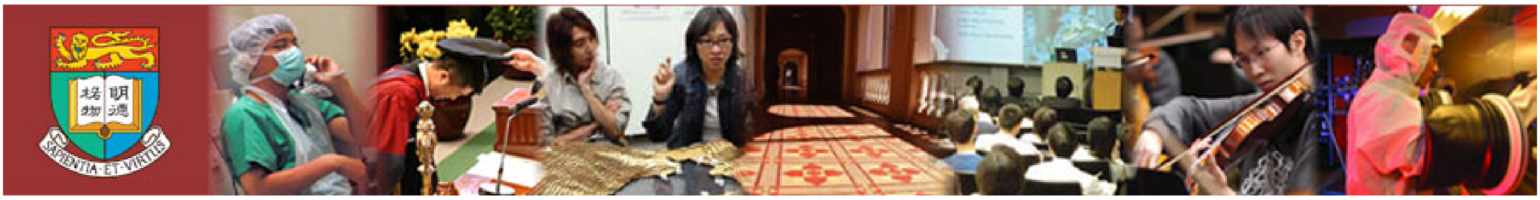

Title	Phonological short-term memory capacity and non-adjacent dependency-learning
Author(s)	Mo, Wing-yi; 毛穎怡
Citation	Mo, W. [毛穎怡]. (2014). Phonological short-term memory capacity and non-adjacent dependency-learning. (Thesis). University of Hong Kong, Pokfulam, Hong Kong SAR.
Issued Date	2014
URL	http://hdl.handle.net/10722/238931
Rights	

Phonological Short-term Memory Capacity and Non-Adjacent Dependency-Learning

Mo Wing Yi

A dissertation submitted in partial fulfilment of the requirements for the Bachelor of Science (Speech and Hearing Sciences), The University of Hong Kong, June 30, 2014.

Phonological Short-term Memory Capacity and Non-Adjacent Dependency-Learning

Abstract

This study investigated the relationship between phonological short-term memory capacity and non-adjacent dependency-learning. Forty university students were exposed to four-element strings in which the first element was dependent to the last element. Participants were then tested with a discrimination task in which they were required to discriminate the trained dependencies from the untrained ones. Participants were also tested on their phonological short-term memory capacity and nonverbal intelligence. Results demonstrated that the performance of the discrimination task was positively correlated with the phonological short-term memory capacity. The study suggested that the non-adjacent dependency-learning performance increased with the phonological short-term memory capacity providing implication on typical and atypical language acquisition.

Introduction

Dependency learning and language acquisition

Dependency is a regularity embedded in a sequence of elements, such that an element is dependent on the preceding element, or one element can predict the next element. It can exist in simple sequences (*e.g.*, counting, singing musical notes in scale, and tying shoelaces) or in high-level cognitive tasks relating to event knowledge (*e.g.*, cooking a dish or buying things in the supermarket), analysis and planning. Therefore, many activities in daily life involved dependencies. Researchers have suggested that dependencies can be learnt rapidly, implicitly and invariant of age (Saffran, Aslin, & Newport, 1996; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). Some dependencies are more predictable and easier to learn but some are not. Mechanism of learning the dependencies, especially those embedded in sound strings, has gained researchers' interests. Researchers have defined dependency learning as the abstraction and generalization of the dependencies after an extensive exposure of exemplars of the sequences that share the same regularity (Saffran, 2001). They have characterized the mechanism of dependency learning through investigating and comparing the ability of participants to acquire the dependencies, with various features, such as variability (Gómez, 2002) and acoustic similarity (Creel, Newport, & Aslin, 2004), or under different learning conditions such as modality of exposure (visual *vs*. auditory; Frank and Gibson, 2011), or with different participant features such as age group (Saffran et al., 1997).

Researchers have suggested that dependency learning may play a critical role in different aspects of language acquisition, including word segmentation, syntax and morphology (Morgan, Meier, & Newport, 1987; Saffran, et al., 1996; Saffran, 2002). In the formation of linguistic phrases and words, the existence of some word classes or morphemes may form dependencies, governed by grammar. Inflection is the change of word form by adding an inflectional morpheme to a word while derivation is the change of word class or word meaning by adding a derivational morpheme (Bubeník, 1999). The use of these grammatical morphemes frequently involves dependencies. There are two types of dependencies which commonly exist in both inflectional (*e.g.*, English) and non-inflectional language (*e.g.*, Chinese). Adjacent dependency is the dependency between two consecutive elements. Examples in languages are the dependencies between subjects and verbs (*e.g.*, I go, She writes), those between determiners and nouns (*e.g.*, a car, an apple, the orange), and those between derivational morphemes *un*- and adjectives or adverbs (*e.g.*, unhappy, unfortunately) in English, and the dependencies between degree adverbs and adjectives in Chinese (*e.g.*, 很開心, 更漂亮). Non-adjacent dependency is the dependency between two consecutive elements with intervening elements in between. Examples in languages are the dependencies between auxiliaries and inflectional morphemes in English (*e.g.*, is eating, has fallen), those between temporal adverbs and post verb particles (*e.g.*, 曾經去過, 仲未食得), and those between prepositions and action verbs (e.g., 妹妹被哥哥讚, 姐姐把褲摺好, 弟弟

向媽媽揮手) in Chinese. Through investigating the mechanism of dependency learning, researchers may learn more about the mechanism of language acquisition.

