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Reading at the speed of speech: Alignment of eye-movement sampling in reading with the speech production rate.

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Abstract

Across languages, the speech signal is characterized by a predominant modulation of the amplitude spectrum at ~4-5 Hz, reflecting the processing of linguistic information chunks (i.e., syllables or words) approximately every 200 ms. Interestingly, ~200 ms is also the typical duration of eye fixations during reading. Prompted by this observation, we estimated the frequency at which German readers sample text, and demonstrate that they read sentences at a rate of ~5 Hz. We then examined the generality of this finding in a meta-analysis including 14 languages. We replicated the empirical result for German and observed that fixation-based sampling frequencies vary across languages between 3.9 and 5.2 Hz. Remarkably, we identified a systematic rate reduction from easy to difficult writing systems. Finally, we directly investigated in a new experiment the association between speech spectrum and eye-movement sampling frequency at a person-specific level and found a significant correlation. Based on this evidence, we argue that during reading, the rate of our eye movements is tuned to supply information to language comprehension processes at a preferred rate, coincident with the typical rate of speech.

Significance Statement

Across languages, speech is produced and perceived at a rate of ~4-5Hz. When listening to speech, our brain capitalizes this temporal structure to segment speech. We show empirically that while reading our eyes sample text at the same rate, and generalize this finding in a meta-analysis to 14 languages. Reading rates vary between 3.9 and 5.2Hz – i.e., within the typical range of the speech signal. We demonstrate that the difficulty of writing systems underpins this variance. Lastly, we also demonstrate that the speech rate between persons is correlated with the rate at which their eyes sample text. The speech rate of spoken language appears to act as a driving force for the voluntary control of eye movements during reading.

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Introduction

When we listen to speech, our brain entrains to the frequency at which linguistic information enters the auditory system. For example, when spoken words are presented at a consistent rate of 4 Hz, the frequency spectrum of simultaneously measured electrophysiological brain activity shows a prominent peak at around 4 Hz (1), suggesting that the temporal structure of the linguistic stimulus drives neural processes in the auditory and language systems. Natural speech – which is considerably more variable in the time domain – produces characteristic frequency correlates in the theta-band of human electrophysiological brain activity, i.e., between 4 Hz and 8 Hz (2). This, in turn, is consistent with the demonstration that independent of language, the amplitude modulation spectrum (3) of speech peaks at a frequency of 4.3 to 5.5 Hz (4, 5). These findings derive from corpora of spoken language, and suggest that roughly every 200 ms, informative speech chunks (e.g., syllables or words (6, 7)) are produced by the speaker (4, 5) and thus processed by the brain when listening to speech (8). The linguistic relevance of the amplitude modulation spectrum is demonstrated by observations of reduced speech intelligibility when manipulating the speech signal, e.g., by noise (3).

Here we investigate whether the temporal structure of processing written language (i.e., reading) is related to the speed of speech, i.e., the rate at which the language system processes spoken content. Interestingly – and, we hypothesize, not accidentally – the duration of a typical eye-fixation during reading is very similar to the typical speech rate, i.e. between around 200 ms for orthographically transparent languages like German or Finnish (9, 10) and 250 ms for character-based writing systems like Chinese (10, 11).

Abundant research has used eye movement recordings to study reading with high temporal resolution. This work explores the influence of various characteristics of the perceived words (such as their length, frequency of occurrence, or predictability given the sentence context; for a review see (11), but also group comparisons, for example between dyslexic and typically developing readers (12, 13). Among various measures that can be derived from eye movement recordings, including saccade length or word skipping rate (11), timing measures like the *duration of fixations* are the most frequently examined variables and are generally considered precise markers of reading speed. However, unlike in other research fields (e.g., attention, (14)), eye-movements in natural reading have so far not been investigated from a frequency perspective. While the observed fixation durations suggest that written text may be sampled in a very similar time domain as speech perception, the sampling rate of reading has not been explicitly examined. Consequently, important open questions emerge, including (i)

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whether written language is sampled at similar frequencies as spoken language, (ii) whether the eye's sampling frequency for reading differs to non-linguistic tasks, (iii) whether the sampling rate of reading differs between languages or writing systems, and (iv) whether the speed of reading is directly related to a given person's speech rate.

Here we aim to answer these foundational questions. In a first step, the sampling frequencies of 50 native speakers of German were determined while reading sentences as well as during a non-linguistic control task, building on established empirical data (15). To determine the generality of the results and investigate possible cross-linguistic differences in the sampling rate of reading, we next conducted a meta-analysis of 124 original studies from 14 different languages. To this end, we implemented a frequency analysis for fixation durations extracted from published eye tracking studies of natural (sentence or paragraph) reading. Finally, we determined the eye-movement sampling frequencies and the speech production rates of 48 non-native learners of German, which allowed us to directly correlate the rates of reading and speech production. Both experiments and the meta-analytic results support the hypothesis of a sampling rate of reading that has an upper limit at around 5 Hz (i.e., in the same range of the language independent speech rate), which can be reduced by the demands of a more complex writing system (e.g., character vs. alphabetic based scripts) or by low language skill (e.g., in second language learners).

Experimental comparison of reading and scanning rates

50 healthy volunteers read sentences from the Potsdam Sentence Corpus (144 sentences presented as a whole; 1,138 words; see Ref. (9)) while movements of their right eye were tracked at a resolution of 1,000 Hz. As a non-linguistic control task, participants scanned 'z-strings' that were constructed by replacing all letters of the sentence stimuli by the letter 'z'. For example, the sentence "*Ein berühmter Maler hat sich selbst ein Ohr abgeschnitten" (A famous painter cut off his own ear.)* was transformed to "*Zzz zzzzzzzzz Zzzzz zzz zzzz zzzzzz zzz Zzz zzzzzzzzzzzzz*." (See Materials and Methods for details, and Ref. (15) for a previous publication of this dataset). Previous research (15–17) established that scan-path parameters (i.e., the number of fixations) were largely similar between sentences and z-strings, which qualified them as control stimuli for reading experiments. To underscore this, we here explicitly tested for the equivalence (18, 19) of important scan path characteristics, i.e., the number of fixations by line and the number of re-fixations per word (equivalence bounds set to ±.5 standardized mean difference, following Ref. (18)). We found significant equivalence between reading and scanning with respect to the mean number of fixations (reading: 8.3 fixations;

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scanning: 8.0 fixations; indicated by a significant equivalence test: *t*(49) = 3.1; p = .002) and re-fixation probabilities (reading: 28 %; scanning: 32 %; *t*(49) = 1.8; p = .039). These results suggest comparable scan paths in reading and z-string scanning. However, when separating re-fixation probabilities between intra- and inter-word regressions, we found a significant difference between reading and scanning (inter-word re-fixations: reading: 10 %; scanning: 4 %; *t*(49) = 5.3; p < .001; intra-word re-fixations: reading: 18 %; scanning: 28 %; *t*(49) = 4.5; p < .001). In the following analyses of sampling frequencies, we explicitly account for this difference in re-fixation behavior.

Fixation durations. After data preprocessing (leading to a removal of 3.1% of the data), we estimated the mean fixation duration separately for each participant and experimental condition. Figure 1a shows that fixation durations (presented here as subject-specific means) are shorter for reading than scanning (average: 197 ms vs. 249 ms, respectively; Effect size: 52 ms; Cohen's d = 1.57; *t*(49) = 11.1; p < .001). This has been reported previously for this dataset (15) and replicates earlier results for German (16), English (20), and French (17) in which fixation durations increased from reading to scanning between 38 and 42 ms.

