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Pre- and Post-head Processing for Single- and Double-Scrambled Sentences of a Head-Final Language as Measured by the Eye Tracking Method

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Abstract Using the eye-tracking method, the present study depicted pre- and post-head processing for simple scrambled sentences of head-final languages. Three versions of simple Japanese active sentences with ditransitive verbs were used: namely, (1) SO_1O_2V canonical, (2) SO_2O_1V single-scrambled, and (3) O_1O_2SV double-scrambled order. First pass reading times indicated that the third noun phrase just before the verb in both single- and double-scrambled sentences required longer reading times compared to canonical sentences. Re-reading times (the sum of all fixations minus the first pass reading) showed that all noun phrases including the crucial phrase before the verb in double-scrambled sentences required longer re-reading times than those required for single-scrambled sentences; single-scrambled sentences had no difference from canonical ones. Therefore, a single filler-gap dependency can be resolved in pre-head anticipatory processing whereas two filler-gap dependencies require much greater cognitive loading than a single case. These two dependencies can be resolved in post-head processing using verb agreement information.

Keywords Head-final language · Gap-filling parsing · Scrambling · Pre-head and post-head processing · Eye-tracking

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Introduction

A head-final language (*head* refers to a verb) is a language in which a verb is positioned at the end of the sentence as in Japanese. *Pre-head anticipation processing* has been proposed by various studies (e.g., Kamide et al. 2003; Kamide and Mitchell 1999; Miyamoto and Takahashi 2002, 2004), for processing sentences of such languages by enabling language users to incrementally construct syntactic structure without seeing the head verb. However, these studies used either self-paced reading (e.g., Miyamoto and Takahashi 2002, 2004; Kamide and Mitchell 1999) or eye-tracking on multiple pictures with an auditorily-presented sentence (e.g., Kamide et al. 2003). The former, self-paced reading method locks a participant's reading into a specific region and cannot measure backward reading times. The latter, eye-tracking method also does not allow participants to listen to an auditorily-presented sentence again. Consequently, neither method is able to measure post-head processing. It is rather problematic that pre-head anticipation processing is strongly bound to sequential stimulus presentation, which does not allow participants to re-read or re-think once the head verb has become known. It is expected that the head verb provides syntactically-required elements of argument information, which permit native Japanese speakers to confirm whether or not the verb syntactically and semantically matches previously-seen noun phrases. Therefore, by utilizing the eye-tracking method with visually-presented sentences to measure eye fixations and gazing times of each phrase both forward and backward (e.g., Findlay and Gilchrist 2003; McConkie and Rayner 1975; Rayner 1998; Staub and Rayner 2007), the present study investigated both pre-head anticipation processing and post-head syntactic and semantic matching.

Nonconfigurational and Configurational Syntactic Structure

Unlike the strict SVO (subject, verb and object) word order of English, sentences in some languages can be presented in multiple orders. For instance, the head-final languages of Japanese, Korean, Mongolian and Turkish can feature OSV order as well as the canonical order of SOV. In an extreme case, the Sinhalese language spoken in Sri Lanka can exhibit up to six different orders with no specific requirements; SOV is considered as the canonical order, while OSV, SVO, OVS, VSO and VOS are possible scrambled orders (e.g., Gair 1998; Miyagishi 2003). Since there is no substantial difference among the syntactic positions of phrases of scrambled sentences, Farmer (1984) and Hale (1980, 1982, 1983) claimed that the Japanese language has what they referred to as a "flat" nonconfigurational structure. In this structure, noun phrases can be generated freely in any position within a sentence. For example, an SOV-ordered simple sentence, *Mary-ga ringo-o tabe-ta* meaning 'Mary ate an apple' [$_{S}$ NP-*ga* [$_{VP}$ NP-*o* V]] can be correctly expressed by re-ordering the nominal noun phrase *Mary-ga* and the accusative noun phrase *ringo-o* in OSV order as *Ringo-o Mary-ga tabe-ta*, without varying the essential meaning of the SOV canonical order. Therefore, given the nonconfigurational structure, we expected no difference in reading times for sentences with the different SOV and OSV word orders. In fact, a nonconfigurational structure was supported by some psycholinguistic studies (e.g., Nakayama 1995; Yamashita 1997) that found no difference in processing speed between canonical and scrambled orders as measured by the self-paced reading method.

A configurational, as opposed to a noncofigurational structure, was proposed by several linguists (e.g., Hoji 1985, 1987; Miyagawa 1989, 2010; Saito 1985; Saito and Hoji 1983), to support their claim that an instance of phrasal movement results in a free word order phenomenon. Ross (1967) originally referred to this as "scrambling". The movement of noun phrases from their original position in a canonically-ordered sentence produces their derived positions. In this structure, *Mary-ga ringo-o tabe-ta* reflects the canonical SOV order of an active sentence with a transitive verb. The scrambled OSV order is created by moving the accusative noun phrase *ringo-o* to the initial position of the sentence. The scrambled order requires a syntactic operation of phrasal movement from a trace (t_1) in the canonical position to the sentence initial position (NP-o_1) as in [$_S$ NP-o_1 [$_S$ NP-*ga* [$_{VP}$ t_1 V]]]. In the configurational structure, SOV was expected to be more quickly processed than the scrambled order of OSV. Support for the configurational structure has also been substantiated by other recent psycholinguistic studies (e.g., Koizumi and Tamaoka 2004, 2010; Mazuka et al. 2002; Miyamoto and Takahashi 2002, 2004; Tamaoka et al. 2005), which found a delay in reading scrambled sentences in comparison to their minimally-paired canonically-ordered sentences.

Among studies that found scrambling effects, Tamaoka et al. (2005) observed consistent inhibitory effects of scrambled order in four different types of active, passive, potential and causative sentences, strongly suggesting that native Japanese speakers use the canonical order of sentences as the base structure in sentence processing. In this sense, the findings of scrambling effects fit nicely into the *canonical order strategy* model proposed by Fodor et al. (1974), which treats the first noun phrase of a sentence as a subject. As described in the experiments of Tamaoka et al. (2005), a delay in sentence processing (i.e., scrambling effects) is observed when the subject is not initial information. The present study also adheres to the model of canonical order strategy, assuming that native Japanese speakers would be able to process sentences using a base structure of SOV canonical order. Nevertheless, the base structure of canonical order per se does not sufficiently depict the processing of scrambled sentences. In addition to the canonical order strategy, the mechanism of *gap-filling parsing* will be necessary to explain the processing of scrambled sentences.

