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Lexical tone in word activation

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Chapter 2

Phonological Competition in Mandarin Spoken Word Recognition

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Abstract

Most of the world's languages use both segment and lexical tone to distinguish word meanings. However, the few studies on spoken word recognition in tone languages show conflicting results concerning the relative contribution of (sub-)syllabic constituents, and the time course of how segmental and tonal information is utilized. In Experiments 1 & 2, participants listened to monosyllabic Mandarin words with the presence of a phonological competitor, which overlaps in either segmental syllable, onset and tone, rhyme and tone, or just tone. Eye movement results only confirmed the segmental syllable competition effect. Experiment 3 investigated the time course of segmental vs. tonal cue utilization by manipulating their point of divergence (POD) and found that POD modulates the look trajectories of both segmental and tonal phonological competitors. While listeners can use both segmental and tonal information incrementally to constrain lexical activation, segmental syllable plays an advantageous role in Mandarin spoken word recognition.

Keywords: Mandarin spoken word recognition; Eye-tracking; Phonological competition effects; Lexical tone

The majority of the world's languages are tonal, in which pitch variation, known as lexical tone, distinguishes word meanings (Yip, 2002). For example, in Mandarin Chinese, the same segmental syllable *ma* means 'mother' with a high-level tone but 'horse' with a low (dipping) tone. Thus, it is expected that speakers of tonal languages such as Mandarin Chinese need to utilize tonal information effectively for successful and efficient spoken word recognition. Despite the importance of tone in the lexicon of the majority of the world's languages, existing models of spoken word recognition (SWR) have only begun to investigate the role of lexical tone. Understanding lexical processing in tonal languages would provide insights into the potential universal and diverse patterns of SWR across languages of the world and benefit the development of existing SWR models, which have based mainly on data from Indo-European non-tonal languages (e.g., Luce & Pisoni, 1998; McClelland & Elman, 1986; Marslen-Wilson 1987; Gaskell & Marslen-Wilson 2002; Norris, 1994; Norris, McQueen, & Cutler, 2000).

One broad consensus in current models of SWR is that the process of recognizing a word is incremental. Listeners activate several possible word candidates as the incoming speech signal unfolds. Sub-lexical phonemic features influence online lexical processing (e.g., Dahan, Magnuson, Tanenhaus, & Hogan, 2001; McMurray, Clayards, Tanenhaus, & Aslin, 2008; Salverda, Dahan, & McQueen, 2003). There is some evidence from tonal languages, mainly limited to Mandarin Chinese (cf. Burnham et al., 2011 for Tai tones), that suggests incremental activation and competition of sub-lexical phonologically similar word candidates (e.g., Lee, 2007; Liu & Samuel, 2007; Malins & Joanisse, 2010; Sereno & Lee, 2010; Zhao et al., 2011). Despite possible similarities of SWR processes across tonal and non-tonal typologically different languages, several issues, as detailed out below, have remained outstanding and need to be clarified for SWR in tonal languages. Briefly speaking, in tonal languages, it is commonly recognized that segmental and suprasegmental tonal information both play a role during SWR (e.g., Malins & Joanisse, 2010; Malins & Joanisse, 2012a; Zhao et

al., 2011). What has remained open is how exactly segmental and tonal cues are taken up and processed during SWR. At the segmental level, the non-tonal syllable seems to play a critical role as a functional unit of processing (e.g., Sereno & Lee, 2015; Zhao, Guo, Zhou, & Shu, 2011). Relatedly, overlaps in sub-syllabic constitutes (segmental syllable onset and rhyme) have been found to exert no influence on Mandarin lexical competition (see Malins & Joanisse, 2010 for a null rhyme competition effect; see Zou, 2017 for a null onset competition effect). Given the different experimental paradigms/designs and their different levels of sensitivity to the time course of speech processing, it remains debatable whether segmental syllables are processed incrementally or holistically. The present study aimed to employ the eye-tracking technique to address the following issues by seeking answers to three specific research questions: 1) Do segmental syllables have a special status in Mandarin lexical processing? 2) What are the relative contributions of sub-syllabic segmental constituents (such as onsets and rhyme) and suprasegmental lexical tone? 3) What is the time course of segmental and suprasegmental processing and cue utilization during online lexical processing?

2.1 The Role of Segmental Syllable in Spoken Word Recognition

One issue to be resolved is the role of the non-tonal segmental syllable as a primary and holistic processing unit during SWR. Thus far, Mandarin has served as the main empirical base in the extant literature. It is well-known that Mandarin syllables differ from syllables of Indo-European languages in several aspects. First, Mandarin syllables consist of both segmental and suprasegmental information, i.e., lexical tone. The segmental syllables in Mandarin are simple in structure and have a relatively small number of syllable types. For example, they do not have consonant clusters, and only two nasal consonants (/n/ and /ŋ/) are allowed as codas. The total number of syllables is also rather limited; about 1,200 tonal syllables and 400 segmental syllables. Second, most morphemes in Mandarin are monosyllabic (i.e., segmental syllable plus tone), rendering

syllables as a unit of meaning. Last but not least, the writing system in Mandarin is based on syllable-sized characters, reinforcing the notion of the syllable as a holistic unit. These unique properties have motivated researchers to entertain the idea that Mandarin syllables may be an ideal lexical processing unit.

The evidence on the role of syllable and sub-syllabic units in SWR, however, has been mixed. Zhao et al. (2011) proposed that Mandarin SWR is "syllable-based holistic processing rather than phonemic segment-based processing." In Zhao et al. (2011), Mandarin speakers made semantic judgments on pictures while listening to an auditory distractor word. Event-related potentials (ERPs) showed that when the distractor mismatched the name of the picture in either onset, rhyme, tone, or the whole syllable (see Table 1 for sample stimuli used in the study), N400 (a negative ERP component elicited with semantic or phonological violations of expectations; Kutas & Hillyard, 1984; Praamstra & Stegeman, 1993) was elicited. Crucially, the earliest and highest amplitude was elicited by the whole syllable (i.e., segmental and tonal) violation. Sereno & Lee (2016) reached a similar conclusion with two auditory lexical decision tasks. In their study, participants' responses were only facilitated when the primes and targets had overlapping segmental syllables or syllables, and no priming effect was found for those with only partial segmental overlap (i.e., onset and tone overlaps; rhyme and tone overlaps).

Counter evidence against segmental syllables as the basic unit of processing in SWR has also been reported. With EEG recording, Malins & Joanisse (2012a) asked participants to make judgments on whether the auditory words and simultaneously presented pictures match or not. The picture names overlapped with the auditory words in either segmental syllable, onset, rhyme, tone, or unrelated (see Table 1 for sample stimuli). Results showed that all conditions modulated the phonological mapping negativity effects (PMN; an ERP component associated with pre-lexical processing; Connolly & Phillips, 1994; Newman & Connolly, 2009) and N400 effects (associated with lexical word meaning processing; Kutas & Hillyard, 1984; Praamstra & Stegeman, 1993).

Moreover, the PMN effects did not differ between the rhyme, tone, and the unrelated condition, suggesting that neither syllable nor segmental syllable in Mandarin merits any special status as a holistic processing unit. More recently, Ho et al. (2019) investigated the role of syllables in Mandarin word processing in sentence context with the cross-modal priming paradigm. In this task, prime words were embedded in the middle of a visually presented sentence, while target words were embedded in a following aural sentence. The targets and primes were mismatched in onset, tone, or syllable (see Table 1 for sample stimuli). Compared with identical sentences, all three critical mismatching conditions modulated PMN and N400 components. Crucially, the smallest amplitudes for PMN and N400 components were elicited by the whole syllable mismatching condition. This was interpreted as due to the lack of phonological competition between target and prime by Ho et al. who further suggested that Mandarin listeners process spoken words segment by segment rather than by the whole syllable.

It is clear that the above studies differed in the experimental paradigms employed, the specific behavioural and neural measurements taken, and the exact segmental conditions compared. More research on the topic is necessary to clarify the role of segmental syllable as a holistic unit of lexical processing. Experiment 1 aimed to address this issue.

Table 1. *Experimental conditions and sample stimuli of previous studies and the present study. All listed previous studies were discussed in the Introduction in the same order.*

Study	**Task**	**Conditions**	**Sample Stimulus *(Pinyin)***	**Shared Information**	**Divergent Information**
Zhao, Guo, Zhou, & Shu, 2011	Picture/spoken word/picture task	Match	*bi2-bi2*	Phonemes & tone	None
		Onset Mismatch	*bi2-li2*	Rhyme and tone	Onset
		Rime Mismatch	*bi2-bo2*	Onset and tone	Rhyme
		Tone Mismatch	*bi2-bi3*	Phonemes	Tone
		Syllable Mismatch	*bi2-ge1*	None	Phonemes & tone
Sereno & Lee, 2015	Auditory priming paradigm, Experiment 1	Tone-segment Overlap	*ru4-ru4*	Phonemes & tone	None
		Segment-only Overlap	*ru4-ru3*	Phonemes	Tone
		Tone-only Overlap	*sha4-ru4*	Tone	Phonemes
		Unrelated	*qin1-ru4*	None	Phonemes & tone
	Auditory priming paradigm, Experiment 2	Tone-segment Overlap	*ru4-ru4*	Phonemes & tone	None
		Only-onset segment Overlap	*ru4-re4*	Onset & tone	Rhyme
		Only-rime Overlap	*ru4-pu4*	Rhyme & tone	Onset
		Unrelated	*ru4-qin1*	None	Phonemes & tone
Malins & Joanisse, 2012a	Picture/spoken word matching task	Segmental	*hua1-hua4*	All phonemes	Tone
		Cohort	*hua1-hui1*	Onset, glide and tone	Rhyme
		Rhyme	*hua1-gua1*	Rhyme and tone	Onset
		Tonal	*hua1-jing1*	Tone	Phonemes
		Unrelated	*hua1-lang2*	None	Phonemes & tone

Study	**Task**	**Conditions**	**Sample Stimulus *(Pinyin)***	**Shared Information**	**Divergent Information**
Ho et al., 2019	Cross-modal priming paradigm	Match	*jia1-jia1*	Phonemes & tone	None
		Onset Violation	*jia1-xia1*	Rhyme and tone	Onset
		Tone Violation	*jia1-jia4*	Phonemes	Tone
		Syllable Violation	*jia1-tang2*	None	Phonemes & tone
Malins & Joanisse, 2010	Visual World Paradigm	Segmental	*chuang2-chuang1*	Phonemes	Tone
		Cohort	*chuang2-chuan2*	Onset, glide, and tone	Rhyme
		Rhyme	*chuang2-huang2*	Rhyme and tone	Onset
		Tonal	*chuang2-niu2*	Tone	Phonemes
Zou, 2017	Visual World Paradigm	Segmental	*chuang1-chuang2*	Phonemes	Tone
		Cohort	*chuang1-che1*	Onset and tone	Rhyme
		Rhyme	*chuang1-guang1*	Rhyme and tone	Onset
		Tonal	*chuang1-ji1*	Tone	Phonemes
The present study	Visual World Paradigm, Experiment 1&2	Segmental syllable	*chuang2-chuang1*	Phonemes	Tone
		Cohort	*chuang2-cha1*	Onset and tone	Rhyme
		Rhyme	*chuang2-huang2*	Rhyme and tone	Onset
		Tonal	*chuang2-ya2*	Tone	Phonemes
	Visual World Paradigm, Experiment 3	Segmental Early	*dian4-dou4*	Onset and tone	Rhyme
		Segmental Late	*xue3-xuan3*	Onset, glide, and tone	Rhyme
		Tonal Early	*ying1-ying3*	Phonemes (nasal onset)	Tone (onset and offset)
		Tonal Late	*chou3-chou2*	Phonemes (obstruent onset)	Tone (offset)

2.2 Relative Weighting of Sub-syllabic Constituents in Spoken Word Recognition

A second issue is whether, and if so, to what extent sub-syllabic segmental constituents (i.e., onset and rhyme) and lexical tone affect lexical activation. Continuous mapping models such as TRACE (McClelland & Elman, 1986) predicted that word candidates with the same onset are activated earlier and greater than word candidates with the same rhyme. Such a prediction was confirmed for English by a seminal eye-tracking study by Allopenna, Magnuson, & Tanenhaus (1998) with the visual world paradigm. In this study, participants were asked to follow instructions (e.g., *Pick up the beaker*) and move objects around on a computer screen. They looked at both the target *beake*r and its phonological competitors (i.e., the cohort competitor *beetle* and the rhyme competitor *speaker*). Moreover, participants' eye fixations towards cohort competitors were significantly earlier than those of rhyme competitors.