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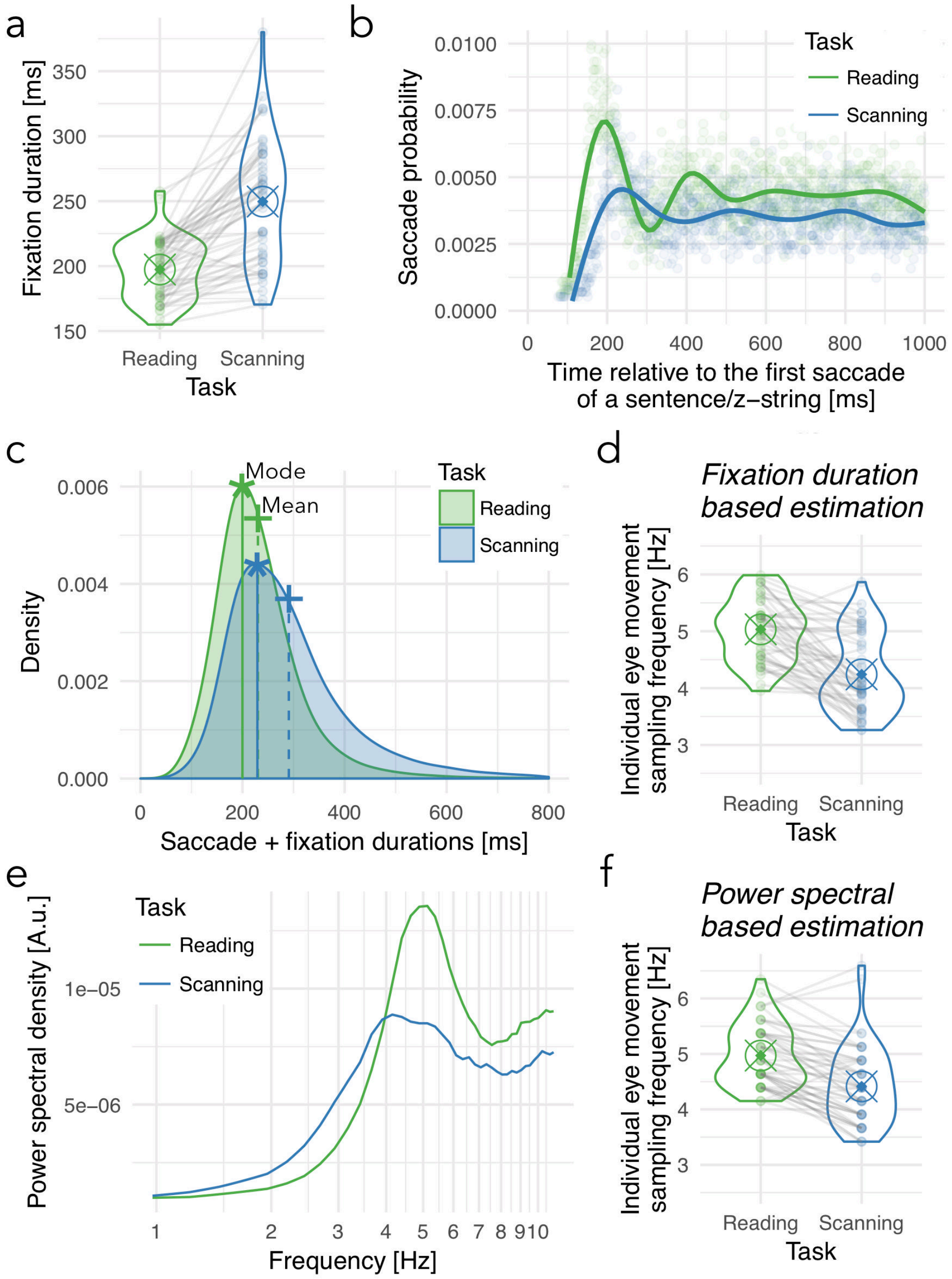

Figure 1. Reading-related sampling rates. (a) Subject-specific mean fixation durations from 50 participants (dots) and the overall mean (crossed circle) while reading sentences on the Potsdam sentence corpus (9) and scanning z-strings. Lines connect reading with z-string scanning data, per subject, to visualize effects at the single-subject level. Violin plot shows the distribution of individual means (Blue: Scanning; Green: Reading; similar in d and f). (b) Mean saccade probability (over all participants and stimuli, separated by task) relative to the first saccade of the sentence, with a non-linear regression line. (c) The sampling period t of one event is here defined as the duration of a fixation plus its preceding saccade. Displayed is the distribution of these sampling periods for sentence reading (green) and z-string scanning (blue), with estimated means (+ symbol and dashed lines) and modes (* symbol and solid lines). (d) Subject-specific mean sampling frequencies f (i.e., equals to 1/t) and the overall mean (crossed circle) based on the sampling periods shown in c. (e) Power-spectrum for reading and z-string scanning, estimated across all participants. (f) Individual peak frequencies estimated from individual power spectra and their mean (crossed circle). See Methods for details.

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Eye-movement sampling rate differs between reading and non-linguistic control task. As a first characterization of rhythmic eye movement patterns during reading, we plotted the saccade probability, relative to the time point of the first saccade of each stimulus sentence (Figure 1b; one probability value per sample; sampling rate 1,000 Hz). This analysis demonstrates distinct peaks visible at regular intervals, providing initial evidence that eye-movements follow a rhythmic structure in both reading and scanning, but – importantly – more pronounced and faster during reading. To quantitatively estimate the dominant sampling rate, we adopted two procedures: on the one hand, sampling rates were estimated from the fixation durations. Secondly, we also applied a classical frequency analysis. While we consider the former approach important because fixation durations are also the basis for the subsequent meta-analysis, the second approach allows us to evaluate the validity of the fixation duration-based frequency estimation.

To estimate sampling rates from fixation durations, we first added to each fixation duration (N = 112,547) the duration of the preceding saccade, to estimate the respective sampling period (i.e., the time from the start of a saccade to the start of the next), which we here denote *t*. Figure 1c shows the distribution of all sampling periods across all participants, separately for reading and z-string scanning. Note that the mode (solid line) – by definition – represents the predominant sampling period better than the mean (dashed line) for ex-Gaussian distributions which are typical for fixation durations (21) and reaction times (22). We then estimated an eye movement sampling frequency *f* for each participant and condition, by dividing 1 sec by the subject-specific mode of the sampling period in seconds. This analysis revealed a higher average sampling rate for reading relative to the control task, i.e., 5.0 Hz vs. 4.2 Hz, respectively (Figure 1d). This difference was significant (Cohen's d = -1.16; $t(49) = -8.2$; $p < .001$), and 45 out of 50 participants showed a numeric reduction of the sampling frequency from reading to scanning (grey lines in Fig. 1d). We find virtually the same pattern of effects when regressive saccades are removed from analysis (i.e., when analyzing only single fixation cases; Cohen's d = -1.0; t(49) = -6.9; p < .001; absolute values: 4.9 and 4.2 for reading and scanning) and when we restrict the analysis to inter-word re-fixations (Cohen's d = -0.8; t(48) = -5.5; p < .001; absolute values: 5.2 and 4.6 for reading and scanning, respectively; note no such cases were found in the scanning task of one participant). The sampling rate of reading and scanning, thus, is similar between forward-oriented and regressive eye movements ($r = 0.6$; $t(96) = 6.7$; $p < .001$).

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Finally, we reproduced this result with a canonical frequency analysis, which was implemented by estimating the power spectra of reading vs. z-string scanning. For each task, we created a time series starting with the first saccade of the first participant and ending with the last fixation of the final participant. This time series was set to 1 at the exact time of saccade onset, and 0 elsewhere (at the sampling rate of the eye tracker, i.e., 1,000 Hz). Subsequently, the power spectra of these task-specific event time courses were estimated via the Fourier Transform to visualize the periodic signal component across subjects (see Materials and Methods for details). Corroborating the results of the first analysis approach, a prominent peak was found at 5 Hz for reading and a somewhat less pronounced peak at around 4 Hz for scanning (Figure 1e). To compare the frequency analysis results for reading and scanning, we next estimated separate power spectra for each participant. Individual peaks were retrieved, averaged (Figure 1f), and submitted to a t-test. This analysis reproduces the sampling frequencies estimated from the mode of the fixation durations, with frequencies of 5.0 Hz and 4.4 Hz for reading and scanning, respectively (Cohen's d = -1.12; $t(49) = -7.9$; $p < .001$). There was a high correlation between the two analysis approaches (reading: $r = .80$; $t(48) = 9.3$; $p < .001$; scanning: $r = .62$; $t(48) = 5.5$; $p < .001$), which indicates a high validity of the sampling duration based frequency estimations. As a final control, we estimated the eye-movement sampling rate based on the mean fixation durations and found lower rates for reading (4.5 Hz) and scanning (3.7 Hz), indicating that a mean-based procedure is inadequate.

To summarize, A quantitative frequency-domain characterization of eye-tracking data shows that the predominant sampling frequency during reading in German, across participants, is found at ~5 Hz. This frequency representation of the reading process converges with the predominant modulation frequency of the speech signal between 4 and 5 Hz (4, 5) – which in turn has a clear reflection in the neuronal response to speech (2). We observed the ~5 Hz peak during reading using two different analysis strategies, i.e., when estimating sampling frequencies from saccade and fixation durations as well as when analyzing in the frequency domain the sequence of saccade events over time. Note that saccade onsets are the appropriate event for generating this time series, as they are the re-occurring event and can be measures with high accuracy (23). Attentive scanning of z-strings shows highly similar scan path characteristics in comparison to reading (16, 17), but a significantly lower sampling frequency, at ~4 Hz, convergent with findings from non-linguistic attentional reorienting tasks (14, 24). While z-string scanning produced longer mean fixation durations than reading, an analysis of the pupil response in the same dataset had indicated higher cognitive effort during reading (15). We interpret this dissociation between cognitive effort and reading time as evidence for the

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operation of additional cognitive processes beyond the perceptual and attentional mechanisms involved in scanning the stimuli. This may, e.g., involve reading-specific processes like grapheme-to-phoneme conversion, as well as linguistic processes like lexical-semantic access. Given that reading takes place at a higher rate despite being cognitively more demanding than the control task, and given the high degree of similarity to the dominant sampling rate of spoken language, we tentatively propose that the reading system may provide visual-orthographic information to our brain's higher-level linguistic processors at the same temporal rate at which they receive auditory speech. As such, the observed sampling rate of 5 Hz may reflect a cortical computation principle.

