# Iambic-trochaic grouping in native listeners of Papuan Malay, Akan and German

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Grouping helps listeners to break down the speech signal into smaller units. Specific acoustic cues, in particular duration and intensity, have been reported to determine grouping of disyllabic units across languages (Iambic-Trochaic Law - ITL). The ITL states that iambic grouping is obtained from syllabic sequences alternating in duration, whereas trochaic grouping is obtained from those alternating in intensity. Speakers of different languages vary in the extent to which they use the ITL. It has been proposed that this linguistic modulation of the ITL relates to cross-linguistic differences in prosody. The present study further investigates the predictions of the ITL in two under-researched languages, Papuan Malay and Akan, for which there is controversy on the existence of word stress. They are compared to German, a well-researched language with variable word stress. A perceptual grouping task used in previous work is replicated with listeners from each language. The results show considerable cross-linguistic differences and shed light on acoustic perceptual properties in Papuan Malay and Akan. The outcomes reconfirm cross-linguistic variability and modulation of the applicability of the ITL across languages.

## I. INTRODUCTION

Prosodic typology aims at understanding the differences and similarities in intonation, speech rhythm and stress (henceforth prosody) across languages (e.g. Jun, 2005; Jun, 2014). Current prosodic theory is, however, still mainly based on well-studied languages spoken in the Global North, especially English (e.g. Himmelmann and Ladd, 2008). Although research is slowly advancing by taking more understudied languages into account, much work still remains before prosodic theory becomes globally valid. This holds in particular for supposedly universal prosodic processing mechanisms, such as the Iambic-Trochaic Law (ITL; Bolton, 1894; Woodrow, 1909; Hayes, 1995). This phonological law makes predictions about intensity and duration as cues to prosodic grouping. That is, "elements contrasting in intensity naturally form groupings with initial prominence" and "elements contrasting in duration naturally form groupings with final prominence" (Hayes, 1995, p.80). Pitch has been argued to have the same grouping effect as intensity, that is, with higher pitches being perceived as initial (trochaic) prominences (e.g. Nespor *et al.*, 2008). It has been shown that these principles do indeed often underlie the way listeners parse speech and speech-like sequences of sounds (see Crowhurst, 2020 for an overview). It should be noted, however, that the ITL makes independent predictions about the use of specific acoustic cues, and does not discuss how various cues could be used simultaneously, which is likely the case in natural speech processing. Importantly, it has also been shown that the extent to which the ITL is used in a certain language depends on its prosodic structure, in particular on its word prosodic patterns such as word stress (Bhatara *et al.*, 2013) and on its phrase prosodic characteristics (Crowhurst and Teodocio Olivares, 2014). Note that we use 'word stress' to refer to prominence patterns at the word and/or lexical level, also called 'lexical stress' in other work, unless specified differently. The majority of the studies on the ITL has focused on listeners of Indo-European languages. The few exceptions include Japanese (Iversen *et al.*, 2008), Zapotec (Crowhurst and Teodocio Olivares, 2014), Basque (Molnar *et al.*, 2016), Chaozhou (Yiu, 2019) and Korean (Arvaniti and Jeon, in press). Since the prosody of Indo-European languages is not necessarily representative, it is important to include more languages that do not make use of word or phrasal stress in the same way as Indo-European languages, as to reduce the confound of word or phrasal stress experience effects on rhythmic grouping. The current study does so by investigating Papuan Malay and Akan, two typologically different languages that have thus far received limited attention in the literature, with the goal of better understanding the potential universality of the ITL. Papuan Malay (ISO 639-3: PMY) is a Malayo-Polynasian language spoken in Eastern Indonesia, and Akan (ISO 639-3: AKA) a Kwa language (Niger-Congo group) spoken in Ghana. Both languages belong to families that received no attention so far with regard to the ITL. Papuan Malay and Akan will be compared to German, a language in which strong ITL effects have been found in the past (Bhatara *et al.*, 2013, Exp.1).

In the following, we first provide an overview of experimental research testing the ITL across languages, establishing that its effects are modulated by prosodic properties of the native language (Section I A). Second, we will summarize the most relevant studies on Papuan Malay and Akan (Section I B and I C), before outlining the research questions and hypotheses of this study (Section I D).

## A. Cross-linguistic modulation of the ITL

Recent research has tested the predictions of the ITL on a number of different languages. The most relevant findings are discussed in this section, with particular focus on intensity and duration (for a comprehensive literature review, see Crowhurst, 2020).

The experimental task most commonly used to test the ITL is a forced choice task presenting sequences of sounds to listeners. The sounds in the sequence alternate in acoustic prominence, either by a manipulation of duration (short vs. long), intensity (soft vs. loud), pitch (low vs. high), or a combination of these cues. The magnitude of manipulation has varied across studies, ranging from no difference (control condition) to typical maxima of 200 ms duration difference (e.g. Bhatara *et al.*, 2013), 12 dB intensity difference (e.g. Hay and Diehl, 2007 and one octave pitch difference (e.g. De La Mora *et al.*, 2013). The type of sounds range from speech and speech-like to non-speech and musical ones. Speech and speech-like stimuli are useful to test native listeners of a particular language. Non-speech and musical ones have the advantage, however, of allowing the comparison of listeners of various languages using the same set of stimuli, as done in the current study, and therefore not giving listeners of a particular language any advantage over others (see Section I D). Participants in the experiments typically indicate whether the sound sequence they heard consists of repeated trochees or iambs, that is, whether they perceived the sequence as made up of sound pairs with initial or final prominence. The predictions made by the ITL for each acoustic cue are provided schematically in Table I.

TABLE I. Overview of ITL predictions for each acoustic cue (| = predicted perceived boundary)

<table>
<tr><th>Cue</th><th>Sequence</th><th>Predicted perceived grouping</th><th>Group (foot)</th></tr>
<tr><td rowspan="2">Intensity</td><td>soft-loud-soft-loud-soft-loud</td><td>soft|loud-soft|loud-soft|loud</td><td rowspan="2">loud-soft (trochaic)</td></tr>
<tr><td>loud-soft-loud-soft-loud-soft</td><td>loud-soft|loud-soft|loud-soft</td></tr>
<tr><td rowspan="2">Duration</td><td>short-long-short-long-short-long</td><td>short-long|short-long|short-long</td><td rowspan="2">short-long (iambic)</td></tr>
<tr><td>long-short-long-short-long-short</td><td>long|short-long|short-long|short</td></tr>
<tr><td rowspan="2">Pitch</td><td>low-high-low-high-low-high</td><td>low|high-low|high-low|high</td><td rowspan="2">high-low (trochaic)</td></tr>
<tr><td>high-low-high-low-high-low</td><td>high-low|high-low|high-low</td></tr>
</table>

In the literature, ITL effects are linked to both phrase-level and word-level prosodic characteristics, a distinction that we maintain in the current study. Several studies predicted cross-linguistic differences regarding rhythmic grouping related to the listeners' experience with phrase-level prosody. Indeed, it was found, for example, that American English listeners showed ITL-conform grouping for intensity and duration, whereas Japanese listeners only had clear and expected grouping preferences for intensity (Iversen *et al.*, 2008). The language difference found for duration in this study was explained by differences in phrase level prosody, which tends to be iambic in American English, but without strong prominence differences in Japanese (Crowhurst, 2020). Certain languages show a complete lack of ITL-conform grouping preferences. For example, in a comparison between Mexican Spanish and American English (Crowhurst, 2016), only the latter showed a clear grouping preference (iambic, confirming Iversen *et al.*, 2008). It was argued that the combination of right-heading in phonological phrases and final lengthening is more common in American English than in Mexican Spanish, which contributed to this effect, i.e. leading to American English listeners' stronger association of longer duration with final syllables (Crowhurst, 2016). In a similar vein, phrasal prominence differences between Iberian Spanish and Basque were shown to elicit opposite groupings based on duration as a cue, i.e. short-long (ITL-conform, iambic) in Iberian Spanish and long-short (ITL-violating, trochaic) in Basque (Molnar *et al.*, 2016).

Regarding the word level, two studies that compared native listeners of Standard German and European French found ITL-conform results in listeners of both languages, though these were overall more ITL-conform for German than for French. One of the studies used syllable sequences (Bhatara *et al.*, 2013) and the other non-speech sound sequences (Bhatara *et al.*, 2016). In the latter, the presented sound sequences differed in variability, such that they were made up of either 16 different sounds obtained by combining spectral and temporal properties of multiple musical instruments (high variability) or made up of only one of these (low variability). Variability was manipulated to test whether the predictions of the ITL depend on the complexity of stimulus material across languages, with ITL-conform grouping of the high variability stimuli being interpreted as an indicator of strong ITL-conformity. Low variability sequences showed ITL-conform results for both German and French listeners. High-variability sequences still showed ITL-conform results for German listeners, but chance-level responses for the French ones. Musical experience had no significant effect in German, whereas in French, listeners with higher levels of musical experience (e.g., playing an instrument) were more ITL-conform in their responses than the ones with less musical experience. Follow-up studies, however, found that grouping was affected by the musical rhythm perception acuity in German (Boll-Avetisyan *et al.*, 2017; Boll-Avetisyan *et al.*, 2020).

