine the domain-specific effects on statistical learning. Findings of reduced learning when engaged in either verbal or visuospatial concurrent tasks would indicate a domain-general effect, which, when taken together with the cognitive load results, may further implicate the central executive component of working memory. Domain-specific effects, on the other hand, would be reflected in lower scores when engaged in same-domain (verbal) working memory tasks regardless of cognitive load. Such a pattern would suggest a specific role of the phonological loop in supporting implicit learning.

Method

Participants

Participants in the present study consisted of 110 adults (M_{age} = 20.22 years, SD_{age}= 3.35, N_{male} = 30). Nineteen students were recruited from a senior-level high school Psychology and Human Development course as part of a course project. Sixty-nine students were recruited from the undergraduate psychology pool at Western University and received course credit for study completion. Twenty-two students were recruited from the summer undergraduate psychology pool at Western University and received $10.00 for study completion. All subjects reported being monolingual English speakers and had no uncorrected vision or hearing difficulties.

Procedure

Upon arrival, participants received a letter of information, signed a consent form, and completed a short questionnaire to obtain the following demographic information: Age, gender, first language, number of years speaking English, and presence of vision or hearing difficulties. Testing took place in either a quiet computer testing lab (<8 participants) where the task was administered via individual PCs, or within a quiet testing room (1 participant) where the task was administered via a laptop computer. After completing the questionnaire, participants completed the listening phase (artificial language exposure) of the study while engaged in one of five concurrent working memory task conditions (no load; verbal, low load; verbal, high load; visuospatial, low load; visuospatial, high load). Participants were quasi-randomly assigned to one of the five conditions such that equal numbers completed each condition with no participant factors determining group assignment. If participants were being tested in a computer testing lab, all participants were entered into the same condition. If participants were being tested privately, they were randomly assigned with the constraint of obtaining matched group sizes. An attempt was made to keep group sizes approximately equal as data collection progressed. Random draws from a group were discarded if a group was larger than all others. Immediately following the language exposure and working memory task completion, participants completed the test phase. Following study completion, participants were administered a debriefing form detailing the experimental manipulation.

Listening phase: Artificial language exposure.

Artificial language stimuli. The artificial language employed in the present study was based on the stimuli described by Saffran, Newport et al. (1996). The language consisted of four consonants (p, t, b, d) and three vowels (a, i, u) which, when combined, rendered an inventory of 12 CV syllables. These syllables were then combined to create six trisyllabic "words" in an artificial language: *patubi, tutibu, babupu, bupada, dutaba, pidadi*. Some syllables from the inventory occur more often within the language than others (e.g.: *bu* occurs in three words, whereas *ti* occurs in one word). The word corpus in the present artificial language used all 12 syllables, differing from the Saffran et al. (1996) corpus, in which the syllable *di* was not included. Transitional probabilities of syllables varied, and were higher within words (Range: 0.33 to 1.0) than across word boundaries (Range: 0.1 to 0.2).

Recording the artificial language stimuli. Unlike Saffran et al.'s (1996) synthesized stimuli, the artificial language in the present study was constructed from audiorecordings of a female native-English speaker using a neutral vocal effort. Although the majority of available evidence is based on findings from exposure to synthetic speech samples, more recent work of Saffran and colleagues (Graf, Estes et al., 2007) and similar studies (Lew-Williams et al., 2011; Pelucchi, Hay, & Saffran, 2009, Experiment 1) have employed naturally produced speech and found similar effects.

Recordings were made in a double walled IAC sound booth with a pedestal microphone (AKG C 4000B) located approximately 30cm from the speaker's mouth and routed to a USBPre 2 pre-amplifier (Sound Devices). Digitization was performed via soundcard, and recordings were made with commercially available SpectraPuls software

(Pioneer Hill Software, 2008). Recordings were made of each of the 12 target syllables in the middle of a three-syllable sequence, within every coarticulation context required for the language. For example, the syllable *tu* occurred in two words in the artificial language, *tutibu* and *patubi.* For the word *tutibu* in the continuous artificial language stream, the word-initial syllable *tu* could be preceded by the word-final syllables for the remaining five words, *bi, pu, da, ba,* or *di*, and followed only by *ti*. Thus, recordings of these six iterations were made. Alternatively, for the word *patubi*, the word-medial syllable *tu* would be preceded only by the word-initial syllable *pa* and the word-final syllable *bi.* Thus, recordings of this one iteration were made. Eight repetitions of each sequence were recorded, and the token with the most neutral pitch contour and best sound quality was chosen and uploaded into Sound Forge Audio Studio (Sony) editing software.

Creating the artificial language. Middle syllables from the recorded tokens were extracted by identifying the final offset of vowel oscillation in the previous syllable to the offset of vowel oscillation in the target syllable. The continuous artificial language stream was created by concatenating the medial syllables to create random sequences of the words. In this way, all syllables were spliced together in the same way throughout the entire language regardless of whether the syllables were within a word or across word boundaries. The language maintained a consistent speech rate (3.1 syllables/s) using a time stretch and was normalized to a pitch of F0 = 196 Hz using Sound Forge Audio Studio (Sony). There were no pauses between words. As such, there were no acoustic cues to word boundaries. The artificial language was comprised of 490 tokens of each of the six words occurring in a random order, with the constraint that the same word never occurred twice in a row. This created 28 minutes of auditory language stimuli, divided into four listening blocks of seven minutes each.

Listening phase procedure. The listening phase involved exposure to 28 minutes of an artificial language divided into four 7-minute listening blocks, with 3-minute breaks in between each block. Following Saffran, Newport, et al. (1996), participants were told they would hear a nonsense language. No information was provided about the length or the number of words within the language in all conditions. Those in the no load task condition were seated in front of a computer displayed stimuli from the working memory task, but were not instructed to attend to or perform memory operations on the working memory stimuli. Those in a working memory task condition were instructed to complete the working memory task, and this was highlighted to them as the primary task. This deliberate use of vague instructions regarding the artificial language was done to minimize the chance of participants trying to explicitly learn or "figure out" the language during the experiment.

Concurrent working memory tasks.