Constraints of non-adjacent dependency learning

Researchers proposed that the mechanism of learning non-adjacent dependencies involved more constraints than that of learning adjacent dependencies. They also found that some types of non-adjacent regularities were easier to learn than the others. Gómez (2002) first studied the constraints of element variability using auditory strings. Forty eight adult learners (undergraduate students) and forty eight infant learners aged 18 months 18 days in average were exposed to the successive *AXB* units in which the elements *A* and *B* form dependencies. The adult learners were exposed to three dependencies (*e.g., pel-puser-rud, vot-puser-jic, and dak-fengle-tood*) with different set-size (*2, 6, 12, or 24*) of middle intervening *X* elements, while the infants learners were exposed to two dependencies and *X* elements with set-size *3, 12 or 24*. The participants were then tested to discriminate the trained dependencies from the untrained ones. The adult learners responded through pressing a keyboard while the infant learners responded though head turning. The results showed that the degree to which the non-adjacent dependency *A_B* was learnt increased evidently under situations of greatest variability of *X* in both adults and infants. Gómez suggested that if *X* was more variable, the adjacent dependency (*i.e., AX* and *XB*) were less stable to be learnt, and therefore people changed their attention to the relatively stable non-adjacent dependency (*i.e.*, *A_B*).

While some researchers studied the mechanism of non-adjacent dependency learning through manipulating the features of the regularities, Frank and Gibson (2011) proposed that memory constraints of learners might also contribute to the failures in non-adjacent dependency-learning tasks. The memory constraints they referred to was the capacity to retain the stimuli for sufficient duration for learning. They replicated Gómez’s (2002) study but alleviated the memory demand on adult learners by presenting visual stimuli concurrently instead of presenting auditory stimuli sequentially. Sixteen adult learners (undergraduate students) were presented with the *AXB* units written on separate index cards, followed by a discrimination test. In this condition, the adult learners were able to learn the non-adjacent dependencies with only six *X* elements, which were shown to be hard for participants to acquire via sequential auditory presentation in Gómez’s study. Frank and Gibson suggested that the memory constraints limited the accessibility of the stimuli for the process of abstracting the dependencies. However, they could not verify whether the ease of abstracting the dependencies was due to the reduced memory demand only, or due to the difference between auditory processing versus visual processing, or both. Also, they study the memory factor though reducing the memory demands of the dependency learning task only, but not increasing the memory demands or varying the memory capacity of individuals.

Objective of the current study

Given that Gómez (2002) used sequential auditory presentation, the memory constraint could be referred as the capacity to retain the auditory information. This capacity was termed as phonological short-term memory capacity (Baddeley, 2010). However, everyone had different memory capacity, the dependency learning effect of individuals with different memory capacities might also vary. The research gap was that whether there might be a possible relationship between phonological short-term-memory (*STM*) capacity and non-adjacent dependency-learning (*NAD*-learning) when the auditory stimuli were sequentially presented. We hypothesized that the participants having larger phonological STM capacity would have better performance in learning the non-adjacent dependencies. It was because storing of more string stimuli would allow more information to be processed when abstracting their regularities. Therefore a positive correlation between the phonological *STM* capacity and the *NAD*-learning performance was expected. If this was the case, it would further our understanding on typical and atypical language acquisition, for example, specific language impairment (*SLI*). Researchers found that *SLI* frequently co-occurred with phonological short-term memory deficits, which may underpin the language learning difficulties (Archibald & Gathercole, 2006; Montgomery & Evans, 2009).

The purpose of the current study was to investigate the relationship between phonological *STM* capacity and *NAD*-learning performance in adults. Apart from the performance in *NAD*-learning, which was represented by the performance scores in the discrimination task, and the phonological *STM* capacity in recalling digits, pseudomorphemes and pseudosyllables, we also measured the participant's nonverbal intelligence. Brooks, Kempe and Sionov (2006) found that nonverbal intelligence correlated with their artificial language learning task, which was similar to a dependency learning task. Therefore, we should take the individual differences in nonverbal intelligence into account. The study investigated the correlation of the performance in *NAD*-learning task and the phonological *STM* capacity with the nonverbal intelligence as a control variable.

Method

Participants. Forty undergraduate students at the University of Hong Kong, the Chinese University of Hong Kong and the Hong Kong Polytechnic University, aged between 18 years old to 23 years old, participated in this study. All participants were reported to have normal hearing.

Design. Each participant completed a *NAD*-learning task, three phonological *STM* tests and a nonverbal intelligence test. The *NAD*-learning task involved a training phase and a testing phase. In the training phase, each participant was assigned to one of the two groups following Gómez (2002) design.