The differences in ITL-conformity in rhythmic grouping between German and French listeners were attributed to cross-linguistic differences in word-level prosody. That is, German is analyzed as a language with variable word stress, although the trochaic pattern, signaled by duration and intensity, is predominant (e.g., Dogil, 1999, Röttger *et al.*, 2012). French is a language with phrase level intonational structure which does not have word stress (Delais-Roussarie *et al.*, 2015; Michelas and Dufour, 2019). German listeners therefore have more linguistic experience with the acoustic cues of intensity and duration indicating the word stress, which made them respond more ITL-conform, even for stimuli with high acoustic variability, then the French ones (Bhatara *et al.*, 2016). Further evidence of the relevance of word level prosody to the ITL is attested by a study on the realisation of lexical tones in Chaozhou (Southern Min) disyllabic words (Yiu, 2019). These words were produced conform the ITL, with more intensity or duration depending on whether tone sandhi aligned to the first or or second syllable respectively. Related studies furthermore suggest that bilingual experience with variable word stress languages can affect rhythmic grouping, and that the age of acquisition of the second language plays a role (Boll-Avetisyan *et al.*, 2017; Boll-Avetisyan *et al.*, 2020). French late learners of German showed limited differences in their rhythmic grouping performance when compared to monolingual speakers of French: only those with high degrees of oral input showed German-like grouping preferences (Boll-Avetisyan *et al.*, 2016). From-birth simultaneous French-German bilinguals, however, showed strong German-like rhythmic grouping preferences irrespective of their degree of German input (Boll-Avetisyan *et al.*, 2020).

The studies discussed above show that the grouping predictions of the ITL differ across languages. Prosodic grouping preferences are affected by prosodic structure, in particular word and phrasal prominence, musical experience, musical aptitude, or a combination of these factors. Linguistic prominence is a particularly important factor, because intensity and duration can both be reliable cues to word stress, regardless of whether the stress pattern is iambic or trochaic (e.g. Revithiadou, 2004; Gordon and Roettger, 2017). Thus, in the study of the ITL, both grouping *and* prominence marking need to be taken into account, as these are two important prosodic functions attested cross-linguistically (e.g. Moghiseh *et al.*, 2023). The next two sections discuss prosodic properties related to the word and the phrase level in the two understudied languages under investigation.

### B. Papuan Malay

Papuan Malay is spoken by around one million speakers in the Eastern Indonesian provinces Papua and West-Papua (Kluge, 2017). It is a Trade Malay variety (Paauw, 2009) that likely developed from the variety spoken in the Moluccas around the 14th century as a result of spice trading. It was more firmly established around the 18th and 19th century due to the Dutch colonial rule, making this language one of the youngest of the Trade Malay varieties (Kluge, 2017).

Research on the prosody of Papuan Malay has examined both production and perception at the word and phrase level. As for the word level, this language has regular penultimate word stress, cued by duration, spectral tilt and vowel quality, and more weakly by intensity (Kaland, 2019). Stress is ultimate if the penultimate syllable consists of schwa or /ɛ/. Listeners were shown to be sensitive mainly to deviations from the regular pattern (i.e., ultimate word stress; Kaland, 2020), that is, assuming the regular penultimate word stress pattern by default. These results corroborate studies showing that the more predictable stress patterns are, the less sensitive listeners are to their cues (e.g., Peperkamp *et al.*, 2010). Lexical analyses using word lists showed that Papuan Malay word stress information is available for listeners to reduce the number of word candidates in online processing and that the position of the stressed syllable is determined by the segmental make-up of syllables (Kaland *et al.*, 2021). In a follow-up study, listeners were asked to guess the target word based on parts of that word in increasing length (gating task). Listeners were indeed able to make use of word stress information to accurately guess the target word from a near-minimal word stress pair (Kaland, 2021). However, it is unlikely that the form of word stress attested in Papuan Malay is lexical, in the sense that its (high) regularity does not seem to require lexical storage. Recent findings indeed show that memory recall of word stress patterns is indeed challenging to Papuan Malay listeners (Kaland, 2024). The outcomes thus far suggest that the ITL would apply to a reduced extent in Papuan Malay, as listeners' sensitivity to word prosodic cues appears limited.

Regarding Papuan Malay phrase level prosody, studies have shown that listeners tend to agree on the location of where they hear boundaries more than on the location of (phrase-medial) prominences (Riesberg *et al.*, 2018; Riesberg *et al.*, 2020; but see Ladd and Arvaniti, 2023 for a discussion on the elicitation paradigm). The Papuan Malay results led to the question of whether prominence marking does indeed have a prosodic function in this language, in the sense that it can be conceptually separated from boundary marking in prosodic theory, as often done in the literature (e.g. Jun, 2014; Cole and Shattuck-Hufnagel, 2016; Moghiseh *et al.*, 2023). This interpretation found support in acoustic analyses of phrase-level f0 movements in scripted and spontaneous speech, showing that highlighting by means of pitch accents is largely absent, or restricted to phrase-final positions (Kaland and Baumann, 2020; Kaland and Gordon, 2022; Kaland *et al.*, 2023). Finally, we are unaware of studies on the nature of the interaction between word level and phrase level prosody in Papuan Malay. Regular word stress in the form just described for Papuan Malay does not imply that stressed syllables are anchors to phrase level accents, as often reported for languages such as English, Greek or Portuguese (i.e. *head languages* in Jun, 2014). Thus, the role of Papuan Malay word stress in prosodic structure is still open to investigation, although the language could be tentatively classified as a head/edge language (cf. Kaland and Baumann, 2020 and Kaland *et al.*, 2023). The minimal assumption is that word stress is a functional cue for word segmentation, given its default location (penultimate syllable).

In summary, Papuan Malay offers an interesting test case to test the effects of the ITL given its unique prosodic properties, such as regular penultimate word stress (Kaland, 2021), which is largely unpredicted by typological work on languages in the area (e.g. Goedemans and van Zanten, 2014), and its unclear relation between word stress and phrase-level prosody (Kaland *et al.*, 2023). Indeed, in Papuan Malay, the predominant penultimate stress pattern, which is marked mainly by duration contrasts (Kaland, 2019), might in fact lead to a trochaic grouping bias. That is, given these specific premises, duration contrasts might not lead to iambic grouping in this language.

### C. Akan

Akan is spoken in Ghana as a national language. Different Akan dialects are mutually intelligible, and Asante Twi is the most widely spoken and studied dialect. It was probably established as a language at the time of the Ghana Empire, around 300 CE, playing an important role in salt and gold trade with different parts of North and East Africa. Akan language features are found in Ndyuka (or Aukan), an English creole spoken in Suriname and French Guiana as a result of trans-Atlantic slave trade.

Although there are no in-depth studies of word stress for this language, it is assumed that there is none (Dolphyne, 1986; Kügler, 2016). The syllable is analyzed as the tone-bearing unit in Akan. There are high and low lexical tones (H and L) that are used to distinguish word meanings as well as for grammatical functions, mainly in verbs (Kügler, 2016). At the phrase level, Akan lexical tone is characterized by downstepping H-tones that follow L-tones, with pitch reset at sentence-internal phrase boundaries. In surface realizations, phrases tend to have a typical overall downtrend for this reason. This downtrend has a 'terracing' nature in the sense that the downtrend shows a step-wise lowering of f0 (Clements, 1979). When compared to declarative sentences, polar questions are marked by lengthening, intensity increase and lowered pitch of the final syllable (Saah, 1988; Rialland, 2007; Genzel, 2015).

Some studies have investigated the rhythmic nature of Akan in production and perception. One study carried out a speech cycling task (Anderson, 2009), in which participants repeated phrases a large number of times at a medium or high tempo, in this way inducing a (more) rhythmic version of their productions. The impressionistic analysis of where the rhythmical beats occurred in the phrases, led to a tentative conclusion that Akan could be stress-timed (Anderson, 2009). A similar conclusion was reached on the basis of Akan poem recitations, for which prominent beats were annotated, showing stable timings across various kinds of tempo (Purvis, 2009). It should be noted that both of these studies relied on impressionistic data by the authors themselves, who were native speakers of a so-called stress-timed language (English). A more recent, quantitative study sought to determine the rhythm-class (stress-, syllable-, or mora-timed) in which Akan falls; it found that Akan did not clearly pattern with any rhythm class (Boll-Avetisyan *et al.*, 2020). It needs to be noted that no study has managed to provide an accurate metric to capture the alleged rhythm-class distinctions (e.g., Arvaniti, 2012), which has led to rethinking the way speech science has defined language rhythm (e.g., Nolan and Jeon, 2014; Albert and Grice, 2026). In summary, Akan has a tonal system and supposedly has no word stress, although in-depth acoustic and perceptual investigations are lacking (e.g. Genzel, 2015; Kügler, 2016), and studies on the phrase level are very limited. Thus, there is at present little to no solid basis for hypothesizing about the nature of prosodic grouping in Akan, and the need for further research on this language is evident.

