Attending multiple languages: the relation between individual multilingual language use and attentional control

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Abstract

Individuals speaking multiple language have been asserted to have a cognitive advantage, perhaps specifically in the domain of selective attention, although this claim has recently been challenged. The diversity of multilingual experiences and use seems of great importance here, and suggestions have been made that advantages especially emerge for individuals with higher ‘multilingual load’, referring to language experience and use factors including duration of multilingualism, number of languages mastered, and use of multiple languages in daily life. We captured multilingual language diversity using a language entropy measure, which encompasses several language use factors into one metric. We related individual differences in language entropy to selective attention as measured with an attentional blink (AB) task in 53 diverse multilingual individuals. During task performance, brain activity in the lateral prefrontal cortex was measured using fNIRS. We found no support for the claim that language diversity, or other individual factors related to language experience and use, influence AB magnitude. However, relations with T1 identification accuracy were observed and brain activity in the DLPFC during the attentional blink task also related to higher language diversity, jointly suggesting that language diversity may promote alertness and attention. This study is the first to relate simultaneous behavioral and brain attentional blink data to the language entropy measure.

Keywords

Attentional control, multilingualism, bilingualism, language entropy, language diversity, attentional blink, rapid serial visual presentation task, cognitive advantages, fNIRS, prefrontal cortex.

Introduction

Individuals who use multiple languages in daily life need to process and control these languages continuously and simultaneously [1][1]. Managing multiple languages in one mind is therefore a complex cognitive operation, requiring cognitive control abilities such as attention, inhibition, monitoring and switching [2][2]. The continuous utilization of these cognitive processes has been argued to drive neurocognitive adaptations and influence cognitive control, perhaps specifically attentional systems [3–6][3–6]. Despite the fact that many studies provide evidence in support of this claim, sometimes labeled the ‘bilingual advantage’, the phenomenon is being disputed by a substantial number of studies (cf., [7,8][7,8] for recent overviews). This has raised questions regarding the nature and specificity of multilingualism as a cognitively enhancing life experience. Inconsistencies in findings could, for example, be explained by variability in study samples, where factors that vary between individuals are not taken into account. The current debate has therefore in turn sparked a re-evaluation of the definition of multilingualism [9–12][9–12] and more research is conducted detailing the diversity of multilingual experiences and backgrounds (cf. [8][8]). Multilingual experiences are now more often approached as multifaceted and continuous [13,14][13,14]. However, whether individual differences in the range of multilingual experiences and backgrounds actually relate to differences in cognitive performance and thus could explain part of the inconsistency in findings, is poorly investigated. The current study will address this challenge by examining the relation between diversity and continuity in individual multilingual language experiences and cognition, focusing specifically on attention.

Individual differences in multilingual experiences

For a long time, the ‘bilingual advantage’ was predominantly studied by comparing relatively small groups of monolinguals to groups of bilinguals. However, by using such a dichotomous classification, information about the heterogeneity of multilingual language profiles is lost. While multilingualism is typically used as an umbrella term to capture a wide group of individuals [15][15], no two multilinguals are the same as they differ greatly in terms of language experience and use. These

differences in individual language experiences have in the past been put forward as confounding factors in studies evaluating the effects of multilingualism [16,17][16,17]. But rather than a confounding factor, those differences might well form the essence of the cognitive benefits to be gained from multilingualism [9][9]. The current tenet of the field has therefore shifted towards a more detailed assessment of individual differences and away from binary group designs comparing monolinguals and multilinguals [18,19][18,19].

As is becoming more and more evident, an approach where individual differences in multilingual experiences and usage form the foundation is necessary to advance the field. This can be done by studying and describing multiple (continuous) language experience factors. Individual differences in language experience and use are typically driven by many different factors. Such differences may pertain to language proficiency levels, age of acquisition, the number of languages spoken or indeed the languages themselves. Besides that, there is increased focus on factors related to the social contexts in which these languages are used such as frequency and intensity of language use, switching behavior between languages or immersion in a multilingual environment [9,14][9,14].