However, the effect of sub-syllabic units (i.e., cohort and rhyme) reported for English seems less reliable in Mandarin SWR. With the same visual world paradigm, Malins & Joanisse (2010) examined the effect of phonological similarity on Mandarin word recognition. Their results showed that given a target such as *chuang2* 'bed', both segmental syllable (*chuang1* 'window') and cohort (*chuan2* 'boat') competitors distracted fixations towards target pictures significantly, with no difference between the two conditions in terms of effect size and time course. However, in contrast to the findings of Allopenna et al. (1998), rhyme competitors (e.g., *huang2* 'yellow') did not influence participants' gaze patterns more than unrelated distractors. These findings led Malins & Joanisse (2010) to propose that sub-syllabic constitutes weigh differently in Mandarin and English SWR.

Results reported in Malins & Joanisse (2010) are not fully replicated. Zou (2017) used a similar design and investigated phonological competition effects in

Mandarin SWR. Although the goal of the study was to examine SWR by second language learners of Mandarin (with Dutch as the first language), native Mandarin listeners were also included as a control group. Zou (2017) showed that the presence of rhyme competitors distracted participants' looks to targets the most. In contrast, the cohort competitors did not, which presents an opposite pattern from Malins & Joanisse's study. Another difference between Malins & Joanisse (2010) and Zou (2017) is the role of lexical tone in SWR. Malins & Joanisse (2010) reported an early interference effect of tonal competitors. Zou (2017), however, did not observe this effect. Similar to Zou (2017), Connell (2017) examined the process of word recognition in L1 and L2 Mandarin listeners with a visual world eye-tracking experiment. Unlike Malins and Joanisse (2010), in which comparable effects of segmental syllable and cohort competition were found, Connell (2017) found significantly more target eye-fixations in the segmental syllable condition than in the cohort condition. Overall, these different results raise further questions about the role of all sub-syllabic units (i.e., onset, rhyme, tone) in Mandarin spoken word processing.

It is worth noting that discrepant results between Malins & Joanisse (2010) and Zou (2017) are likely to lie in two major differences in their methods. One is the stimuli used for different competitor conditions, and the other is the different preview times for participants to view pictures before listening to the auditory stimuli.

About the stimuli, there are two differences. One concerns the cohort competitors. Malins & Joanisse (2010) defined the cohort competitors as sharing onset, tone, and the glide or rhyme with the targets (e.g., *hua1* 'flower'- *hui1* 'grey'; *tu3* 'dirt'- *tui3* 'leg'). In Zou (2017), cohort competitors were controlled more consistently as sharing only the lexical tone and the first phoneme in the onset (e.g., *tang2* 'candy'- *tou2* 'head'). The other concerns the repeated items. In Malins & Joanisse (2010), a few items were used repeatedly, especially in the tonal condition. For example, all tonal competitors were also presented as segmental/rhyme competitors; the word *mi3* (rice) was not only used as a tonal

competitor for both target word *xin1* (heart) and *tu3* (dirt), but also a segment competitor for target word *mi4* (honey). This led to an overall unequal number of occurrences for various phonological competitors and increased familiarity with tonal competitors. Zou (2017) avoided using the same stimuli for different phonological competitors.

As for the preview time difference, Malins & Joanisse (2010) allowed for a preview time of 1500 ms while Zou (2017) presented the pictures and auditory stimuli simultaneously. Preview time has been shown to affect phonological competition effects in the visual world paradigm (Huettig & McQueen, 2007; Huettig et al., 2011). Huettig & McQueen (2007) found that when participants viewed pictures at sentence onset (with an estimation of 700 ms -1000 ms preview time), substantial online phonological competition effects were found during Dutch word recognition. However, no phonological competition effect was found when participants viewed pictures with a preview time of 200 ms. Huettig & McQueen (2007) thus proposed that a 200 ms preview may not be sufficient for participants to retrieve the names of the displayed objects and associate them with locations in their visuospatial working memory. It is worth noting that Huettig & McQueen (2007) adopted a modified version of the visual world paradigm in which no target, but three different types of competitors were presented. Also, their participants were not instructed to give any explicit response. Given that how participants approached this task is still unclear (Magnuson, 2019), it leaves open the question of the impact of preview time on phonological competition effects. Specifically, is a 200 ms preview a prerequisite for observing phonological competition using a standard visual world paradigm? More importantly, to what extent the length difference of preview time could help to account for the discrepant results in Mandarin SWR.

To summarize, the different findings on the role of sub-syllabic constituents in Mandarin SWR may have resulted from different preview times and the unequal occurrences of the same stimuli as various phonological competitors. Therefore, new experiments with stricter control of stimuli

(Experiment 1) and different preview time (Experiment 2) would illuminate resolving the conflicting results.

2.3 Segment and Lexical Tone Processing in Mandarin Spoken Word Recognition

Whether the primary processing unit in Mandarin is a segmental syllable or a sub-syllabic unit, the third issue to address is when exactly segmental information and tonal information are recognized and utilized during SWR. Existing studies on the role of lexical tone in spoken word processing have mainly focused on whether lexical tone plays a similar role as segments. Using various behavioral tasks, a perceptual disadvantage of lexical tone, compared with segmental information, has been reported in earlier studies (Cutler & Chen, 1997; Taft & Chen, 1992; Yip, 2001; Ye & Connine, 1999, experiment 1). Such a view has also been supported by a few recent studies (e.g. Hu et al. 2012 with comparison to vowels; Sereno & Lee 2015 with comparison to segmental syllables; Gao et al., 2019 with comparison to segmental syllables). This body of literature reasoned that tonal information plays a weaker role during lexical processing because such information "often arrives later than does information about the vowel that bears the tone" (Cutler & Chen, 1997) and is "less informative than segmental information" (Tong et al., 2008).

An increasing number of studies, many with experimental techniques that are more sensitive to the time course of speech processing, have provided evidence that lexical tonal information is processed timely and can play an essential role during SWR. For example, Schirmer et al. (2005) showed that mismatched tonal and segmental (rhyme) targets induce comparable ERPs in Cantonese word processing with a sentence completion task. They thus argued that tone and segment play comparable roles and are accessed with a similar time course during spoken word processing. Using the visual world paradigm, Malins and Joanisse (2010) found comparable competition effects between cohort and

segmental competitors (in terms of amplitude and time course). This was interpreted as evidence that tonal and segmental information is accessed concurrently during online SWR.

Connell, Tremblay, and Zhang (2016) tapped into this debate by examining the low-level perceptual difference between tone and segments with a gated AX-discrimination task. Their native Chinese listeners showed a delay of about 28ms to perceive tonal contrast than segmental contrasts even when they have comparable acoustic divergent points. This raises a question: if there is indeed a delay of tonal perception, why is it not reflected in time-sensitive online experiments? Connell (2017) examined this issue further by conducting an eye-tracking visual world experiment. With the acoustic and perceptual divergence points strictly controlled, Connell found that lexical tones are used no later and even more rapidly than segments in constraining word activation. One possible explanation is that lexical tones are more efficient in eliminating potential lexical candidates than vowels. If this is the case, tonal information must be used in lexical access even before the tone can be recognized. Qin (2017) looked into this issue by conducting an eye-tracking experiment with tone pairs that either has early pitch height overlapping (T1-T2) or not (T1-T4). Qin found a larger target-over-competitor activation when there was an early pitch height difference. This suggests that pitch height information can be used early to constrain word recognition. Overall, findings of Connell (2017) and Qin (2017) and previous online studies, have provided evidence that lexical tone can be used before being recognized in lexical access.

Nevertheless, no studies have systematically examined and compared how the point of divergence (hereafter POD) affects tone and segments processing in Mandarin SWR with paradigms such as the visual world paradigm that are sensitive to the time course of speech processing. Experiments are needed to address the following open questions. First, given that there is evidence for holistic processing of syllable in Mandarin (Zhao et al., 2011), whether and how does POD affect the spoken word recognition process? Second, does lexical tone

(with early/late diverging pitch contours) constrain word recognition more than vowels? Answers to these questions would lend strong evidence to the exact time course of how the two tiers of information (i.e., segmental vs. tonal) are utilized for SWR. Experiment 3 was designed to fill this knowledge gap, which also serves to replicate existing findings in Qin (2017) and Connell (2017).

To summarize, the present study consists of three experiments and aimed to clarify the role of segmental syllable and sub-syllabic constituents in Mandarin SWR, as well as to investigate the time course of when segmental and suprasegmental tonal information is utilized during lexical processing. All three experiments were conducted within the visual world paradigm (Allopenna et al., 1998; Tanenhaus et al., 1995).

2.4 Experiment 1

Experiment 1 examined the role of segmental syllable, sub-syllabic segmental constituent (onset and rhyme), and lexical tone in Mandarin SWR, as indexed by how much participants' visual attention on the target word is disrupted by the presence of a phonological competitor (with an overlapping segmental syllable, onset, rhyme or tone) when they listen to a target Mandarin word.

Given the debates in the existing literature, particularly the discrepancies between Malins & Joanisse (2010) and Zou (2017), our goal was to replicate some of the findings conceptually to resolve the discrepancies. We followed Malins & Joanisse (2010) for most of the design, but made some necessary modifications as motivated earlier:

First, we avoided using the same stimuli as different phonological competitors and kept the number of occurrences of tonal competitors the same as other competitors. This would ensure that the tonal competitor effect reported in Malins & Joanisse (2010) is introduced by lexical tone overlap and not due to the effect of familiarity. Note that following both studies, we made sure that there was an equal number of reciprocal trials in which the role of target and competitor in

critical trials was reversed. Thus, participants' chances of hearing the target and competitor in a trial remained the same. Additionally, we also made sure participants' chances of seeing the target and competitor pictures were the same by arranging competitors of one target as unrelated distractors of another. In this way, participants' chances of predicting the targets and developing strategic responses were controlled to be small.

Second, we changed a subset of the stimuli used in the cohort condition. Following Zou (2017), we defined the cohort competitor as sharing only the first onset phoneme with the target. This is because our stimuli are monosyllabic words. In SC, monosyllables either constitute a word or at least a morpheme; the syllable structure (C)V(C) (with optional onset and coda) which serves as the bearing unit of lexical tone is also relatively simple. Based on such characteristics, previous studies on Chinese lexical access often examined the role of onset and rhyme, respectively (e.g., Ho et al., 2019; Yip, 2001; Zhao et al., 2011; Zou, 2017). With an auditory priming lexical decision task, Yip (2001) observed that onset and tone overlapping between target and prime elicited an inhibitory effect whereas rhyme and tone overlapping introduced a facilitatory effect in Cantonese. The first onset phoneme (plus lexical tone) likely plays an independent and rather different role from rhyme (plus lexical tone) in Chinese. Thus, to better compare the relative contribution of sub-syllabic constituents in SC, we selected words that share the first onset phoneme and tone with targets as cohort competitors, despite that traditionally cohort words for studies in Germanic and Romance languages have been defined as sharing two or more phonemes (Marslen-Wilson, 1987).

