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Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 43(43)

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Publication Date

2021

Simulating the factors that correct the erroneous process of phonological generation in Japanese

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Abstract

Language acquisition is supported by an ability called phonological awareness, which allows children to become intentionally aware of phonological units. It is known that erroneous pronunciation appears during the formation of phonological awareness. To clarify children's internal processes during this formation, this research aims to examine the factors that correct an erroneous phonological generation process. To do this, we utilized the innate and experiential factors of the memory retrieval mechanism in the cognitive architecture ACT-R. Specifically, we performed simulations to examine the interaction tasks that contribute to the acquisition of phonological awareness. As a result, it was shown that repeating a single task causes incorrect convergence, and that this convergence can be prevented by performing other kinds of learning between tasks. In the future, it will be necessary to examine learning between tasks that can be associated with real situations, and to confirm the overall process of phonological awareness formation.

Keywords: cognitive modeling; phonological awareness; Japanese; ACT-R

Introduction

Language development is an experiential process that begins from an innate basis that is largely common among modern people. We have common vocal and aural organs, and we use primitive cognitive functions, such as joint attention (Baron-Cohen, 1997) or role reversal imitation (Tomasello, 1999), helping children to acquire language-specific structures in their mother tongue.

Among the many aspects of language acquisition, phonological segmentation is the most prominent example of such an experiential process based on innate bias. Infants initially have the opportunity to separate sounds into various types of segments, like syllables or morae. The basis for acquiring such a variety of segments converges into a system for processing a series of units defined by the mother tongue as the child interacts with adults in the culture. This developmental process is partly attributed to an ability called phonological awareness (Stahl & Murray, 1994), which enables one to intentionally pay attention to the phonological aspects, such as phonemes and rhythms, of oral language.

Cognitive functions such as phonological awareness are especially central to speech-language pathology, which targets the early developmental process, because researchers and practitioners in the field have many opportunities to encounter phonological errors and are required to work out individual cases of such errors (Kubozono, 1989; Grandin & Panek, 2013).

Thus, the role of phonological awareness and the age at which phonological awareness is formed have been clarified by experimental and clinical field research. However, the cognitive process by which an innate basis leads to erroneous phonological states and then recovers through proper phonological awareness is not clear. To clarify this internal processes, the present study constructs a computational model representing (1) the development process that leads to erroneous phonological generation, and (2) the experiential factors involved in the suppression of phonological errors. To achieve these goals, we use the basic cognitive functions implemented in the cognitive architecture ACT-R (Adaptive Control of Thought-Rational; Anderson, 2007).

Related Research

In this section, we first introduce previous research on language development and the formation of phonological awareness. Next, we introduce cognitive modeling and cognitive architecture and review the language learning research using cognitive models.

Studies of Phonological Awareness

Phonological awareness has been experimentally investigated by several researchers. In a longitudinal study, Carroll et al. (2003) examined the order in which some types of units can be recognized by preschool children. This study shows the order of awareness of large units (syllables and rimes), which are followed by the awareness of small units (phonemes). In clinical settings, phenomena indicating errors of phonological awareness have been observed. For example, it has been reported that children with autistic spectrum disorder (ASD) have difficulty becoming aware of silent consonants (Grandin & Panek, 2013).

To discuss such errors more formally, we need a framework that separates continuous sounds into discrete units. There are various types of sound units and representations of sound. The current study utilizes the distinctive feature (Chomsky & Halle, 1968), which is the basic unit for distinguishing phonemes and is defined as a binary variable, with a value of (+) or (−), that is classified according to the movements of vocal organs such as the tongue and throat.