Despite the increased awareness, the number of studies that investigate multilingualism from the perspective of individual differences (using rather than controlling the heterogeneity within multilingual populations) and employing within-group approaches is low but growing. Past work has shown language experience factors such as second language (L2) proficiency [20][20], switching between languages [21], amount of daily L2 use [22], and intensity of daily language use in different social contexts [9] to be the best predictors of cognitive performance. The study by Pot and colleagues [9] remains one of the few behavioral studies incorporating a broad range of individual language factors instead of factors in isolation. With studies examining how multilingualism as a multifaceted continuous experience relates to cognitive performance at a behavioral level thus remaining scarce, relatively more work has examined the potential neurocognitive effects of individual multilingual life experiences.

The brain has been suggested to adapt structurally and functionally to multilingual experience factors related to language use and context [23–27]. These studies show that specific language experience factors are related to specific characteristics of the brain. Following these results, it has

been suggested that “the brain constantly adapts to be maximally effective at handling the cognitive load of the communicative environment” [27]. Notably, these neural effects do not always coincide with behavioral effects. For example, no relation between language experience factors and behavioral performance (on the Flanker task) were found [27], which is in line with other studies showing differences in brain activity but not in task performance [28,29]. Importantly, neural adaptations of the brain related to multilingual experiences are not static but can change over time. Depending on the stage of language learning and multilingual use, brain networks constantly respond to changes in the individual language context, as is posited in the Dynamic Restructuring Model (DRM) [30].

Studies examining the neurocognitive effects of individual multilingual life experiences underscore the importance of looking at multilingualism effects holistically, integrating brain functioning with overt behavior. They furthermore highlight the complexity of multilingualism as an interactive and dynamic process and the need for approaches that put the language experiences of individual multilinguals at the foundation of any study into their effects. The issue of how to best operationalize multilingualism as a multifaceted continuous experience has yet to be resolved, but recently new approaches have been suggested. For instance, a bilingual quotient to capture the degree of multilingualism in a single number has been put forward [13]. Similarly, language entropy has been proposed as a multifaceted continuous measure to capture diversity in context-dependent multilingual language use [14].

Attention

Other than looking more closely at multilingual experiences, researchers have also looked more closely at the nature of the cognitive outcomes themselves. Earlier studies have pointed to inhibitory control as being enhanced in multilinguals [31]. Recently the attentional system has been proposed as a focal point for work examining the cognitive effects to ensue from multilingualism, modulated by experience and training, and is likely to improve as a result of lifelong demands imposed by having to navigate in a multilingual environment [6]. This is corroborated by studies showing a relation between better performance on selective attention tasks and multilingualism [32,33] and the finding that this relation can be modified depending on language context [34].

Selective attention can be measured in a spatial and in a temporal dimension. The latter is most pertinently measured using the Attentional Blink (AB) task that has been shown to effectively measure individual differences in selective attention [35]. While the spatial dimension has been studied extensively in relation to multilingualism, the temporal dimension has not. However, when it comes to regulating the incoming flow of information in multilingual contexts, the temporal aspect of it is of great importance. Especially in multilingual environments that show substantial language diversity, cues often follow in rapid succession and temporal integration of this information is important. Moreover, adequate performance on the AB task depends on the functioning of lateral prefrontal brain regions [36,37] that are also recruited in multilingual language control [38]. This makes the AB task especially suited to study how individual variations in multilingualism relate to cognitive control at multiple levels (brain, behavior), in order to explore whether individual language use and experience variation explains variation in the cognitive advantage associated with multilingualism.

Attentional blink task

The availability of a person's attention across time has been commonly assessed on the basis of the AB task, partly due to its robustness and insensitivity to practice effects [35,39]. As part of the AB task (or Rapid Serial Visual Presentation [RSVP] task), two targets must be identified amongst a rapid stream of distractor stimuli, requiring sustained attention. The attentional blink (AB) denotes the well-established effect that individuals frequently fail to report the second target (T2) when this appears within close temporal proximity (~200 – 500 ms) of the first target (T1) [40,41]. The task allows for the temporal aspects of cognitive processes that underlie the selection and consolidation of information to be isolated and studied.