### D. Research aims

It appears from the literature reviewed above that the extent to which the ITL affects speech processing differs across languages. The impact of one's native language on the extent to which the ITL effects hold is termed the 'nurture' component in Crowhurst (2020, p.8), as opposed to automatic and 'innate' psycho-acoustic effects of certain cues on prosodic grouping. From this language-specific modulation, one could thus speculate that the strength of the grouping effects found in experiments testing the ITL can provide a way to gain insight into the (perception of) prosody of the languages under investigation (the extent to which this speculation holds being further discussed in Section IV). The current study, which explores ITL effects in listeners of Papuan Malay and Akan, will therefore contribute to our understanding of prosodic grouping cross-linguistically as well as to the description of these two understudied prosodic systems.

The present study focuses on the possible effects of duration and intensity variation on grouping, which are the original parameters refered to by the ITL. F0 was not tested, as there are reasons why f0 might not be a (strong) cue for both Papuan Malay and Akan (although this could be directly investigated in future studies). In Papuan Malay, f0 is the weakest correlate of word stress (Kaland, 2019), so it is expected to have little to no effect on prosodic grouping at the word (i.e. foot) level. Pitch could nevertheless be a useful perceptual grouping cue at the phrase level in this language. In Akan, it is unlikely that word level tone contributes to grouping, as it is mainly used to signal lexical distinctions and verbal inflection. So far, the only other tone language for which the ITL was tested is Zapotec (Crowhurst and Teodocio Olivares, 2014), revealing ITL-conform results for intensity, and ITL-violating ones (long-short preference) for duration. Given the role of f0 in tone languages, it is possible that there are different demands on the use of other acoustic cues, such as intensity and duration, compared to non-tone languages. This could in turn affect the interaction between tone and grouping. This option was not explicitly discussed for the Zapotec results in Crowhurst and Teodocio Olivares (2014), but it remains a theoretical possibility.

To test the effects of duration and amplitude, we adapted the paradigm used in Bhatara *et al.* (2016) using a subset of their stimuli to reduce the overall duration of the experiment. The use of non-speech stimuli allowed us to use the same materials across all three languages, without giving listeners of a language any advantage. Note that non-speech stimuli might limit the generalizations that can be made from the results of this task, a point that is further discussed in Section IV. The fact that similar effects were found with speech and non-speech stimuli in the studies comparing German and French suggests similar effects might be found with speech stimuli in the present study. In addition, we used two levels of variability in the stimuli (high and low). This allowed us to test the extent to which ITL effects were modulated by stimulus properties, in addition to the individual cues (see also Section I A).

To provide context and comparison, and validate this modified procedure, we also tested German adults. Of the two languages previously tested (French and German), we chose German because it provided clear ITL effects, stronger than those found in French. Including German was also of interest to reassess the crucial outcome of ITL-based grouping in German not just for trochaic intensity-based variation, but also for iambic duration-based variation (Bhatara *et al.*, 2013, Exp.1). Indeed, cross-linguistically, the latter is less commonly attested than the former (Crowhurst, 2020). Moreover, the German duration-based effects are particularly relevant for testing the ITL in a cross-linguistic context, because they were observed despite an overall bias for trochaic grouping.

Our working predictions for each language, based on prior findings and the potential role of language-specific prosody, were as follows. Starting with German, a language with variable word stress (which should increase sensitivity to word stress, cf. Peperkamp *et al.*, 2010) and a predominant trochaic word stress pattern, we expected to replicate the results previously found. That is, a sensitivity to both duration and intensity cues conforming to the ITL predictions, which is found for both low- and high-variability sequences, the latter attesting heightened conformity to the ITL. We also expected to replicate trochaic perception of the control sequences, which was explained as a bias stemming from the predominant trochaic pattern at the word level (Bhatara *et al.*, 2016).

For Papuan Malay, the high predictability of word stress assignment (penultimate syllable) was expected to reduce sensitivity to word stress cues such as duration and intensity compared to German listeners (e.g., Peperkamp *et al.*, 2010). We therefore expected weak ITL-conform grouping that might only be found with the low variability stimuli (but not the high variability ones). Moreover, the predominant penultimate stress pattern, which is marked mainly by duration contrasts (Kaland, 2019), might lead to a trochaic grouping bias. As a result of this, duration contrasts might not lead to iambic grouping in this language.

For Akan, we hypothesized that listeners' sensitivity to intensity and duration would follow the general predictions of the ITL, but effects might be weak given the claim that this language has no word stress (Genzel, 2015; Kügler, 2016). To what extent this expected reduced sensitivity provides (indirect) information about the prosodic properties of this language will be further discussed in the discussion.

## II. METHODS

### A. Participants

We tested 21 native speakers of Papuan Malay (19 female, 2 male, $M$ age = 25, age range: 18-36), recruited and tested in Sentani, Papua (Indonesia), 24 native speakers of Akan (Asante Twi dialect; 9 female, 15 male, $M$ age = 22, age range: 18-27), recruited and tested at the University of Ghana, Legon, in Accra (Ghana), and 26 native speakers of German (20 female, 6 male, $M$ age = 23, age range: 19-32), recruited and tested at the University of Potsdam, in Potsdam (Germany).

All participants had acquired these languages from birth, and spoke them at a native level. Because of the high prevalence of from-birth-multilinguals, in particular in Papua and Accra, multilingualism was not an exclusion criterion. Knowledge of other languages was evaluated using language background questionnaires, taking into account the cultural and linguistic situation of each population. The questionnaire asked which language(s) the participant spoke in different settings (at home, at work, at school, etc.) and with different people (family, friends, colleagues). Some Papuan Malay participants also spoke Indonesian (2), Yali (2), Biak (1) and English (1). All Akan participants were multilingual and spoke English (22), French (2), Bono (2), Ewe (1), Sefwi (1) or Fante (1). All German participants were multilingual and also spoke English (all), French (12), Spanish (8), Russian

(3), Italian (1), Korean (1) or Portuguese (1). The Papuan Malay and Akan participants (not the German ones) also carried out other experimental tasks for different research projects (Papuan Malay: auditory working memory, Akan: semantic processing; both not reported here). The order of the two experiments was counterbalanced, participants were given a break between the tasks, and no spill-over effects were expected given the different nature of the tasks. Lastly, participants were asked whether they had any hearing problems. None of them in any of the languages reported having such problems.

### B. Stimuli

The sound sequences used in this study were generated from long-term average spectra and temporal structures, each taken from four different musical instruments (see Agus *et al.*, 2012 and Bhatara *et al.*, 2016 for further details). The long-term average spectra were taken from a bassoon, cello, clarinet and a trumpet. The temporal structures, in particular onset structures, were taken from a violin, trombone, English horn, and an alto saxophone. The combination of a spectrum and a temporal structure was called a 'chimera', and one for each of the possible combinations (4 x 4) was generated. The default average intensity of each of these chimeras was set to 60 dB, duration to 260 ms, and f0 to 200 Hz. The final 5 ms were a raised cosine fade out to 0 dB. The chimeras reflected the characteristics of a 'syllable', that is, the part that represented the building block for a sequence.

High variability sequences consisted of varying chimeras. They were generated by concatenating all of the 16 chimeras, and repeating the result once, such that the total length of a default sequence was 32 x 260 = 8320 ms. Low variability sequences consisted of 32 repetitions of a single chimera: the combination of trombone temporal structure and cello spectrum. During the first three seconds, each sequence was faded in whilst masking white noise was fading out (both raised cosine). This was done in order to mask the start of the sequence, as to avoid that the initial chimera would affect the responses. Note that the sequences had no pause between the chimeras (the ones used in the 'no pause' condition in Bhatara *et al.*, 2016).

Intensity contrasts were obtained by amplifying every other chimera in the sequence by either 2, 4, 6 or 8 dB. Duration contrasts were obtained by lengthening every other chimera in the sequence with either 50, 100, 150 or 200 ms. For each sequence there were two prominence variants; one variant started with the weak chimera (either soft or short) and the other variant started with the strong chimera (either loud or long). This was done, in addition to the white noise fading, to avoid biasing listeners' prosodic grouping choices by the prominence of the initial chimera in the sequence. In other words, listeners could not identify the actual start of the sequence. In control sequences (either high or low variability), there were no such intensity or duration contrasts between the chimeras. The high variability controls were selected randomly from the ones in Bhatara *et al.* (2016). For the low variability controls there was only one variant.

### C. Design

In total, 108 stimuli were presented to participants. Half of them had high variability, and the other half had low variability. For each level of variability, 6 control, 24 intensity and 24 duration sequences were presented. For each acoustic cue, half of the sequences started with weak prominence, and the other half started with strong prominence. See Table II for an overview of the number of stimuli in each experimental condition.