Gap-Filling Parsing and Anticipatory Processing

Since native Japanese speakers read a sentence from the initial noun phrase, it is difficult to construct a syntactic structure with *trace* moved to the frontal position without seeing an entire sentence. In psycholinguistic studies, *gap-filling parsing* has been used to explain the delay in processing scrambled sentences. Gap-filling parsing was utilized by Frazier and others (Crain and Forder 1985; Frazier 1987; Frazier and Clifton 1989; Frazier and Flores D'Arcais 1989; Stowe 1986), as being especially useful in identifying a *wh-* filler in English. A sentence-initial *wh-* phrase triggers a search for its gap to establish filler-gap dependency. This parsing strategy has been applied to explain the processing of scrambled sentences in Japanese (e.g., Koizumi and Tamaoka 2004, 2010; Miyamoto and Takahashi 2002, 2004; Tamaoka et al. 2005). However, it should be noted that because the studies by Tamaoka and his colleagues (e.g., Koizumi and Tamaoka 2004, 2010; Tamaoka et al. 2005) used sentence correctness decision tasks by presenting minimally-paired whole sentences with canonical and scrambled orders, they cannot provide evidence of the crucial phrase where gap-filling parsing occurs.

A phrase-by-phrase study of the processing of Japanese canonical and scrambled sentences using eye-tracking was conducted by Mazuka et al. (2002). They reported an extra cognitive loading required for SOV-structured sentences with scrambled word order in both the first pass and regression times at the crucial phrase of the second agreement position.

They created paired directly-comparable sentences as in *Mariko-ga otooto-o yon-da* [Mariko-NOM brother-ACC Verb] meaning 'Marito called [her] younger brother' and its scrambled condition *Otooto-o Mariko-ga yon-da* [brother-ACC Mariko-NOM Verb]. In this pair, the second phrase of the scrambled sentence (i.e., *Mariko-ga*) is crucial to establish a single filler-gap dependency. However, the same-positioned phrase of the baseline canonical sentence is *otooto-o* 'brother'. *Mariko* is a proper noun while *otooto* is a general noun. As one can easily guess from daily life, the general noun 'brother' is more frequently used than the proper noun 'Mariko'. Thus, a difference in speed for the lexical processing of paired nouns per se (e.g., 'brother' versus 'Mariko') can create a significant delay at the crucial phrase.

Stimulus sentences in Mazuka et al. (2002) contain the scrambled sentence *Mariko-o Otooto-ga yonda* [Mariko-ACC brother-NOM Verb], which can be compared with the canonical order of *Mariko-ga otooto-o yonda* [Mariko-NOM brother-ACC Verb]. However, this sentence includes a center-embedded sentence as in *Mariko-o [soto-de buranko-ni notteita] otooto-ga yonda* [Mariko-ACC (outside swinging on a swing) brother-NOM called], so that this possible candidate is not appropriate for comparing scrambled sentences to the canonical baseline. Therefore, to date, no eye-tracking study has reported either a processing delay or extra cognitive loading by first pass reading in Japanese, nor have they determined regression/re-reading times at the crucial phrase where a filler-gap dependency is resolved.

According to 'head-driven' parsing (Pritchett 1991, 1992), the parser makes noun phrase attachments based on a head verb. If this is so, strictly speaking, the parser for the Japanese language is unable to make any attachment until seeing the head verb. In this parsing model, native Japanese speakers, therefore, cannot process a noun phrase until seeing the head at the end of sentence. Considering an example sentence such as *Utukusii nagai kami-no syoozyo-ga 50-meetoru no puuru-de oyoi-da* 'A beautiful long-haired girl swam in a 50-m pool', native Japanese speakers have to wait until seeing the past-tense verb 'swam' (*oyoi-da*) at the end of the sentence before the initiation of sentence parsing. This seems far too long to wait in initiating sentence processing.

Instead of head-driven parsing, some studies (e.g., Aoshima et al. 2004; Inoue and Den 1999; Inoue and Fodor 1995; Kamide et al. 2003; Kamide and Mitchell 1999; Miyamoto and Takahashi 2002, 2004; Ueno and Kluender 2003) suggest that native Japanese speakers can anticipate ensuing phrases from previously-given syntactic and semantic information before seeing the final verb. In the case of OSV-ordered Japanese active sentences $[_S$ NP-o_1 $[_S$ NP-*ga* $[_{VP}$ gap_1 V]]], when an accusative case-marked NP-*o* (or O) comes first, native Japanese speakers may assume an empty subject, constructing $[_S$ ec_{sub} [NP-*o* ...]] with the anticipation of a following verb. Using the aforementioned sentence, native Japanese speakers will assume 'I' (or *watashi-ga*) after reading the first noun phrase *ringo-o*, expecting to have a verb such as *tabe-ta* 'ate' to complete the sentence 'I ate an apple'. However, when the nominative NP-*ga* (*Mary-ga*) comes after NP-*o* (*ringo-o*), native Japanese speakers will treat the displaced NP-*o* as a *filler*, and create its *gap*, resulting in a syntactic structure which includes a *filler-gap dependency* $[_S$ NP-$o_1$$[_S$ NP-*ga* $[_{VP}$ gap_1 ...]]]. Then, they anticipate a transitive verb to complete an active sentence. As such, in the strict version of pre-head anticipatory processing, filler-gap dependencies can be resolved in sequential order without reference to the ending verb. This anticipatory processing seems to fit nicely into the model of *minimal attachment* proposed by Frazier and Rayner (1982), who investigated parsing in structurally ambiguous sentences (i.e., garden path sentences) using eye movements.

Pre-head anticipation processing (e.g., Aoshima et al. 2004; Inoue and Den 1999; Kamide et al. 2003; Kamide and Mitchell 1999; Miyamoto and Takahashi 2002, 2004;

Ueno and Kluender 2003) assumes processing to be sequential with no extra cognitive load for canonical sentences of head-final languages. However, although phrasal structure is constructed incrementally according to the sequence of given information before seeing the head verb, it may still play an important function in finding noun phrase agreement or in establishing filler-gap dependency when confronting a non-canonical sentence such as one with single-/double-scrambled order or long-distance scrambling. Native Japanese speakers may need the head verb information to resolve filler-gap dependency. Since Vitu et al. (1998) suggested refixations and regressions of eye movement reflect difficulties of text reading, regressions in eye movements will be able to capture the function of the head verb in relation to a filler-gap dependency. Thus, utilizing an eye-tracking method, the present study investigated the phrase-by-phrase on-line processing of simple Japanese sentences with canonical and scrambled orders. Although the present study uses the case of the Japanese language, the investigation may bear application to other languages that allow scrambling such as Korean, Mongolian, Sinhalese, and Turkish.