Interpretations of the attentional blink vary in terms of their proposed mechanisms [39,42]. Underlyingly, the AB is thought to stem from a combination of factors, including attentional control mechanisms for the selection and consolidation of the targets, and a sub-optimal distribution of attentional resources [35]. Accuracy in reporting T1 reflects efficient target processing [43,44] and is

therefore related to more general attentional control processes, while the AB specifically relates to selective attention processes of multiple targets across time. Most research suggests that the AB follows from a delay in allocating attention to the second target, causing a problem in consolidating and reporting the second target. Often, substantial individual differences in AB performance are found, likely related to differences in the timing or control of attention, or more specifically to differences in processes of selective attention involved in the selection of relevant targets and consolidating them into memory [45].

Individual differences in the AB have, for example, been found for individuals with different levels of executive control: individuals with higher levels of executive control have demonstrated a smaller AB and thus better performance [35]. Also, individuals who are experienced in open forms of meditation, where attention is not focused on an object but remains open to everything that happens, show better AB performance (smaller blinks) [46,47]. Other studies have shown that individuals who tend to have a more broadened attention (global attention) perform better on the AB task compared to individuals who tend to focus their attention more to local features [48,49]. These results are in line with the finding that the AB is reduced when attention is directed away from the task by adding another task or by adding a distracting mental activity [50–52].

Only few studies to date have directly linked attention to multilingualism on the basis of the AB task. Contrary to expectations, the studies to date indicate poorer attentional control, as evidenced by a larger AB in multilinguals vs monolinguals [53], and in multilinguals with higher vs lower L2 proficiency [54], although not consistently [55]. The larger AB was explained as an overexertion of attentional control in bilinguals, to ward off distractors and shield T1 processing. These studies either used a binary comparison of monolinguals and multilinguals or looked at a single multilingualism experience factor. However, as stated before, multilingualism is a multifaceted experience, shaped by many different factors. A more recent study on the AB in multilingual individuals examined – in two experiments – how attention was influenced by variation in multiple different language experience factors: frequency of language use, frequency of language switching, language similarity, age of acquisition (AoA), and language proficiency [56]. While not replicated in experiment 2, results from experiment 1 and an analysis that combined data of both experiments demonstrated that less

typological similarity between L1 and L2 (i.e., more linguistic distance) and more balanced language use predicted a smaller (rather than larger) AB magnitude. This effect was explained as successful distractor filtering and is more in line with the presumed cognitive advantage ascribed to multilingualism.

The studies using the AB task to study attention in multilingual individuals differ greatly in the population tested. Although all studies included ‘multilingual’ individuals, the way multilingualism has been defined varied substantially. The most recent study by Yamasaki and colleagues [56] defined multilingualism most broadly, allowing for substantial variability within the study’s sample. It is precisely this variability in individual multilingual language experience that is increasingly thought to be of great importance in relation to executive control and ideally is represented in a single metric covering multiple aspects of multilingualism. But even in the Yamasaki et al. study [56], multilingualism was defined one-dimensionally, and important other aspects relating to multilingual languages use were not highlighted. To date, a multifaceted approach to multilingualism is currently missing.

The current study

The recent suggestion that a potential multilingual advantage lies in attentional systems [5,6] is accompanied by the recognition of the importance of considering individual differences in multilingual experiences [10,12]. It follows that a study of a varied range of individual multilingual experience factors in relation to attentional control can lead to important insights as to the nature of any multilingual cognitive advantage. Index measures that consider multiple facets of multilingual experiences might be of great value in detailing the intricate link between multilingualism and cognition. A single metric integrating multiple aspects of multilingualism has the potential to avoid problems of collinearity between different multilingual language use factors and reduce multiple testing confounds. A multilingual language entropy measure is promising in this regard: it considers not only the number of spoken languages but notably also the percentage of time they are spoken [24]. Language entropy therefore indexes the relative balance, and thereby diversity, in multilingual

language use of an individual. Most notably, the relationship between different individual language experience factors, specifically language entropy, and attention has not been studied before.