TABLE II. Overview of the total number ($N$) of stimuli (108) broken down by the experimental conditions *variability*, *acoustic contrast*, *initial chimera* and *contrast level*

| Variability | $N$ | Acoustic contrast | $N$ | Initial chimera | $N$ | Contrast level | $N$ |
|---|---|---|---|---|---|---|---|
| High | 54 | Control | 6 | - | 6 | - | 6 |
| | | Intensity | 24 | Strong | 12 | 2 dB | 3 |
| | | | | | | 4 dB | 3 |
| | | | | | | 6 dB | 3 |
| | | | | | | 8 dB | 3 |
| | | | | Weak | 12 | 2 dB | 3 |
| | | | | | | 4 dB | 3 |
| | | | | | | 6 dB | 3 |
| | | | | | | 8 dB | 3 |
| | | Duration | 24 | Strong | 12 | 50 ms | 3 |
| | | | | | | 100 ms | 3 |
| | | | | | | 150 ms | 3 |
| | | | | | | 200 ms | 3 |
| | | | | Weak | 12 | 50 ms | 3 |
| | | | | | | 100 ms | 3 |
| | | | | | | 150 ms | 3 |
| | | | | | | 200 ms | 3 |
| Low | 54 | Control | 6 | - | 6 | - | 6 |
| | | Intensity | 24 | Strong | 12 | 2 dB | 3 |
| | | | | | | 4 dB | 3 |
| | | | | | | 6 dB | 3 |
| | | | | | | 8 dB | 3 |
| | | | | Weak | 12 | 2 dB | 3 |
| | | | | | | 4 dB | 3 |
| | | | | | | 6 dB | 3 |
| | | | | | | 8 dB | 3 |
| | | Duration | 24 | Strong | 12 | 50 ms | 3 |
| | | | | | | 100 ms | 3 |
| | | | | | | 150 ms | 3 |
| | | | | | | 200 ms | 3 |
| | | | | Weak | 12 | 50 ms | 3 |
| | | | | | | 100 ms | 3 |
| | | | | | | 150 ms | 3 |
| | | | | | | 200 ms | 3 |

### D. Setup and procedure

The experiment was run using PsyToolkit (Stoet, 2010; Stoet, 2017), which generates html pages for each stimulus. For each auditory stimulus, which was played automatically, two pictures were displayed. Each picture consisted of two vertical bars; one short and one long, displayed next to each other (Figure 1). In one picture, the short bar appeared on the left and the long bar on the right (short-long; corresponding to iambic perception), whereas in the other picture the long bar appeared on the left and the short bar on the right (long-short; corresponding to trochaic perception). Participants' task was to listen to the stimulus and click on the picture that corresponded with how they perceived the grouping. Participants were instructed to give an answer as soon as they could, that is, without having to wait until the stimulus had been fully played. Once participants had made their choice, their answer was saved and a 500 ms pause occurred before automatically playing the next stimulus and re-displaying the respective pictures. The two pictures were displayed in two orders; iamb-left, trochee-right and vice versa, which was determined randomly at the start of the experiment for each participant (43.7% and 56.3% respectively). The display order did not change during the experiment.

Before the start of the experiment, participants were asked to report which languages they spoke at a native level to assess their multilingualism. Thereafter, they received instructions about the experimental task in their native language. Some Akan participants were given additional instructions in English. After the first instructions they completed a training round consisting of four stimuli with the most extreme acoustic contrasts from the low variability set: either 200 ms for duration or 8 dB for intensity, each of them in both orders (strong first, weak first). This was done to provide participants with the stimuli that were hypothesized to be the clearest acoustically, in order to make their choice for iamb or trochee the easiest. Note that with more subtle acoustic contrasts, potentially inaudible to participants, the task may not have been immediately clear to them.

For the variability condition, each participant heard the stimuli in one of two block orders: either high-low or low-high. Within each block order, the order of the stimuli was randomly determined for each participant at the start of the test session. For Papuan Malay and German, the experiment was run in online mode, thus collecting the responses on a web-server. For Akan, the experiment was run in offline mode due to an unstable internet connection. Responses were therefore collected locally on the experiment computer. The experimental procedure was otherwise identical for all three experiments (i.e., for each language). Similar laboratory settings were created for all three experiments. That is, participants carried out the task in a room without background noises or distractions, and used headphones. For each stimulus, the block order, picture display order, name of stimulus wave-file (consisting of: variability, cue, initial chimera, contrast level), picture chosen and reaction time relative to the start of the stimulus were saved.

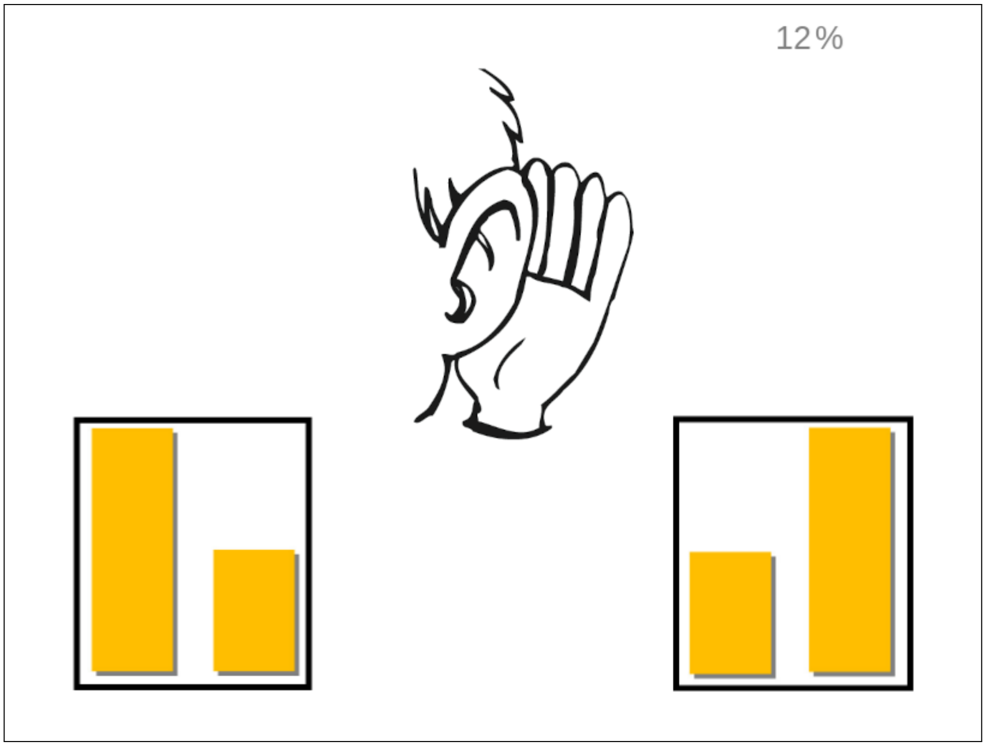


FIG. 1. Screenshot of the experiment displaying long-short bars on the left (trochaic) and short-long bars on the right (iambic).

### E. Statistical analysis

The statistical analyses were run in two steps. First, modeling was done per language to test the effects of several factors on participants' responses against chance level. This was done as a pre-assessment to obtain the factors that had a significant effect on the responses. Second, a final model for participants' responses was constructed including the relevant factors obtained in the first step. The results of the first step are discussed in this section. The main results obtained from the final model are discussion in the results section (III).

Generalized linear mixed model (GLMM) analyses were run on the binary responses (0 for iambs, 1 for trochees) using the `lme4` package (Bates *et al.*, 2015). First, four models per language were run to check for effects against chance level. This was done using the explicit syntax that removes the intercept (after which chance level is reached when $\beta$=0): `response ~ -1 + factor ...`). Each model had a single different fixed factor, either *cue* (successive differences contrast coded, three levels in the order: intensity, control, duration), *variability* (treatment coded, two levels: low, high), *sequence order* (successive differences contrast coded, three levels in the order: strong first, control, weak first) or *block order* (treatment coded, two levels: high first, low first). In each of the four models participant and item were random intercepts. These models were used to select which factors would be included in the final model.

