The Learning Mechanism of Nominal Classification Systems: A Cognitive Neuroscience Perspective

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Summary of Doctoral Dissertation

The Learning Mechanism of Nominal Classification Systems: A Cognitive Neuroscience Perspective

(名詞類別システムの学習メカニズム

-- 認知神経科学的検証 --)

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1. Introduction and Literature Review (Chapter 1 and 2)

Learning a second or third language requires learning grammatical rules to communicate effectively in each language even though adults show great individual differences in learning them. Previous neuroimaging studies have identified important brain areas involved in grammatical rule learning such as the left inferior frontal area (particularly the pars opercularis) and motor areas (e.g., precentral gyrus and supplementary motor area) (Hauser, Hofmann, & Opitz, 2012; Opitz & Friederici, 2003; 2004). In the case of individual differences, working memory and language analytic ability have been shown to be important cognitive individual differences that predict successful grammatical rule learning (Martin & Ellis, 2012; Robinson, 1997).

While these previous studies have been invaluable in the understanding of the brain areas related to second language grammar learning, they have focused exclusively on the learning of abstract grammar rules with no reliance on conceptual or cultural information. To date, it seems there are no neuroimaging studies investigating the learning of the diverse set of grammar rules that rely on conceptual knowledge such as nominal classification systems or the individual differences that affect their learning. Nominal classification systems lie at the intersection of language and culture continuum because they require the incorporation of specific cultural or semantic information into the grammar. This is because they are grammatical systems that categorize nouns into distinct semantic categories. But while the formal expression of nominal classification systems differs, the unifying factor behind nominal classification systems is their semantic basis. Without the semantic basis, the grammatical rules cannot be learned or inferred.

This dissertation study aims to address the linguistic diversity gap in grammatical rule learning in cognitive neuroscience by focusing on the learning of nominal classification rules. The first goal of this study is to investigate how nominal classification rules are learned in the brain. The second goal is to comparatively investigate, under the same conditions, how two individual differences (working memory and language aptitude) associated with grammatical learning influence the learning of nominal classification rules both at the neural level and behavioral level. Like the fMRI literature, more studies are needed on different linguistic structures to understand which rules are (un-)affected by working memory or language analytic ability.

In order to achieve the two goals of the doctoral study, the following research questions were formulated:

1. What are the neural correlates of learning nominal classification rules? More specifically, are additional brain areas recruited in addition to those recruited during abstract rule learning or are only the same brain areas involved in learning?

2. Do individual differences in working memory or language analytic ability (or both) predict learning of nominal classification rules?

3. Do working memory and language analytic ability correlate with brain activation associated with learning nominal classification rules during learning?

2. Experiment 1 Behavioral Experiment (Chapter 3)

When it comes to learning a second language (L2), most adults differ quite remarkably in their success and overall attainment. Two factors, among many, that account for these individual differences is working memory and language analytic ability, a subset of language aptitude. Both working memory and language analytic ability have predicted success in learning grammatical rules such number agreement and word order structures such as subject-verb inversion of location/movement adverbials and constituent order (Kempe, Brooks, & Kahrkhurin, 2010; Martin & Ellis, 2012; Tagarelli, Mota, & Rebuschat, 2015; VanPatten & Smith, 2015).

These studies have helped piece together potential roles working memory and language analytic ability might influence; however, there is little research directly comparing working memory and language analytic ability especially during the learning of nominal classification systems. Hence, Chapter 3 aimed to answer the following research question from the doctoral dissertation:

- Do individual differences in working memory or language analytic ability (or both) predict learning of nominal classification rules?

2.1 Methods

2.1.1 Participants

The participants in this experiment were 30 native speakers of Japanese (*Average age* = 18.73, *SD* = 1.04). During the recruitment period, participants with more than one-month experience living abroad, language certifications or majoring in Linguistics and/or related fields were excluded from this study. Participants also completed a questionnaire containing questions about age, education level, languages studied, and total years of foreign language study.