If the ~5 Hz sampling rate indeed represents the application of a more fundamental property of cortical computation to reading, it should generalize across languages and writing systems. Importantly, writing systems differ substantially between languages (10, 25), and even within writing systems, the mapping from orthography to meaning differs between languages (26). For example, the letter *a* in *cat* vs. in *ball* maps onto two different speech sounds in English, whereas it maps onto only one speech sound in the German translations of these words, i.e., *Katze* and *Ball.* This letter-to-sound correspondence strongly influences reading acquisition (27), so that among the alphabetic writing systems, opaque orthographies (i.e., writing systems with inconsistent letter-to-sound correspondence like English) are associated with lower reading accuracy during the first years of learning to read. Contrary to the claim of language-independent fixation durations, these differences between writing systems would be suggestive of cross-linguistic differences in the efficiency of reading. Recent experimental evidence like, e.g., the observation of longer fixation durations for Chinese as compared to Finnish or English (10), seems to support this prediction. Given that German is a relatively transparent and thus easy-to-process orthography among the alphabetic writing systems (e.g. 130 vs. 226 grapheme-to-phoneme rules for German and English, respectively; (26)), we conjectured that the empirically determined sampling rate of ~5 Hz may only be achieved when reading highly transparent orthographies like German. The sampling rate of 5 Hz, thus, may represent an upper bound for the sampling of written text during reading.

Beyond these differences between writing systems, languages also differ in other linguistic characteristics. For example, despite the rather consistent peak frequency across languages, the remaining cross-linguistic variation of the peaks of the amplitude modulation spectrum between languages (i.e., peaking between 4 and 5 Hz) may be computationally relevant. If eye movement sampling of written text were indeed causally related to language-

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specific rates of speech production and perception, we might expect a positive correlation across languages between the rates of eye movement sampling and the peak of the speech amplitude modulation spectrum. To test this prediction in a meta-analytic fashion, we extracted language specific peak frequencies of speech from Refs. (4, 5). Finally, languages also vary in the density of semantic information, i.e., linguistic information per syllable (28). Information density may indirectly, i.e., via the processing load associated with each piece of the input, also influence the rate of reading. To investigate the language generality of the 5 Hz sampling in reading and potential cross-linguistic influences, and to test the competing hypotheses discussed, we conducted a meta-analysis of 124 reading studies that measure eye movements in 14 different languages.

Cross-linguistic meta-analysis of reading rates

We compared the sampling frequency of reading in 14 different languages, based on 1,420 fixation duration estimates extracted from 124 studies published between 2006 and 2016. In addition to this cross-linguistic comparison, we examined (a) possible differences between character-based vs. alphabetic writing systems, (b) the effect of letter-to-sound correspondence among the alphabetic writing systems, (c) the cross-linguistic correlation of eye movement sampling frequency and the language-specific peak of the speech modulation spectrum, and (d) the association between reading rates and information density across languages.

All studies selected for inclusion into the meta-analysis reported mean fixation durations. However, as shown in Figure 1c, mean fixation durations are not a consistent and valid representation of the predominant sampling duration in the fixation data – and accordingly also not the preferred basis for calculating the sampling rate of reading. We therefore used 29 full empirical datasets to develop a transformation function that allowed us to estimate the mode from the mean fixation durations reported in the original publications (see *Materials and Methods* and SI Appendix S1 for details). In brief, this involved fitting ex-Gaussian distributions to the empirical distributions of these datasets, retrieving distributional parameters, and on this basis optimizing a regression-based transformation that estimates the mode from the mean (see *Materials and Methods* and SI Appendix S1 for details). For the meta analysis, mean durations were extracted from published studies and transformed to the mode. The sampling period t (i.e., the interval from saccade onset to the end of the following fixation; see above) was obtained by adding an estimate of the saccade duration (i.e., the mode saccade duration of the dataset of Study 1; 29 ms), and in a last step the sampling frequency was calculated as $f = 1/t$.

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Fixation duration and sampling frequency: Descriptive statistics. Figure 2 shows that the majority of fixation durations derived from the reading studies were between 200 and 300 ms (upper panel), which transforms to mean sampling frequencies between 3.9 and 5.2 Hz (lower panel). Note that for estimating the range, we excluded Arabic (3.1 Hz) since only one original study was available for that language. By relating these data to the empirically observed range of the peaks of speech modulation spectra, i.e., from 4.3 to 5.5 Hz (4, 5), we observe (a) that the mean reading-related sampling rates of all included languages fall within the maximum of one standard deviation from range of means in the speech modulation spectra (Figure 2, lower panel, dotted lines) and (b) that 10 of the 14 languages fall between the minimum and the maximum reported mean of the peaks of the language-specific speech amplitude modulation spectra (Figure 2, lower panel, dashed lines). Of the 1,420 individual sampling rate values derived from the included studies, only 3.0% were lower and only 0.3% were higher than one standard deviation around the mean of the speech modulation spectrum reported by (4) (see Fig 3, lower panel, dotted lines in the violin plot). Nevertheless, the mean sampling rate of reading observed when averaging across all languages is at the lower bound of the speech modulation range (see Fig 3, lower panel, dashed line in the violin plot).

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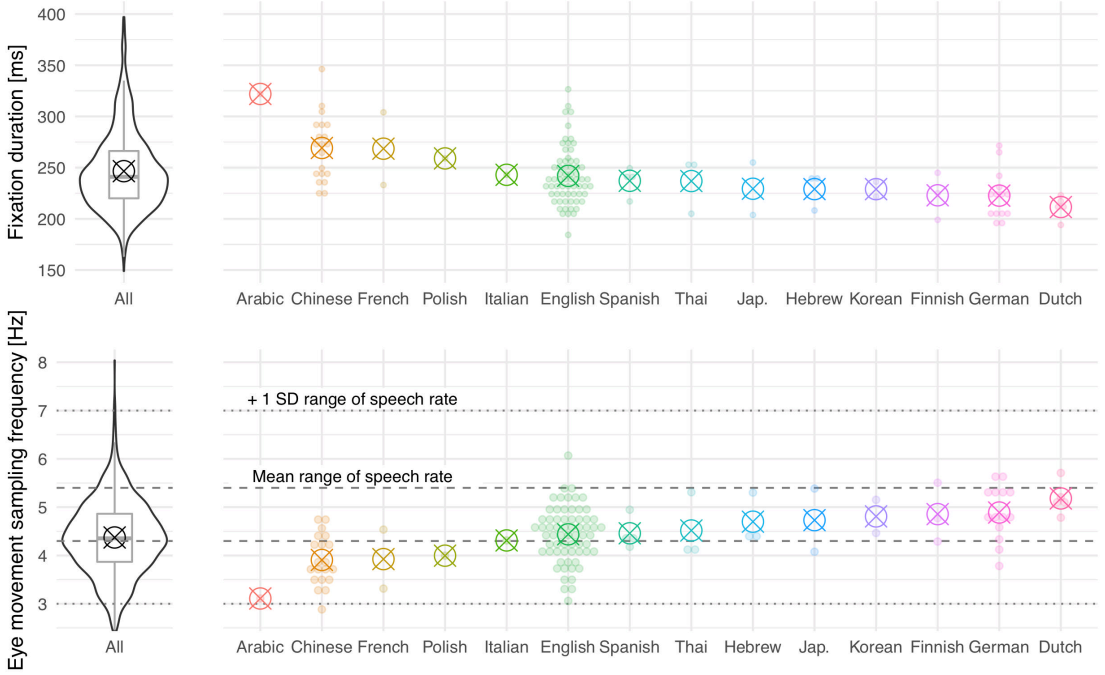

Figure 2. Meta-analysis of reading-related sampling rates. Fixation durations (upper panel) and corresponding eye movement sampling frequencies (lower panel) for 14 different languages. Violin plots (left) represent the respective distributions of all 1,420 duration / frequency values extracted from the included studies, independent of language. Embedded boxplots show the median as well as one (box) and two (whiskers) standard deviations, crossed circles reflect the mean. In the right panel, dots reflect each study (mean number of fixation durations per study: 12.4); crossed circles reflect the mean across studies for each language. In the lower panel the dashed and dotted lines represent the range of means and the maximal standard deviation from range of means, respectively, of the amplitude modulation spectrum that was empirically determined for speech in independent work (i.e., read out from Figure 3c in (4) and from Figure 7 in (5)). For Arabic, 1 study/ 12 fixation durations are available, Chinese 20/205, Dutch 5/45, English 65/965, Finnish 3/21, French 2/3, German 14/48, Hebrew 3/28, Italian 1/1, Jap. 2/12, Korean 2/39, Polish 1/1, Spanish 4/10 and Thai 3/30.