TABLE III. Results of the GLMMs against chance level ($\beta$=0) per factor and language

| Factor | level | Papuan Malay | Akan | German |
|---|---|---|---|---|
| cue | control | $\beta$=-0.08, $SE$=0.17, $z$=-0.49, n.s. | $\beta$=0.07, $SE$=0.16, $z$=0.46, n.s. | $\beta$=0.70, $SE$=0.24, $z$=2.97, $p$ <0.01 |
| | duration | $\beta$=-0.25, $SE$=0.11, $z$=-2.23, $p$ <0.05 | $\beta$=-0.27, $SE$=0.09, $z$=-3.06, $p$ <0.01 | $\beta$=-0.69, $SE$=0.13, $z$=-5.35, $p$ <0.001 |
| | intensity | $\beta$=0.01, $SE$=0.11, $z$=0.06, n.s. | $\beta$=0.20, $SE$=0.09, $z$=2.33, $p$ <0.05 | $\beta$=0.86, $SE$=0.13, $z$=6.49, $p$ <0.001 |
| variability | high | $\beta$=0.00, $SE$=0.10, $z$=-0.01, n.s. | $\beta$=0.12, $SE$=0.08, $z$=1.49, n.s. | $\beta$=0.18, $SE$=0.15, $z$=1.17, n.s. |
| | low | $\beta$=-0.27, $SE$=0.11, $z$=-2.41, $p$ <0.05 | $\beta$=-0.24, $SE$=0.10, $z$=-2.39, $p$ <0.05 | $\beta$=0.03, $SE$=0.23, $z$=0.13, n.s. |
| seq. order | control | $\beta$=-0.09, $SE$=0.19, $z$=-0.46, n.s. | $\beta$=0.09, $SE$=0.19, $z$=0.48, n.s. | $\beta$=0.71, $SE$=0.36, $z$=1.96, $p$ <0.05 |
| | strong first | $\beta$=-0.12, $SE$=0.11, $z$=-1.08, n.s. | $\beta$=0.09, $SE$=0.10, $z$=0.91, n.s. | $\beta$=0.03, $SE$=0.18, $z$=0.16, n.s. |
| | weak first | $\beta$=-0.10, $SE$=0.11, $z$=-0.89, n.s. | $\beta$=-0.12, $SE$=0.10, $z$=-1.27, n.s. | $\beta$=0.12, $SE$=0.18, $z$=0.68, n.s. |
| block order | high first | $\beta$=-0.16, $SE$=0.14, $z$=-1.10, n.s. | $\beta$=0.09, $SE$=0.09, $z$=0.94, n.s. | $\beta$=0.14, $SE$=0.16, $z$=0.86, n.s. |
| | low first | $\beta$=-0.07, $SE$=0.12, $z$=-0.60, n.s. | $\beta$=-0.11, $SE$=0.10, $z$=-1.15, n.s. | $\beta$=0.14, $SE$=0.16, $z$=0.85, n.s. |

The results of the individual GLMMs against chance level (Table III) per factor and per language show significant ITL-conform effects of cue (PMY: duration, AKA: duration and intensity, DEU: control, duration, and intensity). Second, effects of variability were found for Papuan Malay (low) and Akan (low). Third, an effect of sequence order was found, but only for the control items in German, and not for the sequences that started with a strong or weak prominence in any of the languages. Given this limited effect of sequence order, this factor was not included in the final model (especially sine we verified that including it did not change the other effects). Fourth, block order did not have an effect and was also not included in the final model. Lastly, note that the factor *contrast level* was not included, as it led to a rank-deficient model, which was unable to obtain the results of all (interacting) other factors. The results for the contrast levels are given separately in the next section.

The final model thus included the factor *language* comparing Papuan Malay and Akan against German (successive differences contrast coded, three levels in an order that ensured comparison against German for both other languages: Papuan Malay, German, Akan). The three-way nesting of *language*, *variability* and *cue* were fixed factors, participant and item were included as random intercepts (model was optimized for convergence): `glmer(response ∼ lg / var / cue + (1|pp) + (1|item), df, contrasts = list(lg=contr.sdif,cue=contr.sdif),family = binomial, control = glmerControl(calc.derivs=FALSE))`. The final model was run on the responses collected for all three languages together.

Note that a variant of this model, with the position of the factors *language* and *cue* swapped in the formula, was also run to assess the specific differences between the languages for each level of *cue* and *variability*. The results of this model are given in the appendix. The overall language differences were tested with Tukey pairwise comparisons using the `emmeans` package (Lenth, 2023) with all possible language contrasts: PMY-DEU, PMY-AKA and DEU-AKA. The results of the pairwise comparisons are reported in the following section.

## III. RESULTS

TABLE IV. Mean responses (0 for iambs, 1 for trochees) per language, variability and acoustic cue. Visualization in Figure 2.

| Language | Variability | Acoustic cue | $\mu$ response (sd) |
|---|---|---|---|
| Papuan Malay | high | Intensity | 0.49 (0.50) |
| | | Control | 0.48 (0.50) |
| | | Duration | 0.51 (0.50) |
| | low | Intensity | 0.51 (0.50) |
| | | Control | 0.48 (0.50) |
| | | Duration | 0.35 (0.48) |
| Akan | high | Intensity | 0.56 (0.50) |
| | | Control | 0.53 (0.50) |
| | | Duration | 0.50 (0.50) |
| | low | Intensity | 0.54 (0.50) |
| | | Control | 0.49 (0.50) |
| | | Duration | 0.34 (0.47) |
| German | high | Intensity | 0.66 (0.48) |
| | | Control | 0.65 (0.48) |
| | | Duration | 0.40 (0.49) |
| | low | Intensity | 0.75 (0.43) |
| | | Control | 0.69 (0.47) |
| | | Duration | 0.25 (0.43) |

The results of the final model (Figure 2, Table IV and Table V) showed a significant difference between German and Papuan Malay in overall more trochaic responses for the former than for the latter. Variability showed a trend in Papuan Malay, revealing fewer trochaic responses for items with low variability than for ones with high variability. Variability had an effect in Akan in the same direction: fewer trochaic responses for items with low variability than for ones with high variability. Regarding the effect of the duration cue compared to the control condition, we found that, for the high variability items, fewer trochaic responses for the duration items than for the control items in German; no such effects were found in Papuan Malay and Akan. For the low variability items, all three languages showed effects of duration: fewer trochaic responses for the duration items compared to the control items. Lastly, no effects were found comparing intensity items with control items in any language or variability condition.

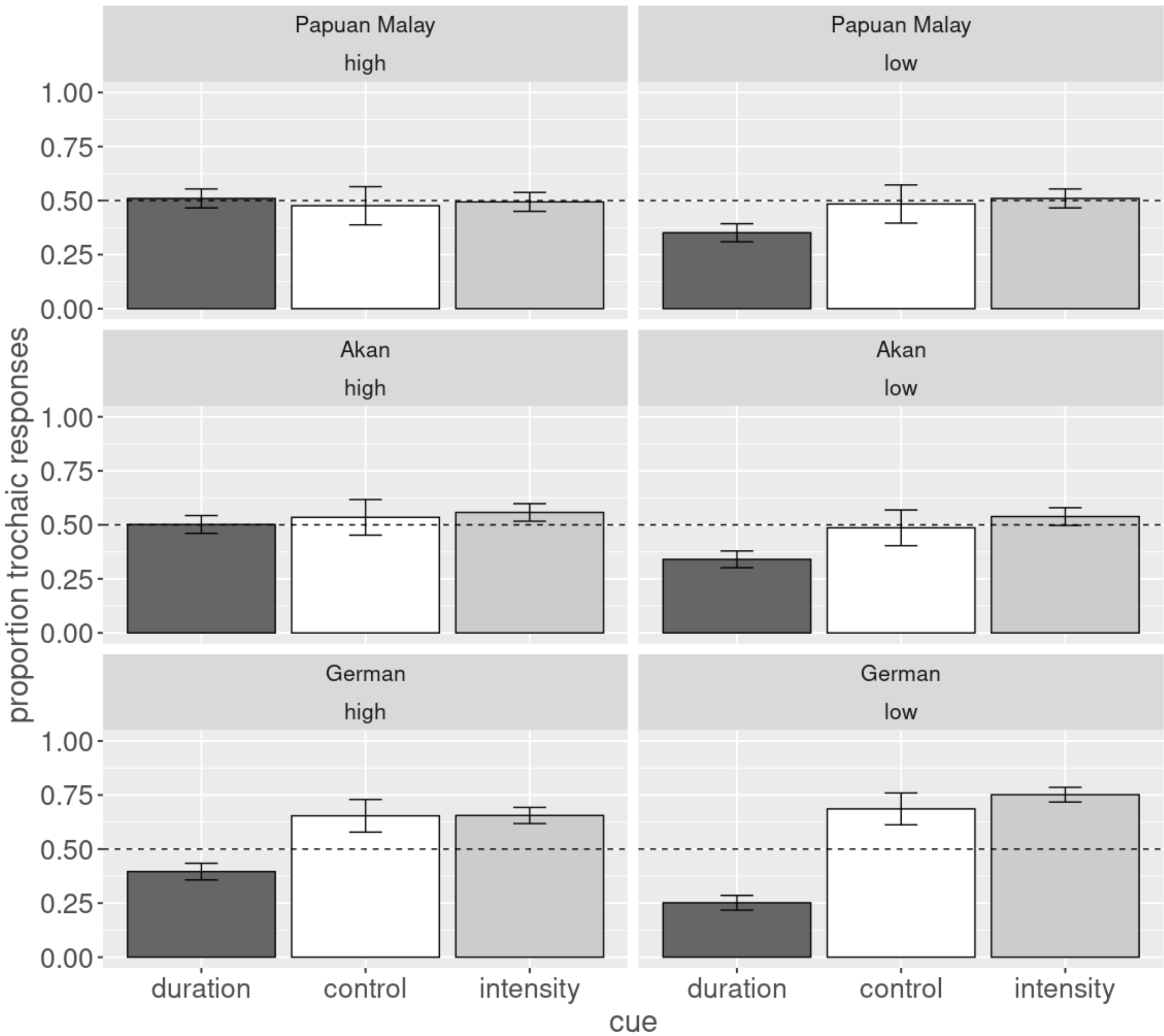


FIG. 2. Average responses (0=iambic, 1=trochaic) and error bars (interquartile ranges) per language, variability (high, low), and acoustic cue (dark grey = duration, white = control, light grey = intensity). Dashed line indicates chance-level responses. Values reported in Table IV.

