Electrophysiological responses to syntactic and "morphological" structures: evidence from Mandarin Chinese

Abbreviated title: Neural responses to morpho-syntax in Mandarin Chinese

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Abstract
What are syntactic relations, and how does our brain infer them from a string of text characters? In the EEG study reported here we aimed to investigate these questions by contrasting syntactically separable compounds (zao4…fan3 → "rebel") and non-separable compounds (chi2yi2 → "hesitate") in Mandarin Chinese. Because both kinds of compounds have non-compositional meanings, their syntactic differences provide an elegant means for dissociating syntactic from semantic relations. Because non-separable compounds fit the traditional criteria for "wordhood", this contrast also provides a means for asking whether syntactic and morphological relations are inferred in qualitatively different ways. We found that, relative to non-separable compounds, syntactically separable compounds elicited a left anterior negativity (LAN) effect between 275-400ms. Even though readers were always presented with the compounds in their unseparated form, our results suggest that the potentially separable compound forms drive the inference of a more complex set of underlying syntactic relations. In a companion manipulation in the same participants, we observed a qualitatively similar LAN effect when comparing non-separable compound nouns with simplex nouns. This finding raises doubts for the existence of a clear-cut distinction between "syntax" and "morphology", at least in processing.

Keywords: syntactic structure, morphological structure, LAN (left anterior negativity), non-lexicalism, lexicalism

1. Introduction

Both in speech and in text, language comprehension requires inferring the grammatical structure intended by the speaker or writer on the basis of the sensory evidence they provide. Much work in psycholinguistics has examined how syntactic relations are inferred during reading; a famously challenging task given that, without prosody, the text input is often compatible with multiple analyses (Frazier & Rayner, 1982; Huang & Ferreira, 2021). In recent decades, many neurophysiological recording studies have investigated the neural responses associated with inferring linguistic relations, for example in the pioneering MEG work by Bemis and Pylkkänen (2011, 2013) which showed a differential neural response in the anterior temporal lobe for a two-word structured condition (e.g., *red boat*) compared with an unstructured one-word condition (e.g., *xkq boat*). While there are now many candidate neural responses associated with inferring grammatical structure (e.g., early responses in the posterior temporal lobe; Flick & Pylkkänen, 2020; Law & Pylkkänen, 2021; Matar et al., 2021), there are inevitable and widely known challenges in manipulating linguistic structure without simultaneously altering conceptual structure and/or phonological structure, in order to "single syntax out" (see, e.g. Pylkkänen, 2019; Călinescu, Ramchand & Baggio, 2023; for discussion). Investigations of syntactic inference are also complicated by ongoing debate about the status of "word structure" or morphology in the language architecture: Is there a sharp distinction between "sentence structure" vs. "word structure", or is syntax "all-the-way-down", removing the need to posit a separate set of word-forming 'morphological' operations (Krauska & Lau, 2023)? If the latter, then models of syntactic inference responses must take this "smaller syntax" into account as well.

In this paper we address both of these questions by taking advantage of the existence of "separable" verb compounds in Mandarin Chinese—compound forms whose meanings are opaque (e.g. *zao4fan3* means "rebel", where *zao4* means "manufacture" and *fan3* means "reverse"), but which, unlike compounds in English, can be syntactically separated while preserving their opaque meaning. This class of compounds contrasts with another set of "inseparable" verb compounds which are matched in conceptual complexity as well as form complexity but which cannot be separated. Here we examine whether this difference in syntactic properties alone results in a neural response that can be unambiguously attributed to the syntactic inference process. At the same time, we also included a second set of conditions in which we compared the response to (inseparable) compound nouns with simplex nouns. By comparing the responses across the two manipulations, we can ask whether the neural signature for a "morphological" contrast is qualitatively similar to a "syntactic" contrast in the same participants.

1.1. Separable and inseparable compounds in Chinese

Although Chinese is sometimes mistakenly characterized as a language "without much morphology", in fact compound forms dominate the vocabulary of modern Chinese, in some estimates as much as 88% of Chinese lexicon (Zhou & Marslen-Wilson, 1994). The current study focuses on the intriguing class of verb compounds in Mandarin Chinese which can be syntactically separated while preserving their opaque compound meaning. Here we will use the term "separable verbs", but in the literature they go by many other names as well, including "ionized forms" (Chao, 1968), "separable words" (Han & Wang, 2022); "splittable compounds" (Siewierska, Xu & Xiao, 2010; Lu, Dai & Wu, 2022), as well as its Chinese name *liheci* (离合词, Petrovčič, 2016; Ye & Pan, 2023).

The separable verb phenomenon has been well-documented and extensively discussed in the theoretical linguistics literature (Chao, 1968; Li & Thompson, 1981; Huang, 1984; Packard, 2000; Xue,

2002; Zhang, 2007; Siewierska, Xu & Xiao, 2010; Wang, 2011; Chan, 2016; Yeh, 2020; Zhu & Liu, 2020; Ye & Pan, 2023), and somewhat similar phenomena have also been documented in other languages, such as Vietnamese (Nhàn, 1984; Noyer, 1998) and Cantonese (Chan & Cheung, 2021; Yip, Lee & Chan, 2021). An example is illustrated in (1). For the separable verb of "造反" (*zao4fan3*, [manufacture]-[reverse], "rebel"), syntactic units can be inserted between the two morphemes, but the meaning remains opaque (i.e., non-compositional; the compound meaning is not transparently derivable as a function of its parts, and thus the compound meaning must be acquired by learners separately from the meaning of its parts). By analogy, if "babysit" in English were a separable compound, one could syntactically separate its parts--e.g., "baby- one time -sit" --while preserving the opaque meaning[1],

(1)	造	了	很	多	次	反
	zao4	le0	hen3	duo1	ci4	fan3
	zao4	ASP	very	many	CL	fan3

"rebelled many times"

One of the primary reasons that separable verbs have engendered so much interest in the literature is because they seem to put pressure on a traditional notion of "word" as a stored object of semantic, syntactic, and phonological form which enters into semantic, syntactic, and phonological relations with other words. Standard, inseparable compounds like "seahorse" may seem to suggest a non-isomorphic pairing of a single concept to multiple form parts, but these cases can still be accommodated in a traditional framework by assuming that "seahorse" is a single phonological form, which corresponds to a single element in the syntactic structure and which in turn maps to a single concept. Separable verbs cannot be handled this way, because they manifestly demonstrate multiple elements that can be manipulated by the syntax but which realize the single stored (opaque) meaning.

The dissociation between conceptual complexity and syntactic complexity evident in Chinese separable verb compounds provides a novel opportunity for investigating the neural correlates of syntactic structure inference in comprehension, as dissociated from conceptual structure inference. In the current study, we do this by comparing the neural response to separable verb compounds with that of a different syntactic class of verbal compounds which, like English compounds, are "inseparable". For example, in the case of the inseparable verb of "迟疑" (chi2yi2, [late]-[doubt], "hesitate"), no syntactic units can be inserted in between the two parts, as illustrated in (2a). Instead, one has to use an expression like the one indicated in (2b). For more examples of separable and inseparable verbs we used, see Table 1.

(2a)	*迟	了	很	多	次	疑
	chi2	le0	hen3	duo1	ci4	yi2
	chi2	ASP	very	many	CL	yi2

Intended: "hesitated many times"

(2b)	迟	疑	了	很	多	次
	chi2	yi2	le0	hen3	duo1	ci4
	chi2	yi2	ASP	very	many	CL

"hesitated many times"

Both separable and inseparable verbs used in the current experiment consist of two morphemes, are opaque in meaning, and are syntactically intransitive (i.e., cannot take direct objects syntactically). Therefore, we can assume that the primary systematic difference between the separable vs. inseparable verbs we used here is in their syntactic representation. We note that different syntactic theories vary in exactly how that syntactic difference is realized. In standard lexicalist theories, inseparable compound verbs are considered to consist of a single syntactic unit (i.e., one "word"; Chung, 2006), and separable compound verbs are taken rather to consist of a complex syntactic structure relating multiple syntactic units (Huang, 1997; Badan, 2013; Pan & Ye, 2015; Chan, 2016; Guo, 2017). Non-lexicalist theories, on the other hand, allow the possibility that inseparable compound verbs also have internal syntactic parts corresponding to their compound phonological form parts. Such theories could posit instead that the ability or inability to be syntactically separated is driven by the two compound classes having distinct kinds of syntactic structure (cf. Zhang, 2007). Regardless of which analysis turns out to be correct, what is important for our first comparison is just that the two types of compounds differ underlyingly in their syntactic representation even when they are not actually separated, and thus that differential neural responses to these two compound types can be attributed to syntactic inference processes.