2.4.1 Method

2.4.1.1 Participants

Twenty (mean age: 20, standard deviation: 0.8; 12 females, 8 males) native Mandarin speakers participated in the experiment. All participants were college students from Shaanxi Normal University. All of them reported normal hearing and no history of speech or language disorders. All participants identified

Standard Chinese as their first language, and none of them speak other regional Chinese dialects. This study was approved by the Ethics Committee at Leiden University Centre for Linguistics. All participants provided informed consent before participation and were paid 30 RMB in compensation for their time.

2.4.1.2 Stimuli

The stimuli consisted of 60 monosyllabic Mandarin words which are easily picturable nouns (see Table A1 in Appendix A). Among the stimuli, 12 were critical targets. For each critical target, competitors of four conditions were defined based on their phonological overlap with the target. Segmental syllable competitor shared all phonemes but differed in tone with the target; cohort competitor shared the initial consonant and tone with the target; rhyme competitor shared rhyme and tone with the target; tonal competitor shared tone alone with the target. See Table 1 for sample stimuli and their comparison with previous studies. No item was used in more than one competitor condition.

Word frequency, as computed with SUBTLEX-CH (Cai & Brysbaert, 2010), was balanced across target words and the four competitor conditions [$F(4, 55) = 0.83$, $p > 0.5$]. All stimuli were recorded through a Sennheiser MKH416T microphone (44.1 kHz, 16 bit) at the Phonetics Lab of Leiden University, produced by a female native speaker of Standard Chinese who was born and grew up in Beijing. Each word was read four times in isolation using a randomized list. One token of each word was chosen based on its clarity. All stimuli were normalized for intensity at 70dB. The matching pictures were real object pictures selected with the assistance of three native Chinese speakers who did not participate in the experiment.

2.4.1.3 Procedure and Design

To ensure participants were familiar with all stimuli, a naming task was assigned preceding the eye-tracking recording. During the naming session, participants were shown the pictures and asked to name them with appropriate

Standard Chinese words. If the name produced was not the intended word, participants were provided with the intended name.

During the subsequent experiment, participants were tested in a sound-attenuated booth at the Psychology Lab of Shaanxi Normal University. While performing the task, participants' eye movements were recorded with SR Eyelink Portable DUO eye-tracker at a sampling rate of 500Hz. For visual stimuli display, a 24-inch DELL U2412M monitor was located behind the eye-tracker. The camera of the eye-tracker was at a distance of about 52 cm from the participants' eye, which was fixed with the help of a chin rest. The auditory stimuli were played over a Beyer DT-770 Pro dynamic headphone at a constant and comfortable hearing level.

Before the test, participants' eye gaze position was validated and calibrated with a 9-point grid. At the beginning of each trial, a central cross appeared on the screen for 500 ms. Participants were asked to look directly at the fixation for a drift check. Four pictures then appeared on the screen for 1,500 ms before an auditory word. The four pictures (300 × 300 pixels) were placed top-left, top-right, bottom-left, and bottom-right; each comprising a distinct quadrant of the display. Participants were required to click on the picture that matches the auditory word with a mouse. The next trial appeared 1,000 ms after the click. The target picture's position was counterbalanced so that the target picture appeared an equal number of times in each location, and did not appear in the same location in two consecutive trials.

All the instructions were given in Standard Chinese. Participants were first asked to complete a practice block of four trials. In total, there were 360 trials for four blocks of 90 trials. The block order was counterbalanced across participants. Between each block, participants were given time to rest and proceed as they wish. Each of the syllable, cohort, rhyme, and tonal conditions has 36 trials, in which the participants listened to the targets with corresponding phonological competitors in the display. Additionally, there was a baseline condition in which no competitor but only distractors were presented along with the target. Following

the design of Malins & Joanisse (2010), half of the trials (180) were fillers, in which the role of target and competitors were reversed (i.e., the phonological competitors were played as auditory targets). This was done so that the chances of hearing the target and competitors with the same display were equal. Furthermore, to balance the overall occurrences of target and competitor items as picture displays, competitors were taken as unrelated distractors in another set of stimuli. The same target did not appear in three consecutive trials. After the test, participants were asked to fill in a language background questionnaire.

2.4.2 Data Analysis

2.4.2.1 Analysis of Behavioural Data

Reaction time and response accuracy for mouse clicks were collected for statistical analysis. Reaction times were calculated with respect to the onset of the auditory word. Trials for which the reaction time was shorter than 250 ms were excluded for both accuracy and RT analyses. Furthermore, only correct responses were considered for RT analyses. RTs were analysed using the generalized linear mixed-effects model (GLMM) to account for the skewed distribution without the need to transform raw data (Lo & Andrews, 2015). A backward algorithm was used to select the model (Barr et al., 2013). A maximum model including fixed effects of experimental conditions, by-subject and by-item random intercept, by-subject and by-item random slopes for experimental conditions was constructed first. If a model failed to converge, we first increased the number of iterations, then simplified the model by removing correlation parameters and the random structure's main effects (Brauer & Curtin, 2018). Fixed effects and the random structure were tested by comparing the likelihood ratio test with the simpler model. Response accuracy was modelled using the same approach using GLMM. All the analyses were run in the R software (R Core Team, 2021) with the package *lme4* (Bates, Mächler, Bolker, & Walker, 2015).

2.4.2.2 Analysis of Eye-Tracking Data

We excluded trials for which the target was not correctly identified and trials for which the reaction time was shorter than 250 ms. The time window of 200-980 ms post auditory stimuli onset was chosen as our interest period. The lower boundary was chosen because there is a 200 ms delay to launch an eye movement (Hallett, 1986), while the upper boundary reflects when there were approximately maximum looks towards the targets. As the gaze position and duration of participants' eye fixation were recorded, looks toward targets, competitors, and distractors during the interest period were collected. The collected eye-tracking data were first down sampled to 50Hz (a 20 ms bin), following the tutorial of Porretta et al. (2018). Then, the proportions of fixations to target, competitor, and distractors at each time point were calculated by dividing the sum of fixations on the four pictures (target, competitor, and two distractors) by the number of fixations toward each picture type. The eye-fixation data in the visual world paradigm is intrinsically binary, i.e., participants are either looking at the target/competitor or not. It has been questioned that treating the eye-tracking data as a ratio variable on a linear scale averaging across conditions may cause problems such as data distortion and the violation of the assumptions of parametric statistics (Huang & Snedeker, 2020). To avoid these issues, we performed empirical logit transformation with weights for variance estimation on eye-fixation proportions following the advice of Mirman (2014) and Porretta et al. (2018).

We used generalized additive mixed modelling (GAMM; Wood, 2011; Wood, 2017) to analyse the eye-tracking data. GAMM is a type of generalized mixed-effects model that uses smooth functions to model the non-linearity between predictor(s) and the dependent variable. The smooth function (e.g., the thin plate regression spline) combines a number of pre-defined basic functions by multiplying them with individual coefficients. With cross-validation or maximum likelihood estimation, GAMM adds a penalization to the estimation of the

coefficients to avoid over-fitting and minimize errors. GAMM is well-established and has been applied to eye movement data of the visual world paradigm (e.g., Nixon et al., 2016; Nixon & Best, 2017; Porretta et al., 2018).

We used the *mgcv* package (version 1.8-23; Wood, 2011; Wood, 2017) in R (R Core Team, 2021) to implement GAMM. The model was fit by first entering all predictors of interest. Model comparison was conducted by means of $\chi 2$ tests of fREML scores, using the "compareML" function in the *itsadug* package (Van Rij et al., 2020). Model residuals were examined to check for non-normality, heteroscedasticity, and auto-correlation. The model summary of GAMM includes parametric coefficients and smooth terms. The parametric coefficients can be interpreted the same way as linear models, with the intercepts indicating the overall heights of the trajectories. The smooth terms capture the shape of the looking trajectories. To test the statistical difference between each experimental condition, we used ordered factors to model the difference smooth. The p-value in the smooth terms thus indicates the statistical difference between the trajectories in terms of shape. To control the family-wise error rate, the Holm–Bonferroni method was applied to adjust the p-values (Holm, 1979). We also plotted the difference smooths with *tidymv* (Coretta, Van Rij, & Wieling, 2021) to show when and how the look trajectories differ.

2.4.3 Results

2.4.3.1 Behavioural Data

Reaction time and response accuracy for mouse click are shown in Table 2. For reaction time, the maximum likelihood estimation of the maximum model and the simplified random slope models failed to reach convergence. The best-fit model included fixed effects of experimental condition, by-subject and by-item random intercepts (note that random-intercepts-only models may inflate Type-I error rate; Barr et al., 2013). The fixed effects of experimental conditions ($\chi 2$ (4) = 81.221, $p < 0.001$) suggested that participants' reaction time differed across conditions. Post-hoc analysis revealed that only when segmental syllable

competitors were present, participants took longer time to identify the targets (segmental syllable condition: $p < 0.001$; cohort condition: $p = 0.454$; rhyme condition: $p = 0.775$; tonal condition: $p = 0.075$). The error rate was low in each condition (all approximately under 1%). Thus, no further analyses were conducted on the response accuracy.

Table 2. *Mean Reaction time (ms) and response accuracy percentage of Experiment 1. Standard Errors are in parentheses.*

Condition	Reaction Time (SE)	Percent Accuracy (SE)
Baseline	1053 (25.4)	99.7 (2.32)
Cohort	1067 (29.4)	98.9 (8.65)
Rhyme	1056 (26.9)	99.8 (2.05)
Segmental syllable	1116 (31.2)	99.4 (3.41)
Tonal	1088 (32.6)	99.7 (2.76)

2.4.3.2 Eye Movement Data

Looks to target

The final model of target fixations includes a fixed effect of condition, a smooth term of time, a smooth over time for each level of condition, and a non-linear random effect of subject by condition. The final model explains 98.4% of the deviance. The summary of model fit is provided in Table 3. The upper half of this table presents the parametric coefficients of the model. The first row presents the intercept of the baseline condition. The following rows indicate the changes in the intercept for the other four experimental conditions. As shown in Table 3, no condition was found to be significantly different from the baseline condition in the intercept.

The second half of Table 3 describes the thin plate regression spline smooths for different levels of conditions over time. The first smooth presents the trajectory of the (empirical logit transformed) proportions of eye fixations over time for the baseline condition. The next four smooths evaluate the curves'

difference with respect to the baseline condition. The model summary indicates that there was a significant difference between the segmental syllable and the baseline conditions ($p < 0.005$).

The smooths for all levels of conditions are visualized in Figure 1A. Figure 1B plots the difference between the two smooths comparing the segment and baseline condition.