2.1.2 Measures of Individual Differences

To assess participants working memory ability, a Japanese-translated shortened operation span task was used (Foster et al., 2015). It has been a widely used measurement in research (Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005). The operation span task consisted of two practice trials to familiarize them with the task. For the task, participants first decided whether a math equation is correct or incorrect. After deciding, participants see a letter that they must remember. After 2-5 trials, participants are asked to recall the letters in the correct order.

Participants completed the Llama F test, a measure of language analytic ability (Meara, 2005). Participants were presented 20 pictures along with a sentence in an unknown language. During the learning phase, participants were asked to find the rules, presumably using inductive reasoning as suggested by Meara (2005). After the learning phase, participants took a test where they were presented with a picture matching one of two sentences. They had to decide which sentence was grammatically correct.

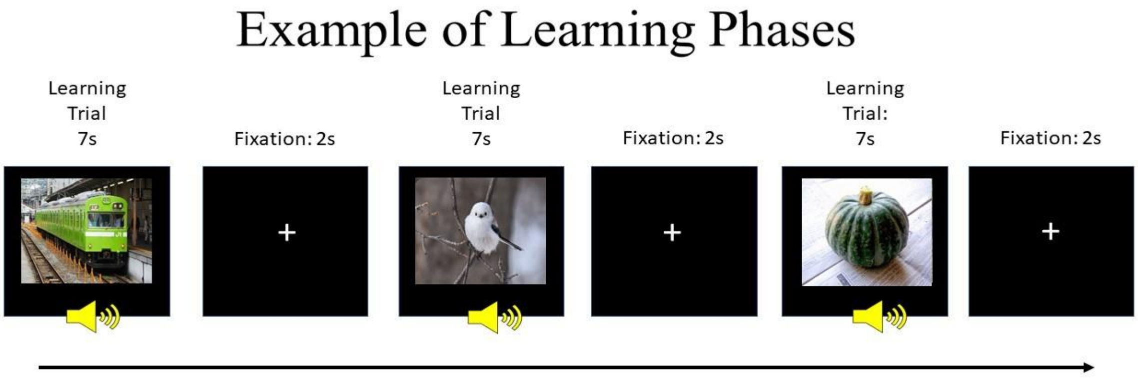

Figure 1. Examples of trials during the learning phase for experiment 1. Participants heard the noun and its corresponding demonstrative.

2.1.3. Semi-Artificial Language

The semi-artificial language was adapted from Dardon and Tanabe-Ishibashi (2020). The semi-artificial language consisted of 36 two-mora concrete nouns that were divided into three semantic-based classifications: animate, small inanimate, and large inanimate. The target grammar was agreement rules between a noun's classification and a demonstrative unique to it. The participants were told that all three demonstratives translated as *this*. There were 12 nouns for each noun class. To learn these rules, one must generalize a conceptual category based on the semantics of the nouns with no formal cues to category (Aikhenvald, 2000).

2.2 Procedure

Before proceeding to the learning portion of the task, participants were required to learn the vocabulary for their experiment. Only after reaching 100 percent on a translation test of the vocabulary did participants continue to the learning portion.

During the learning phases of the experiment, participants were instructed to discover the grammatical rules of the semi-artificial language. Participants learned the semi-artificial language over 3 learning phase (see Figure 1). fMRI scanning took place during the learning phases. During the learning phase, participants listened to 12 randomized correct noun-demonstrative combinations with each noun-demonstrative combination including a picture of the noun to prevent ambiguity. Participants were never exposed to the noun-demonstrative combination visually. No incorrect noun-demonstrative combinations were presented so participants had to induct the rules strictly from positive evidence.

After each learning phase, participants were tested on their knowledge of the rules (three total tests). They were presented the written form of the word and its corresponding picture on the screen. Participants were asked to produce the word with the correct demonstrative (agreement rule). Except for the final test, test words were taken from the learning phase that followed. For example, generalization 1 test words were the same words presented in learning phase 2. The final test followed the exact methods described above but differed slightly. Immediately after finishing the last learning phase, participants were shown 21 novel nouns and their Japanese meaning with their corresponding picture. Participants did not need to memorize the 21 words. The written form of the novel nouns was presented on the screen. Participants were asked to produce the word with the correct agreement form. The final generalization test was done this way to test whether participants could generalize the rules to unencountered items since the first two test phases consisted of nouns the participants were already familiar with.