TABLE V. Results of the final GLMM. PMY = Papuan Malay, AKA = Akan, DEU = German, lg = language, var = variability, ctl = control, dur = duration, int = intensity. Notation as {factor.level}, nesting indicated with colon.

| Factor | $\beta$ | $SE$ | $z$ | $p$ |
|---|---|---|---|---|
| (Intercept) | 0.13 | 0.06 | 2.18 | <0.05 |
| lg.DEU-PMY | 0.32 | 0.14 | 2.29 | <0.05 |
| lg.AKA-DEU | -0.17 | 0.13 | -1.24 | n.s. |
| lg.PMY : var.low | -0.19 | 0.12 | -1.63 | =0.10 |
| lg.DEU : var.low | -0.02 | 0.11 | -0.19 | n.s. |
| lg.AKA : var.low | -0.32 | 0.11 | -2.88 | <0.01 |
| lg.PMY : var.high : cue.ctl-int | -0.07 | 0.21 | -0.35 | n.s. |
| lg.DEU : var.high : cue.ctl-int | -0.01 | 0.20 | -0.04 | n.s. |
| lg.AKA : var.high : cue.ctl-int | -0.09 | 0.20 | -0.47 | n.s. |
| lg.PMY : var.low : cue.ctl-int | -0.11 | 0.25 | -0.43 | n.s. |
| lg.DEU : var.low : cue.ctl-int | -0.34 | 0.24 | -1.38 | n.s. |
| lg.AKA : var.low : cue.ctl-int | -0.21 | 0.24 | -0.91 | n.s. |
| lg.PMY : var.high : cue.dur-ctl | 0.14 | 0.21 | 0.66 | n.s. |
| lg.DEU : var.high : cue.dur-ctl | -1.09 | 0.20 | -5.50 | <0.001 |
| lg.AKA : var.high : cue.dur-ctl | -0.14 | 0.20 | -0.68 | n.s. |
| lg.PMY : var.low : cue.dur-ctl | -0.57 | 0.25 | -2.30 | <0.05 |
| lg.DEU : var.low : cue.dur-ctl | -1.93 | 0.24 | -7.92 | <0.001 |
| lg.AKA : var.low : cue.dur-ctl | -0.62 | 0.24 | -2.62 | <0.01 |

The pairwise comparisons (Table VI) showed significant differences between German and the other two languages, with no difference between Papuan Malay and Akan. From the model variant (Appendix), it can furthermore be observed that the language differences between German and the two other languages were found at all levels of the factors *cue* and *variability*.

TABLE VI. Results of the Tukey pairwise comparisons for *language*. PMY = Papuan Malay, AKA = Akan, DEU = German.

| Contrast | $\beta$ | $SE$ | $z$ | $p$ |
|---|---|---|---|---|
| PMY - DEU | -0.41 | 0.12 | -3.37 | <0.01 |
| PMY - AKA | -0.09 | 0.12 | -0.74 | n.s |
| DEU - AKA | 0.32 | 0.12 | 2.72 | <0.05 |

Lastly, because Bhatara *et al.* (2013) and Bhatara *et al.* (2016) analyzed contrast levels and found significant effects, we present descriptive results of the effects of contrast levels in the current experiment (as mentioned earlier, contrast level could not be fitted into the statistical model due to the reduced number of items and number of trials in each level), see Figure 3 for duration and Figure 4 for intensity. The results confirm the cue effects reported above. For duration, in the high variability condition, we observe a visual effect of contrast level in German only, while in the low variability condition, such a visual effect of contrast level is most clear in German, but also to a lesser extent in Akan and even less so in Papuan Malay. For intensity, no clear trends are observed.

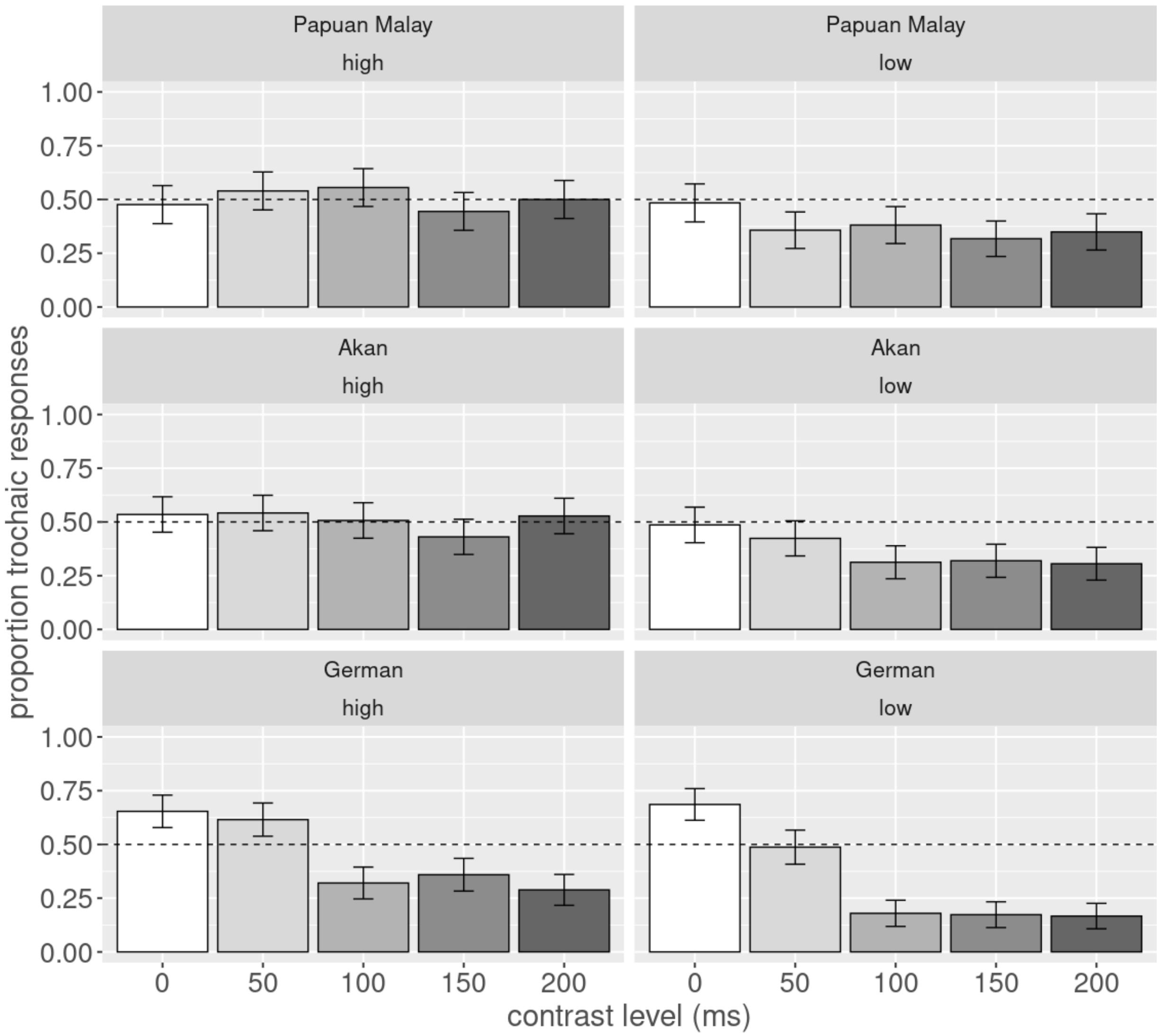


FIG. 3. Average responses (0=iambic, 1=trochaic) and error bars (interquartile ranges) per language, variability (high, low), and contrast level for duration with increasing darkness indicating increasing acoustic contrasts (0 = control). Dashed line indicates chance-level responses.