Table 3. *GAMM analysis of fixation proportions to targets in Experiment 1 with 1500 ms preview time.*

	Estimate	Std. Error	t value	*p*-value
Intercept	0.467	0.126	3.716	<0.001
Cohort–Baseline	-0.017	0.179	-0.097	0.923
Rhyme–Baseline	0.007	0.181	0.039	0.969
Segmental syllable–Baseline	-0.161	0.179	-0.896	0.370
Tone–Baseline	0.014	0.179	0.079	0.937
	edf	Ref.df	F	*p*-value
s(Time)	8.658	8.739	175.435	<0.001
s(Time): Cohort–Baseline	1.001	1.001	0.043	0.836
s(Time): Rhyme–Baseline	1.001	1.001	1.027	0.311
s(Time): Segmental syllable–Baseline	4.037	4.389	4.197	0.002
s(Time): Tone–Baseline	1.001	1.001	0.615	0.433

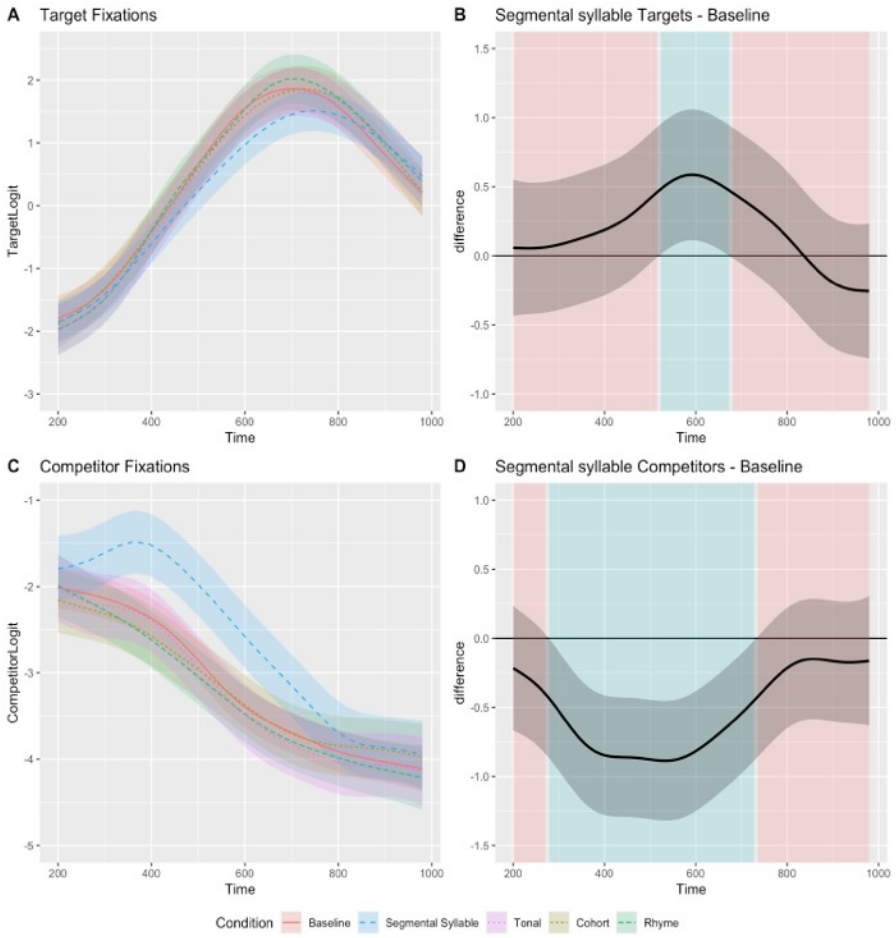

Figure 1. *Estimated smooths for all conditions and smooth differences in Experiment 1. A. Smooths of target fixations for all conditions; B. Difference between the two smooths comparing the segmental syllable and baseline condition of target fixations model; C. Smooths of competitor fixations for all conditions; D. Difference between the two smooths comparing the segmental syllable and baseline condition of competitor fixations model. The pointwise 95%-confidence intervals are shown by shaded bands. The green background in B and D indicate that the shaded confidence band is significantly different from zero.*

Looks to competitors

Same as target fixations, the final model of competitor fixations includes a fixed effect of condition, a smooth term of time, a smooth over time for each level of condition and a non-linear random effect of subject by condition. The final model explains 97.2% of the deviance. The summary of model fit is provided in Table 4.

Table 4. *GAMM analysis of fixation proportions to competitors in Experiment 1 with 1500 ms preview time.*

	Estimate	Std. Error	t value	*p*-value
Intercept	-3.179	0.096	-33.283	<0.001
Cohort–- Baseline	-0.009	0.140	-0.063	0.950
Rhyme- Baseline	-0.054	0.127	-0.422	0.673
Segmental syllable–- Baseline	0.536	0.169	3.170	0.002
Tone–- Baseline	-0.030	0.135	-0.224	0.823
	edf	Ref.df	F	*p*-value
s(Time)	7.675	8.050	32.905	<0.001
s(Time): Cohort–- Baseline	1.000	1.000	0.738	0.390
s(Time): Rhyme- Baseline	1.001	1.001	0.114	0.736
s(Time): Segmental syllable–- Baseline	5.396	5.811	5.230	<0.001
s(Time): Tone–- Baseline	1.000	1.000	0.075	0.785

The parametric coefficients of the model indicate that only the segmental syllable condition was significantly different from the baseline condition in intercept ($p < 0.005$). In the segmental syllable condition, the empirical logit of eye-fixation proportions towards competitors was higher than that of the baseline condition by 0.536.

The smooth terms of the GAMMs (as shown in Table 4) indicate that there was a significant difference between the segmental syllable and the baseline conditions over time ($p < 0.001$). The smooths for all levels of conditions are

visualized in Figure 1C. Figure 1D plots the smooth difference between the segmental syllable and baseline condition.

2.4.4 Discussion

Results of Experiment 1 showed a significant segmental syllable competitor effect, confirming findings reported in Malins and Joanisse (2010) and Zou (2017). Different from findings in Malins and Joanisse (2010) but confirming Zou (2017), there were no cohort and tonal competition effects. Note that the different cohort effects are likely due to the different definitions of the cohort (see further discussion below). Furthermore, different from Zou (2017), no rhyme competition effect was observed, confirming the lack of rhyme competition effect reported in Malins & Joanisse (2010). The different findings in the rhyme condition may be in part due to the different preview times. The possible effects of preview time on spoken word processing were addressed in Experiment 2.

To summarize, our study confirmed that segmental syllable competitors exhibit a larger competition effect over cohort, rhyme, and tonal competitors. The results thus lend further support that segmental syllable has an overall advantage over sub-syllabic segmental constituents and lexical tone during SWR. The effects of sub-syllabic units seem much more variable and seem to be subject to the influence of factors such as preview time.

2.5 Experiment 2

Experiment 2 aimed to investigate the impact of preview time on the phonological interference effects during lexical processing. In this experiment, we changed the preview time to 200 ms (from the 1500 ms in Experiment 1) while keeping everything else the same across the two experiments. If the amount of preview time given to participants is indeed a critical factor for some of the inconsistent findings, we should observe different results from Experiment 1, in similar ways as some of the results of Malins & Joanisse (2010) differ from that of Zou (2017).

We opted for a 200 ms preview instead of no preview for two main reasons. First, preview time allows listeners to perform object recognition, visual search, and other non-lexical processes before the onset of the spoken word; without it, listeners must attend to visual properties simultaneously, which has been found to add noise to the phonological competition effects (Apfelbaum, Klein-Packard & McMurray, 2021). Second, as mentioned earlier, 200 ms has been found to be insufficient for observing phonological competition with a non-standard visual world paradigm (Huettig & McQueen, 2007). Whether such a short preview time would delay or even cancel phonological competition effects with a standard visual word paradigm has been questioned since and is worthy of further investigation (Magnuson, 2019).

2.5.1 Methods

2.5.1.1 Participants

Twenty-three (mean age: 19, standard deviation: 1.8; 14 females, nine males) new native Mandarin speakers participated in the experiment. As in Experiment 1, all participants were college students from Shaanxi Normal University, with normal hearing and no history of speech or language disorders. All participants speak Standard Chinese and no other Chinese varieties. This study was approved by the Ethics Committee at Leiden University Centre for Linguistics. All participants provided informed consent before participation and were paid 30 RMB in compensation for their time.

2.5.1.2 Stimuli

The same stimuli of Experiment 1 were used.

2.5.1.3 Procedure and Design

The same procedure of Experiment 1 was used, except that the amount of time given to participants for viewing the pictures before the auditory stimuli was shortened from 1,500 ms (in Experiment 1) to 200 ms.

2.5.2 Results

2.5.2.1 Behavioural Data

Reaction time and response accuracy for mouse click are shown in Table 5. The best-fit reaction time model included fixed effects of experimental condition, by-subject, and by-item random intercepts. There was significant effect for fixed effects of experimental condition ($\chi2(4) = 37.521$, $p < 0.001$). Post-hoc analysis revealed that only in the segmental syllable condition, reaction time was significantly different from the baseline condition (segmental syllable condition: $p < 0.005$; cohort condition: $p = 0.175$; rhyme condition: $p = 0.464$; tonal condition: $p = 0.445$). For the best-fit accuracy model, the fixed factor of condition did not improve model fit, which suggested that participants' response accuracy did not differ across conditions ($\chi2(4) = 4.6957$, $p = 0.32$).

Table 5. *Mean Reaction time (ms) and mean percent response accuracy of Experiment 2. Standard Error are in parentheses.*

Condition	Reaction Time (SE)	Percent Accuracy (SE)
Baseline	975 (41.9)	96.9 (2.12)
Cohort	976 (39.9)	97.6 (1.29)
Rhyme	988 (46.3)	99 (0.81)
Segmental syllable	1054 (43.8)	98.2 (1.05)
Tonal	995 (46.5)	98.0 (1.25)

2.5.2.2 Eye Movement Data

Looks to target

The model of target fixations includes the main effect of condition, a smooth term of time, a smooth over time for each level of condition and a non-

linear random effect of subject by condition. The final model explains 98.5% of the deviance. The summary of model fit is provided in Table 6[2].

The parametric coefficients of GAMM analysis indicate that no condition was significantly different from the baseline condition in intercept. The smooth terms indicate that there was a significant difference in target fixations between the syllable and baseline conditions over time ($p < 0.001$). The smooths for all levels of conditions are visualized in Figure 2A. Figure 2B plots the smooth difference between the segmental syllable and the baseline condition. [3]

Table 6. *GAMM analysis of fixation proportions to targets in Experiment 2.*

	Estimate	Std. Error	t value	*p*-value
Intercept	0.116	0.206	0.565	0.572
Cohort – Baseline	-0.076	0.300	-0.254	0.800
Rhyme – Baseline	0.007	0.273	0.027	0.979
Segmental syllable – Baseline	-0.212	0.274	-0.776	0.438
Tone – Baseline	-0.001	0.280	-0.005	0.996
	edf	Ref.df	F	*p*-value
s(Time)	8.609	8.686	121.067	<0.001
s(Time):Cohort – Baseline	1.000	1.000	1.910	0.167
s(Time):Rhyme – Baseline	1.000	1.000	0.988	0.320
s(Time): Segmental syllable – Baseline	5.445	5.863	5.050	<0.001
s(Time):Tone – Baseline	1.000	1.000	0.484	0.486

[2] While Table 6 shows a significant difference between the segmental syllable and baseline condition, the plot of the difference smooth in Figure 2B did not show any difference over time. This discrepancy was most likely due to the use of different R packages ("mgcv" for the model summary; Wood, 2011; "tidymv" for visual inspection; Coretta, 2020). Given that model summary using ordered factors as significance testing are generally more reliable than visual inspections in GAMM (Soskuthy, 2021), we referred to the model summary as the final results of significance testing.