2.3 Results

A multiple regression analysis was used to determine which factor, working memory or language analytic ability, better contributed to the learning of nominal classification rules. Working memory made the largest significant contribution (b = .37, p < .05) to the generalization task while language analytic ability made no significant contribution (b = .13, p = .47).

3. Experiment 2 fMRI Experiment (Chapter 4)

The second experiment aimed to investigate the neural correlates of learning nominal classification systems. As outlined earlier, previous studies have focused on the learning of abstract grammar rules with no reliance on conceptual or cultural information. This is unfortunate because if researchers are to arrive at a true model of second language learning, a variety of grammatical constructions found across the world need to be investigated and incorporated into that model.

In addition, the second experiment investigated the roles of working memory and language analytic ability at the neural level. Taking into account the methods and findings from the behavioral study in Chapter 3, a direct comparison of working memory and language analytic ability during the learning of the same grammatical structure is needed to elucidate their influences at the neural level during learning since no studies have investigated this line of research.

To address these issues, the aim of the current experiment was to answer the following research questions of the doctoral study:

- What are the neural correlates of learning nominal classification rules? More specifically, are additional brain areas recruited in addition to those recruited during abstract rule learning or are only the same brain areas involved in learning?

- Do working memory and language analytic ability) correlate with brain activation associated with learning nominal classification rules during learning?

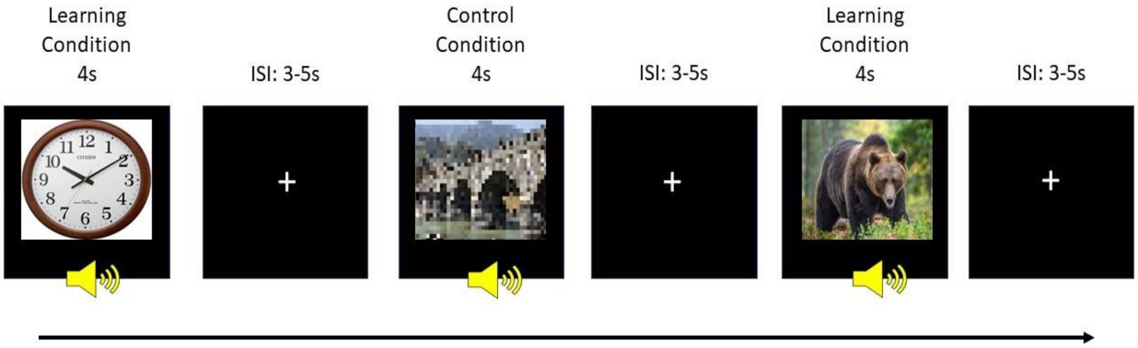

Figure 2. Experiment 2 trials for the learning phases. Learning phases contained boy a learning condition where participants heard the correct noun-demonstrative combination and a control condition where participants heard a reversed audio sound.

3.1 Methods

3.1.1 Participants

Participants were 37 healthy, right-handed Japanese native speakers (Age 18-24, 17 females). One participant was discarded because they were not a native speaker of Japanese. During the recruitment period, participants with more than one-month experience living abroad, language certifications or majoring in Linguistics and/or related fields were excluded from this study. Participants completed a questionnaire containing questions about age, education level, languages studied, and total years of foreign language study.

3.1.2 Semi-Artificial Language

The semi-artificial language was adapted from Dardon and Jeong (2020), and similar to the one employed for the individual differences study in Chapter 3. In contrast to the semi-artificial language in Chapter 3, which used pseudowords, this version consisted of 72, two to three syllable, concrete Japanese nouns with the nouns borrowed from Japanese (the participants native language) to control for any individual differences in vocabulary. This is because even though Chapter 3's behavioral study tried to control for vocabulary, there still could have been individual differences in vocabulary. Previous neuroimaging and behavioral studies have used participant's native language vocabulary in this manner in order to target specific grammatical phenomenon and, since this study is focused primarily on *learning* grammatical rules requiring semantic/conceptual knowledge, not on learning any individual words, we followed the design of these previous studies (Tamminen et al., 2016). Nouns were divided into three semantic-based classes i.e., noun classes: animate (e.g., dog), small inanimate (e.g, apple), and large inanimate (e.g., train). The target grammar was agreement between a noun class and a demonstrative roughly translated as *this* to each noun class.