The goal of the current study is therefore to evaluate the relation between language entropy and selective attention in a population of multilingual young adults, while also exploring the effect of other multilingual language use and experience factors. It is hypothesized that language entropy relates to enhanced selective attention as measured by means of the attentional blink task. Multilingual individuals with higher language entropy indices are expected to be better in regulating the flow of information presented in the AB task, reflected in overall higher levels of target accuracy and a smaller attentional blink.

Speaking multiple languages has been shown to influence not only cognitive functioning, but also the neural networks involved in performing the cognitive tasks. Although ample work has examined the potential neurocognitive effects of individual multilingual life experiences (see above), none of this work has targeted attentional tasks specifically. The few studies that have addressed this issue suggest that multilinguals exert greater left prefrontal activation during cognitive control tasks requiring attentional systems [57–59]. The current study aims to advance insight of how individual variations in multilingual experiences impact brain functioning involved in selective attention. It is hypothesized that individuals with higher language entropy recruit left prefrontal brain areas to a larger extent compared to individuals with lower entropy.

Method

Participants

Fifty-five first-year students (33 females) participated in the study, all of whom were enrolled in the English track of the psychology undergraduate degree program of the University of Groningen in the Netherlands. This track is especially chosen by non-Dutch speakers, most pertinently German L1 speakers. To be eligible for participation in the study and to ensure some homogeneity, students had to speak German on a native level. It was reasonable to assume that this population spoke at least also English (given that proficiency in English is an admission requirement, and given that it is the

language of instruction of their degree program) and likely also other languages to various degrees. More details as to the participants' language background can be found in the Results section below. Participants received study credits for their participation. The study was approved by the local ethics committee of the faculty of Behavioral and Social Sciences of the University of Groningen and written informed consent was given by all participants.

Materials, equipment, and procedure

After obtaining demographic information pertaining to age, sex, nationality, and education, participants completed the Language Experience and Proficiency Questionnaire (LEAP-Q; [60]) and the Bilingual Switching Questionnaire [61] to elicit information on language use and language switching behavior, respectively. Participants also performed a language proficiency task for German and English (see below for details) and an attentional blink (AB) task. During the AB task, functional near-Infrared Spectroscopy (fNIRS) measurements were taken to measure brain activity. Due to technical issues, fNIRS was only recorded for a subset of the participants ($n=27$). The questionnaires and tasks were always administered in the same fixed order.

Language use, experience, and background

Language use, experience, background and self-rated proficiency were assessed using a slightly modified version of the German LEAP-Q [60]. It assessed language use information including 1) mastered languages, 2) how often - at the time of testing - participants used and were exposed to their indicated spoken languages (indicated as the percentage of time but also whether they spoke the language on a daily/weekly/monthly basis), 3) the age of acquisition (defined as the onset of learning; in years) for German and English, 4) the culture with which they identified most (open question; not used in current analyses), 5) how they rated their own German and English proficiency (on a scale from 0-10) for reading, writing, speaking, and listening skills, and 6) how frequently (on a scale from 0-10) they were exposed to German and English while interacting with family or friends or when listening to radio/music or TV. Language attitude towards German and English was assessed on the

basis of two additional questions: ‘I enjoy speaking this language’ and ‘It is important for me to be able to speak this language’, to which participants responded on a 5-point Likert scale, ranging from ‘strongly disagree’ to ‘strongly agree’. While not in the original questionnaire, such attitudinal factors were deemed important, as they have been found to exert an influence on any effects to ensue from multilingualism (cf. [9]).