Assumptions of Eye Movements in the Present Study

A 'simple' sentence in the present study is defined as one constructed of noun phrases with no adjectives and adverbs. For instance, a Japanese sentence with a ditransitive verb is constructed of three noun phrases (hereafter, NP), nominative (NP-NOM), dative (NP-DAT) and accusative (NP-ACC), plus a verb. Take an example of a sentence like *Tom-ga Mary-ni hon-o kaeshi-ta* meaning 'Tom returned a book to Mary' (Tom-NOM Mary-DAT book-ACC return-PAST). The final verb 'returned' functions to make relations among the three nouns, 'Tom', 'Mary' and 'book'. It is noted that *-ga* is the nominative case-marker, *-o* the accusative case-marker and *-ni* the dative case-marker. These three noun phrases without an ending head verb can have multiple candidate verbs such as *age-ta* 'gave', *kashi-ta* 'rented', *nage-ta* 'threw', or even *yomase-ta* 'caused to read'. Although all information provided by previous noun phrases allows native Japanese speakers to predict some information including an upcoming verb, the potential of multiple verb choices may require native Japanese speakers to check for syntactic and semantic relations of already-seen noun phrases after seeing the head verb. If the head verb is merely used for checking whether or not the final syntactic and semantic structure matches with previously-seen noun phrases, the processing can be accomplished without reading backward.

To speculatively demonstrate the on-line performance of filler-gap dependencies with simple sentences, the present study compared scrambling effects employing minimally different syntactic structures with a baseline of processing times for canonical sentences. The following structures, comprised of three noun phrases and a single verb, will provide a foundation for clarifying the pre- and post-head verb processing mechanism for establishing filler-gap dependencies in an eye-tracking experiment.

E.g., Tom returned a book to Mary.

(1) Canonical order (SO_1O_2V; O_1 = an indirect object and O_2 = a direct object):
$[_S$ NP-*ga* $[_{VP}$ NP-*ni* $[_{V'}$ NP-*o* V]]]
Tom-ga Mary-ni Hon-o kaeshi-ta.

(2) Single-scrambled order (SO_2O_1V, a single gap within the verb phrase):
$[_S$ NP-*ga* $[_{VP}$ NP-o_1 $[_{VP}$ NP-*ni* $[_{V'}$ gap_1 V]]]]
Tom-ga Hon-o Mary-ni kaeshi-ta.

(3) Double-scrambled order (O_1O_2SV, two gaps outside of the verb phrase):
$[_S$ NP-*ni*$_1$ $[_S$ NP-*o*$_2$ $[_S$ NP-*ga* $[_{VP}$ *gap*$_1$ $[_{V'}$ *gap*$_2$ V]]]]]
Tom-ni Hon-o Mary-ga kaeshi-ta

Sentence (1) is the base line canonical order. Assuming pre-head anticipation processing based on previous studies (e.g., Aoshima et al. 2004; Inoue and Den 1999; Kamide et al. 2003; Kamide and Mitchell 1999; Miyamoto and Takahashi 2002, 2004; Ueno and Kluender 2003), sentence (2) may require extra processing time at the stage of the third noun phrase (NP-*ni*) to resolve the single filler-gap dependency between NP-*o*$_1$ and *gap*$_1$ before seeing the ending verb. Relatively longer eye fixations or duration will be expected in the third phrase for sentence (2) than for sentence (1). Nevertheless, since sentence (2) has only a single filler-gap dependency within the verb phrase, native Japanese speakers may not require extra cognitive loading at the third noun phrase to solve this dependency, and consequently, they may not read backward after seeing the head verb. If so, regressions in eye movements would not be observed in sentences (1) and (2).

Sentence (3), however, is a more complex case than sentence (2), being a double scrambling condition. When a dative-marked NP of *Tom-ni* is read, native Japanese speakers will construct $[_S$ ec_{sub} $[_{VP}$ NP-*ni*...]] in anticipation of an accusative-marked NP-*o* to follow. Then, native Japanese speakers will keep an empty category (or empty subject) and create the phrasal structure $[_S$ ec_{sub} $[_{VP}$ NP-*ni*$_1$ $[_{VP}$ NP-*o* ...]]], expecting a verb to complete the sentence. After these two noun phrases, they unexpectedly encounter a nominative-marked noun phrase, *Tom-ga*. At this stage, they have to delete an empty category and create two filler-gap dependencies as $[_S$ NP-*ni*$_1$ $[_S$ NP-*o*$_2$ $[_S$ NP-*ga* $[_{VP}$ *gap*$_1$ $[_{V'}$ *gap*$_2$...]]]]]. Extra reading time, which will be observed by fixations and durations of eye movements longer than sentence (1), and possibly (2), may be needed at the third phrase, NP-*ga*, which initiates the gap-filling parsing for two gaps. There are still multiple candidate verbs that may follow these noun phrases; only the ending verb can provide information regarding semantic relations for these noun phrases.

The strict version of pre-head anticipation processing predicts no backward reading for scrambled sentences (2) and (3). In other words, the information gathered in pre-head processing can resolve even two filler-gap dependencies, while the head verb at the end of sentence simply fills the position of the verb phrase. However, double-scrambled sentences may exhibit a more complex process of resolving filler-gap dependencies. Lewis (1996) proposed two (or three) as the magical number in sentence processing. She explained that two (or three) anomalies in a single sentence are far more difficult to process than a single anomaly. Quantitative change from a single gap to double may display a similar tendency. In other words, two gaps may require extra loading of short-term memory far heavier than a single gap. Then, the information of the head verb will be used for resolving two dependencies in sentence processing by native Japanese speakers. The eye-tracking method of the present study may show the post-head reading observed as regressions.

It should be noted that eye-tracking data need to be carefully treated because readers can read a wider visual span beyond the specific phrase where their eyes are fixated (e.g., Henderson and Ferreira 1990; Morrison 1984; Rayner and Fischer 1996). When eyes are fixated on the third-positioned noun phrase before the ending verb, the verb can be seen together with the previous noun phrase. Thus, eye-tracking data should be cautiously interpreted using all results of the first fixation times, the first pass reading times, re-reading times and regression-in/regression-out frequencies together. The present study aims to depict phrase-by-phrase processing of simple sentences with canonical and single-/double-scrambled orders through the careful handling of eye-tracking data.

Method

Participants

Eighteen native Japanese speakers (7 females and 11 males) who were either undergraduate or graduate students at the University of Tokyo in Japan participated in the present experiment. Ages ranged from 21 to 27 years, with the average age being 23 years and 1 month with a standard deviation of 2 years and 0 months on the day of testing.