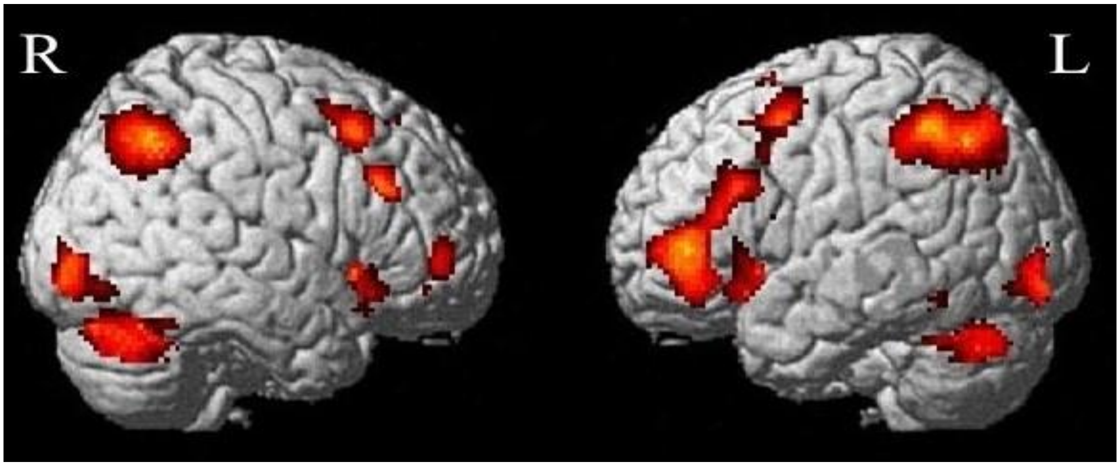

Figure 3. Whole-brain activation for showing activation during learning relative to control. Posterior cingulate not shown. $p < .05$ FWE corrected at cluster level. *Note*. R= right, L= left

Participants were told that there were rules governing the demonstratives, but they all translated as *this*. There were 18 nouns for each noun class.

3.1.3 Measures of Individual Differences

Like in experiment 1, to assess participants working memory ability, a Japanese-translated shortened operation span task was used (Foster et al., 2015). To measure language analytic ability, participants completed the Llama F test, a measure of LAA (Meara, 2005).

3.2 Procedure

During the learning phases of the experiment, participants were instructed to discover the grammatical rules of the semi-artificial language. Participants learned the semi-artificial language over 3 learning phase (see Figure 2). fMRI scanning took place during the learning phases. During the learning phase, participants listened to 18 randomized correct noun-demonstrative combinations with each noun-demonstrative combination including a picture of the noun to prevent ambiguity. Within these 18 correct noun-demonstrative combinations, six of them reflected the animate rule, the other six reflected the small inanimate rule, and the last six reflected the large inanimate rule. Participants were never exposed to the noun-demonstrative combination visually. No incorrect noun-demonstrative combinations were presented so participants had to induct the rules strictly from positive evidence.

For the control condition, they heard the same 18 noun-demonstrative combinations but with the audio in reverse and a blurred mosaic picture. Before the start of the experiment, participants were told that both a picture and a mosaic picture would appear randomly, so they had to stay alert. This was done to prevent participants from sleeping during the learning