The second comparison in the study was designed to get at this further question about the mental representations underlying morphological complexity. A traditional, "lexicalist" approach to the language architecture has as a key component the construct of "word", a 1-to-1-to-1 mapping across form, syntax, and meaning. In this kind of approach, within-word operations belong to "morphology", and are qualitatively different from the inter-word operations beyond, which belong to the separate computational

[1] Note that the analogy is inexact as English doesn't have verb-verb compounds; this is only meant to give an intuition.

system of “syntax”. However, an increasing body of theoretical linguistic research questions these assumptions, suggesting that lexical knowledge includes many-to-one mappings much more complex than the traditional “word” (e.g., Jackendoff & Audring, 2020) and that structural relations within words are not qualitatively distinct from those between words, i.e. “syntax all the way down” (Halle & Marantz, 1993; Noyer, 1998; Siddiqi, 2010; Harley, 2014; Embick, 2015; Preminger, 2021). Part of the motivation for these new “non-lexicalist” approaches comes from recognizing that linguistics has in fact not been able to find a definition of “word” that successfully extends across the natural human languages of the world (Haspelmath, 2011; Yang, van den Bosch & Frank, 2020; Inbar, Grossman & Landau, 2020; Preminger, 2021; Yang, 2022; Krauska & Lau, 2023; for discussions centering on Chinese, see Wang, 2000; Xu, 2008; Chen, 2015). Many common intuitions about wordhood appear to relate to text spacing conventions in writing, and in writing systems without spaces like Chinese, speaker judgments about word boundaries show much more disagreement (Hoosain, 1992; Tsai, McConkie & Zheng, 1998; Yan et al., 2012; Liu et al., 2013). The separable verb compounds we examine here themselves illustrate this difficulty, as their combination of syntactic separability and semantic opacity has elicited a long-standing debate on whether a Mandarin separable verb is one word or two words (Chao, 1968; Li & Thompson, 1981; Huang, 1984; Packard, 2000; Xue, 2002; Zhang, 2007; Wang, 2008; Chan, 2016; Duanmu, 2017; Yeh, 2020; Myers, 2022; Ye & Pan, 2023).

In this experiment we took the opportunity to explore the distinction between “morphological” and “syntactic” structure by introducing a second pair of conditions in which the items differ in morphological complexity, but do not differ in their ability to be visibly separated in the syntax. This second comparison made use of transliteration-based loanwords in Mandarin like *pi1sa4* (from “pizza”), which are unambiguously simplex (cf. Hsu, Pylkkänen & Lee, 2019; Wei et al., 2023). We compared the ERP response to these simplex nouns with inseparable compound nouns to yield what would be traditionally considered a “morphological structure” contrast, and we then conducted a topographical similarity analysis to evaluate whether this effect is qualitatively similar to the “syntactic structure” contrast between separable and inseparable verbs, as might be predicted by “syntax-all-the-way-down” theories.

We focused our analyses in the current ERP study on the well-studied left anterior negativity (LAN) response, which prior work has implicated in both syntactic and morphological processing. Many ERP studies have demonstrated modulation of the LAN by manipulations of grammatical agreement (Molinaro, Barber & Carreiras, 2011; Caffarra, Mendoza & Davidson, 2019), syntactic complexity (Carreiras et al., 2010; Lau et al., 2023), as well as morphological complexity (Regel et al., 2019; Wei et al., 2023). Particularly relevant for our study, Wei et al. (2023) reported results from a contrast between Mandarin compounds and simplex words (with a variety of part-of-speech, including loanword nouns as in our current study) showing an increased LAN response for compounds relative to simplex words. Here we build on this prior work to ask whether differences in the underlying syntactic structure of different compound types can also modulate the LAN response, and how qualitatively similar these “syntactic” effects are to “morphological” ones.

Table 1. Examples of the separable verbs, inseparable verbs, compound nouns and simplex nouns that we used in the current experiment.

Contrasts	Experimental conditions	Examples	Pinyin transcriptions	Meaning	Properties of note
the syntax contrast: **separable verb minus inseparable verb**	**separable verb**	造反 跑步 退休	zao4fan3 pao3bu4 tui4xiu1	[manufacture]-[reverse], “rebel” [run]-[step], “jog” [back]-[rest], “retire”	Syntactically separable Opaque in meaning, syntactically intransitive, disyllabic
	inseparable verb	迟疑 社交 败北	chi2yi2 she4jiao1 bsi4bei3	[late]-[doubt], “hesitate” [society]-[communicate], “socialize” [fail]-[north], “lose (in wars)”	Syntactically inseparable Opaque in meaning, syntactically intransitive, disyllabic
the “morphology” contrast: **compound noun minus simplex noun**	**compound noun**	热狗 大衣 酸奶	re4gou3 da4yi1 suan1nai3	[hot]-[dog], “hotdog” [big]-[clothes], “overcoat” [sour]-[milk], “yoghurt”	2 morphemes Opaque in meaning, disyllabic
	simplex noun	披萨 夹克 拿铁	pi1sa4 jia2ke4 na2tie3	“pizza” “jacket” “latte”	1 morpheme, transliteration-based loan words Opaque in meaning, disyllabic

2. Results

2.1. The LAN (left anterior negativity) analysis

Our primary set of analyses were focused on the left anterior negativity, for which we used an ROI of left centro-frontal electrodes and time window of interest (275-400 ms) based on Wei et al.’s (2023) study (Figure 1c). As illustrated in Figure 1a-b, LAN differences were observed in both the “syntax” contrast between separable and inseparable verbs, and the “morphology” contrast between compound nouns and syntax nouns. In the “syntax” contrast, the LAN response in the 275-400 ms time window was significantly more negative for separable verbs than inseparable verbs (paired t test, two-tailed, $t(23)=-2.49$,

p=0.044<0.05; Figure 1e). In the “morphology” contrast, the LAN response in the 275-400 ms time window was significantly more negative for compound nouns than for simplex nouns (paired t test, two-tailed, $t(23)$=-2.22, p=0.037<0.05; Figure 1d), replicating the pattern Wei et al. (2023) observed for the same contrast in a visual lexical decision paradigm.

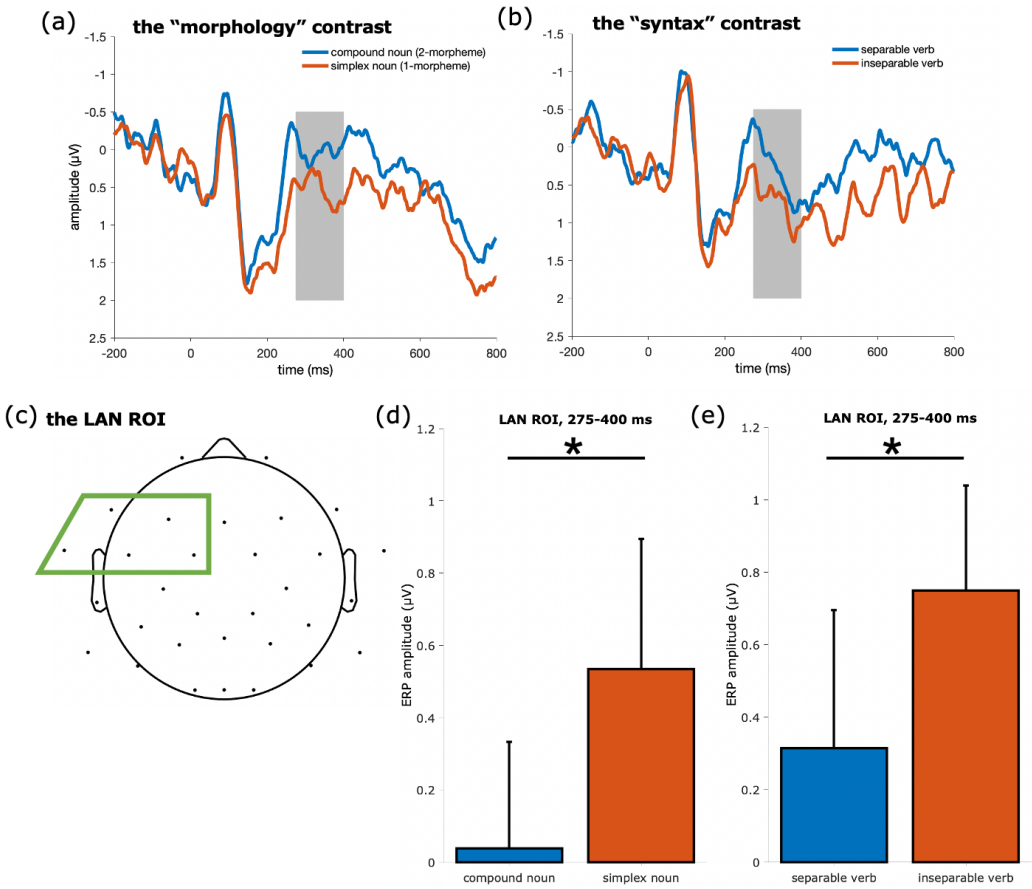

Figure 1. Results of the LAN (left anterior negativity) analysis.
(a) The average amplitude within the LAN ROI -200:800 ms around the onset of critical word for compound nouns and simplex nouns. The a priori time window of 275-400 ms is highlighted with gray shade;
(b) The average amplitude within the LAN ROI -200:800 ms around the onset of critical word for separable verbs and inseparable verbs. The a priori time window of 275-400 ms is highlighted with gray shade;
(c) The LAN ROI in the current study (F3, F7, FC5, FC7, FT9), marked within the green contour, informed by Wei et al. (2023);
(d) Mean response and standard error within the 275-400 time window in the LAN ROI for the “morphology” contrast (*: p<0.05);
(e) Mean response and standard error within the 275-400 time window in the LAN ROI for the “syntax” contrast (*: p<0.05).

Visual examination of the scalp topography across 275-400 ms for the two contrasts (Figure 2), suggests that although the topography of the two effects is similar when averaged across the full time-window of interest, there may be some variation in the evolution of the two effects across time. A left-negativity/central-positivity pattern appears to be strongest early in the time-window in the syntax contrast (around 275-325ms) and slightly later in the “morphology” contrast (around 350-400 ms). This impression was validated by the topographical similarity analysis reported next. For the ERP waveforms of all scalp electrodes, see Supplementary Materials.