The distinctive feature defines innate phonetic elements as units, but there are varieties of the combinatorial system, namely languages, around the world. According to Trubetzkoy (1969), such systems fall into two groups, namely "mora languages" and "syllable languages," based on the smallest prosodic unit that is used in that language. In Japanese, which is one of the mora languages, the mora is defined as a unit of duration (Port et al., 1987). The Japanese morae consist of five vowels (*a, i, u, e, o*), 59 vowel-consonant combinations (*ka, ki, ku, ke, ko, sa, si, etc.*), and some special mora. Basically, one mora corresponds to one *kana* (Japanese character). In other words, Japanese phonic elements have a clear connection with written symbols. We think that this characteristic offers an advantage for modeling phonological awareness in a symbolic cognitive architecture. Therefore, in this study, we focus on Japanese morae.

In the Japanese language, reports have shown that two- or three-year-old children who have a developmental disorder confuse certain sounds (e.g., confusion between /r/ and /d/; Kobayashi, 2018), and have difficulty distinguishing between different vowels and vowel-consonant combinations (e.g., /a/ and /ka/; Ishida & Ishizaka, 2016). These reports show commonalities with the English reports previously mentioned (Grandin & Panek, 2013).

Several Japanese studies on phonological awareness have used the popular word game *Shiritori* as a task. In *Shiritori*, players take turns uttering a word (noun); the word must begin with the mora that the previous word ended with. For example, after a player answers *"ri-n-go"* (meaning apple), the next player continues with *"go-ri-ra"* (meaning gorilla). To avoid looping, the game ends if a player repeats a word that has already been used as an answer in the game (e.g., *"ma-su-ku"* (mask) $\rightarrow$ *"ku-ru-ma"* (car) $\rightarrow$ *"ma-su-ku"* $\rightarrow \cdots$).

Takahashi (1997) examined the conditions required for being able to play *Shiritori* and the stages of phonological awareness formation through a cross-sectional developmental experiment involving children having typical development. This research indicated that playing *Shiritori* requires the ability to divide sounds into morae and having a mental lexicon indexed by phonemes, and that the acquisition of kana characters is effective for indexing vocabulary by morae. In other words, playing *Shiritori* requires a phonological awareness that focuses on morae. This study also shows that children who do not have the phonological awareness required for *Shiritori* can participate in *Shiritori* with adult assistance.

Kubozono (2000) also conducted an experiment that examined the *Shiritori* process in a four-year-old Japanese child to present the phonological awareness formation process. In this experiment, the participants made errors concerning the mora unit (e.g., *"ta-i-yo-u"* (sun) $\rightarrow$ *"yo-u-gu-ru-to"* (yogurt)). In these examples, it is thought that the participants perceived the sound, which was usually divided into two morae in Japanese (*"yo-u"*), as a single unit. These reports show that errors in phonological systems can be observed in a word game.

Based on these findings, the current study focuses on phonological manipulation skills, such as extracting an ending from a word and retrieving a word by its initial sound. We also use *Shiritori* as a task, with reference to Takahashi's and Kubozono's work.

Cognitive modeling

Cognitive modeling is an approach to understanding and explaining the mechanisms of human cognition and cognitive processes. Many studies have so far been conducted to model the development process of phonological elements using artificial neural networks (ANN). For example, Matusevych et al. (2020) showed that by inputting a multilingual speech corpus into an autoencoder, language-specific phonological structures could be extracted. However, most studies using ANN encounter a black-box problem, which means the learned structure is difficult to explain. For ANN models such as autoencoder, it is difficult to incorporate innate factors into the structure of the model in a top-down manner.

In comparison, research has been conducted using cognitive architecture as another approach to cognitive modeling. A cognitive architecture is a basis for cognitive modeling that integrates cognitive functions that commonly appear in various tasks. From among the various cognitive architectures that have been developed, we selected ACT-R (Anderson, 2007) for use in this study. Because ACT-R is based on psychological experiments of thinking and memory, it enables us to comprehensively grasp various phenomena related to human cognition. What the current study focuses on is the knowledge possessed by the ACT-R model that can be expressed as discrete symbols by the modeler. It would be useful to consider how to map continuous sounds to a series of phonological units (i.e., symbols) in accordance with the knowledge representation in ACT-R to explain phonological awareness through modeling.