Language switching

Information about language switching behavior was collected using a German translation of the BSWQ [61]. Although the original BSWQ consists of 12 items that tap into switching, in the current study four of the items were conflated into two items for efficiency reasons, resulting in a total of 10 items (see Supporting Information S1 File for the questionnaire). Questions were answered on a 5-point Likert scale ranging from 1 (never) to 5 (always). The resulting switching score is the sum of all items and indexes a tendency to switch between languages. Additionally, this score was decomposed into a contextual switch sub score, which indicates a tendency to switch languages in particular contexts, a general language switch score to indicate a tendency to switch from German to English overall, or vice versa, and an unintentional switch score to measure the degree of (un)awareness of switches [61].

Language proficiency

In addition to the self-reported language proficiency collected by means of the LEAP-Q questionnaires, objective language proficiency was assessed using the LexTALE language proficiency test [62]. The LexTALE is a short test to measure vocabulary knowledge, is easy and quick to administer, and is frequently employed as a language proficiency measure [13]. The test comprises 60 words, 20 of which are non-words, and the participant is asked to identify which words are existing words and which are non-words. The percentage of correct responses, corrected for the unequal proportion of existing words and non-words, is the resulting score. The test was performed twice, once for German and once English (in that order).

Stimuli and design attentional blink task

Participants performed an attentional blink (AB) task, requiring them to identify two target letters amongst a rapid stream of digit distractors based on Wierda et al. [51]. The AB task was presented using E-Prime software (version 2.0.10.353), on a PC running windows 7 and a CRT monitor running at a 100 Hz refresh rate, at a viewing distance of approximately 50 cm. Stimuli consisted of digits (2-9) and letters (only consonants, excluding “Q”, “V” and “Y”). All stimuli were presented in black on a white background.

The task comprised one practice block containing 24 trials and four experimental blocks containing 96 trials each. At the beginning of the experiment, participants were first shown an instruction screen describing the task, after which they pressed ‘Enter’ to initiate the task. Each trial started with a fixation cross, which was shown for 750 ms, followed by a blank screen for 100 ms. Subsequently, a rapid visual presentation (RSVP) stream was presented, containing 16 stimuli, each sequentially presented for 90 ms with no inter-stimulus interval. Per block of 94 trials, 50% of the trials presented two targets; 25% of the trials presented a single target and another 25% presented no targets. In all trials with at least one target, the first target (T1) was presented as the fifth item in the stream. In dual-target trials, the second target (T2) was either the third (Lag 3; 50% of dual-target trials) or eighth item (Lag 8) following the first target (T1) in the stream. Typically, the second target is more likely to be missed (i.e. an attentional blink occurs) when presented at Lag 3 than at Lag 8 [35,39]. A trigger was furthermore sent to the NIRS equipment at the onset of each trial (i.e., at the beginning of the stream; see below for more details), and when T1 and T2 were presented.

At the end of the stream, participants were asked to identify the targets in the order in which they had seen them using a keyboard. If the participants had seen no target or failed to recall it, they were asked to press the “spacebar” instead. This meant that – also when there was no first and/or second target – two responses were always required. Subsequent trials did not start until trial responses were given to the current one. Once participants had finished a block, they were given the opportunity

to take a break, and they were instructed to press ‘Enter’ once they were ready to continue. The entire AB task including the practice block took approximately 30 minutes to complete.

fNIRS data acquisition

Brain activity during performance of the AB task was measured using Functional Near-Infrared Spectroscopy (fNIRS). fNIRS is a non-invasive technique that measures the level of oxygenated- and de-oxygenated hemoglobin in the cerebral blood flow [63]. Continuous hemodynamic data were recorded using the NIRScout imaging system and NIRxStar software (NIRx, Berlin, Germany). The sampling rate was approximately 7.8 Hz. In total, 16 optodes (8 sources, 8 detectors) with dual-wavelength (760 and 850 nm) were symmetrically placed in a textile cap (EasyCap, Herrsching, Germany) on the head of the participant, with inter-optode distances from approximately 1.5 to 3 cm (see Table 1 for specific distances for each channel). On each hemisphere, 11 channels (i.e., 11 combinations of 1 source and 1 detector) covered the dorsolateral prefrontal cortex (DLPFC), as shown in Fig 1. The AB task was synchronized with the fNIRS data acquisition. A subject-paced start of each trial provided sufficient trial-to-trial jitter needed for efficient modeling of the BOLD responses recorded by means of the fNIRS set-up. Participants were instructed to move as little as possible during the AB task to minimize the effect of motion on the fNIRS measurement.