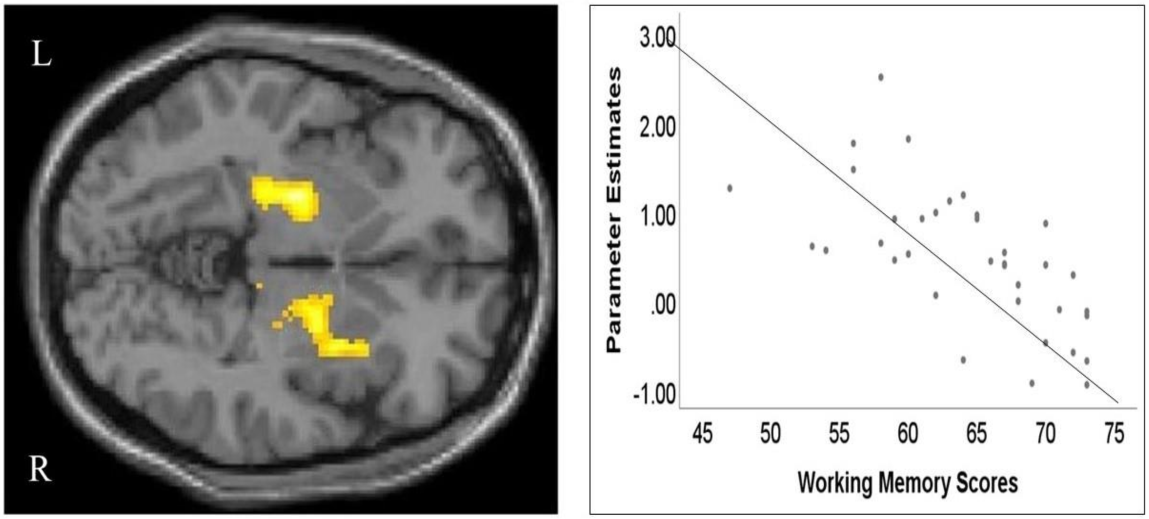

Figure 4. Results of correlation analyses between brain activation and working memory scores in learning phase 3. Brain image shows significant activation in the bilateral thalami. The right figure shows a negative correlation between the mean parameter estimates of peak voxels in the left thalamus and working memory (for illustrative purposes only). *p* < .05 FWE corrected at cluster level.

phases. This control condition was used in order to eliminate low level visual and auditory processing.

After each learning phase, participants performed an offline grammatical judgment task (test phase) that acted as a behavioral indicator of learning. There were 18 total items for the grammatical judgment task (9 grammatical and 9 ungrammatical). Items were taken from the learning phase that preceded the test phase (e.g., test 1 items came from learning phase 1 items). For the last test phase, there were 36 total items. 18 items were taken from learning phase 3 (as done with the test phases 1 and 2) and half of these items were grammatical and ungrammatical; however, the other 18 items consisted of noun-determiner combinations participants were never exposed to. These items were included to measure participants ability to generalize the rules to novel stimuli. As with all other items in the test phases, half were grammatical and ungrammatical.

3.3 RESULTS

3.3.1 Behavioral Results for Learning

The results of the mixed effects model analysis revealed a significant effect for time between test scores 1 and 2 ($\beta = 0.181$, *SE* = .02, *p* < .001), between test scores 1 and 3 ($\beta = 0.189$, *SE* = .02, *p* < .001), but no significant effect of time between test scores 2 and 3 ($\beta = 0.007$, *SE* = .02, *p* = 0.9) (see Figure 4).