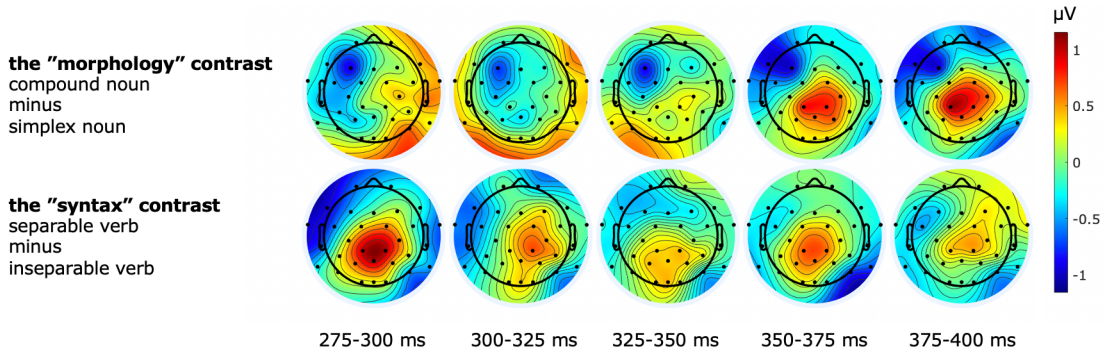

Figure 2. Scalp topography across the time window 275-400 ms for the "morphology" and "syntax" contrasts, averaged every 25 ms.

2.2. The topographical similarity analysis

The second component of our analyses was aimed at explicitly testing the topographical similarity of the "syntax" and "morphology" contrasts across time. This test identified at what points in time the scalp topographies for the two contrasts were similar, in increments of 25 ms (for details see Materials and methods section). The analysis first identified potential clusters with a $p<0.05$ threshold, and retained only clusters that survived a $p<0.001$ threshold with FDR correction. Significant clusters are marked with black contours in Figure 3b and 3d, for the angle (cosine) similarity analysis and projection amplitude analysis respectively. Four significant clusters were identified for the angle similarity analysis, spanning [50:125, 450:475], [300:375, 425:500], [250:375, 350:400], [600:700, 175:275] ms on the x and y axes respectively. Three significant clusters were identified for the projection amplitude analysis, spanning [300:375, 450:475], [275:350, 300:400], [525:625, 225:300] ms on the x and y axes respectively. Indeed, in line with the impression in Section 2.1, the cluster around 350 ms was slightly earlier for the "syntax" contrast compared to the "morphology" contrast; this result is consistent across angle similarity and projection amplitude analyses (for discussions see Section 3.3).

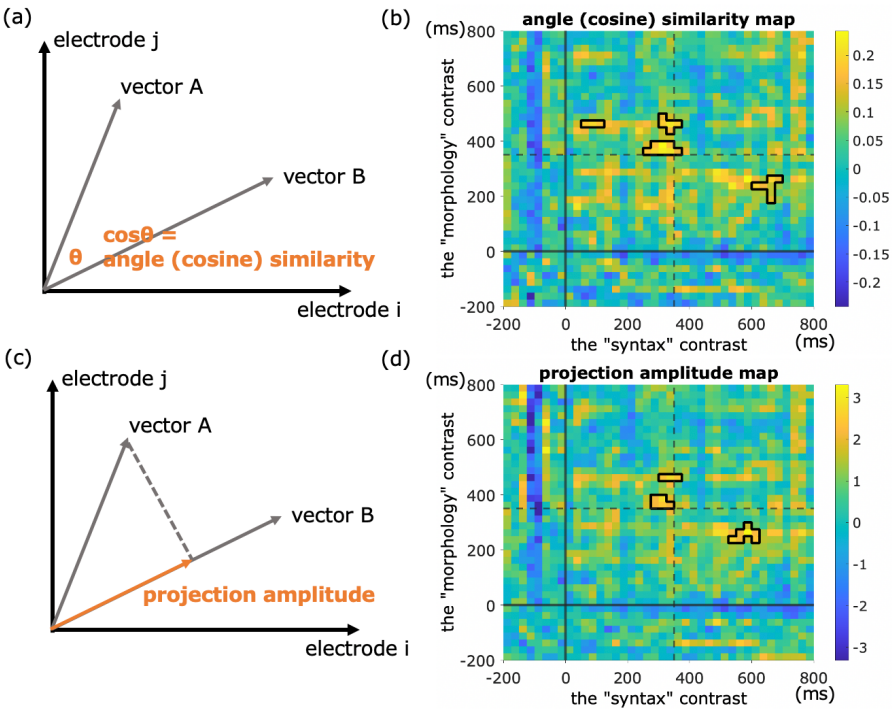

Figure 3. Results of the topographical similarity analyses.
(a) Illustration for the calculation of angle (cosine) similarity;
(b) Angle (cosine) similarity map. The significant ($p<0.001$, FDR corrected) clusters are outlined in black. The solid lines represent the onset of critical stimuli; the dashed lines indicate 350 ms post-stimulus presentation;
(c) Illustration for the calculation of projection amplitude;
(d) Projection amplitude map. The significant ($p<0.001$, FDR corrected) clusters are outlined in black. The solid lines represent the onset of critical stimuli; the dashed lines indicate 350 ms post-stimulus

presentation;

3. Discussion

The current study investigated ERP responses from native speakers of Mandarin Chinese while they read separable and non-separable compounds within sentence contexts. We have reported three main findings. First, we observed a significantly increased LAN (left anterior negativity) for separable verb compounds relative to non-separable verb compounds, even though neither compound was actually separated. Since the two types of compounds were similar in conceptual and form complexity, this LAN effect likely reflects differences in the underlying syntactic structure that must be inferred in the two compound types. Second, we observed a significantly increased LAN for compound nouns relative to simplex nouns, replicating and extending our understanding of an effect previously observed in single-word recognition (Wei et al., 2023). Finally, we found that these "syntactic complexity" and "morphological complexity" effects were qualitatively similar in topography, with only slight differences in temporal evolution. The similarity in the ERP response for the two contrasts is in line with the hypothesis that there is no qualitative difference between morphological and syntactic structure building (the "syntax-all-the-way-down" hypothesis; cf. Oseki & Marantz, 2020; Krauska & Lau, 2023).

3.1. A LAN effect for separable verb compounds

In the current study, we observed a LAN effect for the "syntax" contrast, i.e., between separable and inseparable verbs. This effect was observed in left anterior electrodes in the time window of 275-400 ms. To restate the linguistic fact, the separable verbs differ from inseparable verbs in that they are separable by other syntactic units, suggesting that separable verbs correspond to a more complex syntactic structure compared to inseparable verbs (see Section 1.1). Because both types of verbs are semantically non-compositional and consist of two morphemes, the LAN effect should be attributed to the inference of *syntactic* structure.

Several previous EEG studies have also examined Mandarin separable verbs (Zhang & Jiang, 2010; Gu, Yu & Ma, 2011; Gu et al., 2018), but with a different goal and a correspondingly different approach. As these studies assumed a lexicalist architecture, they asked whether separable verbs are "words" or "phrases" by comparing whether the ERP to separable verbs was more similar to words or to phrases. Zhang and Jiang (2010) found that separable verbs differed from words in many components (P200, N400 and P600) but from phrases only in P600; however, Gu et al. (2018) failed to observe a significant effect for the P600. These mixed results may have arisen due to additional factors in the materials these studies used for comparison; it is unclear whether all the items in the "word" conditions were verbs, and it is also unclear whether transitivity was matched across conditions. Furthermore, although aimed at distinguishing differences between "word" and "phrase" processing, these studies employed lexical decision or semantic categorization tasks, in which phrase comprehension is less likely to proceed normally. To our knowledge no prior study has compared separable and inseparable verbs within sentence contexts while matching their transitivity, which we take to be crucial for evaluating their processing differences.

Our LAN effect is in line with a previous ERP study which observed a LAN effect in a manipulation of Dutch particle verbs (Piai et al., 2013). Dutch particle verbs consist of a particle and a head verb which together can carry an idiomatic meaning, and as in the case of Mandarin separable verbs, they preserve this meaning even when they are syntactically separated. For example, the particle verb *voor-spellen* (before-mirror, "predict/promise") can be separated, with the particle preceding the head verb:

(3)	De	bank	spiegelt	haar	nierwste	klanten	hoge	winsten	voor.
	The	bank	mirrors	her	newest	customers	high	profit	before.

"The bank promises high profits to its latest customers."

Piai and colleagues compared the ERP responses for the head verbs that could appear in particle verbs against "inseparable" verbs that could not form a particle verb with any particle, when they were embedded in sentences. They hypothesized that, although the head verbs could also stand alone, participants would still consider the more complex particle-verb syntactic structure already at the head verb (particularly since participants encountered many particle verbs in the experiment). Indeed, they observed a LAN effect in which the head verbs which could participate in particle verb constructions exhibited a more negative effect in left anterior electrodes between around 300-550ms relative to the verbs that could not, consistent with the hypothesis that the more complex syntax of the particle verb construction put greater demands on working memory. One alternative explanation for this effect was that it could simply reflect greater syntactic uncertainty, although Piai et al. (2013) considered this explanation less likely since they failed to see a difference in the LAN response between head verbs that could take a wider range of particles vs. a smaller range. The current study provides converging support for the hypothesis that mere syntactic structure inference is enough to elicit a LAN effect, as we presented both parts of intransitive separable verbs at once to the subjects, minimizing the role of syntactic prediction.