Working memory task stimuli. The *n*-back task employed in the present study involved presenting one of six alphabetic letters (*P, G, T, K, W, C*) in 72 point sans-sheriff black font on a white background (see Figure 1). Letter case was randomized across trials to avoid reliance on visual recognition of the letter instead of a verbal label when required. The letter on a given trial appeared at random in 1 of 6 positions on the screen. The positions of the letters on the screen were not centered in verbalizable spatial locations (i.e., "top right" or "center" positions were avoided), but appeared in pseudorandom locations. Letter name and position were counterbalanced across trials so that each letter and position occurred with equal probability. Stimuli were presented for a duration of 500 milliseconds (ms), with an interstimulus interval of 2500ms.

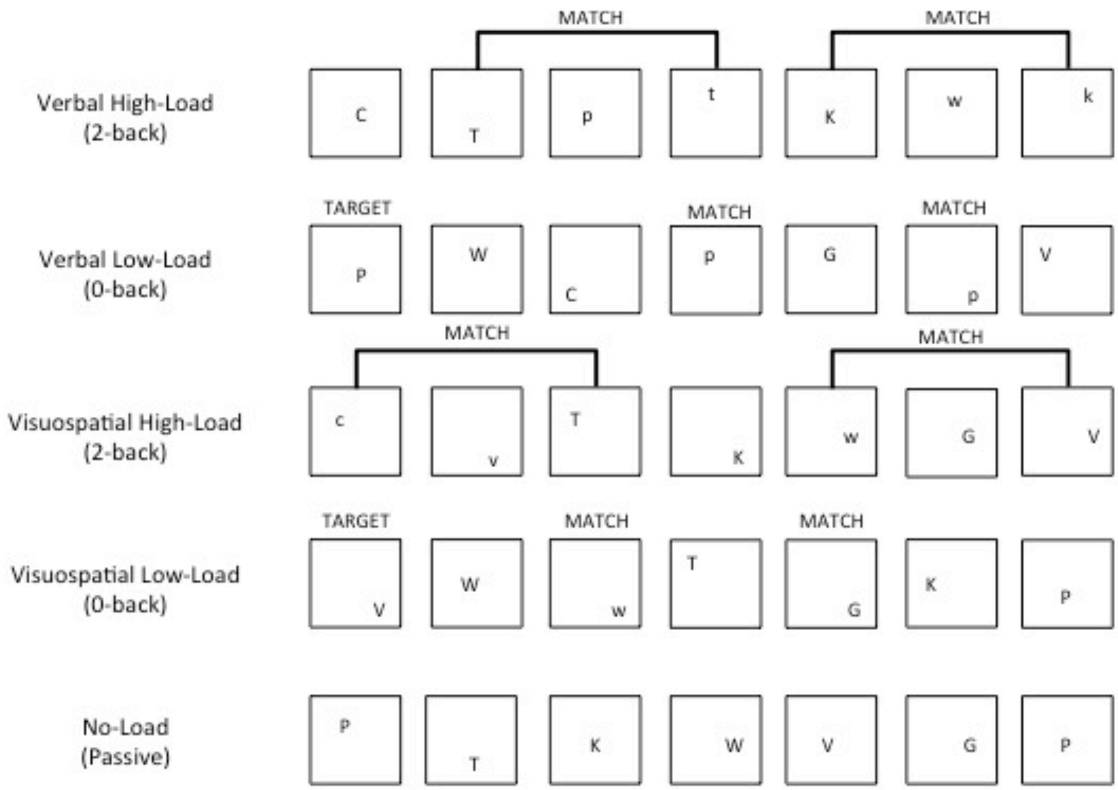

Figure 1. Schematic diagram of events in all task conditions.
Task conditions are labeled on the left-hand column. Each square represents a separate stimulus presentation within each task, as seen on a computer monitor for the participant. Stimuli were presented for 500ms, with a 2500ms blank screen in between each presentation. Correct responses within each *n*-back task condition are labeled "MATCH". Target stimuli for 0-back conditions are labeled "TARGET".

Working memory task procedure. Participants in *n*-back conditions received task instructions pertaining to their respective condition administered via E-Prime 2.08 (Schneider, Eschman, & Zuccolotto, 2002). A script of task instructions for each condition is provided in the Appendix. Stimuli were presented via laptop computer using E-Prime 2.08 software (Schneider et al., 2002). Equivalent stimuli were presented across conditions, while varying the type of processing and working memory requirements. Stimuli were presented concurrently with the artificial language stimuli in four blocks of seven minutes each. Each block contained a series of 140 trials, with matches in 30% of trials. All participants in experimental conditions completed 30 practice trials prior to the beginning of the task. Recall that the artificial language stimuli were presented to participants through headphones during engagement in the *n*-back task or control conditions. The *n*-back stimuli began immediately following the completion of the practice trials. Artificial language stimuli began playing as presentation of the *n*-back stimuli began.

The *n*-back task in the present study employed visuospatial and verbal material. In visuospatial task conditions, participants were instructed to look for matches across locations of stimuli on the screen. During instructions, the term “letter” was not used, and all instructional examples used a red square to demonstrate spatial location. This was done to ensure participants focused on visuospatial location and had no attachment to verbal letter labels. In verbal task conditions, participants were instructed to look for matches across letter names, regardless of letter case.

In 2-back conditions that imposed a heavy load on working memory, participants had to decide if a stimulus on each trial matched a stimulus occurring two trials previously (see Figure 1). This matching was performed on spatial locations for those in the high-load visuospatial working memory condition, and letter names for those in the verbal high-load working memory condition. Subjects had to update the sequence on each trial by retaining the most recent stimulus from two trials back. Subjects were instructed at the start of each block to press space each time they encountered a match to the 2-back stimulus.

In 0-back conditions that imposed a low working memory load, only the spatial location or verbal name of the first stimulus of each block had to be remembered and compared to subsequence stimuli. For those in a visuospatial condition, target locations at the onset of an experimental block were indicated by a red target square. Participants were informed of the target stimulus at the initiation of each block. Participants were instructed at the start of each block to press space each time they encountered a match to the target stimulus

In the No Load condition, participants saw the same sequence of stimuli that participants in the working memory task conditions were exposed to. However, they were not instructed to attend to or respond to the stimuli.

Test phase.