Stimuli. The artificial language used in the *NAD*-learning task was adopted from Gómez (2002), adjusting the syllables to Cantonese pseudosyllables, with set size equaled to 24. The artificial languages were phrases formed from four syllables. Each syllable was checked using the Chinese character database: with word-formations phonologically disambiguated according to the Cantonese dialect (Research Centre for Humanities Computing, Chinese University of Hong Kong, 2003) to ensure that it was not exist in Cantonese.

In the training phase, each participant listened to auditory strings generated by one of the two artificial languages (*L1* or *L2*, shown in *Fig*.1). *L1* was formed from the combination of *aXd*, *bXe* and *cXf*, while *L2* was formed from the combination of *aXe*, *bXf* and *cXd* with each of the 24 X elements. The elements *a*, *b*, *c*, *d*, *e* and *f* were */p*^{h}*ɛp*^{1}*/*, */fɔt*^{1}*/*, */tɛk*^{1}*/*, */tsɪŋ*^{4}*/*, */t*^{h}*un*^{4}*/* and */wyn*^{4}*/* respectively. A full list of elements used to construct the training strings was presented in Appendix 1. In the testing phase, testing strings were formed from *aXd, bXe* and *cXf,* with their counter pair *aXe, bXf* and *cXd* accordingly, with one pair in each trial. Testing strings were divided into two types, namely trained string, in which the *X* elements used for combination were chosen from the training materials, and generalized string in which the *X* elements used for combination were untrained (generalized) items. Four trained *X* element and four untrained (generalized) *X* elements were used to construct the testing strings for both *L1* and *L2*. A full list of elements used to construct the testing strings was presented in Appendix 2. Word tokens were used to generate both *L1* and *L2* strings. They were used for eliminating the talker-induced difference in each string. There were 250-*ms* pauses between each syllable and 750-*ms* pauses between each string such that the participant would be able to distinguish syllables and strings.

Language 1 (*L1*)			Language 2 (*L2*)		
S→{	*aXd*		*S*→{	*aXe*	
	bXe			*bXf*	
	cXf	}		*cXd*	}

$X \rightarrow x_1, x_2, \ldots x_{24}$

Figure 1. Structure of the languages used.

There were three tests to measure the phonological *STM* capacity of participants. For the digit span forward test, stimuli were adopted from the digit span subtest in the Wechsler Adult Intelligence scale – Fourth Edition (*WAIS–IV*; Wechsler, 2008a). More items (*no*. 9-13) were added to avoid the ceiling effect. For the nonword repetition tests with pseudomorphemes and with pseudosyllables, the stimuli were adopted from the nonword repetition test in the Hong Kong Cantonese Oral Language Assessment Scales (*HKCOLAS*; T'sou et al., 2006). One more trial was added for each trial to increase the reliability. A full list of test items in the phonological *STM* tests was presented in Appendix 3. A female speaker recorded all auditory stimuli using a software *AD Sound Recorder (version 3.8*). Each participant listened to the auditory stimuli using a headphone (*Panasonic RP-HT090*).

Procedure. Participants were randomly assigned to one of the two artificial language groups (*i.e., L1* and *L2*). During the training phase of the *NAD*-learning task, participants were instructed to listen to a novel language for a test that followed. They listened to six iterations of training strings in which each contained 72 training strings (3 dependencies × 24 *X* elements). Training phase lasted approximately 32 minutes. Prior to the discrimination test, the participants were instructed that the strings they had listened in the training phase were forming from regularities related to the word order, and they would now hear two auditory strings in each trial, with one followed the same word order as in the training strings, while one did not. They were instructed to press the left button if they thought that the first string followed the regularities and press the right button if they thought that the second string followed the regularities. There were 24 test trials in total.

After the *NAD*-learning task was the phonological *STM* tests. The participants were instructed to recall what they heard after presentation of each testing string and the first test involved number, the second test involved character (pseudomorphemes) and the third test involved non-character (pseudosyllables). Each span (number of digits or syllables) of strings had two trials. If the recall was correct for at least one trial, the span would be increased. This procedure was repeated until the participants recall inaccurately for both trials. The process was audio recorded.

The final test was the nonverbal intelligence test. Raven's Advanced Progressive Matrices (*APM*; Raven, Raven, & Court, 1998d) was conducted. The participants were instructed to finish Set I and Set II without a time limit.

Scoring procedure. For the *NAD*-learning test, the participants' scores were the numbers of correct answers in the discrimination task, with 24 as the maximum. For the phonological *STM* tests, the participants' scores for each part were the numbers of trials that they recalled correctly in that part. For the nonverbal intelligence test, the participants' scores were the numbers of correct answers counting for both set I and set II, with 48 as the maximum.