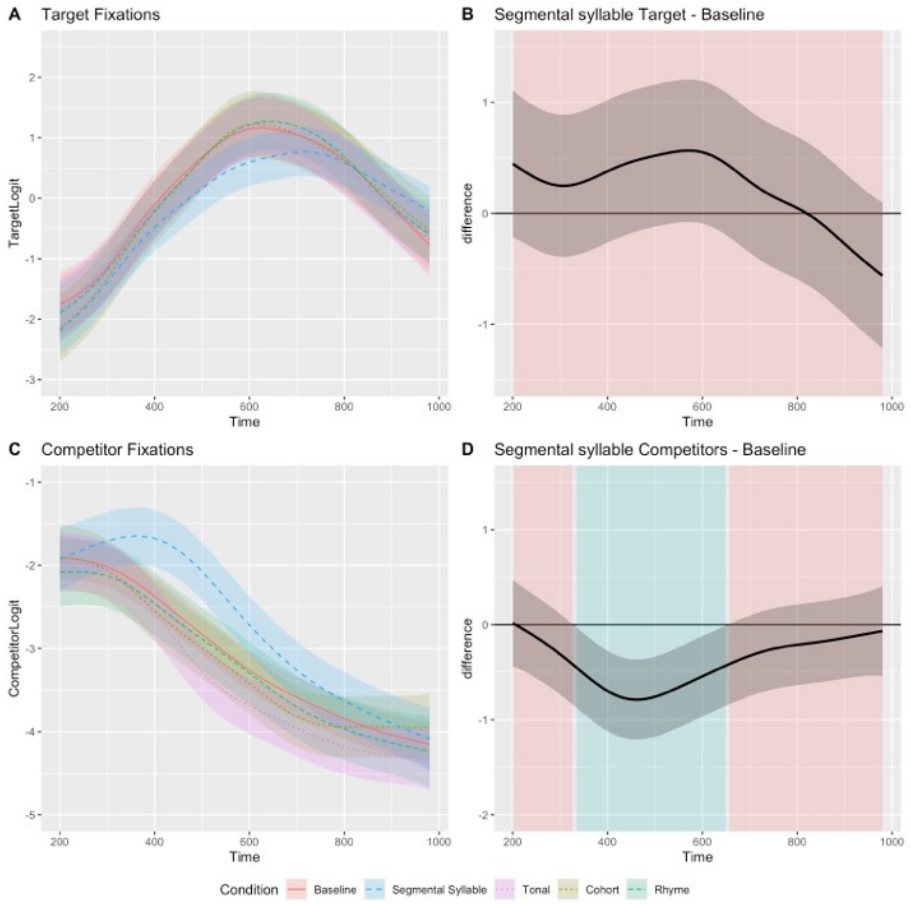

Figure 2. *Estimated smooths for all conditions and smooth differences in Experiment 2. A. Smooths of target fixations for all conditions; B. Difference between the two smooths comparing the segment and baseline condition of target fixations model; C. Smooths of competitor fixations for all conditions; D. Difference between the two smooths comparing the segmental syllable and baseline condition of competitor fixations model. The pointwise 95%-confidence intervals are shown by shaded bands. The green background in B. and D. indicates that the shaded confidence band is significantly different from zero.*

Looks to competitors

The final model of competitor fixations includes a fixed effect of condition, a smooth term of time, a smooth over time for each level of condition and a non-linear random effect of subject by condition. The final model explains 97.1% of the deviance. The summary of model fit is provided in Table 7.

Table 7. *GAMM analysis of fixation proportions to competitors in Experiment 2.*

	Estimate	Std. Error	t value	*p*-value
Intercept	-3.144	0.085	-37.067	<0.001
Cohort – Baseline	0.089	0.098	0.907	0.365
Rhyme – Baseline	-0.129	0.122	-1.058	0.290
Segmental syllable – Baseline	0.408	0.142	2.880	0.004
Tone – Baseline	-0.125	0.110	-1.132	0.258
	edf	Ref.df	F	*p*-value
s(Time)	7.317	7.720	26.253	<0.001
s(Time):Cohort – Baseline	1.000	1.000	0.161	0.688
s(Time):Rhyme – Baseline	1.000	1.000	0.025	0.874
s(Time):Segmental syllable – Baseline	5.125	5.525	4.616	<0.001
s(Time):Tone – Baseline	1.001	1.001	0.153	0.696

The parametric coefficients of the model indicate that only the segmental syllable condition was significantly different from the baseline condition in intercept ($p < 0.005$). In the segmental syllable condition, the empirical logit of eye-fixation proportions towards competitors was higher than that of the baseline condition by 0.408.

The smooth terms of the GAMMs (as shown in Table 7) indicate that there was a significant difference between the segmental syllable and the baseline conditions over time ($p < 0.001$). The estimated smooths for all levels of conditions are visualized in Figure 2C. Figure 2D plots the estimated smooth difference between the segmental syllable and baseline condition.

We examined further the effect of preview time on Mandarin phonological competition effects. Similar general additive modelling procedures described above were applied to the combined data of Experiment 1 and Experiment 2. The interaction of preview time and experimental condition was added to the model and tested for exclusion.

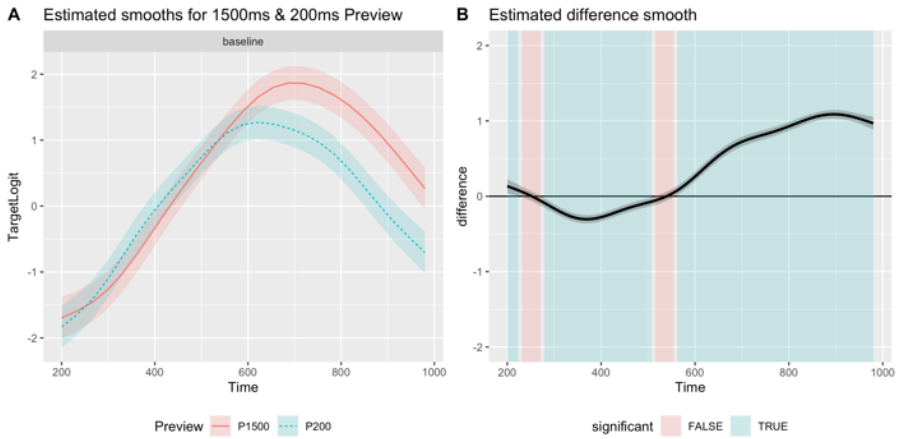

Figure 3. *Estimated smooths and smooth difference of target fixations between Experiment 1 & 2 (1,500 ms & 200 ms). A. Smooths of target fixations with 1,500 ms and 200 ms preview; B. Difference between the two smooths comparing target fixations with 1,500 ms and 200 ms preview. The pointwise 95%-confidence intervals are shown by shaded bands. The green background in B indicates that the shaded confidence band is significantly different from zero.*

Compared with models including the factor of condition, adding preview time significantly improved model fit of target fixations ($p < 0.001$). The interaction between preview and condition did not significantly improve model fit. Coefficients of parameter estimations (see Table 8) showed significant differences in intercept and smooth terms for different preview times (all $p < 0.001$). Figure 3A shows estimated smooths of target fixations of both preview times in baseline condition. Figure 3B shows the estimated smooth difference

between the two preview times. As can be seen from Figure 3A, target eye-fixations reach the peak around 700 ms post stimuli onset in Experiment 1; around 600 ms in Experiment 2. Moreover, the target fixation peak in Experiment 1 has higher empirical logit transformed proportion than in Experiment 2. The estimated difference smooth in Figure 3B shows a consistent pattern. Overall, with a short preview time (200 ms), participants' target fixation proportions reached the peak earlier with a relatively lower proportion compared with a long preview (1,500 ms).

Table 8. *GAMM analysis of fixation proportions to targets in Experiment 1 vs. Experiment 2.*

	Estimate	Std. Error	t value	*p*-value
Intercept	0.493	0.130	3.798	<0.001
Segmental Syllable	-0.347	0.029	-12.022	0.969
Cohort	-0.408	0.029	-13.860	0.969
Rhyme	-0.462	0.029	-15.789	0.314
Tonal	-0.316	0.027	-11.567	0.969
Preview P200-1500	-0.292	0.029	-10.165	<0.001
	edf	Ref.df	F	*p*-value
s(Time):Intercept	8.636	8.712	68.094	0.496
s(Time):Segmental Syllable	3.522	3.818	2.988	0.813
s(Time):Cohort	5.340	5.747	7.028	0.969
s(Time):Rhyme	4.289	4.654	3.455	<0.001
s(Time):Tonal	4.958	5.358	5.729	0.969
s(Time):Preview P200-1500	8.042	8.552	211.766	<0.001

As for the model of competitor fixations, the interaction of preview time and condition also significantly improved model fit ($p < 0.001$). Same as modelling target fixations, five ordered factors each presenting the difference between two preview times of one condition was created. Table 9 shows the estimations of parametric coefficients and smooth terms of the final model. The results show that while there was no significant difference between Experiment 1

and Experiment 2 in the baseline condition (intercept: $p = 0.910$; smooth term: $p = 0.720$), there were significant differences in the cohort condition (intercept: $p < 0.05$; smooth term: $p < 0.001$), the segmental syllable condition (smooth term: $p < 0.001$), the rhyme condition (intercept: $p < 0.05$; smooth term: $p < 0.001$), and the tonal condition (intercept: $p < 0.05$; smooth term: $p < 0.001$). Figure 4 shows the estimated smooth differences between two preview times for each experiment condition. Compared with Experiment 1, the segmental syllable competitors in Experiment 2 have more competitor fixations around 440-600 ms post stimuli onset, but fewer competitor fixations before 380 ms and after 800 ms post stimuli onset (see Figure 4B); the cohort condition has more competitor fixations around before 300 ms and after 640 ms, but fewer fixations during around 320-560 ms (see Figure 4C); the rhyme condition has more competitor fixations around 220-340 ms and 480-560 ms (see Figure 4D); the tonal condition has more competitor fixations before around 380 ms, 580-600 ms, but less during around 400-520 ms (see Figure 4E). As for the baseline condition, there is no significant difference between Experiments 1 and 2 (see Figure 4A). Overall, while the preview time difference (1,500 ms vs. 200 ms) did not affect the fixation in the baseline condition (in which no phonological competitors were presented), it did affect fixations towards different types of phonological competitors at different time intervals along the time course of recognizing the targets.

Table 9. *GAMM analysis of fixation proportions to competitors in Experiment 1 vs. Experiment2.*

	Estimate	Std. Error	t value	*p*-value
Intercept	-3.130	0.074	-42.544	<0.001
Baseline	-0.004	0.034	-0.113	0.910
Segmental syllable	0.055	0.040	1.383	0.500
Cohort	0.104	0.037	2.806	0.020
Rhyme	-0.100	0.031	-3.212	0.007
Tonal	0.121	0.036	3.348	0.005
	edf	Ref.df	F	*p*-value
s(Time)	6.403	7.101	42.484	<0.001
s(Time):Baseline	2.206	2.605	1.167	0.720
s(Time):Segmental syllable	6.976	7.705	15.890	<0.001
s(Time):Cohort	7.668	8.234	5.769	<0.001
s(Time):Rhyme	4.480	5.312	15.325	<0.001
s(Time):Tonal	7.802	8.372	17.400	<0.001

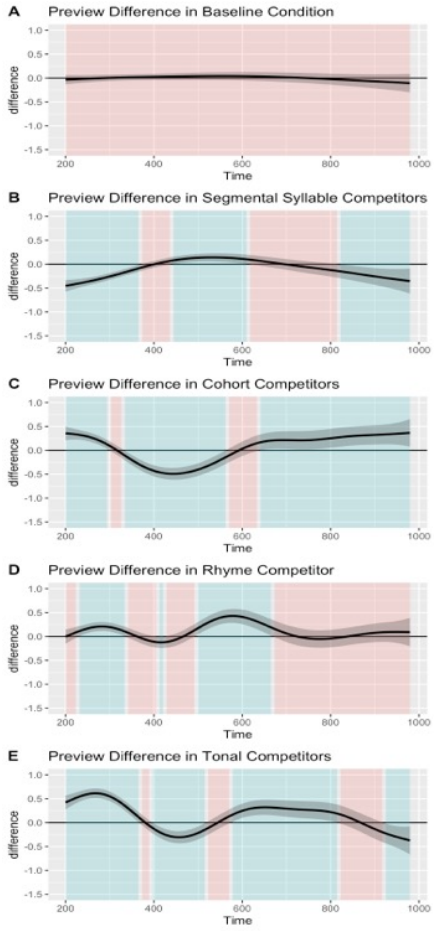

Figure 4. *Estimated smooths difference of competitor fixations between Experiment 1 & 2 (1,500 ms & 200 ms). A. Smooths difference between preview times in the baseline condition; B. Smooths difference between preview times for competitor fixations in the segmental syllable condition; C. Smooths difference of cohort competitor fixations between preview times; D. Smooths difference of rhyme competitor fixations between preview times; E. Smooths difference of tonal competitor fixations between preview times. The pointwise 95%-confidence intervals are shown by shaded bands. The green background indicates that the shaded confidence band is significantly different from zero.*

2.5.3 Discussion

As in Experiment 1, we found a robust competition effect when the segmental syllable competitors were present but null effects for the cohort, rhyme, and tonal competitors in Experiment 2. Nevertheless, with a close look at the effect of preview time on each experiment condition, we found that different preview times did affect participants' visual attention to targets and phonological competitors differentially. With a short preview time, target eye-fixations reached the peak sooner. Moreover, the peak of target fixation proportions with a short preview was lower than that with a long preview. These indicated that participants completed the visual search faster. It is likely that the short preview time created an overall faster rhythm of the task. Furthermore, under different preview times, there were also slightly different look trajectories for phonological competitors. Participants seemed to pay more attention to different phonological competitors at different time points over the time course of the target recognition. Such differences in competitor fixations between the two preview times need to be further verified.