Effects of orthography on sampling frequency. The observed cross-linguistic differences, arguably, are related to different language characteristics. One plausible hypothesis is that the high perceptual complexity of character-based scripts (as opposed to alphabetic scripts; (25)) may modulate the rate at which written text is sampled. To test this conjecture, Figure 3a shows that the eye movement sampling frequency is significantly lower for Chinese (the only character-based language included; n = 256 estimated sampling rates from 20 studies; mean: 3.9 Hz) than for alphabetic languages (n = 1,215 sampling rates from 97 studies; mean: 4.5 Hz; effect size estimate (Est) of difference: -.70 Hz; Standard error (SE): .13; $t = 5.2$; see *Materials and Methods* for details on linear mixed effects modeling).

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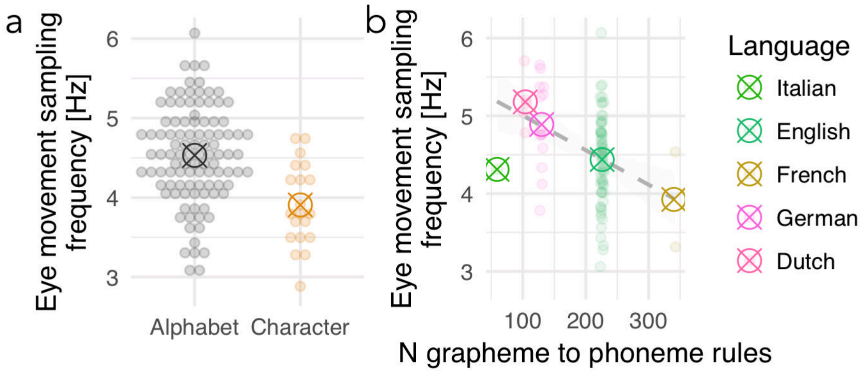

Figure 3. Comparison of writing systems. (a) Character vs. alphabetic contrast including 256 fixation durations from 20 studies of Chinese reading and 1,215 fixation durations from 97 studies of reading in alphabetic languages. (b) The effect of language transparency/opacity. Only studies from alphabetic languages for which the number of grapheme-to-phoneme rules could be quantitatively estimated from published computational models (see Materials and Methods) were used (5 languages with a total of N = 1,026 fixation durations). Note that for Italian, the meta-analysis contained only one study but differences in the number of data points were taken into account in the regression model. Dots reflect each study and crossed circles reflect the mean across studies for each language. The dashed line in (b) represents the approximation of the language transparency/opacity effect based on a linear regression, and shows that Italian, for which only one study is available, only very weakly influence the estimate.

Within alphabetic script languages, the orthographic difficulty of a writing system is likely to influence the speed of sampling the visual input. To examine this, we quantified orthographic difficulty as a continuous predictor representing the number of grapheme-to-phoneme rules (graphemes: letters or letter combinations that map onto one or multiple phonemes, i.e. speech sounds; cf. the example introduced above: to map the letter *a* to phonemes in *cat* and *ball* two rules are needed, while for the German translations *Katze* und *Ball* only one rule is needed) as defined by computationally implemented dual-route models of visual word recognition (e.g. (29)). To date, such implementations are available for five out of the nine alphabetic languages included in this meta-analysis, which restricts this test to Italian, English, French, German, and Dutch (with n = 1, 965, 3, 48, and 45 data points, respectively; see (26) for a detailed comparison of the Dual-Route models). Figure 3b demonstrates that less transparent writing systems (i.e., with greater numbers of grapheme-to-phoneme rules) elicit significantly lower sampling frequencies during reading (Est: -0.10 Hz, SE = 0.03, $t = 3.1$; note that the interpretability of the apparent outlier result for Italian is limited since only one fixation duration was included, which is accounted for by introducing study as a random effect in the mixed model analysis). Interestingly, highly transparent orthographies like German or Dutch produce sampling rates around 5 Hz (Fig. 4b). We argue that the analogy between speech and

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eye-movement sampling during reading can be investigated best in these relatively easy-to-process scripts, since difficulties that arise from the orthographic code are minimal.

Effects of speech rate and information density on sampling rates. Lastly, we examined whether cross-linguistic differences in peak speech rate or information density contributed to cross-linguistic differences in sampling rates (see *Materials and Methods* for details). To control for the strong effects of orthographic differences on sampling rates, linear mixed models were calculated that also included the factor alphabetic vs. character-based script (effect size < -0.57 Hz; SE < 0.15; $t > 4$). Neither the between-language differences in speech frequencies (Est: -0.03; SE = 0.05; $t = 0.6$) nor information density (Est: -0.04; SE = 0.03; $t = 1.2$) showed an effect on the eye-movement sampling rate. In a post-hoc analysis, we separately explored the effect of speech frequencies within alphabetic languages, however including only three languages for which peak speech rates were published (4, 5) and estimates of the number of grapheme-to-phoneme rules were available (i.e., English, French, and Dutch). This analysis also failed to produce a significant effect of speech frequency. Still, the produced result indicated a positive relationship between peak speech modulation rate and eye-movement sampling rate when controlling for grapheme-to-phoneme rules (Est: 0.06; SE = 0.06; t = 1.0). Even though this effect was not significant, we report it to motivate further investigations of the relationship between speech and reading rate.

The meta-analysis shows (i) a replication of the results for German, (ii) a systematic modulation of reading rates by the perceptual difficulty of the orthographic systems, but (iii) similar average sampling rates when reading languages of comparable levels of orthographic transparency (e.g., German, Dutch or Finnish). Reading rates in transparent (i.e., relatively easy-to-process) writing systems fall into the range of mean peak frequencies of the speech signal (i.e., 4.3-5.5 Hz; Refs. (4, 5)). A straightforward interpretation of this result, thus, may be that the linguistic systems underlying speech production and comprehension provide the temporal frame that ‘drives’ the oculomotor machinery in reading. This hypothesis would receive support from the demonstration of a direct relationship between the rate of speech production and the sampling rate of reading, which could establish satisfyingly across languages in our meta-analysis. Therefore we implement an additional investigation of the correlation of speech and reading rates at a subject-by-subject level. We hypothesized that individual (i.e., between-person) differences in the speech production rate should co-vary with individual differences in the sampling frequency of text reading. Study 3 tests this prediction.

Association of individual differences in speech and reading rates

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In this experiment, we test the correlation between a person's peak in the speech modulation spectrum and their specific rate of eye-movement sampling during reading. We recorded from each participant eye movements while reading German sentences (implemented analogous to the reading task in Study 1). In addition, we recorded a speech sample, based on a 'small talk' interview including 22 questions, thereby gathering on average 18 minutes of speech per participant (range: 6 to 28 min). For a first empirical investigation of the relationship between speech and reading rate, we examined second language learners, as we expected higher variabilities in both measures in this sample compared to native speakers, and thus greater chances of detecting associations. However, we controlled statistically for individual differences in reading proficiency by adding a standard measure of reading skill as a covariate to the regression model (see *Materials and Methods* for details). We estimated the eye movement sampling frequency as described in Experiment 1 and the speech modulation spectrum with the procedure provided by Varnet et al. (5).

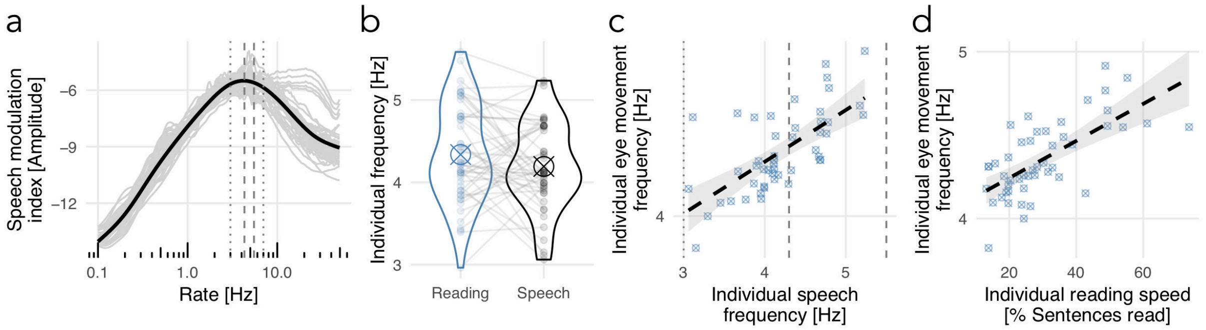

Figure 4. Relationship of speech and reading rates. (a) Speech modulation spectrum from 48 non-native speakers of German. Y-axis: speech modulation index; X-axis: speech rate. For additional orientation, we present the mean range (dashed lines) and standard deviations (dotted lines) of the speech amplitude modulation spectra across languages which were read out from Figure 3c in (4) and from Figure 7 in (5). (b) Eye movement sampling frequency in reading and the amplitude modulation spectrum in speech, for each participant. Lines connect the reading and speech frequencies of each individual, the violin represents the distribution of the data, and crossed circles reflect the mean. (c) Positive correlation of the individual peaks of the speech modulation spectrum (x-axis), reflecting each participant's speech rate, with the eye-movement frequency (y-axis) from the same participants. (d) Correlation between the eye-movement frequency (y-axis) and a paper-pencil based reading score (x-axis) reflecting a positive association of the eye-movement sampling rate and reading performance. Note that in (c) and (d) we present the individual sampling frequencies corrected for either reading skill and speech frequency, respectively, based on predictions from the fitted linear regression models used for statistical analysis.