Although both Mandarin separable verbs and Dutch/German particle verbs are separable, there appears to be intriguing differences between the two phenomena, which would serve as a fertile ground

for future research. Interestingly, for Mandarin separable verbs, the type of syntactic components that could go in between, as well as the syntactic operations that they could undergo (e.g., movement, reduplication) seem to be quite idiosyncratic. As an example, consider 帮忙 (bang1mang2, [help]-[busy], "help") and 费心 (fei4xin1, [cost]-[heart], "take trouble"). Although they are both separable verbs, they exhibit different acceptability profiles when separated by certain syntactic units, and when undergoing movement. While bang1mang2 can be separated in 帮了一个大忙 (bang1le0yi2ge0da4mang2, `bang1` ASP one CL big `mang2`, "did a huge favor"), 费了一个大心 (fei4le0yi2ge0da4xin1, `fei4` ASP one CL big `xin1`, intended "took huge trouble") is unacceptable. While 忙他帮了 (mang2ta1bang1le0, `mang2` he `bang1` ASP, "he helped") is fine, 心他费了 (xin1ta1fei4le0, `xin1` he `fei4` ASP, intended: "he took some trouble") is tricky. This is just one pair of examples among many Mandarin separable verbs, many syntactic components that could go in between, and many syntactic operations that they could undergo (e.g., movement, reduplication of the first part; see Siewierska, Xu & Xiao, 2010; Wang, 2011). This interesting idiosyncrasy remains to be documented comprehensively. How do native speakers come to learn this idiosyncrasy? Are there common factors that could account for the idiosyncrasies in Mandarin separable verbs and in German/Dutch particle verbs (see Trotzke, Qualglia & Wittenberg, 2015; Schoenmakers & Foolen, 2022)? All these interesting questions await future research.

A separate question is where in the brain the LAN effect originates from, and what that indicates about its functional interpretation. Many MEG studies have also tried to single syntax out in order to examine brain responses sensitive to syntactic structures, and they have observed effects in the posterior temporal lobe in somewhat similar time windows (Flick & Pylkkänen, 2020; Law & Pylkkänen, 2021; Matar et al., 2021). For example, Law and Pylkkänen (2021) examined MEG responses in the left posterior temporal lobe (PTL) when a list was embedded in a sentence vs. a longer list, and observed a difference in the 333-389 ms time window. This is also in line with many fMRI studies supporting the involvement of the posterior temporal lobe in syntactic structure inference (Matchin, Hammerly & Lau, 2017; Zaccarella, Schell & Friederici, 2017; Matchin & Hickok, 2020). We thus speculate that our LAN effect may originate from the posterior temporal lobe, which remains to be confirmed by future studies with techniques with a better spatial resolution (e.g., MEG and fMRI).

Although we have argued that our current LAN effect reflects sensitivity to syntactic structure, we should note that it is unclear if the effect reflects the recruitment of stored structured syntactic objects or "active" online structure building. The difference between these two processes is subtle but important. During syntactic structure building in language comprehension, one may consult structured objects (e.g., specific syntactic treelets) stored in long-term memory, but ad hoc syntactic structure building is more than just "reinstantiating" all relevant stored objects. However, it is difficult to empirically disentangle the two processes as of now, because the neural implementation of syntactic structure building remains highly debated (Ding et al., 2016; Ding, 2023; Meyer, 2018; Pylkkänen, 2019; Matchin & Hickok, 2020; Martin, 2020; Murphy, 2020, 2024; Kazanina & Tavano, 2023; Krauska & Lau, 2023), as well as the question of how long-term linguistic objects are stored (Poeppel & Idsardi, 2022; Krauska & Lau, 2023; Murphy, 2024).

3.2. A LAN effect for Mandarin noun compounds relative to simplex forms

Our LAN effect for the "morphology" contrast (i.e., compound vs. simplex forms) in a sentence context replicates Wei et al.'s (2023) earlier findings, with a similar ROI and time window. Wei and colleagues employed a lexical decision task, and observed a LAN effect in comparing Mandarin compounds and simplex forms with a variety of parts-of-speech. Our current study extends and strengthens their findings, as the results of isolated-word paradigms do not always agree with the processing dynamics observed when the same items are embedded in sentential contexts (see Morris, 2017). Mirroring this point, a recent MEG study on auditory word processing revealed different neural substrates when words are processed in isolation vs. in continuous speech (Gaston et al., 2022). Concerns have also been raised about the lack of naturalness of isolated-word comprehension paradigms (Salmelin, Helenius & Kuukka, 1999; Hamilton & Huth, 2020). Our corroborating evidence from a sentence paradigm is thus useful in demonstrating that the differential processing Wei and colleagues observed for compound Mandarin forms in lexical decision generalizes to how they are processed in integrated sentence contexts.

A component that has been argued to be sensitive to morphological structure in the MEG literature is the M350 (Stockall & Marantz, 2006; Fiorentino & Poeppel, 2007; Brooks & Cid de Garcia, 2015; Cavalli et al., 2016; Hsu, Pylkkänen & Lee, 2019; for reviews see Leminen et al., 2019; Royle & Steinhauer, 2023). The term "M350" sometimes refers to different measurements around 350 ms after the word onset, including the RMS (root mean square) peak around 350 ms (Fiorentino & Poeppel, 2007), as well as neural responses in posterior temporal regions around 350 ms (Brooks & Cid de Garcia, 2015; Cavalli et al., 2016; Hsu, Pylkkänen & Lee, 2019). The LAN effect observed in our current EEG study may reflect the same neural processes as M350, based on its time window. However, the neural source of the current LAN effect remains to be confirmed by future MEG studies with better spatiotemporal resolution.

3.3 Similarity between "syntactic" and "morphological" effects

In short, in the current EEG study we observed a similar LAN effect for both the "syntax" and the "morphology" contrasts. With the same left frontal ROI and time window (275-400 ms), we observed a

similar LAN effect that is both sensitive to syntactic structure complexity, but also morphological structure complexity, within the same group of subjects. This observation was corroborated by our topographical similarity analysis across the two contrasts, revealing a significant cluster around 350 ms, suggesting that the scalp distribution around 350 ms is similar across the two contrasts. This scalp distribution manifested as a LAN effect with a centro-parietal positivity. Although a similar topography appeared around 350 ms, that topography seemed to manifest slightly earlier for the "syntax" contrast than the "morphology" contrast. This may be accounted for by the fact that the critical segment in the "syntax" conditions always appeared with a comma (but not for the "morphology" conditions), which may prompt more immediate syntactic inference. Indeed, the exact timing of syntactic structure building could be modified by linguistic factors (Slaats, Meyer & Martin, 2024).

Form-level visual parsing is considered to happen around 170 ms or earlier (Tarkiainen et al., 1999; Salmelin, 2007, 2010; Gwilliams, Lewis & Marantz, 2016; Sigurdardottir, Ólafsdóttir & Devillez, 2021). Based on the later time window of our LAN effect, it is thus likely to reflect abstract (i.e., non-visual) morpho-syntactic processes. In fact, even the ~ 170 ms effects are already affected by morpho-syntactic rules (Gwilliams & Marantz, 2018). From the traditional lexicalist point of view, the shared LAN effect across the "morphology" and "syntax" contrasts may come as a surprise; since a clear cut is assumed between morphological and syntactic rules and representations, the lexicalist view does not predict that they should share linguistic parsing processes, any more than phonology and syntax would be predicted to share linguistic parsing processes. On the other hand, shared process(es) are predicted by non-lexicalist theories of language comprehension (see Oseki & Marantz, 2020; Krauska & Lau, 2023 for review) which hold that there is no qualitative difference between so-called "syntactic" and "morphological" structure inference/building. In other words, syntax is "all the way down".

Interestingly, in prior EEG and MEG work effects in this time-window (LAN and M350) have been argued to reflect structure inference in the neuro-morphology and the neuro-syntax literature respectively, and both have sometimes been suspected to originate from posterior temporal regions as reviewed above (note that although some studies also show evidence for a left frontal source for LAN effects, many of those cases involved grammatical violations; e.g., Friederici & Kotz, 2003; Carreiras et al., 2012). Our current study verifies that a similar effect for "morphology" and "syntax" can be observed within the *same* group of participants. Of course, a similar topography does not guarantee the exact same neural source, yet it provides encouraging *prima facie* evidence awaiting future studies with better spatial resolution to confirm.

4. Conclusion

In the current study, we investigated ERP responses associated with the comprehension of Mandarin separable verb compounds, which allow dissociation of syntactic complexity from semantic morphological complexity. We find that this difference in underlying syntactic complexity is associated with an increased left anterior negativity response between 275-400 ms relative to inseparable compounds, suggesting that comprehenders immediately recognize the syntactic differences between these compound types and strengthening the case that this neural response indexes some aspect of syntactic inference. Our finding that LAN effects across manipulations of "syntax" (separable vs. inseparable verbs) and "morphology" (compound vs. simplex nouns) are qualitatively similar is in line with the predictions of non-lexicalist theories of language comprehension, which proposes that there is no qualitative difference across the neuro-cognitive operations involved in syntactic and "morphological" structure inference and building.