Results

Non-Adjacent Dependency-Learning

Table 1 presents the means and the standard deviations for the scores of the participants in trained strings and the generalized strings, and for the overall scores of the participants (the sum of scores for trained and generalized strings) in each of the two artificial language groups (*L1* and *L2*)

Table 1

Mean scores in NAD-Learning testing phase for trained string and generalized string

Artificial		Non-Adjacent Dependency-Learning		
Language Group	*N*	Trained String	Generalized String	Overall
L1	20	7.05	6.50	13.55
		(2.19)	(2.54)	(4.32)
L2	20	7.60	7.10	14.80
		(2.44)	(2.85)	(4.96)

Standard Deviations appear in parentheses below means.

A mixed design 2-by-2 two-way analysis of variance (*ANOVA*), with artificial language groups (*L1 vs*. *L2*) as a between-subjects variable and string types (trained *vs*. generalized) as a within-subjects variable, was first carried out. There were no significant main effects of artificial language materials, F (1, 38) = .62, p = .44, and string types, F (1, 38) = 2.76, p = .11. There was also no significant interaction effect between artificial language groups and string types, F (1, 38) = .01, p = .94. As there was no significant difference either between the language groups or between the string types, the data was collapsed across language groups and string types in the following analyses. A one sample t-test was carried out to test whether participants' performance was significantly above chance level. The mean of the overall scores for all participants was 14.20, which was significantly different from chance level, t (39) = 3.0, p < .05. This finding suggests that participants were able to discriminate the trained non-adjacent dependencies from the untrained ones.

Correlation between Non-Adjacent Dependency-Learning and Phonological Short-term Memory Capacity

Table 2 presents the means and the standard deviations for the scores in the *NAD*-learning test, the phonological *STM* tests and the nonverbal intelligence test. The Pearson correlation analysis was first carried out to study the relationships between the performance of the *NAD*-learning and the phonological *STM* capacity. There was a significant positive correlation between the scores for the *NAD*-learning test and the scores for the nonword repetition test with pseudomorphemes, r = .383, p < .05, and that with pseudosyllables, r = .346, p < .05. There was a marginal significant positive correlation between *NAD*-learning test and the scores for the digit span forward test, r = .307, p = .05.

There was also a marginal significant correlation between the scores for the nonverbal intelligence test and the scores for the *NAD*-learning test, $r = .264$, $p = .10$. Thus, nonverbal intelligence was controlled to reveal a pure measure of the relationship between the *NAD*-learning performance and the phonological STM capacity. Results show a significant positive correlation between the scores for the *NAD*-learning test and the scores for the nonword repetition test with pseudomorphemes, $r = .370$, $p < .05$, and that with pseudosyllables, $r = .338$, $p < .05$, suggesting that the *NAD*-learning performance increased with the phonological *STM* capacity.

Table 2

Means and standard deviations for Principal Measures (N=40)

Measures	*M*	*SD*
NAD-learning Test	14.20	4.63
Phonological Short-term Memory Test		
Digit Span Forward Test	16.48	3.43
Nonword Repetition Test with Pseudomorphemes	9.35	2.32
Nonword Repetition Test with Pseudosyllables	5.33	1.99
Nonverbal intelligence Test	43.23	3.29

The following was the summary of the main findings for the result analysis. First, the performance of *NAD*-learning did not vary with the artificial language materials and the string types tested. Second, the participants had an above-chance performance in the *NAD*-learning test. And most importantly, answering the research question, the *NAD*-learning performance of the participants increased with the phonological *STM* capacity.

Discussion

The following discussion focus on four particular issues: first, the learning effect of the *NAD*-learning task in our study; second, the relationship between phonological *STM* capacity and the learning effect; third, the implications on future researches and on language acquisition; and forth, the suggestions on further studies.

Learning effect on the Non-Adjacent Dependency-Learning task

Before studying the relationship between phonological *STM* capacity and *NAD*-learning, we had to verify that the *NAD*-learning task in this study could allow a *NAD*-learning effect to occur. The performance of participants on the *NAD*-learning task did not significantly vary with the artificial language materials (*L1* and *L2*). This result was consistent with Gómez's study (2002) that no significant difference was found between the performances of participant groups, which were assigned to learn two different artificial language materials. It implied that the performance on *NAD*-learning was material independent.

The participants' performance on the *NAD*-learning task did not significantly vary with the string types tested (trained strings and generalized strings). This result was consistent with Frank and Gibson's (2011) findings that there were only marginal significant (p = .09) decrements in performance in the generalization condition. The participants had an above-chance performance in the *NAD*-learning test. Accuracy on the grammaticality test exceeding that of chance performance would provide evidence of artificial grammar learning

(Gómez, 1997). It implied that participants' learning effect of *NAD*-learning in this study was observed. This result was consistent with Gómez's (2002) findings that adult learners were able to acquire the dependencies between the first and the last elements when the variability of the second element was 24. Therefore, the current study replicated the Western findings with Cantonese-lite stimuli in a Cantonese population.