Test phase stimuli. Six nonword foils were constructed from the same 12 CV syllables as the artificial language: *pubati, tapudi, dupitu, tipabu, bidata, batipi*. Nonwords were created with the constraint that within word transitional probabilities would be zero based on the participants' previous artificial language exposure. Syllables were drawn from the same recording inventory as the artificial language stimuli, with appropriate coarticulation contexts.

Test phase procedure. Following the *listening phase,* participants immediately entered the *test phase* delivered by E-Prime 2.08 (Schneider et al., 2002). The test format was a two-alternative forced-choice task. Here, a word from the language was paired with a nonword foil in order to test the ability of participants to accurately identify words from the artificial language. For each test item, participants heard two trisyllabic strings separated by 500ms of silence. One of these strings was a word from the nonsense language, and the other a nonword foil. The presentation of a word/nonword pair was randomized across trials. Subjects were instructed to indicate which word "sounds more like something you heard in the language", and to select *"A"* or "*L*" on the keyboard to indicate the first or second string, respectively. The instructions stayed on the screen for the duration of the test phase. Each nonword was paired exhaustively with each word, comprising 36 total test pairs. E-Prime 2.08 software recorded responses automatically.

Data Analysis

It must be noted that, of necessity, the present study was not fully factorial. In the conditions involving a working memory task two factors were manipulated: Domain (verbal; visuospatial) and load (low; high). In both cases, performance was compared to a single control group, that is, the control group for 'no domain' and 'no load' was the same. As such, the study did not have a full 3 (no domain, verbal, visuospatial) x 3 (no load, low load, high load) design because the 'no domain' and 'no load' condition was the same. As a result, a single, omnibus analysis of variance (3 x 3 ANOVA) could not be completed on the data.

Instead, a single one-way ANOVA with a series of planned simple contrasts was conducted to compare the mean of select experimental groups to a reference standard, the control (no load/domain) group. Table 1 describes the contrasts that were conducted. To examine the effect of task domain of an explicit task on implicit learning, Contrast 1 compared the groups completing a verbal task regardless of load (low load; high load) to the control condition, and Contrast 2 compared the groups completing a visuospatial task (low load; high load) to the control group. To examine the effect of task load of an explicit task on implicit learning, Contrast 3 compared the groups completing a low load task regardless of task domain (verbal; visuospatial) to the control condition, and Contrast 4 compared the groups completing a high load task (verbal; visuospatial) to the control group. In the case of significant results in these contrasts, comparisons between relevant individual experimental groups (verbal, low load; verbal high load; visuospatial, low load; visuospatial, high load) and the control group utilizing post hoc tests of least significant difference were planned to examine mean differences between groups.

Table 1. Labeled planned simple contrasts with contrast coefficients from a one-way ANOVA comparing experimental groups to controls

	Condition				
Contrast	Control (no load)	Verbal low load	Verbal high load	Visuospatial low load	Visuospatial high load
1	-2	1	1	0	0
2	-2	0	0	1	1
3	-2	1	0	1	0
4	-2	0	1	0	1

Note. Values represent coefficient weights assigned within the regression model of each planned contrast.

Results

Recall that in the two-alternative forced-choice test, participants identified which of two words came from the artificial language to which they had been exposed during the study. Table 2 presents descriptive statistics of the word identification test scores for each group. The control group had the highest identification scores. Those in both the low load and high load verbal task conditions had the lowest scores, while those in the low load and high load visuospatial task conditions had scores somewhat lower than the control group.

Table 2. Means and effect sizes of word identification scores for each experimental group and controls

		Task domain	
Task Load	No domain	Verbal	Visuospatial
No load	Control		
M (SD)	24.36 (4.30)		
Low load			
M (SD)		21.05 (5.26)*	22.55 (4.15)
d^a		0.77	0.43
High load			
M (SD)		21.09 (4.31)*	21.64 (5.29)
d^a		0.76	0.56

* $p < .05$
Note. $n = 22$ for each group; *a*: Cohen's *d* effect size, calculated as effect size between independent experimental groups and the control group test scores.

Assessing the impact of task domain of an explicit task

The first series of simple contrasts compared word identification test scores across task domains (control, verbal, and visuospatial) within a one-way ANOVA. Levene's test of homogeneity of variances was nonsignificant, F (4, 105) = 0.609, $p > .05$, so equal variances were assumed when examining all contrast results. Contrast 1 comparing the verbal conditions (low and high load) to controls was significant, t (1, 105) = -2.692, p =

.008, indicating that those completing an explicit verbal task scored significantly lower than the control group. Contrast 2 comparing the visuospatial (low and high load) to controls was not significant, although results approached significance, t (1, 105) = -1.856, p = .066, indicating that those in either visuospatial task group did not differ from controls in their word identification scores. Results of post hoc tests on Contrast 1 revealed that those in both the verbal low load (p = .021) and the verbal high load (p = .023) groups had significantly lower word identification scores than controls. The overall one-way ANOVA comparing all groups was not significant, F (4, 105) = 9.917, p > .05.

Assessing the impact of task load of an explicit task

The second series of simple contrasts compared word identification test scores across task load (control, low load, and high load). Contrast 3 comparing the low load conditions (verbal and visuospatial) to controls was significant, t (1, 105) = -2.098, p = .038. Post hoc analyses revealed that those in the verbal low load task had significantly lower word identification scores than controls, p = .021. However, those in the visuospatial low load task did not differ significantly from controls, p > .05. Contrast 4 comparing the high load conditions (verbal and visuospatial) to controls was significant, t (1, 105) = -2.450, p = .016, indicating that those in a high load task group differed significantly from controls. Post hoc tests revealed that those in a verbal high load task had significantly lower word identification scores than controls, p = .023. Those in a visuospatial high load task did not differ significantly from controls in word identification scores, although the difference approached significance, p = .056.