Overall, regardless of having a short or a long preview time (i.e., 200 ms vs. 1,500 ms), the segmental syllable competitor exhibits a significant phonological competition effect. Unlike in Huettig and McQueen (2007), which found reduced phonological competition with a 200 ms preview, our results indicate that the length of preview does not affect the general phonological competition patterns in Mandarin SWR. Possible explanations for such discrepancy and its implications are discussed in the general discussion.

It is necessary to note that both Experiment 1 and 2 have a small size with each having around 20 participants. Brysbaert (2019) recommended at least 50 participants using repeated measures and warned that studies underpower are more likely to miss genuine effects or increase false-positive results in the long run. We recognize the size limitation of our experiments and hereby remind the readers to interpret the results with caution. Given that Experiment 1 and 2

consistently generate the same eye-tracking pattern, however, we also feel that our findings on the segmental syllable condition are unlikely to be false outcomes.

2.6 Experiment 3

Experiment 3 took a closer look at the time course of how listeners utilize tonal and segmental information during online spoken word processing. We manipulated the timing of the point of divergence (POD: early vs. late) for acoustic cues in two information tiers (segmental vs. tonal) and set up five conditions accordingly. To bring the reader's attention to the divergent information, we named the conditions of Experiment 3 by the component that diverged; unlike Experiment 1 and 2, in which the conditions are named by the shared component. The five conditions are the early segmental (diverging) condition, which has word pairs with early diverging segmental information; the early tonal (diverging) condition, which has word pairs with early diverging tonal information; the late segmental (diverging) condition, which has word pairs with late diverging segmental information; the late tonal (diverging) condition, which has word pairs with late diverging tonal information; the baseline condition, which has unrelated word pairs. Participants' gaze patterns across conditions would effectively inform us when and how Mandarin listeners use tonal and segmental information during SWR. We hypothesized that if both lexical tone and segment are utilized during online lexical processing, phonological competition effects (indexed by more eye fixations towards targets and fewer eye fixations towards competitors compared with the baseline condition) should be observed for both tonal and segmental diverging word pairs. In case the utilization of segmental and tonal cues is time-locked to the presence of the cues, significant differences between the early and late diverging word pairs' competition effects should be observed. Specifically, the late conditions should show larger cumulative competition effects than the early ones regardless of the information tier.

Unlike in Experiment 1 and 2, we used Chinese characters as visual displays in Experiment 3. Huettig & McQueen (2007) have reported a stronger phonological competition effect in Dutch when using printed words than pictures as a visual display. They suggested that the version of printed words visual world paradigm is "more sensitive to phonological manipulations than the version using pictures". Experiment 3 tapped into how subtle phonetic cues are used during auditory word recognition. Suppose the use of Chinese characters serves the same function as alphabetic scripts in the visual world paradigm. In that case, it can help to zoom into subtle phonological competition effects that otherwise may not be found. Another benefit of using printed words is that it makes our experiment feasible. This is because we adopted a between-subject design (i.e., participants of Experiment 1 and 2 also participated in Experiment 3). To avoid using the same stimuli, we had only a limited number of picturable nouns available as stimuli, making the design practically infeasible.

2.6.1 Methods

2.6.1.1 Participants

Thirty-seven native Mandarin speakers (mean age: 19, standard deviation: 1.5; 21 females, 16 males) who participated in Experiment 1 or 2 also participated in Experiment 3. The order of participating in Experiment 1 and 3 (or Experiment 2 and 3) was counterbalanced.

2.6.1.2 Stimuli

In a total of 96 Mandarin monosyllable words, two groups of stimuli were used in Experiment 3 (see Table A2 in Appendix A). One group consists of 24 tonal pairs, of which one word differs from the other only in the lexical tone; the other group consists of segmental pairs, of which one word differs from the other only in the segment. Based on the POD, both groups were further classified as with early POD or late POD. The early tonal POD word pairs either had a nasal onset or no onset, so the entire syllable carries tonal information from the beginning of the syllable. Their lexical tones contrast with each other from the

beginning of their tonal pitch contours (e.g., Tone1, high-level tone vs. Tone3, low rising-falling dipping tone; Tone 4, high falling tone vs. Tone 3, low rising-falling dipping tone). The late tonal POD pairs have obstruent onsets that do not carry tonal information. Lexical tones either both start low (e.g., Tone 2, rising tone vs. Tone 3, rising-falling dipping tone) or both start high (Tone 1, high-level tone vs. Tone 4, high-falling tone), so their tonal divergence point occurs late. For word pairs diverging in segmental information, the early POD word pairs share the same onset which contains only one segment and diverges in rime (e.g., *pa2 - ping2*), while the late POD word pairs share not only the one onset segment but also the following glide (e.g., *xue3 – xuan3*), which has been analysed either as part of the onset or part of the rhyme (for further discussion on the treatment of glides, see e.g., Chen & Gussenhoven, 2015). Table 1 provides sample stimuli in Pinyin[3], an alphabetic writing system of Standard Chinese.

As discussed earlier, we used printed words instead of real object pictures as a visual display in this experiment. Word frequency, as computed with SUBTLEX-CH (Cai & Brysbaert, 2010), was balanced across conditions [$F(3, 92)=1.871$, $p>0.1$]. Also, the number of components and strokes of the characters were controlled across conditions [Strokes: $F(3,92)=0.538$, $p > 0.5$; Component: $F(3,92)= 1.564$, $p>0.1$]. All stimuli were recorded in the Phonetics Lab of Leiden University through a Sennheiser MKH416T microphone (44.1 kHz, 16 bit). The speaker is a male native Standard Chinese speaker who was born and grew up in Beijing. Each word was read four times in isolation using a randomized list. One token of each word was chosen based on its clarity and normalized for intensity at 70dB.

[3] Note that the Pinyin system is designed for spelling out the Standard Chinese syllables, not for phonetic transcription or phonological analysis as the international phonetic alphabet.

2.6.1.3 Procedure and Design

The procedure in Experiment 3 was the same as that in Experiment 1. Each of the early segmental, early tonal, late segmental, late tonal, and baseline conditions have 24 trials. Another 72 trials were included as fillers in which no phonological-related items were presented. In total, there were 192 trials distributed in four blocks. As in Experiments 1 and 2, the order of blocks was counterbalanced between participants.

2.6.2 Results

2.6.2.1 Behavioural Data

Reaction time and response accuracy for mouse click are shown in Table 10. The same criteria used for data analysis (as described in Experiment 1) were adopted. To enable better comparison with baseline, we used experimental conditions with five levels of early segmental, late segmental, early tonal, late tonal, and baseline conditions as fixed effects to model fixation proportions to target. The best-fit reaction time model included fixed effects of experimental conditions [$\chi2(4) = 41.802$, $p < 0.001$], by-subject and by-item random intercepts, and by-subject random slop for testing conditions. Post-hoc analysis showed that participants' reaction times in all critical conditions were significantly longer than baseline (early segmental: $p < 0.05$; late segmental, early tonal, late tonal: $p < 0.001$). Furthermore, the reaction time in the early segmental condition was significantly shorter than in the late segmental condition ($p < 0.001$). So did the early tonal condition compared with the late tonal condition ($p < 0.05$). There was no significant improvement in model fit for the best-fit accuracy model after adding fixed effects of experiment conditions [$\chi2(4) = 7.627$, $p = 0.106$], suggesting that response accuracy did not differ across experimental conditions.

Table 10. *Mean Reaction time (ms) and mean percent response accuracy of Experiment 3. Standard Errors are in parentheses.*

Information	Timing	Reaction (SE)	Percent Accuracy (SE)
Segmental	Early	1103 (26)	97.6 (1)
	Late	1256 (38.2)	96.5 (0.8)
Tonal	Early	1160 (25.9)	97.5 (1.5)
	Late	1202 (31.7)	97.8 (1.46)
Baseline		1086 (26)	99.2 (0.8)

2.6.2.2 Eye movement Data

Looks to target

Generalized additive modelling (Wood, 2011; 2017) was also employed to model participants' eye fixations[4]. The same modelling procedure as in Experiment 1 and 2 was applied. The resulting model of target fixations includes a fixed effect for condition, a smooth over time for each level of condition (the baseline, early segmental, late segmental, early tonal, and late tonal conditions), and a non-linear random smooth of subject by condition. This final model explains 97.8% of the deviance. Pairwise comparisons between each level were conducted with ordered factors of different reference levels. The estimates for the parametric and smooth terms are summarized in Table 11[5]. The estimated smooths for all conditions are visualized in Figure 5A.

[4] For the ease of comparison to the existing findings (i.e., Malins & Joanisse, 2010; Zou, 2017), We have also analyzed the eye-tracking data with the growth curve analysis (GCA; Mirman, 2014). The results converge for most analyses except for Experiment 3, in which the results of GAMM are more conservative. Given the discussion in Huang & Snedeker (2020), we report our results based on the GAMM analysis.

[5] While Table 11 shows no significant difference between conditions, the plots of estimated smooth in Figure 6 did show some significant difference over time. The results shown in Table 11 are more conservative because the *p*-values were corrected with the Holm-Bonferroni method (Holm, 1979) to avoid family-wise errors.

Smooth term differences between each level are plotted in Figure 6. As shown in Figure 6, compared with the baseline condition, there are fewer target fixations in early segmental, late segmental, early tonal, and late tonal conditions about 250 ms after the auditory stimuli onset. However, according to the estimated parameters of GAMMs (see Table 11), all the differences against baseline were not statistically different.

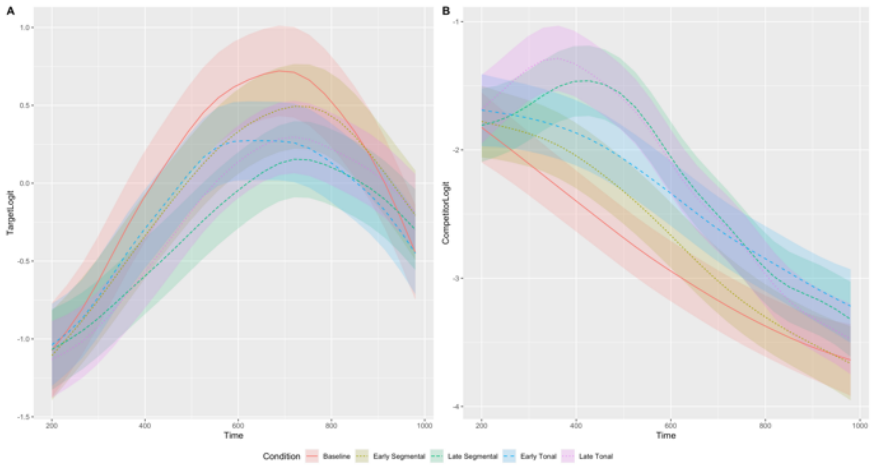

Figure 5. *Estimated smooths for all conditions in Experiment 3. A. Smooths of target fixations for all conditions; B. Smooths of competitor fixations for all conditions. The pointwise 95%-confidence intervals are shown by shaded bands.*