Relationship between Non-Adjacent Dependency-Learning and Phonological Short-term Memory Capacity

Although the participant showed learning effect in the *NAD*-learning task, the proficiency, defined here as how well did the participant learn the dependencies, on the non-adjacent dependencies would varied among participants. The differences of the scores in the *NAD*-learning testing phase among participants reflected the variation in the proficiency. The positive correlations between the *NAD*-learning performance and the nonword repetition tests were more significant than that of the digit span test. It was possibly due to the contribution of the phonological representation of familiar words (*i.e.,* digits in this study) in long term memory to rebuild the faded phonological strings in *STM* as suggested by Hulme, Roodenrys, Brown, and Mercer (1995). Repetition of unfamiliar words (*i.e.,* nonwords in this study) could not benefit from this. Also, the stimuli in the *NAD*-learning task were unfamiliar to the participants. Thus, scores in nonword repetition tests could more reliably represent the phonological *STM* performance of the participants during the *NAD*-learning task.

The results of our study were consistent with Frank and Gibson's (2011) findings that the performance accuracy on dependency-learning tasks increased when the memory retention demands were reduced. More importantly, the results of the current study further extended Frank and Gibson's findings. When auditory stimuli were presented sequentially, the results of the current study suggest that people having higher phonological *STM* capacity performed better in the *NAD*-learning task.

Frank and Gibson's (2011) concluded that decreasing memory retention demands caused the participants to learn the dependencies successfully and hence that the dependency learning mechanism was dependent to memory resources. They referred memory retention as retaining the stimulus materials for long enough time, allowing learning to occur. The duration of retention might vary from the time of a single string to several strings. According to the multicomponent working memory model proposed by Baddeley and Hitch (1974, cited in Baddeley, 2010), phonological loop (phonological *STM*) was responsible for temporally storing of speech-like information. It contained two sub-components, a short term store and an articulatory rehearsal process. They assumed that the store had a limited capacity to store the stimuli as memory traces, which would decay in a few seconds. However, the memory traces could be refreshed by the articulatory rehearsal process. If the number of items to be stored was large, the items might be faded before they were refreshed. It accounted for the capacity in phonological *STM*. This limited capacity in phonological *STM* would cause breakdown in memory retention which was suggested to be a constraints in dependency-learning (Frank & Gibson, 2011). Relating back to our study, people having larger phonological *STM* capacity could retain the stimuli for longer time, and retain more number of exemplars, which were important for abstracting the dependency leading to better performances in the *NAD*-learning task.

Implication on future research on dependency learning

Based on the relationship between phonological *STM* and *NAD*-learning, we suggested that future studies in this area should control the phonological *STM* parameter. Researchers should eliminate the individual differences in phonological *STM* when they would like to compare the performance of dependency learning task among individuals. It is to ensure that the ability (success of failure) of the participants to learn the dependencies is due to the manipulated or targeted parameter rather than the memory constraints of the participants themselves.

Implication on language acquisition

Dependency learning ability was important in grammar acquisition in both inflectional and non-inflectional language. Results of this study may suggest that people having lower phonological *STM* capacity would also have poor performance in syntax acquisition. It may suggest that they could retain the continuous speech stimuli for a shorter time, and could retain less number of language models. This limitation could impede the abstraction of the dependencies between the linguistic elements to occur. It was consistent with Adams and Gathercole's study (2000) that children with better non-word repetition skills produced speech with a wider range of syntactic constructions than children with relatively poor non-word repetition skills. Further studies on individuals having language impairment were required.

Regarding to the possible effects of phonological *STM* on grammar acquisition, children having difficulties in learning grammar might benefit from increasing the phonological *STM* capacity or reducing the demand. There are some clinical implications based on the multicomponent working memory model Baddeley and Hitch (1974, cited in Baddeley, 2010). As a strategy to increase memory capacity, in language training, we can ask the children to repeat the heard sentences containing the targeted syntactic structures. Vocal articulatory rehearsal could help refreshing the word strings before they fade out of the *STM* store. As for reducing the memory demand, in language training, we can produce language models containing the targeted syntactic structure to the children as short as possible to reduce the memory retention demands. As suggested by the word-length effect that the ability for retaining the whole phrase decreases if the length of the phrase increases. To assist daily communication, it is more preferable to use simpler linguistic structures and more familiar words for children's better comprehension.

Shortcoming of this study and suggestion on further studies

Andrade and Baddeley (2011) investigated the effect of phonological *STM* on grammar learning through manipulating the articulatory rehearsal processes. Their study involved a learning task of auditory artificial grammar formed from a vocabulary of spoken Mandarin syllables. They found that repeating the training strings while listening improved grammar learning while this effect was absent when the participants had learnt the component syllables. Their findings suggested that phonological *STM* contributed to artificial grammar learning through effects on learning novel vocabulary. However, the relationship between the phonological *STM* capacity and the pseudosyllables acquisition was not tested in our study. Further studies were required to clarify the relations between phonological *STM*, vocabulary acquisition and dependency-learning.

Due to the limitation of time, this study only investigated the relationship between phonological *STM* capacity and *NAD*-learning. Further studies could investigate the relationship between phonological *STM* capacity and adjacent or higher order dependency-learning. Then we could know whether phonological *STM* capacity is related to all kinds of dependency-learning or not. Also we could compare the effect of phonological *STM* on different kinds of dependency learning. This might also give insight to the contribution of phonological *STM* capacity towards acquisition of different types of grammar.