Further investigation of marginally significant results

The results clearly demonstrate significantly lower word identification scores when participants were completing a concurrent explicit verbal task. The results for the visuospatial and cognitive load conditions were less clear, with marginal or contrasting results in both cases. Figure 2 displays the boxplots for all study groups. The data were normally distributed (skewness = -0.277 – 0.415; kurtosis = -1.436 – 0.484, all groups), yet the verbal high-load (kurtosis = -1.438) and visuospatial high-load (kurtosis = -1.107) groups were somewhat leptokurtic. As a result, additional evidence was sought for the pattern of significant findings revealed in the ANOVAs by comparing mean ranks in nonparametric analyses. Mann-Whitney *U* tests compared the word identification scores for each experimental group to the control group. Results revealed significantly lower word identification scores than controls for those completing a verbal task (low load: $U = 157.50$, $p < .05$; high load: $U = 143.50$, $p < .05$). Those in a visuospatial condition did not differ significantly from controls, and results did not approach significance (low load: $U = 189.00$, $p > .05$; high load: $U = 177.50$, $p > .05$). These results provide additional support for the nonsignificant findings in the ANOVA for the visuospatial compared to control conditions. Regarding the significant findings in the ANOVA for both the low and high load planned contrasts, the nonparametric analyses confirm that these significant findings were driven by the poor performance on the verbal tasks.

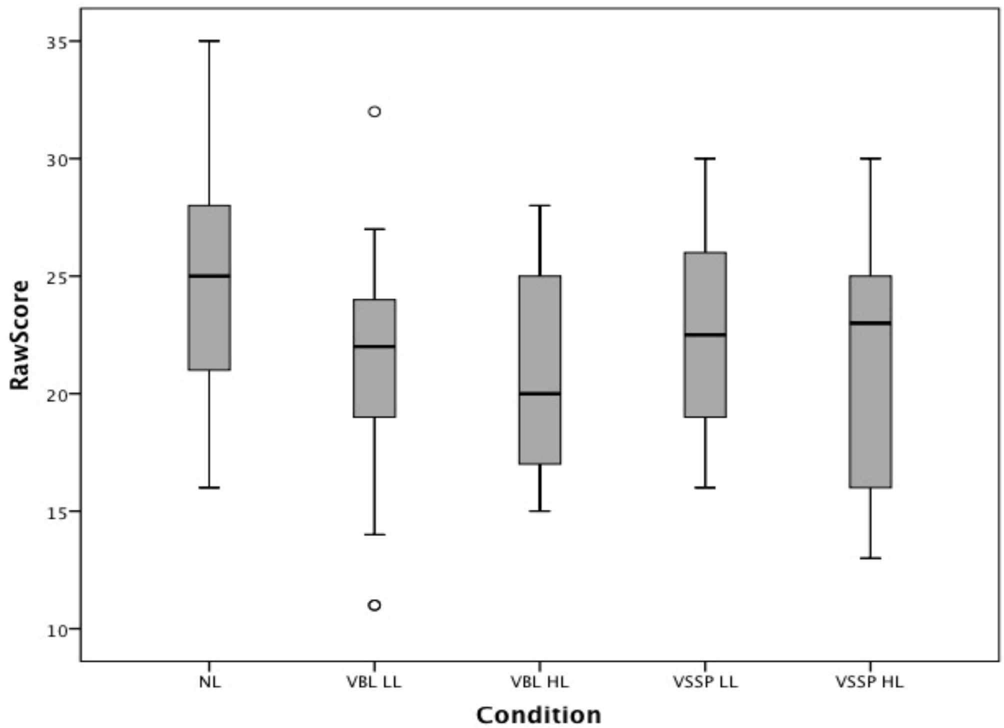

Figure 2. Boxplot of word identification test scores for experimental groups and controls
Note. Raw scores represent total test items correct out of 36. Condition labels are as follows: NL = no load; VBL LL = verbal working memory, low load; VBL HL = verbal working memory, high load; VSSP LL = visuospatial working memory, low load; VBL HL = visuospatial working memory, high load.

Analyzing working memory task scores

In order to ensure that the working memory tasks imposed differing processing loads as hypothesized, performance accuracy on the *n*-back task was compared across groups. Performance accuracy was calculated as a *d'* sensitivity score that takes into account both hits (i.e., correctly responding when required) and false alarms (i.e., incorrectly responding when a response is not required) (Macmillan & Creelman. 1991). *D*' values are presented as *z*-scores, and can be calculated as:

$$d' = z\ (hit\ rate) - z\ (false\ alarm\ rate)$$

Higher positive *d'* z-values represent a higher proportion of hits, with a value of 0 representing chance responding. Descriptive statistics for all groups completing a working memory task are shown in Table 3, and reveal generally higher scores for the low load conditions. A 2 (working memory domain) x 2 (working memory load) between-subjects ANOVA conducted on the *d'* scores revealed one significant effect: The main effect of task load was significant, $F\ (1, 68) = 79.156$, $p < .001$, with those in a low-load task having higher *d*' scores than those in a high-load task. The remaining effects were not significant (task domain: $F\ (1, 68) = .032$, $p > .05$; interaction: $F\ (1, 68) = 1.874$, $p > .05$).

Table 3. Descriptive statistics for working memory *d*' scores with means and standard deviations

	Task Domain		
Task Load	Verbal	Visuospatial	Task Load *M (SD)*
Low Load	3.99 (0.48)	3.72 (1.14)	**3.85 (0.89)**
High Load	1.57 (0.85)	1.93 (1.18)	**1.75 (1.03)**
Task Domain *M (SD)*	2.47 (1.45)	2.65 (1.45)	

Note. Bolded values significantly different at $p < .05$.

Discussion

The present thesis aimed to investigate the cognitive processes supporting statistical language learning by examining the influence of explicit domain-general or domain-specific working memory processing on implicit statistical word segmentation. In this study, adults were exposed to a statistical word segmentation paradigm while concurrently engaged in a working memory or control task. The working memory task varied across domain and load, creating four working memory task conditions: 1) verbal working memory, low load, 2) verbal working memory, high load, 3) visuospatial working memory, low load, and 4) visuospatial working memory, high load. After 28 minutes of exposure to an artificial language, word recognition abilities were analyzed and compared across working memory task groups. As expected, those in the control group (no working memory task) were able to identify words from the artificial language. Also, those concurrently completing either visuospatial working memory task, regardless of task load, chose words from the artificial language at above chance rates. However, those in a verbal working memory task condition, regardless of task load, had significantly lower word identification scores than controls.