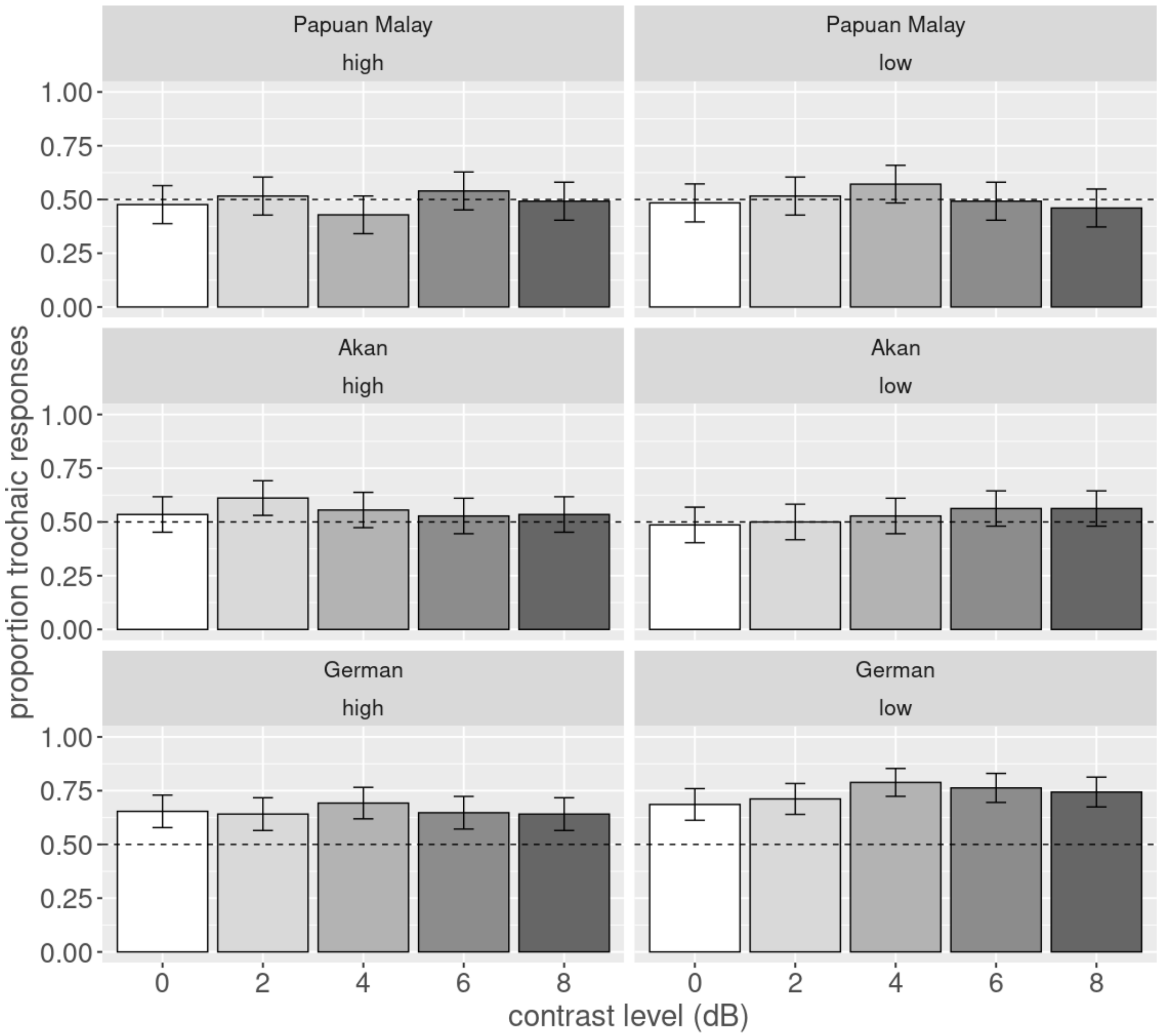


FIG. 4. Average responses (0=iambic, 1=trochaic) and error bars (interquartile ranges) per language, variability (high, low), and contrast level for intensity with increasing darkness indicating increasing acoustic contrasts (0 = control). Dashed line indicates chance-level responses.

## IV. DISCUSSION

The goal of this study was to explore whether speakers of two understudied languages, Papuan Malay and Akan would show rhythmic grouping effects as predicted by the ITL, and to start understanding how these ITL effects might be modulated by their word and phrase prosodic properties. Our expectation was that they would show more consistent rhythmic grouping when hearing low- than when hearing high-variability sequences. For Papuan Malay, we furthermore expected trochaic grouping across conditions, given that the language has fixed penultimate stress mainly cued by duration. The main results from this study show that listeners of Papuan Malay, Akan and German give more iambic responses to duration-contrasted low-variability sequences than to control sequences, which is in line with the ITL. Only German listeners, however, do so for duration-contrasted high-variability sequences (Figure 2 and Table IV). Participants were not found to give more trochaic responses to intensity-contrasted sequences than control sequences in any of the language groups or variability conditions. Although there was an intensity effect for Akan when comparing the responses for intensity contrasted sequences to chance (Table III), that effect was not confirmed when comparing responses to control sequences (Table V). This lack of an intensity effect likely has different causes in the three languages, as further discussed below. Note that this pattern of results puts limits on the extent to which our results provide insight into the prosodic structure of the languages that were tested (as hinted at in Section I D). That is, there appears no straightforward connection between the extent to which listeners were sensitive to the ITL and particular prosodic characteristics of their language. Nevertheless, this study shows that language background has an influence on perception. Thus, there was an effect of variability in Papuan Malay and Akan, but not in German, and an overall trochaic bias only in German. Together, these outcomes conform to the predictions of the ITL for duration (Table I), while providing no support at first glance for intensity-based grouping (see more on this below). Importantly, they also confirm cross-linguistic variability in the use of the ITL. In the following, we discuss in more detail the results for each language separately, starting with German for which we had previous data.

### A. German

The current outcomes for German largely confirm what has been found in previous studies (e.g., Bhatara *et al.*, 2013; Bhatara *et al.*, 2016). First, an ITL-conform sensitivity to duration is replicated. Second, participants responded in similar ways to intensity-contrasted and control sequences, leading to a lack of effect when comparing these two conditions. However, the finding of a trochaic bias in German establishes that this null effect is not due to a lack of sensitivity to intensity contrasts, but rather due to a strong tendency in German to group into trochees (e.g., Röttger *et al.*, 2012). Note that this trochaic bias had been previously found, both in Experiment 1 in Bhatara *et al.* (2013) testing duration and intensity (though not in their Experiment 2 testing duration and pitch), and in Bhatara *et al.* (2016) for control items, in particular with low acoustic variability. Hence, our results confirm German adults' ITL-conform sensitivity to both duration and intensity. Moreover, no effect of variability was found in German, as participants were as good with the high-variability sequences as with the low-variability ones. Sensitivity to the high-variability sequences is taken as evidence of strong use of the ITL in this language. The reasoning is that with high amounts of acoustic variability, listeners are challenged to perceive the ITL-relevant acoustic contrasts in duration and intensity. The high-variability sensitivity in German is further supported by the results for the contrast levels (Figure 3 and Figure

4). This sensitivity is also supported by the results of our additional model showing that German listeners responded more ITL-conform than both Papuan Malay and Akan ones. This is true both for intensity and duration, and they also show a stronger trochaic bias with control sequences, both for low- and high-variability sequences. This higher ITL-conformity in German than in these two languages could be linked to the fact that German has variable word stress. That is, experience with variable stress would lead to high sensitivity to prosodic cues in listeners (for word stress discrimination data, see Dupoux *et al.*, 1997; Peperkamp *et al.*, 2010) compared to no experience with word stress, or highly predictable word stress. Although the word stress distribution is variable within a three-syllable window, the trochaic pattern is nevertheless predominant in German (e.g., Gordon and Roettger, 2017). This was interpreted as the cause of hearing trochees when listening to the control sequences in which no duration/intensity variation was present (Bhatara *et al.*, 2013; Bhatara *et al.*, 2016). Note that although we interpret our findings in relation to word stress properties of German, future studies could explore the contribution of German phrase-level prosody in modulating ITL effects.

### B. Papuan Malay

The Papuan Malay results show that duration is used to group sequences into ITL-conform iambs. However, these effects are less strong than in German. This is attested both by significant differences in performance between the two languages, and by the effect of sequence variability for duration sequences in Papuan Malay, which was interpreted in prior research as evidence of decreased sensitivity (Bhatara *et al.*, 2016). Second, Papuan

Malay speakers perform similarly for intensity and control sequences, at chance level in both cases, a pattern demonstrating failure to use intensity in sequence grouping. The results also fail to establish a trochaic bias in response, as formulated in Section I D, including on the control sequences. Overall, this pattern of results suggests some conformity to the ITL, limited to duration (see also Figure 3 and Figure 4). This outcome is more similar to what has been found for French, a language generally analyzed as lacking word stress, than to what has been found for German, a language with variable word stress. Note that even though Papuan Malay shows similarities to French, the type of word prosodic pattern is different in both languages. Papuan Malay word stress is variable between penultimate and ultimate positions based on segmental content of syllables, whereas in French the ultimate syllable invariably receives the highest prominence at a post-lexical level. The current findings have implications for our understanding of the prosodic properties of Papuan Malay. Recall that word stress distribution is much less variable in Papuan Malay than in German, with approximately a 90/10% division between penultimate/ultimate word stress, making Papuan Malay a language with very regular word stress. As found for word stress pattern discrimination (e.g., Peperkamp *et al.*, 2010) and for the ITL in the case of a language with no word stress (Bhatara *et al.*, 2013, Bhatara *et al.*, 2016), this strong word stress pattern regularity appears to also lower overall sensitivity to prosodic cues for the ITL. Related to this observation, it is interesting that Papuan Malay listeners were more likely to hear iambs cued by duration differences. This result fits previous perception research in which Papuan Malay listeners were found to be more sensitive to acoustic cues to the irregular (ultimate word stress) pattern than ones to the regular pattern (Kaland, 2020). With a highly regular word stress pattern, it could indeed be the case that a sensitivity to the deviant pattern leads to the most efficient perception strategy (see also Sulpizio and McQueen, 2012; Domahs *et al.*, 2012). Another explanation may be found in a higher sensitivity to right-edge dominance at the phrase level, consistent with the findings on the production of phrase final tonal movements (Kaland and Baumann, 2020, Kaland *et al.*, 2023). Yet, it should be noted that the right-edge prominence did not affect the grouping preferences of Papuan Malay listeners for intensity.