There have been many studies on language acquisition using ACT-R (Taatgen & Anderson, 2002; Van Rij et al., 2010; Mätzig et al., 2018). Among them, Nishikawa and Morita (2020) built a model that maps phonological awareness to the knowledge retrieval mechanism of ACT-R. This study showed that sound similarity associated with innate factors in language development, and partial match retrieval based on that similarity can explain the occurrence of errors in the phonological awareness formation process. This study also shows that manipulating the parameters that correspond to the effects of learning associated with experiential factors can reduce the relative importance of similarity and suppress errors. However, the results of this study were obtained by comparing simulations of several conditions in which the parameters were directly manipulated by the researchers in advance, and the process of forming phonological awareness and reducing errors through the performance of the task was not observed. In the current study, we extend this model to phonological awareness formation and error suppression through task performance.

Table 1: Model's declarative memory

(a) Word knowledge

word	sound
ringo	"ringo"
gorira	"gorira"
kuri	"kuri"
…	…

(b) Phonological knowledge

mora	sound
/ri/	"ri"
/go/	"go"
/ku/	"ku"
…	…

(c) Word–mora relationship

word	mora	position
ringo	/ri/	head
gorira	/go/	tail
gorira	/go/	head
…	…	…

Model

In this section, we describe the model constructed to examine the process of phonological awareness formation. The model is based on a previous study (Nishikawa & Morita, 2020) and it includes two agents, playing the *Shiritori* game. One agent is an adult, such as a caregiver, and the other is an infant who is the development subject. In the following, we show how the *Shiritori* process is realized in the ACT-R knowledge structure.

Knowledge Representation

Declarative chunks The declarative module of ACT-R contains knowledge that is required for task execution in the form of chunks. The model in this study retains three types of chunks that relate to word (vocabulary), phonological (mora) knowledge and the association between them (Table 1). The model also has chunks that store the words that have already been used in the current *Shiritori* trial. These chunks do not exist at the beginning of the trial. They are generated and stored as the trial progresses.

Production rules The production module selects and applies rules, and it operates the other modules while using information and states that are held by them. In this model, when the agent receives a word as the partner's answer, it searches for the word according to the rules of *Shiritori*, and then answers.

First, using the word chunk (chunk type a in Table 1) acquired by the aural module, the model retrieves a chunk that connects the word and the ending mora (chunk type c in Table 1). Next, using the retrieved word-mora association knowledge, the phonological knowledge (chunk type b in Table 1) that corresponds to the word ending is retrieved. Then, using this phonological knowledge, the word that begins with the mora is retrieved, and the selected word is held as a candidate answer in the goal module.

After this, the model checks that the stored answer candidate is valid according to the rules of *Shiritori*, such as not having been previously answered in the current *Shiritori* trial. If the current candidate violates these rules, the model searches again for a candidate answer. When the candidate word is confirmed as valid, the model stores it in the declarative module as an answered word and outputs the word through the speech module. During one *Shiritori* task trial, the two agents alternately execute this procedure until the given time limit is reached.

ACT-R Parameters for Knowledge Retrieval

In the process described above, the phonological awareness involved in paying attention to word endings corresponds to the retrieval of phonological knowledge from word knowledge. Knowledge retrieval in ACT-R is controlled by a parameter called activation. An activation value is assigned to each chunk and affects the success or failure of the retrieval and the time required for the retrieval. Among the equation of an activation value represented by the addition of several elements, we will focus on the similarity P_i and base-level B_i terms.