Some participants in the present study demonstrated implicit statistical language learning of an artificial language. Those not engaged in any concurrent task performed above chance in choosing between foils and words from an artificial language after a relatively short exposure to the language. The language contained no additional cues to segment words except for the transitional probabilities within and between syllables. With such impoverished input, it is impressive that participants were able to correctly identify words from the language. This result supports previous findings of implicit statistical word segmentation (Saffran, Newport, et al., 1996), and demonstrates that transitional probabilities might be a cue aiding language learners in segmenting words from fluent speech.

Interestingly, statistical language learning was demonstrated in the present study even when participants were engaged in a concurrent task. Specifically, there were no implicit learning differences between groups engaged in a concurrent visuospatial working memory task and those with no concurrent task. This finding is similar to those from Saffran et al. (1997), in which participants were engaged in a drawing task while concurrently exposed to a statistical word segmentation paradigm. Saffran et al.'s participants were able to identify words from the artificial language, despite explicit task engagement (but see, Ludden & Gupta, 2000). Findings from the current study suggest engaging in an explicit secondary task does not necessarily impair statistical learning. Rather, the results support the idea that implicit statistical learning can occur incidentally, at least when concurrent task demands are visuospatial in nature: Occupying attention with a secondary task did not result in a reduction in implicit learning.

Nevertheless, implicit learning was impaired in some cases in the present study. Participants who were engaged in an explicit verbal working memory task while concurrently exposed to the artificial language were unable to identify words from the artificial language at test at the same level as controls. This finding provides clear evidence of an interference effect of an explicit domain-specific (verbal) working memory task on an implicit statistical language learning task. That is, engagement in explicit verbal processing imposed a limit on implicit verbal learning. Reduced levels of implicit learning have been demonstrated in previous studies when participants were engaged in an explicit secondary task (Ludden & Gupta, 2000; Toro et al., 2005). None of these previous studies, however, considered the domain-specificity of the task.

There are two possible explanations for the interference effect observed in the present study. The first and most compelling argument is that these results represent a true domain-specific finding. It may be that verbal working memory task demands interfered with verbal statistical learning, that is, explicit processing may have constrained implicit learning when material was being delivered in the same domain. One explanation for this interference effect is that the implicit and explicit systems supporting phonological processing are not separable mechanisms. Instead, a single mechanism may operate on similarly coded material. If this is the case, then engaging the mechanism explicitly would limit that mechanism's availability to support implicit learning, and reduced levels of implicit learning would be observed as in the present study. It is important to note that this interference may occur regardless of attentional status. That is, this hypothesis does not require a shift in attention away from an implicit signal and towards another, perhaps explicit, signal. But rather, this hypothesis requires sufficient processing capacity to code material regardless of it being delivered to the system via implicit or explicit processing.

It is interesting to speculate about a candidate process that could support implicit and explicit processing of phonological material. One possibility is the phonological loop component of working memory (Baddeley & Hitch, 1974). Perhaps, the phonological loop encodes information through both conscious and unconscious processes. Despite the focus on the role of the phonological loop in explicit serial recall tasks (Baddeley, 1996; Baddeley, Chincotta, Stafford, & Turk, 2002; Gathercole, Pickering, Hall, & Peaker, 2001), the phonological loop has been considered to support implicit phonological processing as well, as in the well-known cocktail party phenomenon (Cherry, 1953).

Findings such as this have led to the suggestion that phonological information gains obligatory access to the phonological loop regardless of attentional allocation at the time of initial encoding (Baddeley, 1986). Thus, one possible explanation for the domain-specific findings in the current study is that the phonological loop was engaged in processing the phonological information from both the explicit verbal working memory task and the artificial language. It is possible that the demands went beyond the capacity of the phonological loop resulting in reduced learning of the artificial language. Domain-specific capacity, then, may be important for the processing of incoming phonological information regardless of whether the task is implicit or explicit in nature. Further investigation would be needed to examine this influence.

A second explanation for the current findings is that the verbal but not visuospatial tasks imposed a sufficient constraint on attention or limited cognitive resources to impair learning. That is, the effects are due to a domain-general influence, with the particular pattern of findings in the present study related to the stimuli and methods employed. One factor systematically investigated in the present study was the impact of attention-demanding processing load. Statistical language learning being supported by attentional resources would have been suggested if performance was reduced in all experimental conditions. Or, support from domain-general executive processing resources would have been suggested if performance were reduced for those in either high-demand condition, with those in either low-demand condition spared. But, neither of these assumptions were supported: Reduced word identification was observed only for the concurrent verbal task groups, regardless of load. The contrast comparing those in either high-load condition (verbal and visuospatial) was significant, yet post-hoc analyses revealed that this result was due to the performance of those in the verbal high-load condition. Furthermore, results from the nonparametric analyses showed that the visuospatial high-load group did not differ significantly from controls. Additionally, there was no significant difference in performance on the statistical language learning task based on the processing demands (low- or high-load) of the explicit verbal tasks. Thus, general attentional demands of the secondary task or central executive processing load did not differentiate learning effects.

It could be that the attentional demands of the visuospatial and verbal tasks differed, making the effect appear domain-specific when, in fact, it was not. One possibility is that the visuospatial low load condition allowed the participant to focus on only one location to decide if the target was there or not, whereas the verbal low load condition required identification of each letter presented in order to decide if it was the target letter or not. However, response accuracy within the *n*-back task did not differ between the low-load verbal and visuospatial groups (or between the corresponding high load conditions), so a difference caused by secondary task stimuli was not evident. Thus, there is no evidence to suggest that task difficulty differed on a dimension other than working memory load. Given these findings, it would appear that the present study did not find an impact of domain-general processing on implicit statistical word segmentation. However, other domain-general mechanisms supporting statistical language learning cannot be ruled out.

What is important about these findings is the demonstration that implicit statistical language learning can help learners segment words, and there are some constraints on this learning process. Specifically, the availability of phonological processing capacity may be of particular importance. Of course, although statistical word segmentation may be a necessary cue aiding language learners, it is unlikely to be sufficient to surmount the task of language learning. Other cues coexist within natural language input, and the learner likely takes advantage of this combination of cues at all levels of language learning, from word segmentation to grammatical syntax (Romberg & Saffran, 2013; Sahni, Seidenberg, & Saffran, 2010). It is interesting to speculate that within natural language learning, phonological processing capacity may be an important constraint on the ability to combine the necessary cues to uncover regularities within language.