Materials

Three versions of correct active sentences with ditransitive verbs were used for the present experiment: namely, (1) SO_1O_2V canonical $[_{S}\ \text{NP-}ga\ [_{VP}\ \text{NP-}ni\ [_{V'}\ \text{NP-}o\ \text{V}]]]$, (2) SO_2O_1V single-scrambled $[_{S}\ \text{NP-}ga\ [_{VP}\ \text{NP-}o_1\ [_{VP}\ \text{NP-}ni\ [_{V'}\ gap_1\ \text{V}]]]]$, and (3) O_1O_2SV double-scrambled order $[_{S}\ \text{NP-}ni_1\ [_{S}\ \text{NP-}o_2\ [_{S}\ \text{NP-}ga\ [_{VP}\ gap_1\ [_{V'}\ gap_2\ \text{V}]]]]]$. Noun phrases of the base sentences were altered to use minimum-paired single- and double-scrambled orders. For example, the canonical-ordered sentence of *Takahashi-san-ga Tanaka-san-ni hana-o okut-ta* ‘Takahashi presented flowers to Tanaka’, was changed to create a single-scrambled order by altering the accusative case-marked noun phrase and the dative case-marked noun phrase to become *Takahashi-san-ga hana-o Tanaka-san-ni okut-ta*. Likewise, a double-scrambled version was created by putting both the accusative and the nominative case-marked noun phrases before the nominative case-marked noun phrase resulting in *Tanaka-san-ni hana-o Takahashi-san-ga okut-ta*. Family names used for sentences were taken from the 100 most popular names in Japan, so processing these proper names would not affect the processing times when comparing the three sentence conditions. There were 90 target sentences created by making alterations to 30 base sentences. Based on this operation, 30 canonical, 30 single-scrambled, and 30 double-scrambled sentences (a total of 90 ‘YES’ response items, hereafter, ‘correct sentences’) were produced for the experiment. All the correct sentences were in the range of 16–20 characters (M = 17.63 characters) in length including a full stop. Noun phrases and verbs were in the range of 2–6 characters in length (M = 4.16 characters).

Thirty incorrect sentences with canonical noun phrase order were created as a base for correct ‘No’ response items (hereafter, ‘incorrect sentences’). These sentences were altered in the same fashion as correct sentences. As a result, 30 canonical, 30 single-scrambled and 30 double-scrambled sentences in each type (90 in total) were prepared: *Inoue-san-ga Saito-san-ni yotei-o hun-da* ‘Inoue stepped schedule to Saito’ for canonical order, *Inoue-san-ga yotei-o Saito-san-ni hun-da* for single-scrambled, and *Saito-san-ni Yotei-o Inoue-san-ga hun-da* for double-scrambled. All the incorrect sentences were in the range of 16–20 characters (M = 17.52 characters) in length including a full stop. Phrases and verbs were in the range of 2–6 characters in length (M = 4.13 characters). Family names used for these incorrect sentences were also taken from the 100 most popular names in Japan. According to the Latin-square design, these 90 correct and 90 incorrect sentences were divided into three lists of 30 correct and 30 incorrect sentences (10 each of canonical, single-scrambled and double-scrambled for both correct sentences and incorrect sentences). Therefore, each participant saw only one version consisting of 30 correct sentences containing 10 canonical, 10 single-scrambled and 10 double-scrambled, and 30 incorrect sentences containing the same types and numbers.

The experiment also included 15 correct and 15 incorrect filler sentences. With these fillers, the experiment used an equal number of correct and incorrect sentences. In total, each

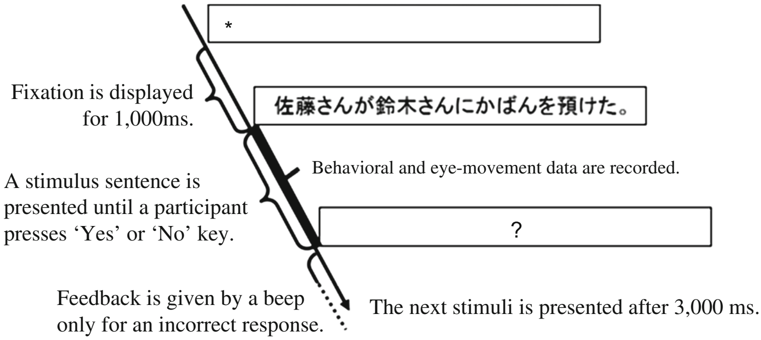

Fig. 1 Procedure of a single trail

of the three sets of stimuli consisted of 90 sentences, 45 correct sentences and 45 incorrect sentences.

Apparatus

An eye-tracking method was used with native Japanese speaking participants. Stimuli were displayed at the center of a monitor (Sony Trinitron MultiScan G520) controlled by a computer with a visual stimulus generator graphics card (Cambridge Research Systems VSG 2/5). All characters were displayed in MS Gothic (Japanese fixed-width font). Each character subtended a visual angle of 0.96° horizontally and vertically. The stimulus sentences were written horizontally in black on a white display. Reading times were measured from the onset of the target stimuli by means of a digital millisecond timer. Although participants viewed the screen with both eyes (binocular), left eye movements were monitored using a dual Purkinje eye tracker (Cambridge Research Systems Video Eyetracker Toolbox 2.10). The resolution of the eye tracker was 0.1° and the sampling rate was 50 Hz (measured every 20 ms).

Procedure

Each participant was seated in front of the monitor in a quiet room. A head and chin rest was used to maintain a viewing distance of 57 cm. Participants were asked to read sentences and perform correctness decisions using response keys connected to a computer. Prior to beginning the experimental session, participants engaged in a 20-point calibration sequence for the eye tracker. Ten practice trials were given. As shown in Fig. 1, in the beginning of each experimental trial, an asterisk '*' appeared for 1,000 ms as a fixation point at the position of the first character of the following stimulus sentence. Immediately after the offset of the fixation point, a stimulus sentence was presented. Participants were required to read each sentence silently and to press a key as soon as they finished reading. Reading times and eye movements were measured from the onset of the sentence to the key press response. Reading times were measured for each phrasal region of eye fixation times.

When a response was registered, the stimulus sentence disappeared and was replaced by a question mark '?'. Participants were required to answer whether or not the stimulus sentence was acceptable, by pressing the 'Yes' or 'No' key. If the correctness decision was incorrect, an auditory beep error message presented feedback to keep the participant's motivation high. The question mark '?' disappeared after this response was made. The next trial began 3,000 ms later. The eye tracker was recalibrated when participants returned for the experiment after an intermission. The entire process took under 30 min for each participant to complete, with the actual experiment requiring about 15 min. Eye fixation durations under 80 ms were not included in the calculation of reading times. Only the data from trials with less than 10 % missing data points (89.4 % of all trials) and in which sentence plausibility decisions were correct were used for data analysis.