Fig 1. Optode placement. Placements of the optodes demonstrated in (a) 2D probe geometry; (b) 2D probe geometry placed on the 10-20 International System map; (c) 3D probe geometry (right view), and (d) 3D probe geometry (frontal view). Sources (S) are presented in red, detectors (D) in blue. A channel is a combination between a source and a detector. L = left hemisphere, R = right hemisphere. Probes were registered to the Colin27 atlas for 3D geometry.

Table 1. Source detector channels and their distances

Channel	Source	Detector	Distance (mm)
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1	1	1	30.40
2	1	3	31.59
3	2	1	30.49
4	2	2	30.77
5	2	4	15.41
6	3	1	20.32
7	3	2	33.16
8	3	3	20.18
9	3	4	36.23
10	4	1	32.93
11	4	3	14.11
12	5	5	29.83
13	5	7	31.43
14	6	5	30.01
15	6	6	30.55
16	6	8	15.30
17	7	5	20.11
18	7	6	32.62
19	7	7	19.96
20	7	8	35.66
21	8	5	31.34
22	8	7	14.69

Data analysis

Data preparation

Questionnaire and AB-data preparation and analysis were done in the R programming environment [64]. Self-rated proficiency per language was initially subdivided in proficiency in speaking, reading, listening, and writing. A mean score over all four skills was calculated and this overall self-rated proficiency score was used in further analyses to reduce the total number of variables. The language entropy index was calculated using the `languageEntropy` syntax for R [24]; [24], which uses the following formula:

$$Entropy = \sum_{i=1}^n P_i \log_2(P_i)$$

where n represents the total number of possible languages that a given person is exposed to and P_i is the proportion of time that they are exposed to language i , as indicated on the LEAP-Q questionnaire. The entropy value is thus an indexical score on a continuum, ranging from using a single language (i.e. no language diversity, entropy = 0) to using two (or more) languages in a balanced fashion (i.e. high language diversity, entropy = $\log_2(\# \text{ languages})$). Note that neither end of the continuum reflects situations that frequently occur in real life. Nonetheless, the continuous scale of the entropy value allows for the assessment of language use in between these extremes.

Outcome measures of the AB task were mean T1 accuracy, conditional T2 accuracy (T2 accuracy given correct T1 identification; T2|T1) and attentional blink magnitude (defined below). Practice trials were left out of the analysis. Average T1 accuracy was calculated over all trials where a T1 occurred. Mean accuracies for conditional correct T2 identification (T2|T1) were calculated for each participant for Lag 3 and Lag 8. Based on the mean accuracies for identifying T1 and T2|T1 at Lag 3, the attentional blink magnitude was computed using the following formula [45]:

$$AB \text{ magnitude} = \frac{\overline{T1} - (T2|T1lag3)}{\overline{T1}} * 100\%$$

where $\overline{T1}$ is the mean accuracy of correctly identifying T1 over all trials in which a T1 occurred, and $T2|T1lag3$ is the accuracy of T2|T1 at Lag 3, given that T1 was correctly identified. Calculated in this manner, the AB magnitude represents the percentage of decrease in T2 performance at Lag 3, relative to average T1 performance. Similarly, AB magnitude at Lag 3 was also calculated relative to T2|T1 performance at Lag 8 instead of average T1 performance.