5. Methods

5.1. Subjects

Subjects were recruited and tested in Shanghai, China, and all of them self-identified as native speakers of Mandarin Chinese. Subjects received monetary reimbursement for their participation. Written consent was acquired from each subject, and the procedures were approved by the Institutional Review Board of the University of Maryland and New York University Shanghai. Two subjects' data were excluded from data analysis because of artifacts (e.g., blinking, drifts) in excessive (≥50%) epochs. The remaining 24 subjects (16 female), had an age of 19-29 (*M*=23). One of the analyzed subjects was left-handed, and all others were right-handed, as measured by a translated version of the Edinburgh Handedness Inventory (Oldfield, 1971).

5.2. Stimuli

We first selected 30 items for each of the four compound types tested in this study: compound nouns, simplex nouns, separable verbs, and inseparable verbs. The compound and simplex nouns were disyllabic, matched in log10 bigram frequency in two large corpora (BCC multi-domain corpus, Xun et al., 2016; simplex: 3.6, compound: 3.7, independent sample t test p=0.33, two-tailed; CCL2024 corpus, Zhan et al., 2019; simplex: 3.9, compound: 3.9, independent sample t test p=0.88, two-tailed), as well as the stroke numbers for each character (1st character, simplex: 8.1, compound: 8.3, Mann-Whitney U test p=1.0, two-tailed; 2nd character, simplex: 6.9, compound: 7.7, independent sample t test p=0.29, two-tailed; the Mann-Whitney U test was administered instead of the independent sample t test whenever at

least one compared distribution did not pass the Shapiro-Wilk test, $p<0.05$). The simplex nouns were transliteration-based loan words. Although a number of these loan words in Chinese are composed of two visually similar characters, for example, 咖啡 (ka1fei1, "coffee"; the two characters share the same radical to the left), 芭蕾 (ba1lei2, "ballet"; the two characters share the same radical on top), we were careful to exclude such items from our stimuli set. The separable and inseparable verbs were intransitive, disyllabic, and matched in log10 bigram frequency in two large corpora (BCC multi-domain corpus; separable: 3.9, inseparable: 3.9, independent sample t test $p=0.92$, two-tailed; CCL2024 corpus; separable: 4.2, inseparable: 4.1, Mann-Whitney U test $p=0.23$, two-tailed), as well as the stroke numbers for each character (1st character, separable: 8.6, inseparable: 8.2, independent sample t test $p=0.55$, two-tailed; 2nd character, separable: 7.9, inseparable: 8.6, independent sample t test $p=0.36$, two-tailed). All compounds used in the study were selected to be intuitively opaque in meaning, in that the meaning did not follow straightforwardly from the meaning of the parts, e.g. for the compound 热狗 (re4gou3, hot-dog, "hotdog"), its meaning isn't a straightforward composition of the meaning of 热 (re4, "hot") and 狗 (gou3, "dog").

We then created a list of 120 sentences that contained the items from the four 30-word compound sets. The idea was to embed the compound words in a low-prediction neutral context. The sentential patterns and example sentences are illustrated in Table 3; for a comprehensive list of our stimuli see Supplementary Materials. Specifically, for the 30 separable and inseparable verb sentences respectively, 1/3 followed "wants to", "doesn't want to" and "really wants to" respectively. In order to control for the semantic congruity of "wants to/doesn't want to/really wants to + verb" (which all consist of 4 characters) across the two conditions, we matched the 4-gram frequency in two large corpora (cf. Lau et al., 2016). Because many of the 4-grams did not appear in the corpus (despite them being large of their kind), we calculated log10(frequency+1) as log10 frequency and employed a Mann-Whitney U test; the two conditions were balanced in 4-gram frequency (BCC multi-domain corpus: separable: 0.39, inseparable: 0.34, $p=0.58$; CCL2024 corpus: separable: 0.38, inseparable: 0.43, $p=0.77$). Two balanced lists of names were created for the separable and inseparable verb sentences and the names were counterbalanced across the 24 analyzed subjects. For separable and inseparable verb sentences, a comma always followed the verbs in order to ensure an intransitive reading, because of an increasing trend in Mandarin where intransitive verbs can be somewhat acceptable with transitive usages (Liao & Tsai, 2023). An additional 60 filler sentences were adapted from another study (Liao & Lau, 2020), rendering 180 sentences for each subject.

Table 3. Example sentential stimuli for our experiment; the critical segment for our analysis is marked in bold.

Compound and simplex nouns
Structure of sentences
[Because] **[compound/simplex noun]** [is] [segment 4] [segment 5,] [therefore/so] [continuation.] [因为] **[compound/simplex noun]** [是] [segment 4] [segment 5,] [所以/因此] [continuation.]
Example:
因为/**热狗**/是/一种/高热量的/食物，/所以/不是很健康。 Because/**hotdog**/is/a.kind.of/high-calorie/food,/therefore/not.very.healthy. "Because hotdog is a kind of high-calorie food, therefore it is not very healthy."
Separable and inseparable verbs
Structure of sentences
[Name] [wants to/doesn't want to/really wants to] **[separable/inseparable verb,]** [so/therefore] [continuation.] [Name] [想要/不想/很想] **[separable/inseparable verb,]** [所以/因此] [continuation.]
Example:
小范/很想/**造反，**/所以/他秘密组织了一支军队。 Fan[name]/really.wants.to/**rebel,**/therefore/he.gathered.an.army.secretly. "Fan really wants to rebel, therefore he gathered an army secretly."

5.3. Procedure

Subjects sat ~ 60 cm in front of the screen. 180 trials were run for each subject (30 trials for each of the 4 conditions + 60 filler sentences), with a different sentence presented in each trial. Each trial began with a fixation cross of 1000 ms, followed by presentation of the segments of this sentence in a segment-by-segment (i.e., RSVP, rapid serial visual presentation) manner, with a presentation duration for 600 ms for each segment, and a 200 ms interval between segments, for a total 800ms stimulus-onset asynchrony (Figure 4). The segments were presented in white characters against a black background, in 60 pt, Yahei font; they were presented at the center of the screen. In 1/3 of the trials, the last segment of the sentence (i.e., the continuation) was colored in green and the subjects were instructed to respond to whether this continuation was congruent in this sentence, by pressing m (incongruent) and n (congruent) on the keyboard with their right hand (the responses did not have a time-limit). In the other 2/3 of the trials, the last segment was presented on the screen in white briefly for 1000 ms, and subjects did not need to

respond. The inter-trial intervals were self-paced; subjects pressed the space bar when they were ready to start the next trial.

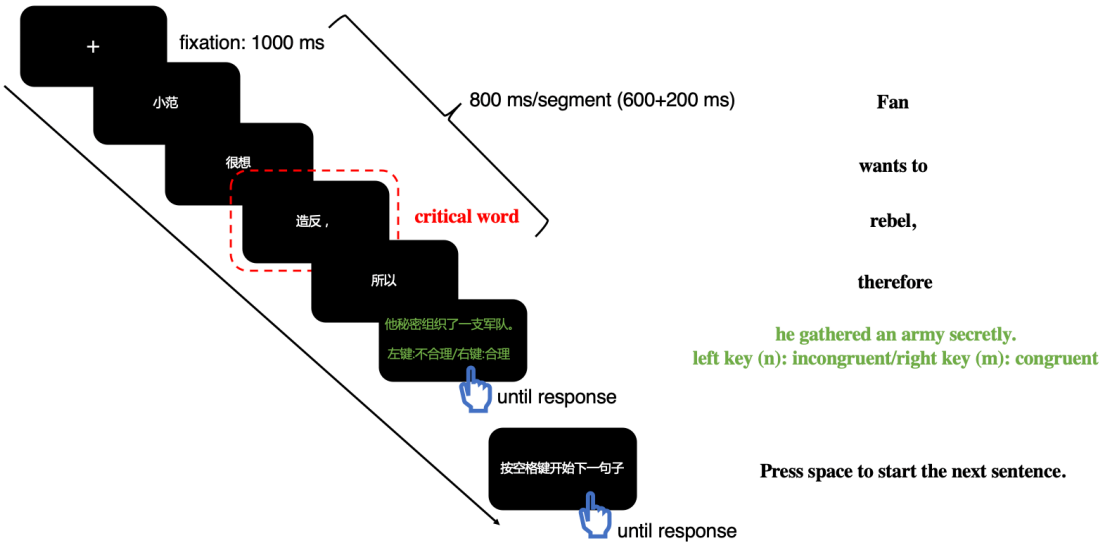

Figure 4. Illustration of a trial in our experiment. The English translation of what is presented on the screen is on the right.

After the experiment, the subjects were administered two post-tests. The first, "separability" post-test aimed at testing their subjective rating of the separability of the 60 separable and inseparable verbs used in the experiment. Subjects rated the acceptability of the separable and inseparable verbs on a 1-7 Likert scale, when they were separated by aspect markers "了" (le0) or "过" (guo4). The aspect marker used for each verb in the post-test was balanced across subjects; for example, half of the subjects were asked to rate the acceptability of "造了反" ([rebel-] le0 [-rebel]), and the other half of the subjects were asked to rate the acceptability of "造过反" ([rebel-] guo4 [-rebel]). Separability by aspect markers is a common and signature property for separable verbs (Siewierska, Xu & Xiao, 2010; Wang, 2011). The second post-test asked subjects to rate the concreteness of the 60 compound and simplex nouns used in the experiment on a 1-7 Likert scale, with an instruction adapted from prior concreteness studies in Chinese (Yao et al., 2017; Xu & Li, 2020).