The training phase of the dependency learning task in our study was longer than that in Gómez’s (2002) study. It was possibly because the duration of each syllable constructing the training strings in our study was longer than that in Gómez’s study. Further studies should try to shorten the duration of the training phase and test whether the learning effect would remain.

Conclusion

The results of the current study demonstrated that the participants were able to learn the dependencies in the non-adjacent dependency-learning task. A significant positive correlation between the performance of the dependency-learning task and the phonological short-term memory capacity was found. It suggested that people having larger phonological short-term memory capacity could retain the stimuli for longer time, and retain more number for exemplars, which allow the abstraction of the dependencies to occur. It implied that individual differences in phonological short-term memory might lead to performance differences in dependency learning tasks. Also, it may suggest that the difficulties in grammar acquisition for language impaired children might be due to the limitation in retaining the speech stimuli for learning the dependencies between the linguistic elements. Further studies were required on individuals with language impairment.

Acknowledgement

I would like to express my gratitude to my supervisors, Dr. Anita Wong and Dr. Linda Iao, for their valuable advice and guidance. I would like to appreciate the participants for earnestly spending their precious time on the experiment. I am glad to have classmates who would sincerely help and encourage each other in this challenging period. I am also grateful to my family and friends for their unlimited support.

References

Adams, A., & Gathercole, S.E. (2000). Limitations in working memory: Implications for language development. *International Journal of Language & Communication Disorders*, *35*(1), 95-116. doi:10.1080/136828200247278

Andrade, J., & Baddeley, A. (2011). The contribution of phonological short-term memory to artificial grammar learning. *The Quarterly Journal of Experimental Psychology*, *64*(5), 960-974. doi:10.1080/17470218.2010.533440

Archibald, L. M., & Gathercole, S. E. (2006). Short-term and working memory in specific language impairment. *International Journal of Language & Communication Disorders*, *41*(6), 675-693. doi: 10.1080/13682820500442602

Baddeley, A. (2010). Short-term Memory. In A. Baddeley., M. W. Eysenck., & M. C. Anderson (Eds.), *Memory* (pp. 19-40). New York: Psychology Press, 2009.

Brooks, P. J., Kempe, V., & Sionov, A. (2006). The role of learner and input variables in learning inflectional morphology. *Applied Psycholinguistics*, *27*(02), 185-209. doi:10.1017/S0142716406060243

Bubeník, V. (1999). *An introduction to the study of morphology*. München, Germany: Lincom Europa.

Creel, S. C., Newport, E. L., & Aslin, R. N. (2004). Distant melodies: statistical learning of nonadjacent dependencies in tone sequences. *Journal of Experimental Psychology:*

Learning, memory, and cognition, *30*(5), 1119-1130. doi:10.1037/0278-7393.30.5.1119

Frank, M. C., & Gibson, E. (2011). Overcoming memory limitations in rule learning. *Language Learning and Development*, *7*(2), 130-148. doi:10.1080/15475441.2010.512522

Gómez, R. L. (1997). Transfer and complexity in artificial grammar learning. *Cognitive Psychology*, *33*(2), 154-207. doi:10.1006/cogp.1997.0654

Gómez, R. L. (2002). Variability and detection of invariant structure. *Psychological Science, 13*(5), 431-436. doi:10.1111/1467-9280.00476

Hulme, C., Roodenrys, S., Brown, G., & Mercer, R. (1995). The role of long-term memory mechanisms in memory span. *British Journal of Psychology,86*(4), 527-536. doi:10.1111/j.2044-8295.1995.tb02570.x

Montgomery, J. W., & Evans, J. L. (2009). Complex sentence comprehension and working memory in children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *52*(2), 269-288. doi:10.1044/1092-4388(2008/07-0116)

Morgan, J. L., Meier, R. P., & Newport, E. L. (1987). Structural packaging in the input to language learning: Contributions of prosodic and morphological marking of phrases to the acquisition of language. *Cognitive psychology*, *19*(4), 498-550. doi:10.1016/0010-0285(87)90017-X

Raven, J., Raven, J. C., & Court, J. H. (1998d). *Manual for Raven's Progressive Matrices and Vocabulary Scales*. (Section 4). Oxford, England: Oxford Psychologists Press

Research Centre for Humanities Computing, Chinese University of Hong Kong (2003). *Chinese character database: With word-formations phonologically disambiguated according to the Cantonese dialect*. Retrieved from http://humanum.arts.cuhk.edu.hk/Lexis/lexi-can/

Saffran, J. R. (2001). The use of predictive dependencies in language learning. *Journal of Memory and Language*, *44*(4), 493-515. doi:10.1006/jmla.2000.2759

Saffran, J. R. (2002). Constraints on statistical language learning. *Journal of Memory and Language*, *47*(1), 172-196. doi:10.1006/jmla.2001.2839

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, *274*(5294), 1926-1928. doi:10.1126/science.274.5294.1926

Saffran, J. R., Newport, E. L., Aslin, R. N., Tunick, R. A., & Barrueco, S. (1997). Incidental language learning: Listening (and learning) out of the corner of your ear. *Psychological Science*, *8*(2), 101-105. doi:10.1111/j.1467-9280.1997.tb00690.x

T'sou, B., Lee, T., Tung, P., Man, Y., Chan, A., To, C. K. S., & Chan, Y. (2006). Hong Kong Cantonese Oral Language Assessment Scale. *Hong Kong: City University of Hong Kong*.