Results

Behavioral Data of Reaction Times and Error Rates

Only correctly identified sentences for the sentence correctness decision were used for reaction time analysis. The statistical tests which follow analyze both participant (F_1) and item (F_2) variability. The means of reaction times and error rates for correct sentences are presented in Table 1.

A one-way analysis of variance (ANOVA) with repeated measures was conducted for reaction time data of canonical, single-scrambled and double-scrambled word orders. Means and standard errors of reaction times for these three sentence types of correct sentences are shown in Table 1. There was a main effect on reaction times for correct sentences [$F_1(2, 34) = 21.03$, $p < .001$, $F_2(2, 58) = 17.07$, $p < .001$]. Multiple comparisons using Tukey's HSD showed that canonical order (M $= 1,490$) had the same processing speed for sentence correctness decision as single-scrambled (M $= 1,544$). However, both of them were significantly faster than double-scrambled (M $= 1,889$). Reaction time data for incorrect sentences did not show a significant main effect [$F_1(2, 34) = 2.14$, $p = .134$, $F_2(2, 58) = 0.97$, $p = .384$].

As for error rates, a one-way ANOVA was conducted for canonical, single-scrambled and double-scrambled word orders. There was a main effect on error rates for correct sentences [$F_1(2, 34) = 10.30$, $p < .001$, $F_2(2, 58) = 11.20$, $p < .001$]. Multiple comparisons using Tukey's HSD showed that canonical order (M $= 1.67$ %) had the same error rates for sentence correctness decision as single-scrambled (M $= 2.22$ %), but both of them showed significantly lower error rates than double-scrambled ($M = 12.92$ %). Error rate data for

Table 1 Behavioral data for correct and incorrect sentences

Sentence type	Correct sentences				Incorrect sentences			
	Reading times (ms)		Error rate		Reading times (ms)		Error rate	
	M	SE	M	SE	M	SE	M	SE
1 Canonical	1,490	121	1.67 %	0.88 %	1,510	97	2.22 %	0.98 %
2 Single-scrambled	1,544	118	2.22 %	0.98 %	1,546	109	2.78 %	1.53 %
3 Double-scrambled	1,889	150	12.92 %	3.02 %	1,583	104	2.22 %	0.98 %
Main effects	***		***		*ns*		*ns*	
Multiple comparison	1 2 3		1 2 3					

M refers to means while SE refers to standard errors
Underlined numerals indicate sentence types differed significantly in multiple comparison
ns refers to 'not significant' * $p < .05$; ** $p < .01$; *** $p < .001$

Table 2 First fixation times in regions of noun phrases and verb for correct sentences

Sentence type	Fixation times (ms) of correct sentences in each region							
	NP_1		NP_2		NP_3		Verb	
	M	SE	M	SE	M	SE	M	SE
1. Canonical	219	11	186	10	214	14	172	18
2. Single-scrambled	223	11	209	16	223	9	139	14
3. Double-scrambled	208	11	206	15	215	11	157	18
Main effects	*ns*		*ns*		* (only F_2)		* (only F_1)	
Multiple comparison								

M refers to means while SE refers to standard errors
ns refers to 'not significant' * $p < .05$; ** $p < .01$; *** $p < .001$

correct 'No' responses did not show a significant main effect [$F_1(2, 34) = 0.10$, $p = .910$, $F_2(2, 58) = 0.10$, $p = .908$].

Behavioral data revealed significant main effects on both reaction times and error rates among canonical, single-scrambled and double-scrambled sentences only for correct sentences, but not for incorrect sentences. Therefore, further analysis was carried out only for data of correct sentences obtained by eye tracking.

First Fixation Times for Each Phrase

The first fixation times for each phrase were calculated by the initial fixation duration while the eye was fixated within the visual region around each noun phrase or the verb. A fixation was defined as a period of time when the eye did not move more than the width of a character (0.96° of arc) for 80 ms or longer. The means of the first fixation times for each phrase are reported in Table 2. For correct 'Yes' responses, the first fixation times of three types of sentences were analyzed by one-way ANOVA with repeated measures. The main effect on the first fixation times for the region of the third phrase (NP_3) was not significant in participant analysis [$F_1(2, 34) = 0.30$, $p = .074$], but significant in item analysis [$F_2(2, 58) = 3.22$, $p < .05$]. Multiple comparisons using Tukey's HSD showed that first fixation durations on the third phrase of single-scrambled sentences were longer than those of canonical sentences.

The main effect for the region of the verb was significant in participant analysis [$F_1(2, 34) = 5.37$, $p < .01$], but not significant in item analysis [$F_2(2, 58) = 2.10$, $p = .131$]. Multiple comparisons using Tukey's HSD showed that first fixation durations on the verb of canonical sentences were longer than those of single-scrambled sentences.

First Pass Reading Times

The first pass reading times were the total of the durations of fixations made on each phrase from the first fixation until the eye moved to another phrase or verb region. For correct sentences, the pre-head reading times for each of the three noun phrases and the verb were examined by one-way ANOVAs. The means of reading times for each phrase are reported in Table 3. The pre-head reading times in the third phrase showed a significant main effect [$F_1(2, 34) = 16.38$, $p < .001$, $F_2(2, 58) = 20.77$, $p < .001$]. Multiple comparisons using Tukey's HSD showed that reading times of the third phrase of both single- and double-scrambled sentences were longer than in canonical sentences. Since both scrambled

Table 3 First pass reading times in noun phrases and verb for correct sentences

Sentence type	Reading times (ms) of correct sentences in each region							
	NP_1		NP_2		NP_3		Verb	
	M	SE	M	SE	M	SE	M	SE
1. Canonical	342	31	278	21	266	22	192	24
2. Single-scrambled	345	34	254	25	377	30	162	21
3. Double-scrambled	347	40	256	28	411	40	167	20
Main effects	*ns*		*ns*		***		*ns*	
Multiple comparison					1 2 3			

M refers to means while SE refers to standard errors
Underlined numerals indicate sentence types differed significantly in multiple comparison
ns refers to 'not significant' * $p < .05$; ** $p < .01$; *** $p < .001$

Table 4 Re-reading times in noun phrases (NP) and verb for correct 'Yes' responses

Sentence type	Reading times (ms) of correct 'Yes' responses							
	NP_1		NP_2		NP_3		Verb	
	M	SE	M	SE	M	SE	M	SE
1. Canonical	48	17	95	28	15	7	7	4
2. Single-scrambled	38	8	66	17	63	17	3	2
3. Double-scrambled	96	19	150	30	175	37	22	9
Main effects	**		*		***		* (only F_1)	
Multiple comparison	2 1 3		2 1 3		1 2 3			

M refers to means while SE refers to standard errors
Underlined numerals indicate sentence types differed significantly in multiple comparison
* $p < .05$; ** $p < .01$; *** $p < .001$

conditions produced one gap for single-scrambled and two gaps for double-scrambled order in the third phrase (NP_3), this result indicates that pre-head parsing involved resolving a filler-gap dependency before the head verb was seen. However, nouns of scrambled order at this phrase are not matched with nouns of canonical order, a finding which is examined further in the Discussion section. No main effects were found in reading times of the regions of the first phrase (NP_1), second phrase (NP_2) or verb.