5.4. Behavioral data analysis and results

Accuracy for the main experiment. Subjects' responses to the continuation judgement task were recorded, and we calculated the accuracy for each subject. The analyzed subjects generally had a high accuracy in the continuation congruity judgements (mean 96%, range 85%-100%).

Ratings for post-tests. For the separability post-test, we first averaged the ratings within the separable and inseparable verb lists respectively for each subject. A paired t test confirmed that the separable verbs we used were indeed more separable than the inseparable verbs (separable: 6.1; inseparable: 2.5; $t(46)=15.43$, $p<0.001$, two-tailed). For the concreteness post-test, we first averaged the ratings within the compound and simplex noun lists respectively for each subject. A paired t test confirmed that the two lists of nouns were matched in concreteness (compound: 6.3; simplex: 6.2; $t(46)=1.29$, $p=0.20$, two-tailed).

5.5. EEG recording

The EEG was recorded using a 32-channel (Fp1, Fz, F3, F7, FT9, FC5, FC1, C3, T7, TP9, CP5, CP1, Pz, P3, P7, O1, Oz, O2, P4, P8, TP10, CP6, CP2, C4, T8, FT10, FC6, FC2, F4, F8, Fp2, Cz) active electrode system (Brain Vision actiCHamp; Brain Products) with a 1000 Hz sampling rate in an electromagnetically shielded and sound-proof room. Electrodes were placed on an EasyCap, on which electrode holders were arranged according to the 10-20 international electrode system. The impedance of each electrode was kept below 25 kΩ. The data were referenced online to electrode Cz. Two additional EOG electrodes (HEOG and VEOG) were attached for monitoring ocular activity. The EEG data were acquired with Brain Vision PyCoder software and filtered online between DC and 200 Hz with a notch filter at 50 Hz.

5.6. EEG data analysis

EEG data were analyzed with EEGLAB and ERPLAB, along with customized MATLAB scripts. The EEG data was first subject to a 0.01 Hz to 40 Hz band-pass filter. Then bad channels were interpolated (spherical, 0-2 bad channels per subject), and the data was re-referenced to the average reference across scalp electrodes. Then, -200:800 ms epochs were extracted and baselined to the mean response between -200:0 ms. Epochs with artifacts were identified and excluded with a simple voltage threshold of -100 to

100 μV. We then reviewed the data, and if needed, adjusted the voltage threshold for individual subjects. A few trials were excluded due to a technical error that resulted in an inaccurate presentation duration. Then the ERPs for each condition were calculated within each subject. The number of trials left for each condition after artifact rejection is as follows: simplex nouns (26.3 trials, range 18-30), compound nouns (26.7 trials, range 21-30), separable verbs (27.3 trials, range 19-30), inseparable verbs (27.0 trials, range 19-30).

The LAN analysis. We averaged the ERPs for each subject within a left (central-)frontal LAN ROI (F3, F7, FC5, FC7, FT9), after Wei et al. (2023). We conducted a paired sample t test (two-tailed) across the average amplitude within the 275:400 ms time window as in Wei et al. (2023).

Topographical similarity analysis. Topographical similarity analysis (i.e., representational similarity analysis, spatial similarity analysis) is an analysis for comparing the topographical distribution of ERP responses that is free from bias in electrode selection (Tian & Huber, 2008; Murray, Brunet & Michel, 2008; Tian, Poeppel & Huber, 2010; Wang, Zhu & Tian, 2019). Quantifying topographical similarity with this method has been used to hallmark similarity in the underlying neural processes in many language comprehension studies (Yang, Cai & Tian, 2020; Wang et al., 2020; Wang & Kuperberg, 2023; Hubbard & Federmeier, 2021; Wei et al., 2023; Zhao et al., 2023; Huang, Feng & Qu, 2023; Ding, ten Oever & Martin, 2023).

For a more stable topography, we first averaged the ERP responses every 25 ms for each subject within the -200:800 ms epochs, collapsing 1000 time points (-200:800 ms) to 50 time points. Then we obtained the scalp topography for the "morphology" contrast (compound minus simplex nouns) and the "syntax" contrast (separable minus inseparable verbs) for each subject respectively. Then, we calculated the angle (cosine) similarity and projection amplitude (Tian & Huber, 2008; Tian, Poeppel & Huber, 2010) across the two contrasts at each of the 20 ms time windows. We treated the ERP amplitudes of each scalp electrode (31 in total) as an unique dimension of a vector. Suppose the ERP amplitudes for the "morphology" contrast at time window i forms an 1x31 vector $\mathbf{A_i}$, and the ERP amplitudes for the "syntax" contrast at time window j forms an 1x31 vector $\mathbf{B_j}$, the angle similarity of the two vectors was calculated as:

$$\text{AngleSimilarity}(i,j) = \frac{\boldsymbol{A_i B_j}}{|\boldsymbol{A_i}||\boldsymbol{B_j}|}$$

And the projection amplitude of the two vectors was calculated as the mean of the projection of vector A_i on B_j and the projection of vector B_j on A_i:

$$\text{ProjectionAmplitude}(i,j) = \left(\left|\frac{\boldsymbol{A_i B_j}}{\boldsymbol{B_j B_j}}\boldsymbol{B_j}\right| + \left|\frac{\boldsymbol{B_j A_i}}{\boldsymbol{A_i A_i}}\boldsymbol{A_i}\right|\right) sign\big(AngleSimilarity(i,j)\big)\ /2$$

We calculated the angle similarity and projection amplitude for every time window of the "morphology" contrast and each time window of the "syntax" contrast. Thus we obtained a 50x50 map for angle similarity and projection amplitude for each subject respectively. First, at each time window (i,j) in the angle similarity map (which contains one single angle similarity value for each subject), we conducted a one-sample t test against 0 (that the two topographies are orthogonal to each other, i.e., not similar at all), $p<0.05$ (uncorrected). Then a set of potential clusters were identified based on temporal adjacency of these significant time windows. After that, for each potential cluster, we calculated the mean within it for each subject, and compared this distribution against 0 (i.e., no similarity) with a one-sample t test, rendering a new *p* value for each temporal cluster. Only the clusters that survived a 0.001 threshold (FDR corrected with the fdr_bh() function, Benjamini & Hochberg, 1995; Groppe, 2023) are outlined in Figure 4b. A similar analysis was run for the projection amplitude map as well (Figure 4d).

References

Badan, L. (2013). Verb-object constructions in Mandarin: A comparison with Ewe. *The Linguistic Review*, 30(3), 373-422.

Bemis, D. K., & Pylkkänen, L. (2011). Simple composition: A magnetoencephalography investigation into the comprehension of minimal linguistic phrases. *Journal of Neuroscience*, *31*(8), 2801-2814.

Bemis, D. K., & Pylkkänen, L. (2013). Flexible composition: MEG evidence for the deployment of basic combinatorial linguistic mechanisms in response to task demands. *PLoS One*, *8*(9), e73949.

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal statistical society: series B (Methodological)*, *57*(1), 289-300.

Brooks, T. L., & Cid de Garcia, D. (2015). Evidence for morphological composition in compound words using MEG. *Frontiers in Human Neuroscience*, *9*, 215.

Caffarra, S., Mendoza, M., & Davidson, D. (2019). Is the LAN effect in morphosyntactic processing an ERP artifact?. *Brain and Language*, *191*, 9-16.

Călinescu, L., Ramchand, G., & Baggio, G. (2023). How (not) to look for meaning composition in the brain: A reassessment of current experimental paradigms. *Frontiers in Language Sciences*, *2*, 1096110.