A potential limitation of the study design is that some differences between verbal and visuospatial working memory processes may have been masked if subjects were unable to ignore task irrelevant attributes. For example, in the visuospatial working memory condition participants were required to look for matches along the trait of spatial location of an alphabetic letter on a screen. However, it could be assumed that the participants in the present study were skilled readers and automatic processing of the letters occurred, regardless of task instruction. While it is possible that subjects encoded both verbal and spatial information in this manner, working memory task instructions specifically highlighted performing memory operations only on relevant stimuli. It is reasonable to assume that participants would have been unaware of patterns amongst the task-irrelevant stimulus attributes. Thus, it is unlikely that they performed memory comparisons on the task irrelevant features. Furthermore, it may have been that the cognitive demands of the visuospatial low-load condition were *too* low to elicit an effect on statistical language learning. As participants were attending to a 0-back match to a target stimuli presented at the onset of each experimental block, it could have been that participants "locked in" their visual focus on that spatial location for the duration of the task. Perhaps, then, participants did not need to engage in additional working memory processing, such as active updating or matching to the target stimuli. This would have been more likely in the visuospatial than the verbal 0-back condition, because those in the verbal 0-back condition would still be required to attend to a letter match that could have appeared in multiple locations on the screen. However, if the visuospatial low-load task were to elicit any processing cost to indicate a domain-general interference effect, we would have seen this in the visuospatial high-load task group as well, and this was not the case. Furthermore, *n*-back accuracy scores in verbal and visuospatial low-load conditions did not differ, suggesting equivalent processing costs across task domains.

A further limitation may be that word identification knowledge of participants could have been better assessed with a different testing methodology. The two-alternative forced-choice procedure used here involves the direct comparison of two exemplars, a word and a nonword. This test requires an explicit judgment of the stimuli. However, the stimuli were to be learned implicitly. Perhaps a procedure using a more implicit test of learning would be a more sensitive measure for determining word identification knowledge. Tests employing serial reaction time (e.g., Misyak, Christiansen, & Tomblin, 2010) or event-related potentials (e.g., Turk-Browne, Scholl, Chun, & Johnson, 2009) might be more suitable for future work. At present, however, the two-alternative forced-choice method is the most widely used amongst adult statistical learning studies, so it can be deemed appropriate for the present study.

Conclusion

It has been proposed that learning language occurs via an implicit statistical learning mechanism. This mechanism may be specifically useful for helping language learners discover the boundaries between words in fluent speech, a finding reliably demonstrated in past research (Saffran, Newport, et al., 1996). What remains poorly understood, however, are the cognitive processes that may support implicit statistical language learning. This thesis sought to examine how engaging in explicit domain-specific (verbal) or cross-domain (visuospatial) working memory tasks of either low or high demand would impair the implicit statistical learning of word boundaries in an artificial language. It was found that engaging in an explicit verbal working memory task of either low- or high- demand impaired the ability to uncover word boundaries, whereas engagement in a visuospatial working memory task did not. The results raise the possibility that implicit and explicit processing of phonological information is supported by a common mechanism, which could be the well-described phonological loop component of working memory.

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Appendix A: Scripts of Task Instructions (All Conditions)

No load

Listening Phase

Welcome to the experiment.

The listening phase will take place in 4 7-minute blocks, with 3-minute breaks in between each block.

You will hear a nonsense language play through your headphones.

Good luck!

Test Phase

Good work - you are almost finished!

Now, we will test your knowledge of the words in the nonsense language.

You will hear two words played through your headphones, one after another. Choose the word that sounds most like something you heard in the language.

There are 36 trials, and this will take about 3 minutes.

The words will come quickly, and can not be repeated, so listen closely.

To select the first word, press "A"

To select the second word, press "L"

Thank you for your participation in the experiment.

Please see the experimenter.

Visuospatial working memory – high-load

Welcome to the experiment.

This experiment will take place in four 7-minute blocks, with 3-minute breaks in between each block. There will be a short test phase at the end of the experiment.

Please make sure you are wearing your headphones.

Working Memory Task Instructions

You are going to see items presented in different locations on the screen, one at a time. Try to remember the positions of the items. Decide if the item on the screen is in the same position as the item you saw TWO BACK.

We will go through some instructions now to show you what we mean.

You will see items come up one at a time in different positions on the screen.

You might see an item here...

Or here...

Or maybe here...

Or in other positions on the screen.

Items will come up on the screen one at a time. The image on the left shows a sequence of screens you might see. Remember the positions of the items you see. When you see a match for an item TWO BACK press SPACE.

Screen 4 is a match for screen 2 in our sequence. It is a match because the item was in the same position TWO BACK. You would press SPACE when the item on screen 4 popped up.

The computer is going to show an example. Try to remember the positions of the items. Decide if the item on the screen is in the same position as the item you saw TWO BACK. When you see a match, press SPACE.

MATCH - Press SPACE

Remember, the red square was in the same spot TWO BACK.

MATCH - Press SPACE

Remember, the red square was in the same spot two steps back.

You can have two matches overlapping. The pattern always continues, even if you have pressed SPACE for a match in between.

You are always looking for an item in the same position as TWO BACK.

Look at the matches in this sequence.

Screen 4 is a match for screen 2.

Screen 5 is a match for screen 3.

The pattern continues, even though the matches overlap.

The computer is going to show an example. Try to remember the positions of the items.

Decide if the item on the screen is in the same position as the item you saw TWO BACK.

When you see a match, press SPACE.

Remember, the pattern continues, even when you have a match in between.

MATCH - Press SPACE

Remember, the red square was in the same spot two steps back.

MATCH - Press SPACE

Remember, the red square was in the same spot two back, and it's still a match even though we had another match in between.

The pattern also continues even if an item was already used as a match.

Here, screen 3 is a match for screen 1.

Screen 5 is a match for screen 3.

The pattern continues. Even though screen 3 was already a match, it is still possible for an item in the same position to be a match two steps after it.

The computer is going to show an example. Try to remember the positions of the items.

Decide if the item on the screen is in the same position as the item you saw TWO BACK.