Re-reading Times

Re-reading times were calculated by the total reading duration (sum of all fixations) minus the first pass reading duration. Re-reading times for each of the three noun phrases and the verb were examined by the same ANOVAs. The means of reading times for each phrase are reported in Table 4. Re-reading times showed significant main effects in all three noun phrase positions. Re-reading times in the first phrase (NP_1) showed a significant main effect [$F_1(2, 34) = 7.31$, $p < .01$, $F_2(2, 58) = 6.52$, $p < .01$]. Tukey's HSD multiple comparisons showed that double-scrambled sentences had longer reading times than either canonical or single-scrambled sentences. In the second noun phrase (NP_2), the re-reading times also showed a significant main effect [$F_1(2, 34) = 5.11$, $p < .05$, $F_2(2, 58) = 5.28$, $p < .01$]. Tukey's

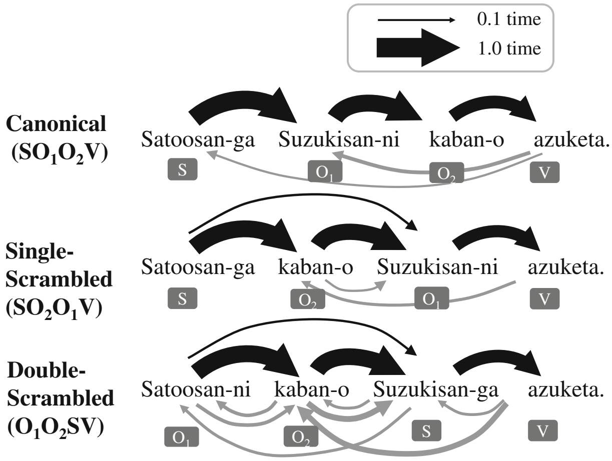

Fig. 2 Phrasal eye movements for three types of sentences. *Note*: Figure 2 depicts an average movement of more than 0.1 times. *Black arrows* above each sentence show eye movements of first pass phrasal reading from one region (a noun phrase or a verb) to another. *Gray arrows* below each sentence show eye movements of second or later pass phrasal reading from one region to another. The size of an *arrow* indicates average frequency of movements. S refers to a subject and V refers to a verb. O_1 refers to indirect object marked by a dative case-maker–*ni* while O_2 refers to direct object marked by an accusative case-marker -*o*

HSD multiple comparisons showed that double-scrambled sentences showed longer reading times than single-scrambled sentences. Likewise, re-reading times in the third phrase (NP_3) showed a significant main effect [$F_1(2, 34) = 15.25$, $p < .001$, $F_2(2, 58) = 21.63$, $p < .001$]. Again, Tukey's HSD multiple comparisons showed that double-scrambled sentences showed longer reading times than either canonical or single-scrambled sentences. Re-reading times in the region of the verb was significant in participant analysis [$F_1(2, 34) = 4.10$, $p < .05$], but not significant in item analysis [$F_2(2, 58) = 2.92$, $p = .060$], which was considered not significant. Tukey's HSD multiple comparisons showed that re-reading times on the verb were longer in double-scrambled sentences than in single-scrambled sentences. In sum, double-scrambled sentences required longer re-reading times in all noun phrases than single-scrambled sentences; the latter had no difference from canonical sentences.

Regression-Out and Regression-In Gaze Phrasal Eye Movements

The trend of gaze phrasal movements more frequent than an average of 0.1 times for the three types of sentences is depicted in Fig. 2. Black arrows above each sentence show eye movements of the first pass phrasal reading while gray arrows below each sentence show eye movements of the second or later pass phrasal reading. The size of an arrow indicates the average frequency of movements. The trend of black arrows indicates that native Japanese speakers read all three types of sentences sequentially from left to right. In contrast, the stream of gray arrows in double-scrambled sentences indicates backward reading or regression from verbs toward the second noun phrase (NP_2), and further from NP_2 to the third noun phrase (NP_3) while canonical and single-scrambled sentences only showed a minor degree of phrasal movement from verb to NP_2. Single-scrambled sentences showed a minor degree of movement from NP_2 to NP_3. Detailed analyses were conducted for regression-out and regression-in frequencies.

Table 5 Regression-out gaze movement for correct sentences

Sentence type	Regressions-out in regions					
	NP_2		NP_3		Verb	
	M	SE	M	SE	M	SE
1. Canonical	0.10	0.03	0.07	0.02	0.36	0.08
2. Single-scrambled	0.08	0.02	0.16	0.05	0.34	0.06
3. Double-scrambled	0.18	0.05	0.32	0.08	0.51	0.09
Main effects	* (only F_2)		**		* (only F_1)	
Multiple comparison	2 1 3		1 2 3		2 1 3	

M refers to means while SE refers to standard errors
Underlined numerals indicate sentence types differed significantly in multiple comparison
* $p < .05$; ** $p < .01$; *** $p < .001$

Regression-out gaze movement is defined as the probability of regressions out of a specific phrase. The mean regression-out frequency for each region in each sentential condition is shown in Table 5. The regression-out in the second noun phrase (NP_2) showed a significant main effect only in item analysis [$F_1(2, 34) = 2.44, p = .102$, $F_2(2, 58) = 3.31, p < .05$]. Tukey's HSD multiple comparisons showed that double-scrambled sentences showed more frequent regression-out gaze movements than single-scrambled sentences. In the third noun phrase (NP_3), the regression-out movement showed a significant main effect [$F_1(2, 34) = 7.65, p < .01$, $F_2(2, 58) = 11.66, p < .001$]. Tukey's HSD multiple comparisons showed that double-scrambled sentences showed more frequent regression-out gaze movements than canonical and single-scrambled sentences. Likewise, the verb region showed a significant main effect only in the participant analysis [$F_1(2, 34) = 3.93, p < .05$, $F_2(2, 58) = 1.78, p = .178$]. Again, Tukey's HSD multiple comparisons showed that double-scrambled sentences had more frequent regression-out movements than single-scrambled sentences. Regression-out gaze movements include frequencies before seeing the verb. For example, regression-out from the third noun phrase can indicate re-reading from NP_3 to NP_2 before seeing the verb. Thus, strictly speaking, only regression-out from the verb can indicate post-head movement. The third noun phrase, being at the position to resolve two filler-gap dependencies seems to be crucial for processing double-scrambled sentences.