Carreiras, M., Carr, L., Barber, H. A., & Hernandez, A. (2010). Where syntax meets math: Right intraparietal sulcus activation in response to grammatical number agreement violations. *NeuroImage*, *49*(2), 1741-1749.
Carreiras, M., Duñabeitia, J. A., Vergara, M., De La Cruz-Pavía, I., & Laka, I. (2010). Subject relative clauses are not universally easier to process: Evidence from Basque. *Cognition*, *115*(1), 79-92.
Cavalli, E., Colé, P., Badier, J. M., Zielinski, C., Chanoine, V., & Ziegler, J. C. (2016). Spatiotemporal dynamics of morphological processing in visual word recognition. *Journal of Cognitive Neuroscience*, *28*(8), 1228-1242.
Chan, H. T. (2016). *Fundamental Principles for Chinese Wordhood: Case Studies on Negation and "Separable" Words*. City University of Hong Kong.
Chan, S. S., & Cheung, L. Y. (2021). Morpho-syntax of non-VO separable compound verbs in Cantonese. *Studies in Chinese Linguistics*, *41*(2), 185-206.
Chao, Y. R. (1968). *A grammar of spoken Chinese*. University of California Press.
Chen, B. (2015). *Ershi shiji zhongguo yuyanxue fangfalun yanjiu [Research on the Methodology of Chinese Linguistics in the 20th Century]*. Shangwu Yinshuguan [The Commercial Press].
Ding, N. (2023). Low-frequency neural parsing of hierarchical linguistic structures. *Nature Reviews Neuroscience*, *24*(12), 792-792.
Ding, N., Melloni, L., Zhang, H., Tian, X., & Poeppel, D. (2016). Cortical tracking of hierarchical linguistic structures in connected speech. *Nature Neuroscience*, *19*(1), 158-164.
Ding, R., ten Oever, S., & Martin, A. E. (2023). Pronoun resolution via reinstatement of referent-related activity in the delta band. *bioRxiv*.
Duanmu, S. (2017). Word and wordhood, modern. In *Encyclopedia of Chinese language and linguistics*.
Embick, D. (2015). *The Morpheme*. De Gruyter Mouton.
Fiorentino, R., & Poeppel, D. (2007). Compound words and structure in the lexicon. *Language and Cognitive Processes*, *22*(7), 953-1000.
Flick, G., & Pylkkänen, L. (2020). Isolating syntax in natural language: MEG evidence for an early contribution of left posterior temporal cortex. *Cortex*, *127*, 42-57.
Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology*, *14*(2), 178-210.
Friederici, A. D., & Kotz, S. A. (2003). The brain basis of syntactic processes: functional imaging and lesion studies. *NeuroImage*, *20*, S8-S17.
Gaston, P., Brodbeck, C., Phillips, C., & Lau, E. (2023). Auditory word comprehension is less incremental in isolated words. *Neurobiology of Language*, *4*(1), 29-52.
Groppe, D. (2023). fdr_bh (https://www.mathworks.com/matlabcentral/fileexchange/27418-fdr_bh), MATLAB Central File Exchange. Retrieved July 6, 2023.
Gu, J., Yang, Y., Ma, Y., & Shen, Z. (2018). A study on phonological character of split words and its neural basis [in Chinese]. *Yuyan Yanjiu [Studies in Language and Linguistics]*, *38*(1), 63-73.
Gu, J., Yu, L., & Ma, P. (2011). A study on liheci based on boundness: evidence from electrophysiology [Jiyu nianzhuoxing de liheci biaozheng yanjiu – shenjing dianshenglixue shiyan zuozheng] [in Chinese]. *Xiandai Yuwen [Modern Chinese]*, *10*, 115-120.
Guo, R. (2017). The mechanism for the formation of separable words and incomplete words [in Chinese], *Yuyan Kexue [Language Sciences]*, *16*(3), 225-249.
Gwilliams, L., & Marantz, A. (2018). Morphological representations are extrapolated from morpho-syntactic rules. *Neuropsychologia*, *114*, 77-87.
Gwilliams, L., Lewis, G. A., & Marantz, A. (2016). Functional characterisation of letter-specific responses in time, space and current polarity using magnetoencephalography. *NeuroImage*, *132*, 320-333.
Halle, M., & Marantz, A. (1993). Distributed morphology and the pieces of inflection, in *The View From Building 20* (pp. 111–176). MIT Press.
Hamilton, L. S., & Huth, A. G. (2020). The revolution will not be controlled: natural stimuli in speech neuroscience. *Language, Cognition and Neuroscience*, *35*(5), 573-582.
Han, X., & Wang, H. (2022). Human cognitive constraints on the separation frequency and limit of separable words. In *Workshop on Chinese Lexical Semantics* (pp. 18-41). Cham: Springer International Publishing.
Harley, H. (2014). On the identity of roots. *Theoretical Linguistics*, *40*(3-4), 225-276.
Haspelmath, M. (2011). The indeterminacy of word segmentation and the nature of morphology and syntax. *Folia Linguistica*, *45*(1), 31-80.
Hoosain, R. (1992). Psychological reality of the word in Chinese. In *Advances in Psychology* (Vol. 90, pp. 111-130). North-Holland.
Hsu, C. H., Pylkkänen, L., & Lee, C. Y. (2019). Effects of morphological complexity in left temporal cortex: An MEG study of reading Chinese disyllabic words. *Journal of Neurolinguistics*, *49*, 168-177.
Huang, C. T. J. (1984). Phrase structure, lexical integrity, and Chinese compounds. *Journal of the Chinese Language Teachers Association*, *19*(2), 53-78.
Huang, C. T. J. (1997). On lexical structure and syntactic projection. *Chinese languages and Linguistics*, *3*(1), 45-89.
Huang, Y., & Ferreira, F. (2021). What causes lingering misinterpretations of garden-path sentences: Incorrect syntactic representations or fallible memory processes?. *Journal of Memory and*

Language, *121*, 104288.
Huang, Z., Feng, C., & Qu, Q. (2023). Predicting coarse-grained semantic features in language comprehension: evidence from ERP representational similarity analysis and Chinese classifier. *Cerebral Cortex*, bhad116.
Hubbard, R. J., & Federmeier, K. D. (2021). Representational pattern similarity of electrical brain activity reveals rapid and specific prediction during language comprehension. *Cerebral Cortex*, *31*(9), 4300-4313.
Inbar, M., Grossman, E., & Landau, A. N. (2020). Sequences of Intonation Units form a ~ 1 Hz rhythm. *Scientific Reports*, *10*(1), 15846.
Jackendoff, R., & Audring, J. (2020). Morphology and memory: Toward an integrated theory. *Topics in Cognitive Science*, *12*(1), 170-196.
Kazanina, N., & Tavano, A. (2023). What neural oscillations can and cannot do for syntactic structure building. *Nature Reviews Neuroscience*, *24*(2), 113-128.
Krauska, A., & Lau, E. (2023). Moving away from lexicalism in psycho-and neuro-linguistics. *Frontiers in Language Sciences*, *2*, 1125127.
Lau, E., Socolof, M., Clarke, N., Asatiani, R., & Polinsky, M. (2023). A subject relative clause preference in a split-ergative language: ERP evidence from Georgian. *Brain and Language*, *236*, 105199.
Law, R., & Pylkkänen, L. (2021). Lists with and without syntax: A new approach to measuring the neural processing of syntax. *Journal of Neuroscience*, *41*(10), 2186-2196.
Leminen, A., Smolka, E., Dunabeitia, J. A., & Pliatsikas, C. (2019). Morphological processing in the brain: The good (inflection), the bad (derivation) and the ugly (compounding). *Cortex*, *116*, 4-44.
Li, C. N., & Thompson, S. A. (1981). *Mandarin Chinese: A functional reference grammar*. University of California Press.
Liao, C. H., & Lau, E. (2020). Enough time to get results? An ERP investigation of prediction with complex events. *Language, Cognition and Neuroscience*, *35*(9), 1162-1182.
Liao, C. H., & Tsai, J. Y. (2023). When “Mary broke up John” becomes acceptable: On the trend of transitivization in Mandarin. Poster presented at the 36th Annual Conference on Human Sentence Processing. Pittsburg, PA, USA.
Liu, P. P., Li, W. J., Lin, N., & Li, X. S. (2013). Do Chinese readers follow the national standard rules for word segmentation during reading?. *PLoS One*, *8*(2), e55440.
Lu, Z., Dai, Y., & Wu, Y. (2022). Spanish L2 Chinese Learners’ Awareness of Morpho-Syntactic Structures in the Reading Comprehension of Splittable Compounds. *Frontiers in Psychology*, *12*, 783869.
Martin, A. E. (2020). A compositional neural architecture for language. *Journal of Cognitive Neuroscience*, *32*(8), 1407-1427.
Matar, S., Dirani, J., Marantz, A., & Pylkkänen, L. (2021). Left posterior temporal cortex is sensitive to syntax within conceptually matched Arabic expressions. *Scientific Reports*, *11*(1), 7181.
Matchin, W., & Hickok, G. (2020). The cortical organization of syntax. *Cerebral Cortex*, *30*(3), 1481-1498.
Matchin, W., Hammerly, C., & Lau, E. (2017). The role of the IFG and pSTS in syntactic prediction: Evidence from a parametric study of hierarchical structure in fMRI. *Cortex*, *88*, 106-123.
Meyer, L. (2018). The neural oscillations of speech processing and language comprehension: state of the art and emerging mechanisms. *European Journal of Neuroscience*, *48*(7), 2609-2621.
Molinaro, N., Barber, H. A., & Carreiras, M. (2011). Grammatical agreement processing in reading: ERP findings and future directions. *Cortex*, *47*(8), 908-930.
Morris, J. (2017). The interaction between storage and computation in morphosyntactic processing. In: Mody, M. (eds) *Neural Mechanisms of Language*. Springer, Boston, MA.
Murphy, E. (2020). *The oscillatory nature of language*. Cambridge University Press.
Murphy, E. (2024). ROSE: A neurocomputational architecture for syntax. *Journal of Neurolinguistics*, *70*, 101180.
Murray, M. M., Brunet, D., & Michel, C. M. (2008). Topographic ERP analyses: a step-by-step tutorial review. *Brain Topography*, *20*(4), 249-264.
Myers, J. (2022). Wordhood and Disyllabicity in Chinese. In C. Huang, Y. Lin, I. Chen, & Y. Hsu (Eds.), *The Cambridge Handbook of Chinese Linguistics* (Cambridge Handbooks in Language and Linguistics, pp. 47-73). Cambridge: Cambridge University Press.
Nhàn, N. T. (1984). *The syllabeme and patterns of word formation in Vietnamese*. New York University.
Noyer, R. (1998). Vietnamese 'morphology' and the definition of word. *University of Pennsylvania Working Papers in Linguistics*, *5*(2), 5.
Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113.
Oseki, Y., & Marantz, A. (2020). Modeling human morphological competence. *Frontiers in Psychology*, *11*, 513740.
Packard, J. L. (2000). *The morphology of Chinese: A linguistic and cognitive approach*. Cambridge University Press.
Pan, H., & Ye, K. (2015). Separable words and cognate objects in Mandarin Chinese [in Chinese]. *Dangdai Yuyanxue [Contemporary Linguistics]*, *3*, 304-319.
Petrovčič, M. (2016). Word Sketches of Separable Words Liheci in Chinese. *Acta Linguistica Asiatica*,