When you see a match, press SPACE.

Remember, the pattern continues. Even if an item was already used as a match (you pressed SPACE for it), it could have a match two steps after it.

MATCH - Press SPACE

Remember, the red square was in the same spot two steps back.

MATCH - Press SPACE

Remember, the red square was in the same spot two steps back. The pattern continues, even though we already had the same match before.

Now that we have given you the instructions, you will do some practice trials that look like the real experiment.

Remember the positions of the items. Press SPACE when an item is in the SAME POSITION as the item from TWO BACK. And remember, the pattern continues, even if you have matches overlapping, or an item was already used as a match.

Answer quickly.

Good work!

We have now finished doing the practice. We are going to start the real experiment.

While you are doing the real experiment, you will hear a nonsense language play through your headphones.

Please make sure your headphones are on.

You will now have a 3-minute break.

If you have any questions, please ask the experimenter.

Do not leave the computer lab.

Test Phase

Good work - you are almost finished!

There were words contained within the nonsense language that played throughout the experiment.

Now, we will test your knowledge of the words in the nonsense language.

You will hear two words play through your headphones, one after another. Choose the word that sounds most like something you heard in the language.

There are 36 trials, and this will take about 3 minutes.

The words will come quickly, and cannot be repeated, so listen closely.

To select the first word, press "A"

To select the second word, press "L"

Choose the word that sounds most like something you heard in the language.

First Word: A   Second Word: L

Thank you for your participation in the experiment.

Please see the experimenter before leaving.

Visuospatial working memory – low-load

Welcome to the experiment.

This experiment will take place in four 7-minute blocks, with 3-minute breaks in between each block. There will be a short test phase at the end of the experiment.

Please make sure you are wearing your headphones.

Working Memory Task Instructions

You are going to see items presented in different locations on the screen, one at a time. You will be asked to watch for items in a particular position. This is your TARGET position. Remember this position. You will need to press the SPACE BAR each time you see an item in the SAME spot as your TARGET position. You will be told the target position at the beginning of each 7- minute block.

We will go through some instructions now.

The red square tells you the position to watch for:

You will see items in different positions around the screen.

You might see an item here...

Or here...

Or maybe here...

Or in other positions on the screen.

You will be told to remember a particular TARGET position, and press SPACE each time an item shows up in that target position.

Be sure to remember this spot, and answer quickly.

For items in spots that are NOT the target position,

DO NOT press SPACE.

The computer is going to show an example...

You will be told to remember a particular TARGET position, and press SPACE each time an item shows up in that target position.

Be sure to remember this spot, and answer quickly.

For items in spots that are NOT the target position,

DO NOT press SPACE.

The computer is going to show an example...

This is the TARGET position.

Press SPACE only when an item is in the same spot as the target position.

NO MATCH - DO NOT press SPACE

NO MATCH - DO NOT press SPACE

MATCH - Press SPACE

NO MATCH - DO NOT press SPACE

MATCH - Press SPACE

Now that we have given you the instructions, you will do some practice trials that look like the real experiment.

Your target position will be presented on the next screen for 3 seconds. Remember this spot. Press SPACE when an item is in the same spot as the target position. Answer quickly.

Good work!

We have now finished doing the practice. We are going to start the real experiment.

While you are doing the real experiment, you will hear a nonsense language play through your headphones.

Please make sure your headphones are on.

Your target position will be displayed on the next screen for 3 seconds. Remember this position.

Test Phase

Good work - you are almost finished!

There were words contained within the nonsense language that played throughout the experiment.

Now, we will test your knowledge of the words in the nonsense language.

You will hear two words play through your headphones, one after another. Choose the word that sounds most like something you heard in the language.

There are 36 trails, and this will take about 3 minutes.

The words will come quickly, and can not be repeated, so listen closely.

To select the first word, press "A"

To select the second word, press "L"

Choose the word that sounds most like something you heard in the language.

First Word: A Second Word: L

Thank you for your participation in the experiment.

Please see the experimenter before leaving.

Verbal working memory – high-load

Welcome to the experiment.

This experiment will take place in four 7-minute blocks, with 3-minute breaks in between each block. There will be a short test phase at the end of the experiment.

Please make sure you are wearing your headphones.

Working Memory Task Instructions

You are going to see letters presented on the screen, one at a time.

Try and remember the letters you see. Determine if the letter currently on the screen is a match in letter name to the letter from TWO BACK. Press SPACE when you see a match.

We will go through some instructions now to show you what we mean.

You will see letters come up one at a time on the screen.

You might see a letter like this...

Or this...

Or this...

Or some other English letters.

Notice how the letters were in upper and lower case.

The image on the left shows an example of screens that might come up, one at a time, in the experiment.

You need to look for when the screen is a letter name match for the screen from TWO BACK.

Screen 4 is a match for screen 2. It is a letter name match from TWO BACK. You would press space as soon as you saw the match on screen 4 pop up. (Case does not matter, what matters is letter name)

The computer is going to show an example. Try and remember the letters you see.

Determine if the letter currently on the screen is a match in letter name to the letter from TWO BACK. Press SPACE when you see a match.

Remember, case does not matter. What matters is letter name.

Answer quickly.

MATCH - Press SPACE

Remember, you saw a "W" TWO BACK.

MATCH - Press SPACE

Remember, you saw a "C" TWO BACK.

It is still a match, even though the case of the letters was different.

You can have two matches cross over. The pattern always continues. Even if you have pressed SPACE for one match, the next item could also be a matching item, where you need to press SPACE again.

Look at the sequence on the left.

Screen 4 is a match for screen 2.

Screen 5 is a match for screen 3.

The pattern continues, even though the matches cross over. You are always trying to remember what was TWO BACK.

The computer is going to show an example. Try and remember the letters you see. Determine if the letter currently on the screen is a match in letter name to the letter from TWO BACK. Press SPACE when you see a match.

Remember, the pattern continues, even if matches cross over.

Answer quickly.

MATCH - Press SPACE

Remember, you saw a "T" TWO BACK.

MATCH - Press SPACE

Remember, you saw a "P" TWO BACK, and it's still a match even though the matches cross over.

The pattern also continues even if an item was already a match, and you pressed SPACE.