Regression-in gaze movement is defined as how often eye gaze enters into a specific region after the first pass reading. The mean gaze movements for each region of three types of sentential condition are shown in Table 6. The first noun phrase (NP_1) showed a significant main effect [$F_1(2, 34) = 3.66, p < .05$, $F_2(2, 58) = 3.33, p < .05$]. However, Tukey's HSD multiple comparisons showed no significant differences among three types of sentences. Likewise, the second noun phrase (NP_2) showed a significant main effect [$F_1(2, 34) = 6.17, p < .01$, $F_2(2, 58) = 4.19, p < .05$]. Tukey's HSD multiple comparisons indicated that double-scrambled sentences showed more frequent regression-in movements than canonical and single-scrambled sentences. Furthermore, the third noun phrase (NP_3) showed a significant main effect only in item analysis [$F_1(2, 34) = 2.76, p = .077$, $F_2(2, 58) = 4.02, p < .05$]. Tukey's HSD multiple comparisons indicated that double-scrambled sentences showed more frequent regression-in movements than canonical sentences, but single-scrambled sentences did not. Regression-in gaze movements indicated

Table 6 Regression-in gaze movement for correct sentences

Sentence type	Regressions-in in regions					
	NP_1		NP_2		NP_3	
	M	SE	M	SE	M	SE
1 Canonical	0.21	0.06	0.27	0.07	0.05	0.02
2 Single-scrambled	0.22	0.05	0.26	0.06	0.10	0.03
3 Double-scrambled	0.38	0.07	0.48	0.09	0.14	0.04
Main effects	*		**		* (only F_2)	
Multiple comparison	*ns*		2 1 3		1 2 3	

M refers to means while SE refers to standard errors
Underlined numerals indicate sentence types differed significantly in multiple comparison
ns refers to 'not significant' * $p < .05$; ** $p < .01$; *** $p < .001$

that eyes moved frequently to the second noun phrase when processing double-scrambled sentences.

Discussion

To depict pre- and post-head gap-filling parsing, the present study investigated the processing of canonical and single-/double-scrambled sentences.

Behavioral data of reaction times for sentence correctness decision only showed significant delay and higher errors only for double-scrambled sentences in comparison to canonical and single-scrambled sentences. The differences between canonical and single-scrambled sentences were 54 ms in speed and 0.56 % in accuracy, neither of which were significant. The overall reaction times and error rates did not distinguish single-scrambled sentences from the baseline of canonical order. On the other hand, double-scrambled sentences showed greater difficulties, with an extra 399 ms in speed and 11.25 % in accuracy as compared with those of canonical order. In terms of behavioral data, single-scrambled sentences seem to display a similar degree of processing difficulty as canonical sentences. As Lewis (1996) suggested, two (or three) anomalies require far stronger cognitive loading than a single anomaly. However, as behavioral data can provide the basis for only an overall estimation, further detailed investigation was carried out by the eye-tracking method (e.g., Findlay and Gilchrist 2003; McConkie and Rayner 1975; Rayner 1998; Staub and Rayner 2007) measuring eye fixation durations and regression frequencies in each phrase.

The first pass reading time showed longer fixation time at the third noun phrase for single- and double-scrambled sentences in comparison to canonical order. This result may suggest that native Japanese speakers resolve filler-gap dependencies just before seeing the final head verb. As the pre-head anticipatory processing (e.g., Aoshima et al. 2004; Inoue and Den 1999; Inoue and Fodor 1995; Kamide et al. 2003; Kamide and Mitchell 1999; Miyamoto and Takahashi 2002, 2004; Ueno and Kluender 2003) expects, both sentences with single-scrambled (SO_1O_2V) and double-scrambled (O_1O_2SV) orders require gap-filling parsing at the third phrase before seeing the head verb. A single-scrambled order has a single filler-gap dependency between NP-o_1 and gap_1 as in $[_S$ NP-*ga* $[_{VP}$ NP-o_1 $[_{VP}$ NP-*ni* $[_{V'}$ gap_1 V]]]] while a double-scrambled order has two filler-gap dependencies, NP-ni_1 and gap_1, and NP-o_2 and gap_2, as in $[_S$ NP-ni_1 $[_S$ NP-o_2 $[_S$ NP-*ga* $[_{VP}$ gap_1 $[_{V'}$ gap_2 V]]]]]. Then, native

Japanese speakers anticipate a ditransitive verb to complete an active sentence. In pre-head anticipatory processing, native Japanese speakers construct phrasal syntactic structures prior to encountering the head verb. However, the strict version of pre-head anticipatory processing cannot be applicable, at least, for the processing of double-scrambled sentences which showed longer re-reading times (the total reading duration minus the first pass reading duration) than single-scrambled sentences.

Before discussing post-head parsing, the explanation of pre-head gap-filling parsing should be carefully interpreted. First, the third phrases of canonical and single-/double-scrambled conditions consist of different noun phrases: inanimate accusative-marked (-*o*) nouns for canonical, dative-marked (-*ni*) proper nouns for single-scrambled sentences, and nominative-marked (-*ga*) proper nouns for double-scrambled sentences. Stated precisely, direct comparison is only possible between single- and double-scrambled conditions: the two scrambled sentences were matched with the same nouns in the same phrasal position and the only differences were case-markers. Second, due to the wide visual span (e.g., Henderson and Ferreira 1990; Morrison 1984; Rayner and Fischer 1996) that human beings have, when eyes are fixated on the third-positioned noun phrase, the ending head verb can be seen together with the previous noun phrase. Given these two reasons, the first pass reading time does not provide sufficient *evidence* to support the pre-head gap-filling parsing, but can, however, suggest the *possibility*.