Figure 4a shows the average speech modulation spectrum across participants (black line) with a peak at 4.2 Hz, and the individual spectra from all 48 participants (gray lines). As expected from language learners, the peak of the spectrum was on the lower border of the cross-linguistic range of mean speech rates ((4, 5); also depicted in Figure 2, dashed lines). The speech rate in these second language learners is thus lower than expected from native speakers.

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Nevertheless, all participants had their mean peak within one standard deviation of the mean range across languages (i.e., > 3 Hz and < 7 Hz). Also, both the speech modulation spectrum and the eye movement sampling frequencies were in a comparable range (Figure 4b), which was confirmed by a significant equivalence test ($t(47) = -2.0$, $p = .03$; implemented following (19)).

Crucially, we identify a positive correlation between the individual speech modulation spectrum and the individual eye-movement sampling frequency (Figure 4c). To quantify the relationship, a linear model was used to estimate the individual eye-movement sampling rate with speech modulation rate as predictor (Effect estimate = 0.32; Standard error = 0.15; $t = 2.1$; $p = 0.04$). Note that we obtained this effect while controlling for reading-related proficiency via a reading test, which relies on a combination of reading speed and access to meaning, and is widely used to screen for reading problems in German (30, 31). The positive association of the reading score and the eye-movement sampling frequency reflects that the eye-movement rate is not only associated with the speech rate but also registers processes specific to reading (Figure 4d; Effect estimate = 0.032; Standard error = 0.016; $t = 2.1$; $p = 0.04$).

Discussion

In this (to our knowledge first) frequency-based investigation of eye movements during reading, we show, first, that reading operates in a comparable frequency domain as the rate of natural speech and, second, that the sampling frequency of the eyes during reading is correlated with the modulation frequency of speech. In Study 1, we support in a frequency-domain analysis previous insights based on fixation duration measures (15–17), i.e., that reading involves a faster sampling of visual-orthographic input than a non-linguistic task with comparable stimulus materials. In the meta-analysis (Study 2), we integrated data from 124 original studies and showed that the text sampling rate during reading is more variable across languages than previously assumed. For example, Rayner (11) claimed even for very distinct orthographies like Chinese and English, that “Chinese readers tend to have average fixations durations that are quite similar to readers of English.” (p. 1461). This is not compatible with our meta-analytic results that show sampling rates varying from around 3.9 to 5.2 Hz between languages.

However, the range of the peaks in the speech amplitude modulation spectrum, in contrast, varies more narrowly around 5 Hz (i.e., Ref. 4: 4.3-5.4 Hz; Ref. 5: 4.3-5.5 Hz), excluding the lower range of frequencies observed for reading. Part of the variability in the sampling rate of reading results from characteristics of the investigated writing systems (i.e.,

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character vs. alphabetic and, among the alphabetic writing systems, many vs. few grapheme-to-phoneme rules). This demonstrates quantitatively that perceptually more difficult writing systems slow down the sampling of written language. Finally, in Study 3, we showed that independent measures of individual reading and speech rates are correlated (in second language learners). Combined, these results suggest that reading, i.e., an internally controlled visual-perceptual process, is related to the rate at which spoken language is produced (and thus also typically perceived) – even in the absence of any speech input or output. We tentatively suggest that this observed association between speech and reading supports the existence of a perceptual principle underlying the temporal structure of linguistic information processing, irrespective of modality.

Eye-movement sampling frequency – a new perspective for reading research. The frequency perspective we advance here is not needed for the analysis of eye movements during reading. In essence, the frequency representation of reading-related eye tracking data is merely a transformation of fixation and saccade duration data. That being said, this novel approach opens up several interesting new research perspectives. For example, it becomes possible to more directly compare reading behavior to evidence from other measurement modalities, such as oscillatory brain activation data (32, 33), and to other cognitive-psychological domains, such as attention (14, 34), which may not have the advantage of exact duration measurements for different events of interest (e.g., during covert attention). Maybe most importantly, the frequency perspective offers direct links to a number of oscillatory phenomena in speech perception (4, 5), including the observation that dyslexic children (35) and adults (36) showed altered cortical tracking of speech signals in the oscillatory domain.

Specificities of eye-movement behavior in reading. Still, eye movements during reading are not merely a sequence of word-to-word fixations; rather, a number of non-sequential phenomena emerge because printed text, unlike speech, relies on a temporally stable representation (i.e., the letters on paper or screen). For example, para-foveal pre-processing (37, 38) describes a perceptual benefit due to the processing of upcoming words, that leads to a reduction in processing time or, in the most optimal case, in skipping the word. On the other hand, multiple fixations on a single word can be observed in cases of perceptual error correction after suboptimal landing at the beginning or end of a word (12, 16, 39) or when a semantic inconsistency, e.g., at the end of a sentence, must be resolved (i.e., by re-reading; (40, 41)). While one might be worried that phenomena like word skipping and intra- or inter-word re-fixations could affect the estimation of eye movement sampling rates during reading, we (12)

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and others (9) have shown that the overall probabilities for word skipping and multiple fixations on a word are comparable when reading the sentence materials used here (i.e., both with a frequency of around 20%). These two phenomena, thus, should balance out, which is supported by our empirical observation that excluding re-fixation cases in post-hoc analysis did not change the pattern of effects. We accordingly propose that these specificities of the reading behavior can be neglected when calculating eye movement-dependent sampling rates of reading.

The characteristics of the fixation behavior can also explain a further interesting phenomenon, i.e., the comparable overall reading times for sentences in character-based vs. alphabetic writing systems, despite the significantly lower sampling rates of the more complex character-based writing systems. Liversedge and colleagues (10) examined eye movements during the reading of sentences with the same content across different languages. Character based presentation (in languages like Chinese, which showed significantly prolonged sampling rates across studies in our meta-analysis) resulted in much shorter sentences in terms of the number of symbols and their visual size on the screen. As a result, fewer fixations per sentence are needed to sample the entire stimulus, while the increased perceptual complexity leads to longer fixation durations. Alphabetic languages, in contrast, elicited more but shorter fixations. We propose that the frequency-domain characterization of reading helps to better understand these types of phenomena.

Conclusion. The frequency spectrum of spoken language is broadly distributed, but mean peaks are surprisingly stable across languages at 4.3-5.5 Hz (4, 5). The auditory and linguistic systems of our brain entrain to this frequency range when listening to naturalistic stimuli. We show that during reading, our eyes sample written text in the same frequency range, which indicates that extracting information from linguistic stimuli follows a similar temporal structure in time irrespective of modality. A plausible account for this overlap is to assume that the linguistic system has a preferred rate of information uptake and acts as an internal generator process controlling the movement of the eyes from word to word during reading. Indirect support for this hypothesis comes, for example, from the observation that readers can experience ’inner speech‘ during reading, and that manipulating the speed of inner speech during reading by associating text for example with fast or slow speakers has a causal effect on reading speed (42–44). Here, in addition, we now provide direct evidence for the existence of a perceptual principle underlying the temporal structure of linguistic information processing, by demonstrating a correlation between reading speed and the speed of speech production, in

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second language learners. This evidence, supports the claim that the rate at which linguistic systems of our brain process spoken language also acts as a driving force for active and voluntary control of eye movements during reading. We speculate that this enables the visual system to supply linguistic information at a rate that is preferred for the brain's language system. The novel frequency perspective on reading that we adopt here opens up new perspectives in reading research, for example for understanding slow or impaired reading or for second language learning.

Materials and Methods

Study 1 and 3, Participants. In Study 1, fifty (13 male; 18–47 years old; M = 24 years) native speakers of German and, in Study 3, forty-nine (13 male; 17–74 years old; M = 24 years) non-native German speakers participated after giving informed consent according to procedures approved by the local ethics committee. All participants had normal vision and were students at the University of Salzburg in Study 1. See our original publication of this dataset (15) for more details. Note that, relative to the original study, one participant was added. For Study 3, participants with varying mother tongues (Arabic, Azerbaijani, Bulgarian, Chinese, English, Farsi, French, Georgian, Indonesian, Italian, Japanese, Persian, Russian, Serbo-Croatian, Spanish, Turkish, Ukrainian, Hungarian, Urdu, and Uzbek) were recruited on campus as part of a larger study. Also note that six of these participants became literate without the acquisition of an alphabetic script.