Table 11. *GAMM analysis of targets' fixation proportions in Experiment 3.*

	Estimate	Std. Error	t value	*p*-value
Intercept	-0.052	0.107	-0.487	0.627
Early Segmental – Baseline	0.056	0.141	0.395	1.000
Late Segmental – Baseline	-0.206	0.143	-1.446	1.000
Early Tonal – Baseline	-0.078	0.143	-0.542	1.000
Late Tonal – Baseline	-0.125	0.138	-0.907	1.000
Early Tonal – Early Segmental	0.097	0.127	0.766	1.000
Early Tonal – Late Segmental	-0.081	0.132	-0.619	1.000
Early Tonal – Late Tonal	0.001	0.126	0.008	1.000
Early Segmental – Late Segmental	-0.178	0.135	-1.325	1.000
Early Segmental – Late Tonal	-0.096	0.129	-0.746	1.000
Late Tonal – Late Segment	-0.047	0.118	-0.400	1.000
	edf	Ref.df	F	*p*-value
s(Time)	8.108	8.265	38.905	<0.001
s(Time):Early Segmental – Baseline	1.571	1.660	1.409	1.000
s(Time):Late Segmental – Baseline	3.995	4.335	3.865	0.053
s(Time):Early Tonal – Baseline	2.825	3.062	0.627	1.000
s(Time):Late Tonal – Baseline	3.617	3.927	3.168	0.268
s(Time):Early Tonal – Early Segmental	1.000	1.000	1.857	1.000
s(Time):Early Tonal – Late Segmental	3.048	3.307	2.207	1.000
s(Time):Early Tonal – Late Tonal	2.410	2.596	1.524	1.000
s(Time):Early Segmental – Late Segmental	3.047	3.307	2.145	1.000
s(Time):Early Segmental – Late Tonal	2.409	2.595	0.615	1.000
s(Time):Late Tonal – Late Segment	1.453	1.520	0.186	1.000

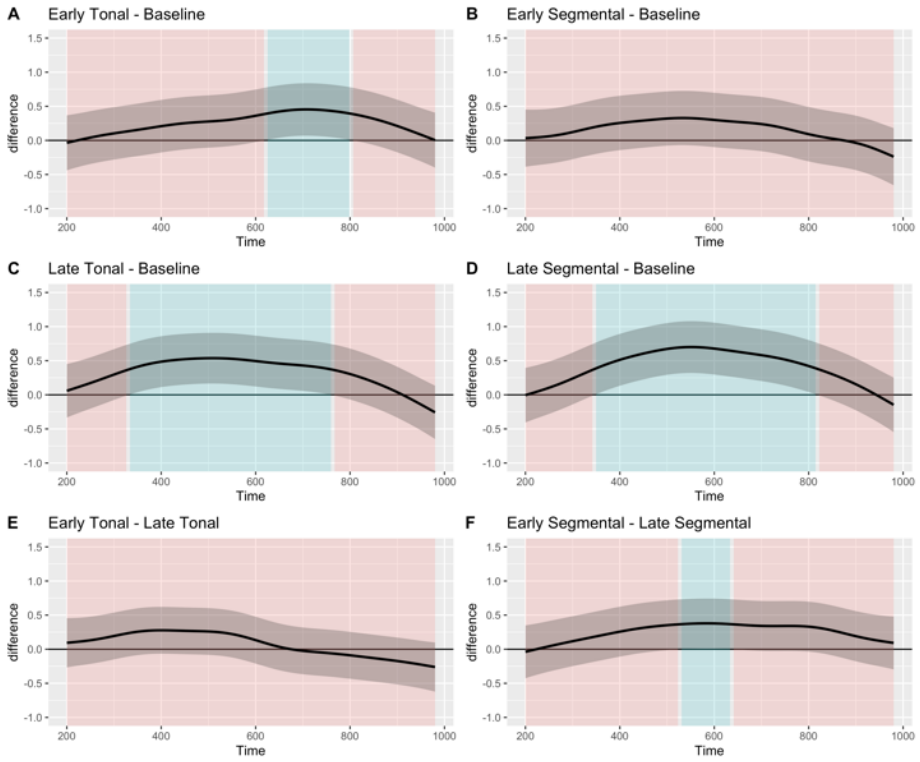

Figure 6. *Estimated smooths difference between experimental conditions for target fixations in Experiment 3. A. Smooths difference between the early tonal condition and the baseline condition; B. Smooths difference between the early segmental condition and the baseline condition; C. Smooths difference between the late tonal condition and the baseline condition; D. Smooths difference between the late segmental condition and the baseline condition; E. Smooths difference between the early tonal condition and the late tonal condition; F. Smooths difference between early segmental condition and the late segmental condition. The pointwise 95%-confidence intervals are shown by shaded bands. The green background indicates that the shaded confidence band is significantly different from zero.*

As for the effect of POD (early vs. late), although proportions of target fixations in both early conditions were slightly higher than that of late conditions

(Figure 6), the differences were not statistically different. The estimated parameters of GAMMs (see Table 11) indicate no significant differences between the information tiers (tonal vs. segmental) either.

Overall, target fixation proportions show two trends: 1) target pictures were less frequently looked at in the early segmental, late segmental, early tonal, and late tonal conditions than in baseline; 2) the late POD conditions generally has a larger effect on target fixations than the early conditions. Although these trends are observable with visual inspection, our GAMM analyses did not yield any statistical significance.

Looks to competitors

Same as models of target fixations, the final model of competitor fixations includes a fixed effect for condition, a smooth over time for each level of condition, and a non-linear random smooth of subject by condition. Pairwise comparisons between each level were conducted with ordered factors. The final model explains 96% of the deviance. The estimated smooths for all levels of conditions are visualized in Figure 5B. The estimates for the parametric and smooth terms are summarized in Table 12.

Table 12. GAMM analysis of competitors' fixation proportions in Experiment 3.

	Estimate	Std. Error	t value	*p*-value
Intercept	-2.789	0.095	-29.305	<0.001
Early Segmental – Baseline	0.126	0.133	0.948	1.000
Late Segmental – Baseline	0.592	0.146	4.053	0.001
Early Tonal – Baseline	0.425	0.136	3.127	0.020
Late Tonal – Baseline	0.613	0.135	4.546	<0.001
Early Tonal – Early Segmental	-0.269	0.117	-2.291	0.198
Early Tonal – Late Segmental	0.162	0.146	1.114	1.000
Early Tonal – Late Tonal	0.182	0.134	1.358	1.000
Early Segmental – Late Segmental	0.431	0.142	3.029	0.025
Early Segmental – Late Tonal	0.451	0.131	3.451	0.007
Late Tonal – Late Segment	0.057	0.142	0.397	1.000
	edf	Ref.df	F	*p*-value
s(Time)	4.622	4.987	15.420	<0.001
s(Time):Early Segmental – Baseline	2.840	3.073	1.257	0.312
s(Time):Late Segmental – Baseline	6.804	7.188	7.339	<0.001
s(Time):Early Tonal – Baseline	2.848	3.080	1.663	0.248
s(Time):Late Tonal – Baseline	6.782	7.160	8.172	<0.001
s(Time):Early Tonal – Early Segmental	1.001	1.001	1.243	0.312
s(Time):Early Tonal – Late Segmental	6.359	6.768	4.281	<0.001
s(Time):Early Tonal – Late Tonal	6.220	6.628	4.769	<0.001
s(Time):Early Segmental – Late Segmental	6.359	6.768	4.522	<0.001
s(Time):Early Segmental – Late Tonal	6.220	6.628	4.690	<0.001
s(Time):Late Tonal – Late Segment	6.220	6.628	4.769	0.312

As we can see from Figure 7, all experimental competitors attract more fixations than the baseline condition after 250 ms post auditory stimuli onset. As GAMMs parameters indicate (see Table 10), model fits of the late segmental, early tonal and late tonal conditions were significantly different from the baseline condition in intercept ($p < 0.001$; $p < 0.05$; $p < 0.001$). As for differences in the estimated smooth terms, only late segmental and late tonal conditions were significantly different from the baseline condition ($p < 0.001$; $p < 0.001$). The

early segmental condition did not significantly differ from the baseline in either intercept or smooth term.

As for the effect of POD (point of divergence in segmental and tonal information), model fits of the early and late segmental conditions significantly differed in intercept ($p < 0.01$) and smooth term ($p < 0.001$), while the early and late tonal conditions significantly differed in smooth term ($p < 0.001$). As Figure 7E and 7F show, participants looked more frequently at the late segmental and tonal competitors than the early competitors.

As for the differences between information tiers (segmental vs. tonal information), participants' competitor fixations in the early segmental condition seem to be overall less frequent than that in the early tonal condition, but the difference was not statistically significant. For word pairs of late POD, segmental competitors had a slightly higher proportion of eye fixations than the tonal competitors at the late time window. The difference was not statistically significant either.

Overall, competitors' eye fixations confirmed the general trends observed with target fixations. First, both tonal (early and late) and segmental (late) competitors attract participants' visual attention; Second, POD affects the proportion of eye-fixations on competitors regardless of the information tier: the later the information diverges, the more frequent eye-fixations on the competitors.

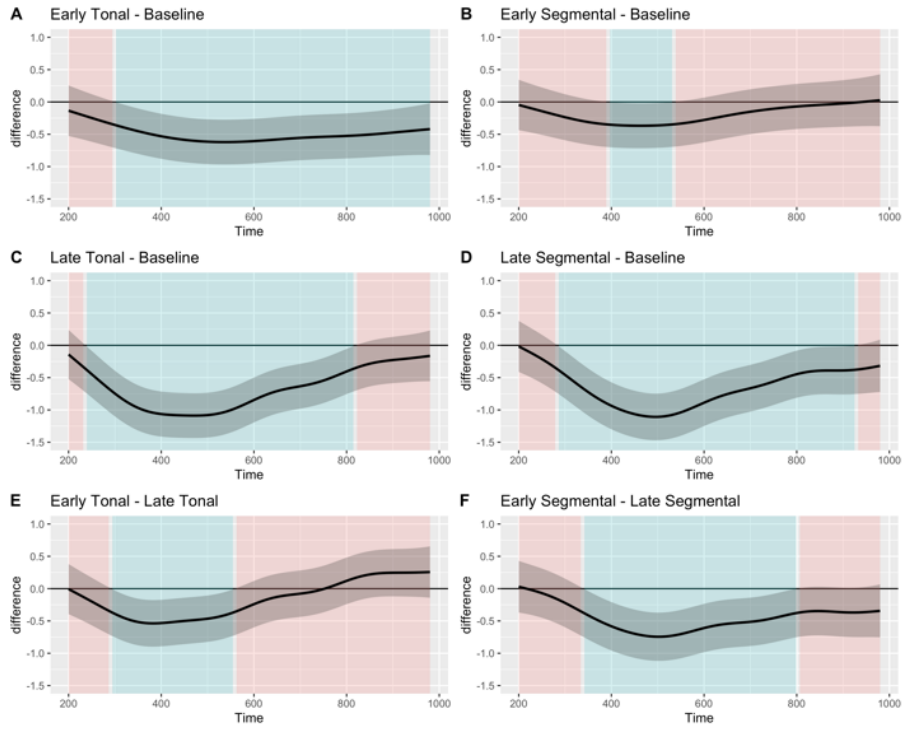

Figure 7. *Estimated smooths difference between experimental conditions for competitor fixations in Experiment 3. A. Smooths difference between the early tonal condition and the baseline condition; B. Smooths difference between the early segmental condition and the baseline condition; C. Smooths difference between the late tonal condition and the baseline condition; D. Smooths difference between the late segmental condition and the baseline condition; E. Smooths difference between the early tonal condition and the late tonal condition; F. Smooths difference between early segmental condition and the late segmental condition. The pointwise 95%-confidence intervals are shown by shaded bands. The green background indicates that the shaded confidence band is significantly different from zero.*

2.6.3 Discussion

Through careful control of the phonological overlap and timing of acoustic information (i.e., the Point of Divergence; POD), we confirmed that phonologically similar words, be it segmental or tonal, drew participants' visual attention more than unrelated distractors. This indicates that similar words with divergent phonemes or lexical tones are co-activated and compete for recognition in Mandarin lexical access. Moreover, the size and the time course of the phonological competition effects were modulated by the timing of the point of divergence in the acoustic signal. The later the information disambiguates, the larger the competition effects. These findings lend solid support to the view that Mandarin listeners use both tonal and segmental information incrementally during Mandarin SWR.