The post-head gap-filling parsing was investigated by re-reading times. Single-scrambled sentences did not show any difference from canonical sentences in any noun phrase. The single-scrambled sentences of the present study were produced by swapping the dative noun phrase and accusative noun phrase. This type of scrambling is called internal verb phrase movement, which may not require much cognitive loading to establish a single filler-gap dependency at the third phrase just before the head verb. In contrast, double-scrambled sentences needed longer re-reading times in the first, second and third noun phrases than single-scrambled sentences. A possible interpretation of these refixation times as an index of parsing difficulties (Vitu et al. 1998) might run as follows. Native Japanese speakers have to resolve two filler-gap dependencies for double-scrambled sentences. To accomplish this, they have to read backward to find appropriate agreement among three noun phrases with information of the ditransitive head verb. This post-head gap-filling parsing, reflected in the re-reading times of the three noun phrases in the double-scrambled sentences, took significantly longer than that of single-scrambled sentences. Since nouns and verbs were identical between the single- and double-scrambled sentences, this post-head gap-filling parsing has a great potential for the processing model for double-scrambled sentences.

Regression-in and regression-out frequencies also provided convincing support for the post-head gap-filling parsing. As indicated by regression-in gaze movements, double-scrambled sentences showed higher regression-in frequency at the second phrase than either single-scrambled or canonical. This result suggests that the eyes of native Japanese speakers move from the verb or the third phrase to the second phrase. In addition, regression-out gaze movements indicated that double-scrambled sentences showed higher regression-out frequency at the third phrase. For double-scrambled sentences, native Japanese speakers read backward from the third phrase to the second or the first. Both regression-in and regression-out gaze movements support the post-head parsing are required to resolve two filler-gap dependencies of double-scrambled sentences.

Synthesizing the findings of significant re-reading times for all noun phrases with the findings of regression-in and regression-out gaze movements, it appears that native Japanese speakers re-read double-scrambled sentences after seeing the head verb (including seeing the verb during fixations at the third phrase) back mostly to the nominative-marked third phrase (NP-*ga*) and accusative-marked second phrase (NP-*o*), and occasionally to the dative-marked first phrase (NP-*ni*) to check verb agreements. Using information of the ditransitive head verb, native Japanese speakers read back to NP-*ni* and NP-*o* to resolve filler-gap dependencies at the third noun phrase (NP-*ga*) for double-scrambled sentences. In sum, the pre-head anticipatory parsing might be enough to establish a filler-gap dependency for single-scrambled sentences. However, the head verb plays an important function for resolving the two filler-gap dependencies of double-scrambled sentences. The present study clearly depicted the post-head gap-filling parsing of double-scrambled sentences.

Appendix: Sentences Used in the Present Experiment

For stimuli of correct 'Yes' decisions (correct sentences), 30 canonical sentences were altered to create 30 single-scrambled and 30 double-scrambled sentences (a total of 90 correct sentences). These stimuli were used for analysis in the present study. In the same manner, for correct 'No' decisions (incorrect sentences), 30 incorrect canonical sentences were altered to make 30 single-scrambled and 30 double-scrambled sentences. The experiment also included 15 unacceptable and 15 acceptable filler sentences. Three examples of correct 'Yes' responses with three word orders are presented here in the "Appendix".

高橋さんが田中さんに花を贈った。

Takahashi presented flowers to Tanaka.

(1) Canonical sentence
[$_S$ NP-*ga* [$_{VP}$ NP-*ni* [$_{V'}$ NP-*o* V]]]
Takahashi-san-*ga* Tanaka-san-*ni* hana-*o* okut-ta.
Takahashi-san-NOM Tanaka-san-DAT flowers-ACC present-PAST
(2) Single-scrambled sentence
[$_S$ NP-*ga* [$_{VP}$ NP-o_1 [$_{VP}$ NP-*ni* [$_{V'}$ gap_1 V]]]]
Takahashi-san-*ga* hana-*o* Tanaka-san-*ni* okut-ta.
Takahashi-san-NOM flowers-ACC Tanaka-san-DAT present-PAST
(3) Double-scrambled sentence
[$_S$ NP-ni_1 [$_S$ NP-o_2 [$_S$ NP-*ga* [$_{VP}$ gap_1 [$_{V'}$ gap_2 V]]]]]
Tanaka-san-*ni* hana-*o* Takahashi-san-*ga* okut-ta.

Tanaka-san-DAT flowers-ACC Takahashi-san-NOM present-PAST

山崎さんが阿部さんに辞書を返した。

Yamasaki returned a dictionary to Abe.

(1) Canonical sentence
[$_S$ NP-*ga* [$_{VP}$ NP-*ni* [$_{V'}$ NP-*o* V]]]
Yanasaki-san-*ga* Abe-san-*ni* jisho-*o* kaeshi-ta.
Yamasaki-san-NOM Abe-san-DAT (a) dictionary-ACC return-PAST
(2) Single-scrambled sentence
[$_S$ NP-*ga* [$_{VP}$ NP-o_1 [$_{VP}$ NP-*ni* [$_{V'}$ gap_1 V]]]]
Yamasaki-san-*ga* jisho-*o* Abe-san-*ni* kaeshi-ta.
Yamasaki-san-NOM (a) dictionary-ACC Abe-san-DAT return-PAST

(3) Double-scrambled sentence
$[_{S}$ NP-*ni*$_{1}$ $[_{S}$ NP-*o*$_{2}$ $[_{S}$ NP-*ga* $[_{VP}$ *gap*$_{1}$ $[_{V'}$ *gap*$_{2}$ V]]]]]
Abe-san-*ni* jisho-*o* Yamasaki-san-*ga* kaeshi-ta.

Abe-san-DAT (a) dictionary-ACC Yamasaki-san-NOM return-PAST

近藤さんに村上さんがビールをすすめた。

Kondo offered beer to Murakami.

(1) Canonical sentence
$[_{S}$ NP-*ga* $[_{VP}$ NP-*ni* $[_{V'}$ NP-*o* V]]]
Kondo-san-*ga* Murakami-san-*ni* biiru-*o* susume-ta.
Kondo-san-NOM Murakami-san-DAT beer-ACC offer-PAST

(2) Single-scrambled sentence
$[_{S}$ NP-*ga* $[_{VP}$ NP-*o*$_{1}$ $[_{VP}$ NP-*ni* $[_{V'}$*gap*$_{1}$ V]]]]
Kondo-san-*ga* biiru-*o* Murakami-san-*ni* susume-ta.
Kondo-san-NOM beer-ACC Murakami-san-DAT offer-PAST

(3) Double-scrambled sentences
$[_{S}$ NP-*ni*$_{1}$ $[_{S}$ NP-*o*$_{2}$ $[_{S}$ NP-*ga* $[_{VP}$ *gap*$_{1}$ $[_{V'}$ *gap*$_{2}$ V]]]]]
Murakami-san-*ni* biiru-*o* Kondo-san-*ga* susume-ta.

Murakami-san-DAT beer-ACC Kondo-san-NOM offer-PAST

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