Similarity As discussed in the previous section, the innate factors in the developmental process can be assumed as the distinctive feature (Chomsky & Halle, 1968). Nishikawa and Morita (2020) incorporated this innate bias into the knowledge similarity between mora chunks. The similarity term P_i of the activation assigned to chunk i is computed using Eq. 1:

$$P_i = \sum_k PM_{ki} \tag{1}$$

This value is computed as the summation of the weighted degree of similarity M_{ki} for each retrieval request k to the chunk i. M_{ki} usually takes a negative value, and P serves as a penalty in the effect of similarity retrieval. In addition, the partial matching that becomes available by introducing similarity makes it possible to reproduce flexible choices and certain types of errors.

Base level The base level is the basic element of the activation that corresponds to learning and forgetting. This model maps the base level to experiential factors in the development process. It is represented by Eq. 2:

$$B_i = \ln\left(\sum_{j=1}^{n} t_j^{-d}\right) + \beta_i \tag{2}$$

That is, the base level of chunks that are used frequently rises and decays according to the last time they were used.

Learning Interactions

Related studies (e.g., Takahashi, 1997) suggest that children who have not fully formed phonological awareness need adult assistance to carry out interactions playing *Shiritori*. The agent in this study also needs assistance to learn.

We assume asymmetric interactions, such as those between children and parents, setting the similarity parameter for only one of the two agents. For the other agent, we incorporated a simple assistance that prompts the agent to answer again when they make a mistake during the task (for example, for the wrong answer of *"o-ka-si"* (sweets) to *"ri-n-go"*, the agent presented *"ri-n-go"* again).

Simulation

Using the model described above, we performed three simulations. The first simulation was a replication of the previous study (Nishikawa & Morita, 2020), which confirmed the influence of knowledge similarity (innate factor) and base level (experiential factor) calculations on the generation of phonological errors. The second and third simulations demonstrated the process of generating phonological errors and the factors that suppress such errors through the sequential *Shiritori* task execution.

Simulation 1: Occurrence and suppression of phonological errors

Simulation settings To demonstrate how the model produces and suppresses errors in Japanese mora using phonological knowledge similarity and base level calculations, we manipulated the similarity weight P (Eq. 1) and the base level offset constant β_i (Eq. 2). The values of P were set to 1, 10, 20, 30, 40, 50 and 60, and β_i was set to 0.1, 10, and 20, respectively. For phonological knowledge, 103 pieces of knowledge were defined based on Japanese morae. The combination of these morae was assigned with similarity computed by the value of cosine of feature vectors defined by Chomsky and Halle (1968). The words in the model in the model were selected from those listed in the Amano and Kobayashi (2008) Japanese word database. Based on the rules of *Shiritori*, we selected 20,544 nouns, excluding homonym duplications, and words consisting of only one mora, such as *"ro"* (furnace) and *"wa"* (ring). Next, referring to the child's associative vocabulary survey (The National Language Research Institute, 1981), 2,054 words were randomly removed and used as model knowledge.

Results and discussion To quantify errors in phonological awareness, we counted mora pairs that combined the endings of the caregiver agent's answer and the initial mora of the child agent's answer (e.g., caregiver's answer *"ri-n-go"* $\rightarrow$ child's answer *"go-ri-ra"*: *"go - go"*, the wrong answer *"ko-n-ro"* (stove) $\rightarrow$ *"o-ka-si"*: *"ro - o"*). We also calculated the entropy of the counted mora pairs to examine the degree of variation (convergence) of the generated mora pairs under each condition. The number of words answered during the *Shiritori* was also observed to check the performance of the *Shiritori* execution.

Figure 1 shows the type and number of mora pairs that appeared in each condition. The graphs that align vertically have different values of P, and the graphs that align horizontally have different values of β_i. The horizontal axis of each graph is the list of mora pairs, and the vertical axis is the number of appearances of that mora pair. In particular, the mora pairs that correspond to the correct retrieval (e.g., *"go-go"*) are indicated by red lines. The numbers shown in the graph are the entropy representing the variation of mora pairs.