Wechsler, D. (2008a). *Wechsler Adult Intelligence Scale—Fourth Edition*. San Antonio, TX: Pearson Assessment.

Appendix 1

Training materials for NAD-learning task

Language 1 (*L1*) was formed from the combination of *aXd*, *bXe* and *cXf*, while language 2 (*L2*) was formed from the combination of *aXe*, *bXf* and *cXd* with each of the 24 X elements. The elements *a*, *b*, *c*, *d*, *e*, *f* and X_1 to X_{24} were as follow.

A		X						B	
a	*pʰɛp*^{1}	X_{1}	*ti*^{1}	*tsʰat*^{1}	X_{13}	*wi*^{1}	*fɔn*^{4}	*d*	*tsɪŋ*^{4}
b	*fɔt*^{1}	X_{2}	*kʰi*^{1}	*sɛk*^{1}	X_{14}	*hy*^{1}	*pɵn*^{4}	*e*	*tʰun*^{4}
c	*tɛk*^{1}	X_{3}	*pʰy*^{1}	*sœk*^{1}	X_{15}	*hɛ*^{1}	*fɐm*^{4}	*f*	*wyn*^{4}
		X_{4}	*pœ*^{1}	*nit*^{1}	X_{16}	*lu*^{1}	*kan*^{4}		
		X_{5}	*fi*^{1}	*nɛp*^{1}	X_{17}	*ly*^{1}*1*	*pɪn*^{4}		
		X_{6}	*pi*^{1}	*tsep*^{1}	X_{18}	*wɛ*^{1}	*tim*^{4}		
		X_{7}	*ku*^{4}	*pʰon*^{4}	X_{19}	*fɛ*^{4}	*tsɔt*^{1}		
		X_{8}	*ki*^{4}	*tsɵn*^{4}	X_{20}	*pa*^{4}	*lip*^{1}		
		X_{9}	*kɛ*^{4}	*sam*^{4}	X_{21}	*mɛ*^{4}	*sit*^{1}		
		X_{10}	*kʰu*^{4}	*mon*^{4}	X_{22}	*tʰa*^{4}	*pʰut*^{1}		
		X_{11}	*jɔ*^{4}	*saŋ*^{4}	X_{23}	*tsi*^{4}	*lak*^{1}		
		X_{12}	*su*^{4}	*lem*^{4}	X_{24}	*fi*^{4}	*mɛk*^{1}		

Appendix 2

Testing materials for NAD-learning task

Testing strings were formed from the combination of *aXd*, *bXe* and *cXf*, with their counter pair of *aXe*, *bXf* and *cXd* accordingly in each trial. Testing strings were divided into two types namely trained string, in which the *X* elements used for combination were chosen from the training materials, and generalized string in which the *X* elements used for combination were untrained (generalized) items. The elements *a*, *b*, *c*, *d*, *e*, *f*, and the trained and untrained (X_{g1}-X_{g4}) *X* elements were as follow.

A		X			B	
a	*pʰɛp*^{1}	X_{2}	*kʰi*^{1}	*sɛk*^{1}	*d*	*tsɪŋ*^{4}
b	*fɔt*^{1}	X_{12}	*su*^{4}	*lem*^{4}	*e*	*tʰun*^{4}
c	*tɛk*^{1}	X_{17}	*ly*^{1}	*tsɪn*^{4}	*f*	*wyn*^{4}
		X_{21}	*mɛ*^{4}	*sit*^{1}		
		X_{g1}	*py*^{1}	*mɛp*^{1}		
		X_{g2}	*kœ*^{4}	*pyn*^{4}		
		X_{g3}	*mœ*^{1}	*kɛm*^{4}		
		X_{g4}	*lu*^{4}	*sip*^{1}		

Appendix 3

Test items for Digit Span Forward Test

Item	Trial 1	Trial 2
1	9-7	6-3
2	5-8-2	6-9-4
3	7-2-8-6	6-4-3-9
4	4-2-7-3-1	7-5-8-3-6
5	3-9-2-4-8-7	6-1-9-4-7-3
6	4-1-7-9-3-8-6	6-9-1-7-4-2-8
7	3-8-2-9-6-1-7-4	5-8-1-3-2-6-4-7
8	2-7-5-8-6-3-1-9-4	7-1-3-9-4-2-5-6-8
9	2-7-8-3-9-4-1-5-0-6	4-3-7-0-8-6-9-1-2-5
10	4-8-6-1-9-3-0-7-5-2-8	6-5-8-1-2-0-4-7-9-3-4
11	2-4-7-6-9-0-2-5-1-7-8-3	4-2-6-8-1-9-8-5-7-1-3-0
12	1-6-7-1-3-8-5-3-9-6-4-0-2	2-9-7-4-8-3-0-1-7-5-6-3-8
13	5-8-7-9-3-5-2-8-1-9-0-4-6-1	2-8-4-1-3-7-8-5-6-9-4-6-0-2