Procedure Study 1. Movements of the right eye were tracked with a sampling rate of 1,000 Hz (Eyelink 1000, tower mount system; SR-Research, Ontario, Canada). We used a forehead and chin rest to fixate the head of participants at a distance of 60 cm from a 21” CRT screen. In the reading task, we used the Potsdam Sentence Corpus (PSC; (9)) which consists of 144 sentences and a total of 1,138 words. Participants were instructed to read silently for comprehension, which was controlled by simple comprehension questions after 38 of the 144 sentences.

As a non-linguistic control task, participants performed a z-string scanning task using stimuli in which all letters of the sentence corpus were replaced by the letter z (preserving letter case, punctuation, and word boundaries; (see (17), and examples above). Participants were instructed to visually scan the meaningless z-strings as if they were reading, but for obvious reasons, no comprehension questions were administered in this condition. Z-string scanning has been used as control task in previous studies (15–17, 20). While it is difficult to

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find a reasonable control task for reading (see, e.g., (16)), z-string scanning proved to be interesting because participants produce similar scan path patterns (i.e., similar number of fixations) as when reading (15–17). Interestingly, while z-string scanning produced longer mean fixation durations than reading, the pupil response indicated higher cognitive effort in reading, in the dataset used here (15). We take this dissociation between cognitive effort and reading time as evidence for the operation of reading-specific cognitive processes that go beyond mere attentional processes.

In each task, a 9-point standard calibration was performed before the 10 practice trials, before the experimental trials, and after a break halfway through the experiment. A calibration was considered accurate when the mean error was below 0.5° of visual angle. Visual stimuli were presented in black letters (mono-spaced, bold Courier New font; 14 pt., width ~0.3°) on white background with a 1,024 × 768 pixel resolution and a refresh rate of 120 Hz, using Experiment Builder software (SR Research, Ontario, Canada). In both tasks, a trial started when an eye-fixation was found at a dot presented 100 pixels from the left margin of the monitor, at the horizontal level of the fixation cross. For this fixation check, real-time analysis of eye-tracking data was used to present the sentence only when a fixation of at least 100 ms was identified on the position of the dot. If no fixation was registered on the dot for 10 seconds, a re-calibration procedure was initiated. Following the fixation check, the stimulus (i.e., sentence or z-string) appeared, with the center of the first word presented at the position of the fixation dot. As a consequence, participants always fixated the center of the first word of the sentence first. Stimulus presentation was terminated when participants fixated an X in the lower right corner of the screen after the sentence was read. As noted, in about 25% of sentences, the presentation was followed by a comprehension question to assure that participants processed sentences semantically. This procedure was practiced in ten trials prior to the main experiment.

Procedure Study 3. Eye movement measurements during reading were acquired using the same stimulus materials and experimental procedures as in Study 1, with three exceptions: We used a desktop-mount eye tracker, a horizontal 3-point calibration procedure, and we did not implement the z-string scanning task. All other parameters were unchanged. To acquire a speech sample from each participant we conducted a brief interview in German, involving 22 questions about, e.g., last weekend's activities (see the full list of questions in SI Appendix S3). Speech was recorded with the Audacity software (Version 2.1.3; https://www.audacityteam.org/) on a standard computer.

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Data analysis: Fixation durations. The first word of each sentence was excluded from analyses, since the first word is known to be contaminated by stimulus onset effects. A total of 994 words were analyzed per subject. For each participant, all fixation durations from all analyzed words were extracted. Words with fixation durations shorter than 60 ms and longer than 1,000 ms and saccade durations longer than 80 ms were removed from the analysis (3.1% of the data) since they likely reflect machine error. On the basis of the remaining fixation durations, the mean was calculated in order to estimate each participant's individual mean fixation duration, separately for the reading and scanning tasks. Note, to account for the ex-Gaussian distributions (see Figure 1c) for the statistical test we implemented a log-transformation resulting in a normal distribution (Kolmogorov-Smirnov test not significant; $D < 0.14$; $p > .7$).

Estimation of the sampling frequency. To estimate the sampling frequency of eye movements in reading, first an event that has a repetitive nature (i.e., that takes place more than once) has to be identified, in our case the repetitive pattern of saccades. Second, the time between the first and the subsequent occurrence is defined as the *sampling period*, which can be transformed into a frequency value. To this end, we used the duration from the onset of a saccade to the onset of the next saccade (i.e., saccade plus fixation duration) to calculate the respective sampling period. Note that we used the EyeLink eye-tracker's built-in saccade detection algorithm, which was recently successfully evaluated and showed the best detection rates for saccade onsets compared to all other algorithms used in the evaluation study (23). The distribution of the sampling period is ex-Gaussian, for both reading and z-string scanning (Figure 1c). Ex-Gaussian distributions are a convolution of a normal distribution and an exponential distribution reflecting the rightward skew. As Figure 1c shows, the central tendency is best represented by the mode, so that all subsequent fixation duration based frequency estimations are implemented by a participant-specific mode (t). These subject-specific mode values are equivalent to the predominant sampling period of the respective participant, which in turn can be transformed to an individual eye movement sampling frequency ($f = 1 / t$).

Power spectrum. We performed a canonical frequency analysis by estimating a power spectrum for reading and scanning. For Figure 1e, we estimated the power spectrum based on a time series starting with the first saccade of the first participant and ending with the last fixation of the final participant for each task. For Figure 1f, the time series was cut into participant-specific time series, so that individual peaks could be recovered for each participant for each task. The time series was implemented as a sparse sequence of zeros and

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ones (resolution: 1,000 entries per second), set to one at time points at which a saccade was initiated, and zero otherwise. Subsequently, a Fast Fourier Transform was used to estimate a power spectrum (power spectral density; *psd_welch* function from MNE-Python; (45) ; 0-100 Hz, length of the FFT used = 4096 samples) for each of event time courses separately.

Speech amplitude modulation spectrum. In a first step, all non-participant audio signals were removed from the speech samples (i.e., interviewer questions and pauses before answers). To obtain the amplitude modulation spectrum we used the procedure described in (5) by adapting the AM_FM_Spectra MATLAB toolbox (https://github.com/LeoVarnet/AM_FM_Spectra). The first adaptation divided the recording of each participant into speech snippets of 10 s length, resulting in a mean number of 110 snippets per participants (range 35 to 167). The second adaptation was an increase in the resolution of the amplitude modulation spectrum by decreasing the widths of the modulation filters from 3 to 10 per octave. After the speech amplitude modulation was estimated for each 10 s speech snip, we retrieved the frequency at the peak of the modulation spectrum. Thereafter, we removed outliers by first eliminating unrealistic values lower than 2 and higher than 10 Hz, and then removed all values larger and smaller than two standard deviations from the mean. This procedure removed 3% of the data. Finally, we estimated the mean across all snips for each participant. Here we found that one participant had a mean amplitude modulation spectrum which was larger than three standard deviations from the mean of the sample; this participant was excluded from analysis.

Meta-analysis. We included empirical studies that report eye-tracking results from natural reading tasks, published between 2006 and 2016. These studies were identified by the search term *eye movement in* "*natural reading*" *or* "*sentence reading*" *or* "*text reading*“ in the *PubMed* (https://www.ncbi.nlm.nih.gov/pubmed) and *PsychInfo* (https://health.ebsco.com/products/psycinfo) databases. Additionally, 10 studies were manually identified (e.g., on the basis of reference lists in published papers). From the resulting sample of 124 articles we extracted 1,420 fixation durations, including mean fixation durations (all fixations on a word combined; 10% of the dataset), first fixation durations (duration of the first fixation on a word; 67%), and single fixation durations (fixation duration in case a word was fixated only once, which is the predominant case for normal readers; (e.g. (9); 23%). A full list of all included studies can be found in the SI Appendix S2. Note that the results of the above-reported experiment and its previous analysis (15) were not included. This meta analytic dataset encompassed 14 different languages, with a range from one (Arabic, Italian, and Polish)

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to 65 (English) retrieved papers. Consistent with a general bias towards English in reading research (46), 68% of fixation durations in our dataset were from English.

Frequency estimation. In order to estimate the predominant sampling frequency, per published study, we have to take into account, once more, the ex-Gaussian distribution of fixation duration data. Following the general trend in the eye movement reading literature, most studies reported only mean fixation durations (see (21) for an exception since, in addition, the fitted ex-Gaussion paramaters were reported). For the purposes of the present meta-analysis, we developed a transformation function that allowed us to estimate the mode from the mean fixation durations reported in the original publications. This transformation function was then applied to transform mean fixation durations extracted from the published original studies into the mode. In the final transformation, the sampling periods (mode fixation duration plus mode saccade duration) were converted in a frequency value.