From these figures, we can observe that many pairs other than the correct pairs (red) appeared in the condition where the value of P was small. In other words, we were able to confirm that the incorporation of sound similarity leads to the misuse of phonological knowledge. Also, as P increases, the entropy decreases. That is, the used mora converge to correct

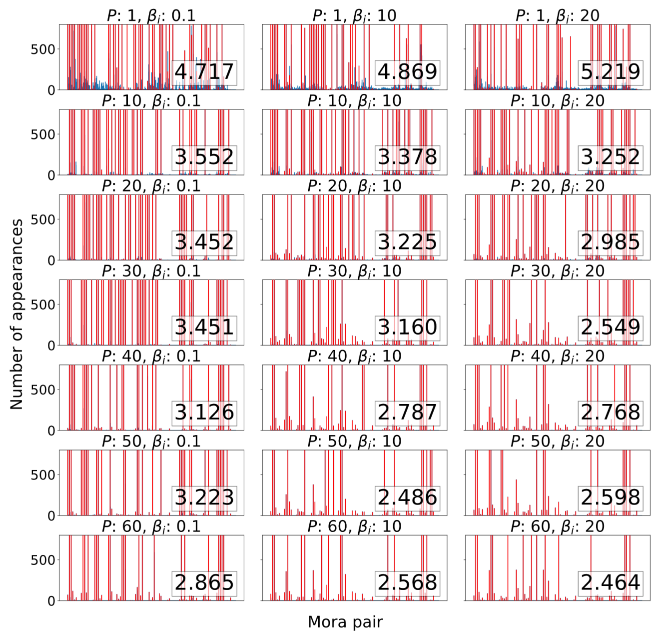

Figure 1: Number of occurrences and variation of mora pairs by P and β_i

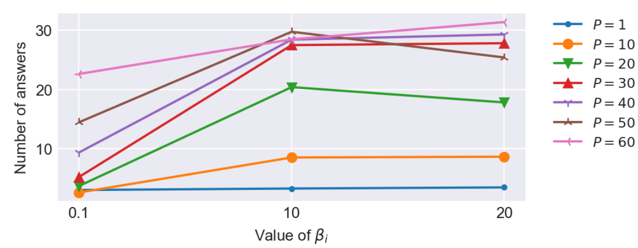

Figure 2: Number of answers per P and β_i

mora pairs as the value of P increases. We can interpret the difference between the P values corresponding to an innate difference in attention to sound. Focusing on the horizontal graphs (with different base-level offset constants β_i), we can see that the entropy decreases as β_i increases (the variation of mora pairs is decreasing) indicating the effect of base level (learning) in the suppression of phonological misuse.

Figure 2 shows the number of words answered (the number of times the *Shiritori* was continued) in each condition. From this graph, we can see that two parameters effectively contribute to the success of this task, suggesting that correct phonological awareness requires both innate and experiential factors.

Simulation 2: Process of Learning through *Shiritori* Task

Simulation settings This simulation was intended to demonstrate the increase in the base level caused by the actual task execution. In this simulation, we performed five *Shiritori* sessions of 600 seconds each. The parameters manipulated in the previous section were fixed (P: 10, β_i: 0.1), and the other

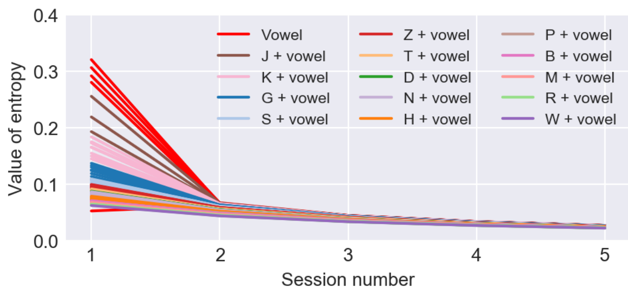

Figure 3: Entropy trend for each session. Each series is colored by the consonants in a mora (red: vowel, blue: *"ga"*, *"gi"*, *"gu"*, *"ge"*, *"go"*, etc.)