6(1), 47-57.
Piai, V., Meyer, L., Schreuder, R., & Bastiaansen, M. C. (2013). Sit down and read on: Working memory and long-term memory in particle-verb processing. *Brain and Language*, *127*(2), 296-306.
Poeppel, D., & Idsardi, W. (2022). We don't know how the brain stores anything, let alone words. *Trends in Cognitive Sciences*.
Preminger, O. (2021). Natural language without semiosis. Presentation at the 14th Annual Conference on Syntax, Phonology and Language Analysis (SinFonIJA 14), (Novi Sad)
Pylkkänen, L. (2019). The neural basis of combinatory syntax and semantics. *Science*, *366*(6461), 62-66.
Regel, S., Opitz, A., Müller, G., & Friederici, A. D. (2019). Processing inflectional morphology: ERP evidence for decomposition of complex words according to the affix structure. *Cortex*, *116*, 143-153.
Royle, P., & Steinhauer, K. (2023). Neural correlates of morphology computation and representation. In *Language Electrified: Principles, Methods, and Future Perspectives of Investigation* (pp. 447-503). New York, NY: Springer US.
Salmelin, R. (2007). Clinical neurophysiology of language: the MEG approach. *Clinical Neurophysiology*, *118*(2), 237-254.
Salmelin, R. (2010). MEG and reading: from perception to linguistic analysis. In *MEG: An Introduction to Methods*.
Salmelin, R., Helenius, P., & Kuukka, K. (1999). Only time can tell–words in context. *Behavioral and Brain Sciences*, *22*(2), 300-300.
Schoenmakers, G. J., & Foolen, A. (2022). At the margins of grammar: Dutch and German verb particles in first sentence position. *Nederlandse Taalkunde*, *27*(3), 368-393.
Siddiqi, D. (2010). Distributed morphology. *Language and Linguistics Compass*, *4*(7), 524-542.
Siewierska, A., Xu, J., & Xiao, R. (2010). Bang-le yi ge da mang (offered a big helping hand): a corpus study of the splittable compounds in spoken and written Chinese. *Language Sciences*, *32*(4), 464-487.
Sigurdardottir, H. M., Ólafsdóttir, I. M., & Devillez, H. (2021). Words as visual objects: Neural and behavioral evidence for high-level visual impairments in dyslexia. *Brain Sciences*, *11*(11), 1427.
Slaats, S., Meyer, A., & Martin, A. E. (2024). Lexical surprisal shapes the time course of syntactic structure building. *OSF Preprints*.
Stockall, L., & Marantz, A. (2006). A single route, full decomposition model of morphological complexity: MEG evidence. *The Mental Lexicon*, *1*(1), 85-123.
Tarkiainen, A., Helenius, P., Hansen, P. C., Cornelissen, P. L., & Salmelin, R. (1999). Dynamics of letter string perception in the human occipitotemporal cortex. *Brain*, *122*(11), 2119-2132.
Tian, X., & Huber, D. E. (2010). Testing an associative account of semantic satiation. *Cognitive Psychology*, *60*(4), 267-290.
Tian, X., Poeppel, D., & Huber, D. E. (2011). TopoToolbox: using sensor topography to calculate psychologically meaningful measures from event-related EEG/MEG. *Computational Intelligence and Neuroscience*, *2011*.
Trotzke, A., Quaglia, S., & Wittenberg, E. (2015). Topicalization in German particle verb constructions: The role of semantic transparency. *Linguistische Berichte*, *2015*(244), 407-424.
Tsai, C. H., McConkie, G. W., & Zheng, X. J. (1998). Lexical parsing by Chinese readers. Poster presented at the Advanced Study Institute on Advances in Theoretical Issues and Cognitive Neuroscience Research of the Chinese Language, University of Hong Kong. Retrieved from http://research.chtsai.org/papers/cht_asi.html, January 18, 2024.
Wang, H. (2000). Hanyu yufa de jiben danwei yu yanjiu celüe [The basic unit of Chinese syntax and its research strategies]. *Yuyan Jiaoxue Yu Yanjiu [Language Teaching and Linguistic Studies]*, *2*.
Wang, H. (2011). *Xiandai Hanyu Liheci Lixi Xingshi Yanjiu [Research on the separated forms of separable words in Modern Chinese]*. Peking University Press.
Wang, L., & Kuperberg, G. R. (2023). Better together: integrating multivariate with univariate methods, and MEG with EEG to study language comprehension. *Language, Cognition and Neuroscience*.
Wang, L., Wlotko, E., Alexander, E., Schoot, L., Kim, M., Warnke, L., & Kuperberg, G. R. (2020). Neural evidence for the prediction of animacy features during language comprehension: Evidence from MEG and EEG representational similarity analysis. *Journal of Neuroscience*, *40*(16), 3278-3291.
Wang, X., Zhu, H., & Tian, X. (2019). Revealing the temporal dynamics in non-invasive electrophysiological recordings with topography-based analyses. *bioRxiv*.
Wei, W., Huang, Z., Feng, C., & Qu, Q. (2023). Predicting phonological information in language comprehension: evidence from ERP representational similarity analysis and Chinese idioms. *Cerebral Cortex*, bhad209.
Wei, Y., Niu, Y., Taft, M., & Carreiras, M. (2023). Morphological decomposition in Chinese compound word recognition: Electrophysiological evidence. *Brain and Language*, *241*, 105267.
Xu, T. (2008). *Hanyu zibenwei yufa dao lun [Introduction to character-based syntax in Chinese]*. Shandong Education Press.
Xu, X., & Li, J. (2020). Concreteness/abstractness ratings for two-character Chinese words in MELD-SCH. *PLoS One*, *15*(6), e0232133.
Xue, N. (2002). *Defining and automatically identifying words in Chinese*. University of Delaware.
Xun, E., Rao, G., Xiao, X., & Zang, J. (2016). Dashuju beijing xia BCC yuliaoku de yanzhi [The

construction of the BCC corpus in the age of Big Data]. *Yuliaoku Yuyanxue [Corpora Linguistics]*, *3*(1), 93-109.
Yan, G., Zhang, L., Zhang, X., & Sun, S. (2012). The processing of “psychological word” in Chinese reading. *Xinli Yu Xingwei Yanjiu [Studies of Psychology and Behavior]*, *10*(3), 183.
Yang, J. (2022). *Discovering the units in language cognition: From empirical evidence to a computational model* (Doctoral dissertation, Radboud University Nijmegen Nijmegen).
Yang, J., Cai, Q., & Tian, X. (2020). How do we segment text? Two-stage chunking operation in reading. *eNeuro*, *7*(3).
Yang, J., Van den Bosch, A., & Frank, S. L. (2020). Less is Better: A cognitively inspired unsupervised model for language segmentation. In *The 28th International Conference on Computational Linguistics* (COLING 2020) (pp. 33-45). Association for Computational Linguistics.
Yao, Z., Wu, J., Zhang, Y., & Wang, Z. (2017). Norms of valence, arousal, concreteness, familiarity, imageability, and context availability for 1,100 Chinese words. *Behavior Research Methods*, *49*, 1374-1385.
Ye, K., & Pan, H. (2023). Liheci ‘Separable Words’ in Mandarin Chinese. In *Oxford Research Encyclopedia of Linguistics*.
Yeh, H. H. (2020). *Chinese verb phrases: Continuum of patterns with different lexical statuses*. Stanford University.
Yip, K. F., Lee, T. T. M., & Chan, S. S. L. (2021). Deriving separable verbs in Cantonese. Paper presented at Buckeye East Asian Linguistics 5. Retrieved from https://kb.osu.edu/bitstream/handle/1811/92948/BEAL_v5_2021_Yip_94.pdf, Jan 18, 2024.
Zaccarella, E., Schell, M., & Friederici, A. D. (2017). Reviewing the functional basis of the syntactic Merge mechanism for language: A coordinate-based activation likelihood estimation meta-analysis. *Neuroscience & Biobehavioral Reviews*, *80*, 646-656.
Zhan, W., Guo, R., Chang, B., Chen, Y., & Chen, L. (2019). Beijing Daxue CCL Yuliaoku de Yanzhi [The building of the CCL corpus: its design and implementation]. *Yuliaoku Yuyanxue [Corpus Linguistics]*, *6*(1), 71-86.
Zhang, N. N. (2007). Root merger in Chinese compounds. *Studia Linguistica*, *61*(2), 170-184.
Zhang, S., & Jiang, H. (2010). An ERP approach on whether split words are words or phrases [in Chinese]. *Yuyan Kexue [Linguistic Sciences]*, *9*(5), 486-498.
Zhao, J., Liu, J., Fan, T., & Chen, Y. (2023). Seeking the neural traces of statistical learning during implicit processing of visual words. *ResearchSqure*.
Zhou, X., & Marslen-Wilson, W. (1994). Words, morphemes and syllables in the Chinese mental lexicon. *Language and Cognitive Processes*, *9*(3), 393-422.
Zhu, J., & Liu, F. H. (2020). Liheci he Cifa Jufa de Fengong – Zaiyi Tongyuan Binyu Shuo [Separable words and the division of labor between morphology and syntax – More on the “cognitive object analysis”]. *Dangdai Yuyanxue [Comtemporary Linguistics]*, *22*, 317-334.