Appendix 3 (*cont.*)

Test items for Nonword Repetition Test with Pseudomorphemes

Item	**Trial**								
Practice	mun^{5} 滿								
	hʊŋ^{2} 恐	tsɪk^{7} 即							
1	tən^{1} 敦								
	nyn^{6} 嫩								
2	kin^{1} 堅	sət^{9} 述							
	k^{h}ei^{3} 冀	pau^{1} 包							
3	ləy5 裡	tɪŋ^{1} 叮	p^{h}ai^{3} 派						
	jɐm^{2} 飲	sim^{4} 蟬	mɐk^{7} 嚜						
4	k^{wh}ɐi^{1} 規	hiu^{2} 曉	tsɪt^{8} 節	lyn^{4} 聯					
	pɛŋ^{2} 餅	k^{h}ɔŋ^{3} 抗	wan^{4} 還	lɔŋ^{5} 朗					
5	p^{h}ui^{5} 倍	tsən^{1} 津	wʊt^{9} 活	tin^{2} 典	mʊŋ^{4} 蒙				
	tsap^{8} 眨	hœŋ^{1} 香	k^{h}ɐt^{7} 咳	tiu^{6} 調	mɐŋ^{4} 盟				
6	sʊk^{9} 淑	min^{5} 勉	hei^{3} 棄	jɪŋ^{4} 迎	k^{h}əy^{1} 區	ts^{h}ɔi^{2} 彩			
	man^{4} 蠻	k^{h}au^{3} 靠	tan^{6} 但	si^{5} 市	hɔi^{1} 開	k^{wh}ɪk^{7} 隙			
7	wɐi^{4} 維	kɪk^{7} 激	p^{h}in^{3} 騙	həy^{2} 許	jʊŋ^{5} 勇	tɔi^{6} 代	sən^{1} 詢		
	tɔk^{9} 踱	wun^{6} 換	t^{h}an^{1} 灘	sei^{2} 死	ham^{3} 喊	p^{h}ɐn^{4} 頻	mui^{5} 每		
8	lɪŋ^{5} 領	mou^{4} 巫	fɐi^{1} 揮	syt^{8} 說	jin^{6} 現	k^{h}ut^{8} 括	p^{h}ɪk^{7} 闢	tsau^{2} 找	
	han^{1} 慳	t^{h}ip^{8} 貼	wai^{6} 壞	təy^{3} 對	kɔn^{2} 趕	ts^{h}ət^{7} 出	jiu^{4} 搖	lou^{5} 老	
9	piu^{2} 表	tɪk^{7} 的	jyn^{5} 軟	t^{h}in^{4} 填	kou^{3} 告	fun^{2} 款	səy^{4} 垂	lət^{9} 律	tsɪŋ^{1} 精
	p^{h}ʊk^{7} 仆	sɐi^{3} 世	tsəy^{2} 咀	pun^{1} 搬	kwɔ^{3} 過	p^{h}un^{3} 判	mei^{4} 微	nai^{5} 奶	maŋ^{4} 盲

Appendix 3 (*cont.*)

Test items for Nonword Repetition Test with Pseudosyllables

Item	Trial 1	Trial 2
Practice	tɐu^{5}	p^{h}ui^{2} k^{h}yn^{1}
1	p^{h}ʊŋ1	kwɐt^{8}
2	mai^{1} hit^{9}	hɛk^{7} tei^{3}
3	p^{h}ɪn^{5} t^{h}yn^{1} lɐi^{3}	kwan^{2} t^{h}yt^{7} fɐi^{4}
4	jai^{1} sɔi^{2} mit^{8} hyn^{4}	pɐu^{3} fʊŋ^{5} hɛŋ^{2} lɐt^{9}
5	sɪŋ^{5} lɵt^{7} pɪk^{9} lɔi^{2} fun^{4}	kɔi^{5} pɐm^{3} tam^{4} mut^{7} ts^{h}ɪk^{9}
6	piu^{6} t^{h}ʊŋ^{5} wut^{8} hei^{4} kw^{h}ai^{1} mau^{2}	sɐn^{3} tœk^{7} kɐm^{4} p^{h}ɔi^{4} k^{h}ʊk^{9} tit^{7}
7	k^{h}ɐi^{4} jɵn^{1} tyt^{8} pui^{2} hʊŋ^{5} sœk^{9} wɪk^{7}	tɛŋ^{4} ts^{h}ɛk^{7} kun^{4} pat^{1} mɐt^{8} t^{h}im^{6} pei^{5}