2.7 General Discussion

The present study examined the role of segmental syllables, sub-syllabic constituents, and lexical tone in Mandarin SWR and the time course of how segmental phoneme and suprasegmental lexical tone are utilized during lexical processing. Our findings suggest that segmental syllable plays a dominant role in Mandarin lexical processing while the effects of onset, rhyme, and lexical tone are more subtle and variable. Moreover, when all else is controlled, both segmental information and suprasegmental information can be used to constrain word competition as soon as their respective acoustic cues are present. Results of the three experiments have implications for both models of word recognition in tonal languages and methodological issues of using the visual world paradigm for SWR.

Experiments 1 and 2 examined the relative contribution of segmental syllable, onset, rhyme, and lexical tone. Specifically, we investigated when and to what extent participants' gazes are distracted by the presence of phonological competitors in recognizing Mandarin monosyllabic words. While Experiment 1

allowed participants to preview the pictures for 1,500 ms before listening to the target, Experiment 2 only allowed a short preview of 200 ms. Both experiments consistently found that only competitors with the same segmental syllable significantly distract participants' visual attention towards the target word. Cohort competitors (with onset and lexical tone overlaps), rhyme competitors (with rhyme and lexical tone overlaps), or tonal competitors (with lexical tone overlap) do not introduce more fixations than unrelated distractors.

Results of Experiments 1 and 2 thus replicate Malins and Joanisse's (2010) findings of the segmental (syllable) competitors and rhyme competitors, but not of the cohort and tonal competitors. Note that we have followed Zou (2017) and defined the cohort competitors as having only onset and lexical tone overlap with the targets. Our results confirmed Zou's (2017) finding of the null cohort effect. The robust cohort competition effect reported in Malins and Joanisse (2010) is likely due to the more extended overlap beyond a single onset phoneme (e.g., *hua1* 'flower' - *hui1* 'grey'; *tu3* 'dirt' - *tui3* 'leg'). Furthermore, by assigning tonal competitors an equal number of occurrences as other types of competitors and thereby avoiding a potential familiarity effect within the experiment, our results confirm the lack of tonal competition effect as in Zou (2017). This suggests that lexical tone alone does not have an impact on Mandarin SWR.

With a short preview time of 200 ms, Experiment 2 replicated the results of Experiment 1. This finding differs from that reported in Huettig and McQueen (2007), which showed a lack of phonological competitor activation with a short preview (200 ms). Huettig and McQueen (2007) proposed that 200 ms may be insufficient for Dutch participants to pre-activate the object names and consequently bias phonologically guided eye-fixations. With a series of eye-tracking experiments, Apfelbaum et al. (2021) have argued that phonological competition is not contingent upon pre-naming or pre-activating names during the preview. Instead, the preview allows participants some time to recognize visual objects so that their eye movements can better reflect lexical processing. Note that one particular design of Huettig and McQueen (2007) is that three types of

competitors, namely the visual, semantic, and phonological competitors, were all presented in one display. It is possible that when the preview is short, the visual search is delayed such that listeners may fixate first and primarily on the visual and semantic competitors in display and may not manage to fixate on the phonological competitor. Our results are consistent with Zou (2017) and Apelbaum et al. (2021), both of which found evidence of phonological competition even without preview. These studies suggest that the length differences in preview time (in our case a difference of 200 ms vs. 1,500 ms) do not influence the general pattern of phonological competition in Mandarin lexical access. Although the length of preview time is not a determining factor in phonological competition, it does influence how participants distribute their visual attention. We found that, with a shorter preview, participants located the target picture faster with fewer fixations. Moreover, there were different fixation patterns for phonological competitors when the preview was short. For example, there were slightly more frequent fixations on the rhyme competitors at a later processing stage than in Experiment 1. Future studies are still needed to fully understand how the length of preview time might affect looks to different phonological competitors.

Experiment 3 zoomed further into the time course of SWR and in particular, listeners' sensitivity to the acoustic details of segmental and tonal information. Word pairs (target and competitor) with divergent segmental information or tonal information were contrasted. With all else controlled, we were interested in whether the lexical co-activation and competition effect is modulated by the timing of the POD (i.e., the point of information divergence; early vs. late) along both the segmental and tonal dimensions. Results show that, while both early and late tonal competitors significantly attracted participants' visual attention, the late tonal competitors (which share the same segment and the onsets of tonal pitch contours with the target) exhibited a significantly larger effect than the early tonal competitors (which share the same segment with the target); segmental competitors only exhibited a significant effect when the

segmental information diverges late (which share the onset, glide, and tone with the target) but not early (which share the first onset phoneme and tone with the target). As for the relative weighting between the role of tone and segments in lexical access, no statistically significant difference was found between either early or late tonal and segmental conditions. Overall, we found that the competition effects were less persistent and weaker when the information diverges early in both conditions. The results of tonal conditions are consistent with the previous findings of Qin (2017), which confirms that lexical tone can be used early to constrain word activation before it is recognized. The results of segment condition provide further evidence against the view of holistic processing in Mandarin lexical access. Together with previous findings, our results show that both tonal and segment phonemic cues are incrementally processed as soon as they arrive.

In sum, the results of Experiments 1 & 2 indicate an advantageous role of segmental syllable over onset, rhyme, and lexical tone in activating word candidates. While Experiment 3 shows that, both tonal and segmental information can be used incrementally to constrain word candidates' activation during the process of Mandarin SWR.

How to model such effects? Previous studies have proposed several accounts of SWR in tonal languages (Gao et al., 2019; Malins & Joanisse, 2012b; Ye & Connine, 1999; Yue, 2016; Zhao et al., 2011; Tong et al., 2014; Shuai & Malins, 2017). The classic TRACE model (McClelland & Elman, 1986) posits a three-layer (word, phoneme, feature) architecture and bi-directional interconnections between layers. Existing models of SWR in tonal languages such as Mandarin typically add the "toneme" (Ye & Connine, 1999; Malins & Joanisse, 2012b; Zhao et al., 2011) or "tone" node (Gao et al., 2019; Yue, 2016) as the representation of lexical tone.

One disagreement among these existing models is whether an extra level of (tonal) syllable (Zhao et al., 2011) or segmental syllable (Yue, 2016; Gao et al., 2019) is necessary. The syllable node in Zhao et al. (2011) incorporates syllabic

morpheme (which includes both segmental syllable and tone) as a phonological representation to store morphemic syllables. By "hiding" phonemes and tonemes, the Reverse Accessing Model (RAM) in Gao et al. (2019) treats atonal syllable (i.e., segmental syllable) as "the earliest and smallest unit of phonological information immediately available for mental operations. In line with the proposal of RAM (Gao et al. 2019), our results also argue for the inclusion of segmental syllables at the sub-lexical level to account for its advantageous role in Mandarin lexical access. However, we remain sceptical about "hiding" phonemes and tonemes. The RAM proposes that tones and segmental phonemes are "hidden", i.e., can only be accessed when the information at the (atonal) syllable level is insufficient for the task at hand. This assumption well-explained the findings of the speeded discrimination tasks in Gao et al. (2019). For instance, it was easier for participants to make identical/different judgments on (segmental) syllables than phonemes or tones, because the latter would require re-activation of the phonemic and tonal information as a mental replay. Nevertheless, this assumption was not made for explaining the findings of the visual world paradigm. If only segmental syllable information is accessible when listeners were presented with spoken words, only words with the same or similar segmental syllable would be co-activated and compete for recognition. However, despite the robust competition effect of segmental syllables, effects of sub-syllabic components have also been found (e.g., late segmental competition effect in our Experiment 3; Malins & Joanisse, 2010; Zou, 2017). These findings of visual world paradigm seem to indicate that all information is maintained and can be used to aid SWR, which agrees more with the assumption of the TRACE model.

Another disagreement in the current models of tone-word recognition is whether the segment and tone processing are integrated (e.g., the TTRACE model; Tong et al., 2014) or separated (e.g., the TRACE-T model; Shuai & Malins, 2017). Zou et al. (2017) showed that native Mandarin listeners found it difficult to attend only to one of these two tiers of information, suggesting that at a certain level of processing, segmental and tonal information are integrated. Furthermore, it is also

relatively easier for them to attend only to segments (compared to only to tone), suggesting an asymmetrical relationship between the processing of these two tiers and, therefore the need for separate processing at other levels. There are also data from neural processing to shed light on this issue. Choi et al. (2017) examined the pre-attentive and phonological perceptual integration of vowels and tones in Cantonese using the oddball paradigm; the mismatch negativity (MMN) suggests the integration of vowel and tone processing at the phonological level. With the violation paradigm, Zou et al. (2020) reported different ERP effects for the rhyme and tone violation conditions, indicating different roles of tone and vowel at different stages of speech processing. Our study was not designed to explicitly test the integration or separation of segment ad tone processing. However, in Experiment 3, we do see substantial time course differences between the tonal and segmental diverging conditions. For example, the tonal condition had a significant early competition effect while the early segmental condition did not. Also, considering previous findings of tonal and segmental processing differences in terms of timing (e.g., Ye & Connie, 1999), speed (e.g., Connell, 2017), and relative weighting (e.g., Zou et al., 2020), it is more prudent for us to posit that at some levels of processing, tone and segments are processed independently, rather than integrated and holistically throughout the SWR process.

Based on our findings and data reported in the literature, we suggest a revised TRACE model for Mandarin SWR with a four-layer structure: syllable (i.e., segmental syllable and tone), segmental syllable, phonemes, and toneme, as well as their respective features. The extra level of segmental syllable accounts for the overall larger and more stable phonological competition effects of segmental syllable over a combination of sub-lexical phonological components (e.g., onset plus tone; rhyme plus tone) during Mandarin SWR. Moreover, with independent representations of phonemes and tonemes, both phonemic and tonal information can be used to resolve phonological competition when the context introduces enhanced sensitivity to the phonological information.

Having an extra unit of segmental syllable also echoes findings during online speech production. With classic paradigms such as implicit priming (Meyer, 1991), previous studies on Mandarin word production found effects of the atonal syllable (i.e., segmental syllable) but not of the initial onsets, which clearly differed from Indo-European languages (e.g., Chen, Lin, & Ferrand, 2003; Chen & Chen, 2013; Chen, O'Seaghdha & Chen, 2016; Wang, Wong, & Chen, 2018). O'Seaghdha (2010) therefore proposed that, whereas the proximate phonological encoding units in Indo-European languages are phonemic segments, it is the atonal syllable that is proximate in Mandarin. Roelofs (2015) adopted the proximate unit principle to the WEAVER++ Model (W. J. M. Levelt et al., 1999). Computational simulation results successfully explained the divergent findings between Mandarin and English, confirming cross-language differences in terms of the phonological planning units. Also adopting the proximate unit principle, Alderete et al. (2019) proposed a two-stage model for tone word production that not only incorporated the primary role of atonal syllables but also an early selection process of lexical tone, similar to the model structure we proposed. Nevertheless, to further explore the relation between tonal word production and recognition, future studies are needed.

Nonetheless, the findings of this study have to be seen in light of limitations. First, according to recent statistical advice (Brysbaert & Stevens, 2018; Brysbaert, 2019), our sample sizes are relatively small, which might reduce power and increase the margin of error. Second, due to the difficulty of finding sufficient items, we followed the design of Malins & Joanisse (2010) in using the targets repeatedly without dividing them into counter-balancing lists. How this practice may affect the data is still unclear, but it should be noted in interpreting the results and be avoided in future studies.

In summary, this study found that Mandarin listeners are sensitive to the unfolding segmental information and suprasegmental information and utilize both to constrain word recognition as soon as possible. Unlike in English or other West-Germanic languages, segmental syllable (syllable without specifying lexical

tone) plays a more advantageous role in Mandarin lexical access. Our results provide further data to adjudicate current and future models of tonal word recognition and shed new insights into the universal and diverse patterns of spoken word recognition across languages.