In brief (for details see SI Appendix S1), the development of this function involved (i) fitting ex-Gaussian distributions to the empirical distributions of fixation durations in the 29 datasets, and (ii) retrieving distributional parameters for each fitted distribution (specifically: μ, the mean of the normally distributed component; σ, its standard deviation; τ, the parameter reflecting the rightward skew, representing the contribution of the exponential distribution). This allowed us to (iii) implement a regression-based transformation function from a mean fixation duration into a mode. Figure 5a presents the final generalized mean-to-mode transformation function, applied to all possible fixation durations in the range covered by the meta-analysis. Figure 5b shows how well the modes of our 29 datasets can be recovered by this function: Despite some unsystematic noise, the numeric transformation was nearly perfect (i.e., beta = 0.95; SE = 0.23; $t(28) = 4.1$). We than used the transformation function to estimate the respective modes from the 1,420 mean fixation durations of the meta-analysis dataset. To obtain the sampling period t (i.e., the interval from the onset of a saccade until the end of the following fixation; see also Study 1, above), a saccade duration estimate of 29 ms (i.e., the mode of saccade durations from the reading dataset used in the first experiment) was added to each of the mode fixation duration. This is feasible since saccade durations do not differ much between persons during reading (e.g. (47): range 20-39 ms, mean: 29 ms). Finally, the sampling period values (t) were transformed into frequency values ($f = 1 / t$).

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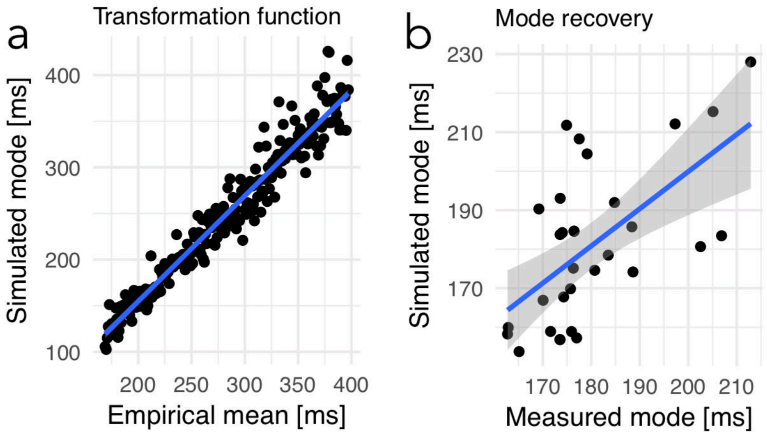

Figure 5. Transformation function for converting mean fixation durations into simulated mode values. The function was established using ex-Gaussian estimations on 29 empirical datasets containing fixation durations. For details see SI Appendix S1. (a) Performance of the final mean-to-mode transformation function (blue line) demonstrated here for all 248 possible fixation durations, i.e., for each millisecond within the range of fixation durations included in the meta-analysis (149 – 397 ms; x-axis: empirical means). (b) Performance of the final mean-to-mode transformation function, as demonstrated by the relationship between empirically measured (x-axis) and simulated (y-axis) modes from the 29 datasets used for establishing the transformation function.

Writing system comparisons. In order to explore whether or not the sampling frequency of reading is influenced by global characteristics of writing systems and languages, we implemented four tests. First, Chinese reading (256 fixation duration data points) was compared to all alphabetic writing systems (1,215 fixation durations). Note that the Korean (alphabetic syllabary orthography; (48)) and Japanese (using a mixture of Kana and Kanji) studies in the meta-analysis could not be clearly assigned to the character or alphabet categories and therefore were not included into this contrast. Second, among the alphabetic scripts we examined the differences in transparency/opaqueness of the letter-to-sound relationship by a continuous predictor representing the number of grapheme-to-phoneme rules as defined by computationally implemented dual-route models (26). A low number of grapheme-to-phoneme rules reflects a high transparency, meaning that letters more consistently represent only one speech sound. For example Italian, Dutch, and German are considered transparent orthographies, with 59, 104, and 130 rules, respectively; see (26)). English and French, in contrast, are typically considered as in-transparent with 226 and 340 rules, respectively, because letters map to multiple speech sounds on a regular basis. Third, we investigated the cross-linguistic relationship between the peak modulation spectra from speech and the mean sampling frequencies in reading, by retrieving the modulation spectra from Chinese, Dutch, English, French, Japanese, Polish, and Spanish (i.e., read out from Figure 3c in (4) and from Figure 7 in

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(5)). The modulation spectra varied from 4.3 Hz in English to 5.5 Hz in Polish. Finally, in the fourth test, we investigated the relationship of eye movement sampling in reading with the information density of a language. This parameter indicates how dense a language codes meaning in texts (28). The density is coded from 0 to 1 and could be retrieved for a subgroup of languages in the present meta-analysis dataset (i.e., Chinese, English, French, German Italian, Japanese, and Spanish) from (28). Density varied from dense languages like Chinese (0.94) to less dense languages like Japanese (0.49).

All four effects were analyzed using linear mixed models (LMM; (49)). In addition to the parameters of interest, we accounted for experimental settings (experiment vs. corpus-based studies), for the different eye trackers used (which may also imply use of different saccade detection algorithms), and for different fixation measures reported (mean, single, or first fixation duration) by introducing these parameters into the LMM as fixed effects. Also, for the modulation spectrum and information density comparisons we added a factor contrasting character-based (i.e., Chinese) vs. alphabetic writing systems, to account for perceptual difficulties, and for all four LMMs we estimated the random effect on the intercept of study, to take into account unspecific differences between studies. t-values larger than 2 were interpreted as significant (cf. (50)).

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Author contributions

B.G., D.P. and C.J.F. designed research; B.G. and S.H. performed Study 1; B.G. and J.G. performed Study 2; B.G. and K.G. performed Study 3; B.G. and J.S. analyzed data; and B.G. and C.J.F. wrote the paper. All authors gave comments on the paper during the process.

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Supplementary Information for

Reading at the speed of speech: Alignment of the eye movements rate in reading with the language processing speed.

Supplementary text for S1
Figs. S1
References S1 for SI reference citations
Supplementary text for S2
References S2
Supplementary text for S3

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Supplementary text for S1

Mean to mode transformation function

The typical distribution of eye fixation duration data in reading is ex-Gaussian (see Figure 1c). For simplification, one can decompose the ex-Gaussian distribution in a normal and an exponential distribution. This decomposition is a simplification on a mathematical level since both the normal and exponential distributions can be modeled easily. Consequently, one can describe the central tendency of the ex-Gaussian distribution by three parameters: the mean and standard deviation of the normal distributed component and the exponential component (i.e., reflecting the skew of the ex-Gaussian distribution). The μ relates to the mean of the normal distribution. The σ refers to the standard deviation of the normal distribution. The τ describes the rightward skew, i.e., representing the contribution of the exponential distribution.

In a frequency analysis one investigates if a reoccurring event, in our case a saccade, has a temporal structure. In Experiment 1, we showed that the mode of the ex-Gaussian distribution of the sampling durations (fixation plus saccade duration) indicates the most common sampling duration, which was found to be the adequate metric for the frequency estimation (i.e., by showing comparable frequency estimates based on mode fixation duration and power spectral estimation approaches but not when using the mean fixation duration). In the eye-tracking literature on reading, it is more typical to report mean fixation durations. Reporting mean not mode fixation durations is a central problem of the current meta-analysis. Accordingly, we developed the mean-to-mode transformation function described here. With this function, we transform the mean fixation durations extracted from papers into mode values.

We implemented the mean-to-mode transformation function in three steps: (i) We fit ex-Gaussian distributions (i.e., by decomposition methods) to existing empirical datasets. (ii) We used fitted ex-Gaussian parameters (μ: mean of the normal distribution; σ: standard deviation of the normal distribution; τ: exponential component describing the rightward skew) to simulate new, informed, ex-Gaussian distributions to derive a transformation function. (iii) We optimize the transformation function to increase transformation accuracy.

(i) Ex-Gaussian fitting to existing empirical datasets. First, we fitted the three ex-Gaussian parameters to 29 empirical datasets containing fixation durations (11 published studies, i.e., three German studies from our lab, (1–3), and multiple English studies (4–10) for which datasets were openly available) using the *mexgauss* function from the *retimes* package in *R* (11). Figure S1a shows two empirical and the respective simulated distribution, including the

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mean and mode of the distribution, exemplarily. Henceforth, we jointly refer to these 29 datasets as the 'simulation data'. Combined we now obtained the exact mean and mode of 29 datasets as well as the μ, σ, τ for each dataset. Note, the main selection criteria for the datasets used in the present study was availability and accessibility of the raw fixation duration values.

(ii) Using fitted ex-Gaussian parameters to simulate new informed ex-Gaussian distributions. With the fitted ex-Gaussian parameters, we estimated, in a next step, three robust linear regression models (rlm function in R from the MASS package; (12)). One for each of the ex-Gaussian parameters (μ, σ, τ) to predict the mean fixation duration (μ: 0.40, SE = 0.09, t = 4.6; σ: 0.14, SE = 0.09, t = 1.5; τ: 0.60, SE = 0.09, t = 6.7). Figure S1b shows the relationships of each parameter to the means from each study.