Screen 3 is a match for screen 1, and screen 5 is a match for screen 3 - even though you already pressed SPACE for screen 3, it can still have a match come after it.

You are always trying to remember what was TWO BACK.

The computer is going to show an example. Try and remember the letters you see.

Determine if the letter currently on the screen is a match in letter name to the letter from TWO BACK. Press SPACE when you see a match.

Remember, the pattern continues, even if the item was already used as a match.

MATCH - Press SPACE

Remember, you saw a "G" TWO BACK.

MATCH - Press SPACE

Remember, you saw a "G" TWO BACK. The pattern continues, even though we already had the same match before.

Now that we have given you the instructions, you will do some practice trials that look like the real experiment.

Remember the names of the letters. Press SPACE when you see the SAME LETTER as the letter from TWO BACK. And remember, the pattern continues, even if you have matches overlapping, or an item was already used as a match.

Answer as quickly as possible.

Good work!

We have now finished doing the practice. We are going to start the real experiment.

While you are doing the real experiment, you will hear a nonsense language play through your headphones.

Please make sure your headphones are on.

Test Phase

There were words contained within the nonsense language that played throughout the experiment.

Now, we will test your knowledge of the words in the nonsense language.

You will hear two words play through your headphones, one after another. Choose the word that sounds most like something you heard in the language.

There are 36 trails, and this will take about 3 minutes.

The words will come quickly, and can not be repeated, so listen closely.

To select the first word, press "A"

To select the second word, press "L"

Choose the word that sounds most like something you heard in the language.

First Word: A   Second Word: L

Thank you for your participation in the experiment.

Please see the experimenter before leaving.

Verbal working memory – low-load

Welcome to the experiment.

This experiment will take place in 4 7-minute blocks, with 3-minute breaks in between each block. There will be a short test phase at the end of the experiment.

Please make sure your headphones are on.

Working Memory Task Instructions

You are going to see different letters presented on the screen, one at a time.

You will be asked to watch for a particular letter. This is your TARGET letter. Remember this letter. You will need to press the SPACE BAR each time you see a MATCH to the TARGET letter. The match can be in upper or lower case, as long as it's the same letter-name. You will be told the target letter at the beginning of each 7-minute block.

We will go through some instructions now.

You will see different letters on each screen.

They might look something like this...

Or some other letters, in either upper or lower case.

You will be told to remember a particular TARGET letter. Press the SPACE BAR each time you see a MATCH, either upper or lower case, for the target letter.

Be sure to remember this letter, and answer quickly.

For letters that are DIFFERENT, DO NOT press SPACE.

The computer is going to show an example...

MATCH - Press SPACE

Now that we have given you the instructions, you will do some practice trials that look like the real experiment.

Your target letter will be in red, and displayed on the next screen for 3 seconds.

Remember this letter. Press SPACE every time you see a match for this letter. Answer quickly.

We are now finished doing the practice. We are going to start the real experiment.

While you are doing the real experiment, you will hear a nonsense language play through your headphones.

Please make sure your headphones are on.

Your target letter, in red, will be displayed on the next screen for 3 seconds. Remember this letter.

Test Phase

Good work - you are almost finished!

There were words contained within the nonsense language you heard throughout the experiment.

Now, we will test your knowledge of the words in the nonsense language.

You will hear two words play through your headphones, one after another. Choose the word that sounds most like something you heard in the language.

There will be 36 trials, and this will take about 3 minutes.

The words will come quickly and can not be repeated, so listen closely.

To select the first word, press "A"

To select the second word, press "L"

Choose the word that sounds most like something you heard in the language.

First Word: A   Second Word: L

Thank you for your participation in the experiment.

Please see the experimenter.

Appendix B: Ethics Approval

Department of Psychology The University of Western Ontario
Room 7418 Social Sciences Centre,
London, ON, Canada N6A 5C1
Telephone: (519) 661-2067Fax: (519) 661-3961

Use of Human Subjects - Ethics Approval Notice

Review Number	12 10 32	**Approval Date**	12 10 24
Principal Investigator	Lisa Archibald/Nicolette Noonan	**End Date**	13 10 23
Protocol Title	Working memory and learning		
Sponsor	n/a		

This is to notify you that The University of Western Ontario Department of Psychology Research Ethics Board (PREB) has granted expedited ethics approval to the above named research study on the date noted above.

The PREB is a sub-REB of The University of Western Ontario's Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement and the applicable laws and regulations of Ontario. (See Office of Research Ethics web site: http://www.uwo.ca/research/ethics/)

This approval shall remain valid until end date noted above assuming timely and acceptable responses to the University's periodic requests for surveillance and monitoring information.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the PREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of research assistant, telephone number etc). Subjects must receive a copy of the information/consent documentation.

Investigators must promptly also report to the PREB:
a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to the PREB for approval.

Members of the PREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the PREB.

Clive Seligman Ph.D.

Chair, Psychology Expedited Research Ethics Board (PREB)

The other members of the 2012-2013 PREB are: Mike Atkinson (Introductory Psychology Coordinator), Rick Goffin, Riley Hinson Albert Katz (Department Chair), Steve Lupker, and TBA (Graduate Student Representative)

CC: UWO Office of Research Ethics

This is an official document. Please retain the original in your files

Curriculum Vitae

Name: Nicolette Noonan

Post-secondary Education and Degrees:
University of Western Ontario
London, Ontario, Canada
2008-2012
B.A. Psychology, Honours Specialization

University of Western Ontario
London, Ontario, Canada
2012-Present
M.Sc. Health and Rehabilitation Sciences
(Speech and Language Sciences)

Honours and Awards:

Western Graduate Research Scholarship
2012-Present

John A. McNee Award in Political Science
2009

Western Scholarship of Excellence
2008-2009

Related Work Experience:

Health Science 2000B: Teaching Assistant
The University of Western Ontario
2014

Research Assistant to Dr. Lisa Archibald
Language and Working Memory Lab, Department of Communication Sciences and Disorders
The University of Western Ontario
2012-Present

Publications:

Noonan, N. B., Redmond, S. M., & Archibald, L. M. D. (*2014*). Contributions of children's linguistic and working memory proficiencies to their judgments of grammaticality. *Journal of Speech, Language, and Hearing Research*.