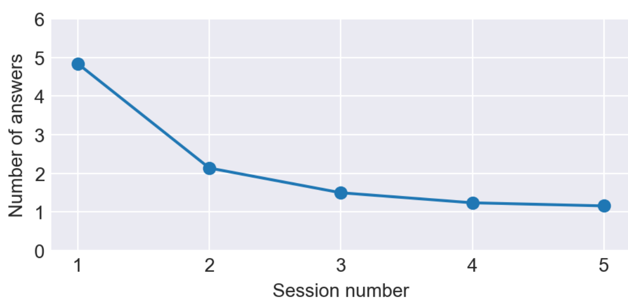

Figure 4: Number of answers per session

conditions were the same as in the previous section.

Results and discussion Figure 3 shows the entropy trend for each session as a function of the number of repeated sessions. Each series in this graph is the entropy of aggregating the mora pairs based on the first mora of the child agent's answer. In other words, it indicates the variety of morae leading to a specific mora perception by the child (e.g., *"ri-n-go"*, *"ko-n-ro"* or *"ne-n-do"* → *"o-ka-si"*). The series in the figure are also categorized as vowels and different consonants with vowels. From the first session in the figure, we can observe a large difference between these categories. The vowels have the highest entropy, indicating that the child agent connected the various end morae uttered by the adult agent to a vowel mora.

Although this trend is rapidly suppressed in the second session, this does not mean the task learning. As can be seen in Figure 4, the number of answers generated in the task decreases as the session progresses. In the later session, the child agent repeated the same word until the end of the session. This simple behavior can be considered as the cause of the decrease in entropy in Figure 3. The small variety in the adult answers in the later session, caused by the discontinuation of the task, also leads to convergence of the entropy.

One possible reason why such word repetition occurs can be found in the previous literature on ACT-R base level learning. Lebiere and Best (2009) indicated default base level learning leads to pathological repetitive behavior and extremely high activation in a specific chunk. In the current simulation, the erroneous experience (the experience of using confused mora) in the first session may lead to the convergence to inappropriate specific chunks. The following simulation was intended to determine which type of chunks (words or mora) causes this erroneous process, and what factors correct this process.

Simulation 3: Learning between Sessions

For the formation of phonological awareness, the convergence to inappropriate chunks, as described in the previous section, must be resolved. To do this, we included some intervention between session intervals. The assumption was that learning during the interval balances knowledge and prevents convergence to incorrect uses of knowledge. Even in a real environment, children do not learn phonological units only by playing *Shiritori*, so we examine the interaction with other learning.

Simulation settings This simulation manipulated the activation of the knowledge in the interval and its relation to success or failure in *Shiritori*. This time, we incorporated a process to make the activation of the knowledge the same as the knowledge with the largest activation. To determine the cause of the failure presented in the previous simulation, this manipulation was applied to each type of knowledge (word, mora, and word-mora; Table 1). Other settings were the same as in the simulation of the previous section.

Results and discussion Again, as in the previous section, we observed the entropy of the mora pairs and the number of answers for each session. Figure 5a-c shows the entropy trend for each session. These are the graphs for each type of knowledge that was manipulated. Figure 6 is the number of answers per session.

As shown in Figure 3, the first session of Figure 5a-c indicates a large difference in entropy between categories and rapidly converges to a specific mora. However, the trend in the number of answers (Figure 6) is different from the previous simulation, showing less of a drop in the number of answers in the condition where we manipulated the activation of mora-related knowledge. In other words, *Shiritori* was successful, and the use of phonological knowledge converged, suggesting that the correct use of phonological knowledge was learned. In other words, the results suggested that inappropriate convergence could be suppressed by appropriate learning and intervention during the interval. Continuing the task with such a balance of knowledge could eventually lead to the formation of phonological awareness.