Now, we can simulate realistic ex-Gaussian distributions (with 500 samples) for any mean value with the *exGAUS* function from the *gamlss.dist* package in R (13). These distributions can be realized by the fitted linear regression coefficients (intercept, beta weight), which describe the relationship of each of the three ex-Gaussian parameter estimates to the mean of the dataset (see Figure S1b). For example, one can go to the graphics and see that with a mean fixation duration of 200 ms one can obtain a μ value of 140, a σ value of 30 and a τ value of 40. Having a value to each of the ex-Gaussian parameters, one can simulate an ex-Gaussian distribution. This simulation then allows us to estimate the mode of the distribution, in our case around 150 ms. As a consequence, one can directly relate the mode of 150 ms to the mean value of 200 ms.

To reduce estimation noise and increase robustness against outliers, we sampled ex-Gaussian distributions, not only for the 29 datasets available but for the whole range of mean fixation durations (149 and 397 ms) from the meta-analysis. From these 248 simulated ex-Gaussian distributions, we estimated the mode values relating each mean to a mode value. Finally, these related mean and mode values allowed us to generate a generalized mean-to-mode transformation function by only one linear regression (e.g., blue line in Fig. S1d). Note, to realize the function in a generalized way, we on purpose neglected the specific experimental manipulations of the different studies of our simulation data.

(iii) Optimizing the transformation function. For initial quality control, we used the fitted linear regression coefficients (intercept, beta weight) from the transformation function to transform the mean fixation duration of each of the 29 simulation datasets into a simulated mode. Since we were also able to measure the mode of these datasets were able to compare the simulated to

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the measured modes for each dataset. In Figure S1c, Level 1, we present the residual errors of the 29 simulated modes, relative to the measured modes. The negative relationship between the measured mode and the residuals (i.e., simulated minus measured mode) indicated a systematic overestimation for low measured modes and underestimation for high measured modes. This is likely caused by imprecisions in the ex-Gaussian fitting procedure. To account for this systematic error, we corrected the simulated modes by a sequential procedure. First, we described the error by a linear model. This model is then used to predict the over/underestimation of a given mode. The prediction is then used to correct the simulate mode values. This correction procedure was applied two times.

Figure S1c, Level 3, shows that after this sequential correction procedure, the final transformation function does not include a systematic error that one would expect to be present in the residuals. Figure S1d, accordingly, shows the final, i.e., corrected, transformation-function, for all possible 248 mean fixation durations. Figure S1e shows the final quality check from the simulation dataset showing the relationship of the measured and simulated modes. Despite some unsystematic noise, this optimized transformation function showed a near-perfect beta of 0.95 (SE = 0.23; t = 4.1).

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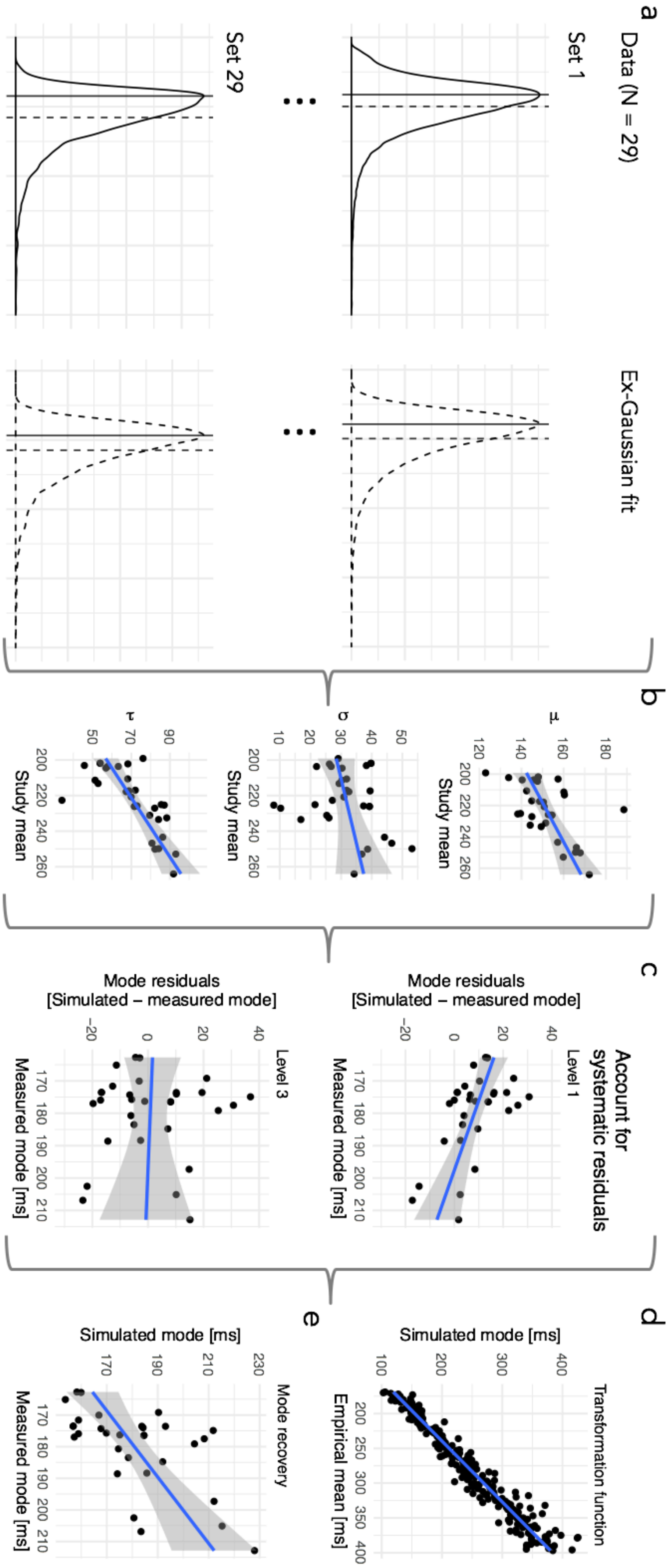

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Figure S1. Development of a transformation function for converting mean fixation durations into simulated mode values. In order to estimate the predominant, i.e., mode, fixation duration from a single mean value extracted from a published empirical study, we implemented the following procedure: (a) First, an ex-Gaussian function was fitted separately to empirical fixation duration distributions of each of 29 independent datasets (left panel; see Materials and Methods), and we extracted the parameters μ, σ, τ describing the fitted ex-Gaussian distribution (right panel). (b) Second, across these 29 datasets, the relationship between the ex-Gaussian parameters and the empirical study means were described by linear models, separately for each parameter. The intercepts and beta-weights resulting from these linear models, for each ex-Gauss parameter, were then used to simulate an ex-Gaussian for each of the 29 empirical mean fixation durations, so that we could compare the empirical and simulated ex-Gaussian distributions. (c) Residuals for the mode estimation showed a systematic error, i.e., an overestimation for low modes and underestimation for high modes (upper panel / Level 1). We accounted for this systematic error, sequentially, by two linear models describing the error; see lower panel / Level 3 for residuals after accounting for the estimation error. (d) Performance of the final mean-to-mode transformation function (blue line) demonstrated for 248 fixation durations, i.e., for each millisecond within the range of the meta-analysis (149 – 397 ms). (e) Performance of the final version of the mean-to-mode transformation function, as demonstrated by the relationship between empirically measured and simulated modes from the 29 datasets used for establishing the transformation function.

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Supplementary text for S2

Please find all references for the Studies included in the meta-analysis in the Reference section S2 (i.e., APA style formatting for convenience).

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Supplementary text S3

The full list of 22 questions from the “small talk” interview we conducted in German.

1. Wie viele Prüfungen hast du jetzt im Semester?
2. Warum studierst du? (ich frage meistens auch noch so allgemeiner, was genau sie studieren, wieso sie sich das rausgesucht haben, was ihnen daran Spaß macht)
3. Hast du dein Wohnort durch das Studium gewechselt?
4. Wie ist die Wohnungssituation für dich in Frankfurt?
5. Hast du schon früher eine Ausbildung/Studium gemacht?
6. Hast du schon mal ein Auslandsaufenthalt gemacht?
7. Hast du eine Zweitsprache? Welche Sprachen sprichst du?
8. Machst du irgendein Sport?
9. Spielst du irgendwelche Computerspiele / hast früher gespielt?
10. Was sind deine Hobbys / Interessen?
11. Was hast du am Wochenende gemacht? (wenn sie sich nicht erinnern können frage ich was sie für das kommende Wochenende vorhaben)
12. In welchen Ländern warst du schon?
13. Was ist dein Lieblingsessen? Was isst du gerne?
14. Wie findest du das Wetter im Moment so?
15. Was ist deine Lieblingsjahreszeit?
16. Machst du irgendein Nebenjob?
17. Hast du für den Sommer / die Weihnachtsferien etwas vor?
18. Isst du gerne in der Mensa?
19. Wo kommst du eigentlich her?
20. Was machst du im Studium im Moment so inhaltlich?
21. Was hast du nach dem Studium vor?
22. Was war dein letzter Kinofilm / Fernsehfilm / Serie, die du geguckt hast?