### C. Akan

The results for Akan follow a very similar pattern to those for Papuan Malay. First, given the lower performance relative to German participants and the effect of variability, they provide evidence of weak sensitivity to duration cues for ITL-conform grouping. Second, no clear evidence of sensitivity to the intensity cue was found. Note that the small effect of intensity against chance level (Table 3) was not confirmed when comparing against the control condition (Table 4). These findings are interesting given the presumed lack of word stress and the lack of direct quantitative studies on word stress in Akan. It is furthermore interesting to observe that Akan was the only language for which intensity contrasts led to increasing trochaic responses when they were larger (low variability sequences in Figure 4), whereas Papuan Malay and German showed the highest number of trochaic responses for the 4 dB contrast level. It is unclear how these patterns should be interpreted, but they might explain the small intensity effect (Table 3). Taken together, based on our interpretation of how the word stress structure modulates sensitivity to prosodic cues, the present results would be in line with assumptions that either Akan does not have word stress, contrary to anecdotal claims in some studies (Dolphyne, 1986; Kügler, 2016), or Akan has a very regular word stress system. It should be noted, though, that these are only speculative suggestions and more direct investigations will be needed to clarify the role of word stress, and phrase-level prosody, in Akan.

### D. Bilingualism

Coming now to the issue of bilinguals, recall that most of our participants reported speaking additional languages beyond Papuan Malay, Akan or German. Although we were not able to collect precise information about the participants' age of acquisition of these additional languages, it is highly likely that the native listeners of Akan in our sample were mostly from-birth multilinguals (see Bodomo *et al.*, 2010; Omane *et al.*). Little is known about word stress in Ghanaian languages, but Ghanaian English, a language that 22 of the 24 participants reported to speak, has recently been shown to have variable word stress (Lomotey, 2018), with pitch, duration and intensity being used as cues to mark prominence (Lomotey and Osei-Bonsu, 2022). The effects of bilingualism reported in previous work (e.g., Boll-Avetisyan *et al.*, 2017; Boll-Avetisyan *et al.*, 2020) thus raise the question of why experience with Ghanaian English word stress did not lead to more ITL-conform rhythmic grouping preferences in Akan multilinguals. To answer this, it would have been necessary to obtain information about the participants' age of immersion with their additional languages and the word stress systems these languages have. This would have been beyond the scope of the present study, and will need to be explored in future research. It is nevertheless possible that the high degree of multilingualism in the Akan participants contributed to the challenge in interpreting their results in the context of the Akan prosodic system (as speculated above).

### E. Conclusion and future directions

In conclusion, the results of the current study reconfirm that the extent to which the effects of the ITL hold cross-linguistically depends largely on the prosodic system of the language under investigation (e.g., Bhatara *et al.*, 2013; Crowhurst, 2020). Our findings confirm German speakers' clear sensitivity to both the duration and intensity cues, and bring new data on two under-researched languages, Papuan Malay and Akan, establishing weaker sensitivity to the sole duration cue in those languages. While duration-based iambic grouping has been found less often than intensity- or pitch-based grouping in previous cross-linguistic research, and has been speculated to be harder to learn (Crowhurst, 2020), the current finding of stronger duration-based effects in two understudied languages highlights the importance of further expanding the range of languages tested on ITL-based grouping in the future.

Our findings are based on the use of non-speech stimuli, because they allowed us to test all languages with the same stimuli, and because prior studies on German and French had found similar effects with linguistic stimuli and the current non-speech ones. Yet, a follow-up of this study could verify that similar effects would be found in Papuan Malay and Akan using speech stimuli, and could also manipulate the stimuli in more natural ways, for example by coupling the changes in duration and intensity (and possibly f0), as found in natural speech productions, in order to improve the representativeness of the results for the specific languages under investigation. Such a simultaneous manipulation was used in Arvaniti and Jeon (in press) testing British English, Greek and Korean listeners. That study found weak confirmation in the first two languages and a trochaic bias for the latter. This finding is particularly interesting in the light of the German trochaic bias that we ascribe to word prosodic (stress) characteristics of German. Korean is analyzed as a stress-less language and was hypothesized to show a strong iambic bias (Arvaniti and Jeon, in press). Apart from other differences in the design and interpretation of the results between that study and ours, it remains an open question exactly how and why these grouping biases occur. Note also that the prosodic properties of Papuan Malay and Akan did not allow us to test whether the ITL relates to grouping or prominence marking, so our study does not contribute to this recent debate (Wagner, 2022; Moghiseh *et al.*, 2023, for related data on English). Last but not least, we emphasize that further studies on a larger range of typologically different languages will be needed to continue specifying the extent to which the ITL is used cross-linguistically, and how it relates to the word and phrasal properties of these languages.

## V. ACKNOWLEDGEMENTS

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## VI. AUTHOR DECLARATIONS

The authors have no conflicts of interest to declare. The experiments reported in this paper have been conducted following protocols and informed consent practices in compliance with the Helsinki Declaration, with approval of the Papuan Malay Bible Translation Team and the Faculty of Arts and Humanities of the University of Cologne. Informed consent was obtained from each individual participant prior to participation.

## VII. DATA AVAILABILITY

Stimuli, data and other supplementary materials are available at https://osf.io/j6srk/.

## VIII. REFERENCES


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## APPENDIX

TABLE VII. Results of the model variant of the final GLMM. PMY = Papuan Malay, AKA = Akan, DEU = German, lg = language, var = variability, ctl = control, dur = duration, int = intensity. Notation as {factor.level}, nesting indicated with colon. Formula:

```
glmer(response ~ cue / var / lg + (1|pp) + (1|item), df, contrasts
= list(lg=contr.sdif,cue = contr.sdif),family = binomial, control =
glmerControl(calc.derivs=FALSE))
```

| Factor | $\beta$ | $SE$ | $z$ | $p$ |
|---:|---:|---:|---:|---:|
| (Intercept) | 0.13 | 0.06 | 2.18 | <0.05 |
| cue.ctl-dur | -0.06 | 0.13 | -0.46 | n.s. |
| cue.int-ctl | -0.36 | 0.13 | -2.85 | <0.01 |
| cue.int : var.low | 0.15 | 0.09 | 1.71 | =0.09 |
| cue.ctl : var.low | -0.01 | 0.20 | -0.03 | n.s. |
| cue.dur : var.low | -0.68 | 0.09 | -7.52 | <0.001 |
| cue.int : var.high : lg.DEU-PMY | 0.69 | 0.16 | 4.38 | <0.001 |
| cue.ctl : var.high : lg.DEU-PMY | 0.75 | 0.27 | 2.83 | <0.01 |
| cue.dur : var.high : lg.DEU-PMY | -0.48 | 0.16 | -3.08 | <0.01 |
| cue.int : var.low : lg.DEU-PMY | 1.10 | 0.16 | 6.78 | <0.001 |
| cue.ctl : var.low : lg.DEU-PMY | 0.87 | 0.27 | 3.23 | <0.01 |
| cue.dur : var.low : lg.DEU-PMY | -0.49 | 0.16 | -3.00 | <0.01 |
| cue.int : var.high : lg.AKA-DEU | -0.43 | 0.15 | -2.83 | <0.01 |
| cue.ctl : var.high : lg.AKA-DEU | -0.51 | 0.26 | -2.00 | <0.05 |
| cue.dur : var.high : lg.AKA-DEU | 0.44 | 0.15 | 2.96 | <0.01 |
| cue.int : var.low : lg.AKA-DEU | -0.98 | 0.16 | -6.28 | <0.001 |
| cue.ctl : var.low : lg.AKA-DEU | -0.86 | 0.26 | -3.32 | <0.001 |
| cue.dur : var.low : lg.AKA-DEU | 0.45 | 0.16 | 2.81 | <0.05 |