3.3.2 Behavioral Results of Individual Differences

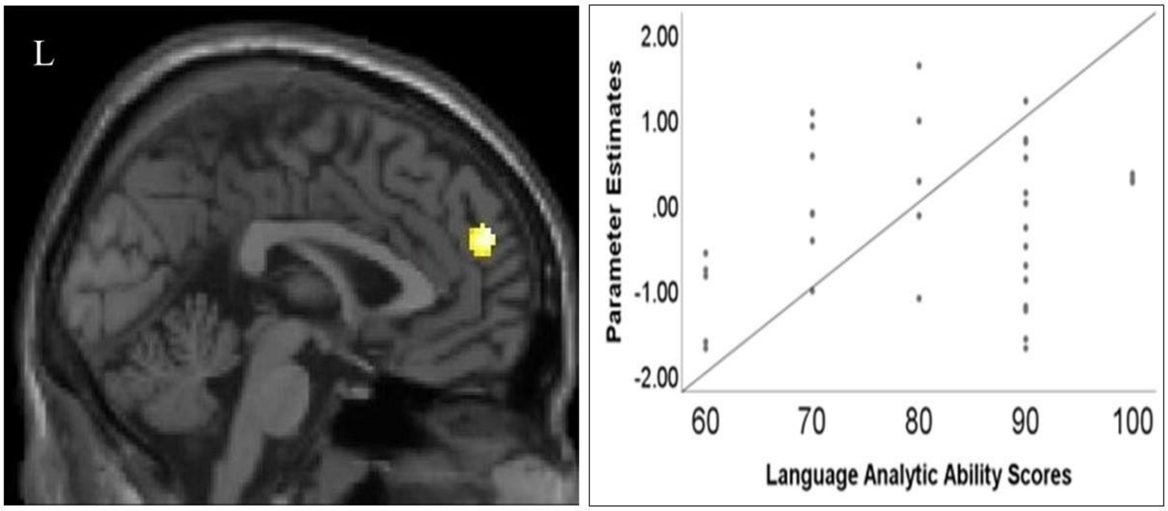

Figure 5. Results of correlation analyses between brain activation and language analytic ability in learning phase 3. Brain image shows significant activation in the left medial prefrontal cortex. The right figure shows a positive correlation between the mean parameter estimates of peak voxels in the left medial prefrontal cortex and language analytic ability (for illustrative purposes only). *p* < .05 FWE with small volume correction.

Correlations analysis between language analytic ability on all test scores and new item test scores revealed a positive correlation between language analytic ability and test scores, *r* = .44, *p* < .01. No correlations were found between working memory and test scores or new item scores.

3.3.3 Whole Brain Analysis Results

A whole brain analysis was performed to investigate mean differences between the learning and control conditions (see Figure 3). This contrast yielded activation in 19 significant clusters: Bilateral inferior parietal clusters, middle frontal clusters, posterior cingulate cortex clusters, anterior cingulate cortex clusters, cerebellum clusters, inferior frontal clusters, inferior occipital clusters, the right superior temporal pole, right lingual gyrus, and the left inferior temporal gyrus. These clusters were then further analyzed as regions of interest (ROIs).

3.3.4 Brain Activation Related to Learning

From the whole brain activation, the following brain areas showed a main effect of learning over time: the left precentral gyrus (Wilks' Lambda = .77, *F*(2, 34) = 4.95, *p* < .05, multivariate partial eta squared = .22), left inferior temporal gyrus (Wilks' Lambda = .75, F(2, 34) = 5.54, *p* < .01, multivariate partial eta squared = .24), left pars triangularis (Wilks' Lambda = .74, *F*(2, 34) = 5.92, *p* < .01, multivariate partial eta squared = .25), left pars opercularis (Wilks' Lambda = .64, $F(2, 34) = 9.20$, $p < .001$, multivariate partial eta squared = .35), the left anterior temporal lobe (Wilks' Lambda = .72, $F(2, 34) = 6.38$, $p < .01$, multivariate partial eta squared = .27) and right anterior temporal lobe (Wilks' Lambda = .76, $F(2, 34) = 5.25$, $p < .05$, multivariate partial eta squared = .23).

3.3.5 Neuroimaging Results for Individual Differences

A regression analysis with Operation Span Task scores (indicator of working memory capacity) as a covariate revealed a negative relationship between working memory capacity and bilateral activation in the thalami during learning phase 3 (Figure 4). A regression analysis with Llama F scores (language analytic ability) as a covariate revealed a positive relationship between language analytic ability and activation in the medial frontal gyrus (after small volume correction (SVC), FWE, $p < 0.05$ at 5mm within the target area) during learning 3 (see Figure 5).

4. Conclusion (Chapter 5)

This doctoral study investigated the neural basis of learning nominal classification rules and how individual differences in working memory and language analytic ability influence their learning. The novel results of the study are summarized below:

1. The left inferior temporal gyrus and bilateral anterior temporal lobes are recruited during learning to successfully learn and generalize nominal classification rules

2. At the behavioral level, both working memory and language analytic ability contribute to learning nominal classification rules dependent on measurement

3. At the neural level, working memory correlated with deactivation of the bilateral thalami, possibly due to involvement in updating/maintenance or working memory's interaction with procedural memory, while language analytic ability correlated with the medial area of the prefrontal cortex, the area known for human reasoning during the learning of nominal classification rules