Summary and Future Work

This study attempted to represent (1) the development process leading to erroneous phonological generation, and (2) the experiential factors involved in the suppression of phonological errors. Regarding the first aim, we presented the convergence of inappropriate knowledge through the sequential *Shiritori* task. We considered that this process has some sim-

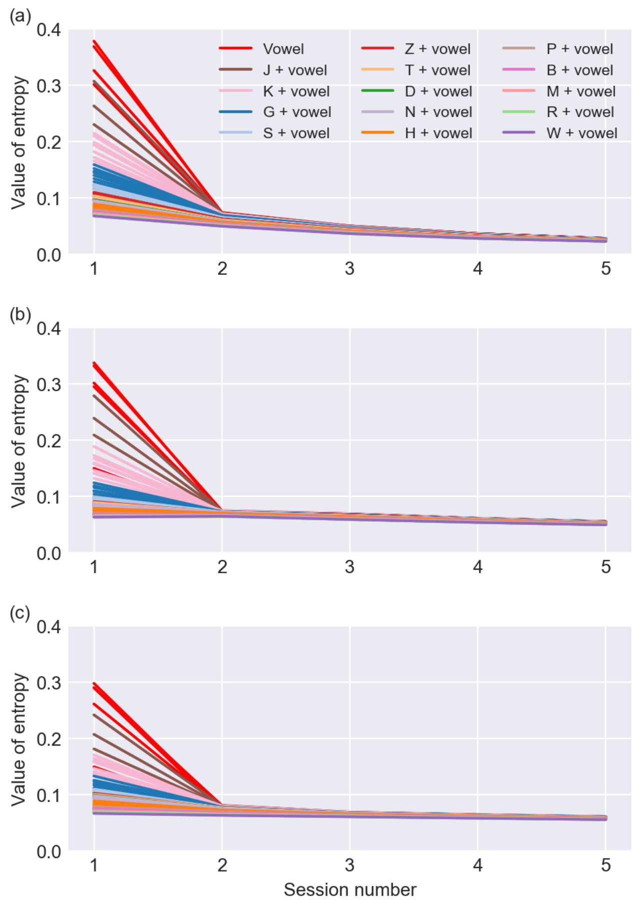

Figure 5: Changes in entropy from using mora knowledge (a: word knowledge manipulation, b: mora knowledge manipulation, c: word-mora knowledge manipulation)

ilarity to the cases of erroneous pronunciation observed in ASD children in the real world, as mentioned in the previous section (Grandin & Panek, 2013; Ishida & Ishizaka, 2016; Kobayashi, 2018). This suggests that the current ACT-R model could help to understand real-world phenomena and eventually support activities improving such erroneous behaviours.

From this point of view, the second objective of this study was to determine the factors that correct such erroneous processes. As a result of directly manipulating the interval learning, we found that balancing mora use was important to recovering and acquiring proper phonological awareness. However, in this simulation, the learning in the interval was only done by direct manipulation of the parameters. In the future, it will be necessary to study and implement interval learning that can be related to actual situations. In addition, evaluating the constructed model is essential. We must ensure that the model is a suitable representation of the actual phonological awareness formation process. This could be done by comparing the model with data such as the classification of

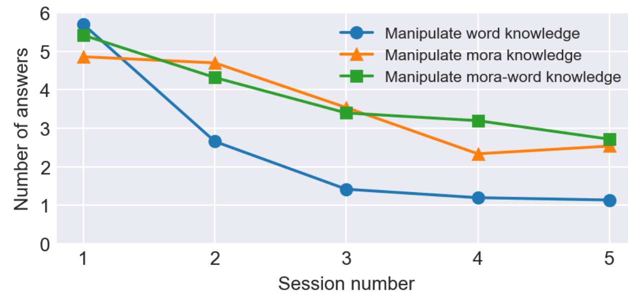

Figure 6: Changes of the number of answers

phonological errors in development (Nakamura et al., 2015).

Acknowledgments

This work was supported by JSPS KAKENHI Grant Numbers JP18H05068, JP20H04996.

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