The current study contributes to new knowledge by demonstrating the novel finding of the anterior temporal lobes and inferior temporal gyrus's significance in successful rule learning. These results contribute to current knowledge by providing evidence of additional brain areas involved in grammatical rule learning and making it clear the importance of investigating typologically diverse grammatical rules and incorporating them into theoretical neuro-cognitive models of second language learning. This study also contributes to the research on the influence of individual differences in second language acquisition. The results from this study demonstrate that working memory and language analytical abilities' role during learning are different and not interchangeable as some researchers suggest (Skehan, 2016). The behavioral results coupled with the fMRI results provide evidence that working memory influences learning via updating and maintenance or interactions with procedural memory, not necessarily rule generalization itself. For language analytic ability, the results of the behavioral and fMRI results show that language analytic ability is tied to reasoning suggesting its importance in generalization rules during the learning process.

5. References

Aikhenvald, A. (2000). *Classifiers: A typology of noun categorization devices*. Oxford: Oxford Press.

Conway, A.R.A., Kane, M., Bunting, M., Hambrick, D.Z., Wilhelm, O., & Engle, R. (2005). Working memory span tasks: A methodological review and user`s guide. *Psychonomic Bulletin & Review*, *12*(5), 769-786.

Dardon, D.E. & Tanabe-Ishibashi, A. (2020). Working memory hinders learning semantic noun classes but aids in learning phonological ones. *Tohoku Psychologica Folia*, *78*, 19-33.

Dardon, D.E., & Jeong, H. (2021). Working memory trumps language aptitude in learning semantic-based linguistic category rules. *Studies in Language Sciences*, *19*, 77-84.

Foster, J.L., Shipstead, Z., Harrison, T.L., Hicks, K., Redick, T.S., & Engle R.W. (2015). Shortened complex span tasks can reliably measure working memory capacity. *Memory & Cognition*, *43*, 226-236.

Hauser, F.A.M., Hofmann, J., & Opitz, B. (2012). Rule and similarity in grammar: Their interplay and individual differences in the brain. *Neuroimage*, *60*, 2019-2026.

Kempe, V., Brooks, P., & Kharkhurin, A. (2010). Cognitive predictors of generalization of Russian grammatical gender categories. *Language Learning*, *60*(1), 127-153.

Leminen, A., Kimppa, L., Leminen, M.M., Lehtonen, M., Makela, J.P., & Shtyrov, Y. (2016). Acquisition and consolidation of novel morphology in human neocortex: A neuromagnetic study. *Cortex*, *83*, 1-16.

Martin, K.I., & Ellis, N.C. (2012). The roles of phonological short-term memory and working memory in L2 grammar and vocabulary learning. *Studies in Second Language Acquisition*, *34*, 379-413.

Meara, P. (2005). *LLAMA Language Aptitude Tests*. Swansea: Lognostics.

Opitz, B., & Friederici, A.D., (2003). Interactions of the hippocampal system and the prefrontal cortex in learning language-like rules. *NeuroImage*, *19*, 1730-1737.

Opitz, B., & Friederici, A.D., (2004). Brain correlates of language learning: The neuronal dissociation of rule-based versus similarity-based learning. *The Journal of Neuroscience*, *24*(39), 8436-8440.

Skehan, P. (2016). Foreign language aptitude, acquisitional sequences, and psycholinguistic processes. In G. Granena, D.O. Jackson, & Y. Yilmaz (Eds.), *Cognitive individual differences in second language processing and learning* (pp. 17-40). Amsterdam: John Benjamins Publishing Company.

Tagarelli, K., Mota, M.B., & Rebuschat, P. (2015). Working memory, learning conditions, and the acquisition of L2 syntax. In Z. Wen, M.B. Mota, & A. McNeill (Eds.), *Working memory in second language acquisition and processing* (pp. 224-248). Tonawanda, NY: Multilingual Matters.

VanPatten, B., & Smith, M. (2015). Aptitude as grammatical sensitivity and the initial stages of learning Japanese as a L2: Parametric variation and case marking. *Studies in Second Language Acquisition*, *37*(1), 135-165.