Behavioral analysis

Descriptive statistics were performed on multilingual experience factors to describe the sample. Pearson's correlations were calculated to check the degree of relatedness between continuous language experience factors and T1 and T2|T1 performance for all lags. To study the relation between language entropy and selective attention, two regression analyses were conducted using language entropy as

main predictor: one with mean T1 accuracy over all conditions in which a T1 occurred and one with AB magnitude as dependent variable. No covariates were added to the model. To detail and explore the individual multilingual experience factors that most strongly predict AB magnitude, a manual backward regression analysis was conducted. This model included 16 variables: language entropy, unintended switching, contextual switching, language switching, German and English AoA, subjective and objective German and English proficiency, German and English media and social exposure and attitude towards German and English as predictors. Variables that contributed least to the model were removed in a stepwise fashion, until all variables with a level of contribution below $p < 0.1$ were removed. Furthermore, one exploratory regression analysis was conducted including all 16 variables mentioned before, to explore the total amount of variance explained by the variety in multilingual experiences.

fNIRS data analysis

Initial processing of the fNIRS data signal was done using the NIRS toolbox (Brain AnalyzIR; available at: <https://github.com/huppertt/nirs-toolbox>), following processing recommendations [65]. Quality of the raw fNIRS signal was inspected visually and we used the QT-nirs toolbox (available at: <https://github.com/lpollonini/qt-nirs.git>) to further assess the quality. The QT-nirs toolbox assessed quality of the data by means of Scalp Coupling Index (threshold = 0.8) and peak power (threshold = 0.1) for each five-second time frame [66]. Time windows that exceeded these thresholds were considered of good quality. The percentage of good quality windows was calculated for each channel. Any given channel was considered of good quality if 75% of the time windows for this channel were of good quality. A participant was removed from further analysis if less than 90% (fewer than 22 out of 24) of the channels showed good quality. This was the case for 5 participants leaving 22 participants for the final fNIRS data analyses.

For each participant, the raw fNIRS intensity signal was converted to changes in optical density and then to changes in oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) [67]. Changes in hemoglobin were computed using the modified Beer-Lambert Law, with

a partial path length correction of 0.1. The optical properties used in the Beer-Lambert conversion were adopted from an earlier study [68]. A general linear model (GLM) was used for first-level (subject-level) analyses in which coefficients were obtained using the autoregressive iteratively-reweighted least squares (AR-IRLS) approach [69]. This robust statistical approach accounts for systemic physiological signals that cause serial auto-correlated noise and outliers due to motion artifacts, making it unnecessary to remove outlier channels [70]. A canonical double-gamma HRF function was used to model the hemodynamic response (oxy-Hb and deoxy-Hb) following the onset of trials (beginning of the stream). Two participants were identified as outlier at this point and were removed from further analyses (20 participants remaining).

The coefficients estimated in the first-level models were entered as dependent variables into a separate mixed-effects model. Task condition (no-target/single-target/Lag 3 blink/Lag 3 no-blink/Lag 8) was entered as predictor variable (fixed effect) and subject as a random effect. To compare differences in activation during the different task conditions, conditions were contrasted using t-tests. In addition, the contribution of language entropy was explored by adding this factor as a fixed effect variable to the mixed effects models. Multiple comparisons were controlled for by using the false discover rate (FDR) correction with the significance level set at .05 ($q \leq .05$) [71]. Only the results for oxygenated hemoglobin are discussed in the current study, as oxy-Hb is more sensitive to regional cerebral blood flow changes [72].

Results

Participant characteristics

All participants were highly proficient speakers of German and English. For most – but not all – participants German was the dominant language (L1) and English the second language (L2). Two participants were excluded from the analysis due to technical problems reading the data files of the AB task. The remaining 53 participants (33 females, 20 males) were 20.6 ($SD = 2.06$) year old on average, with an age range of 18 to 29. The number of spoken languages varied from two to five languages, with substantial variation in the languages themselves. In the overview in Table 2, spoken languages

are given in order of dominance, where L1 is the participants' most dominant language. Although 96% of the participants reported a German nationality, only 83% of the sample indicated German to be their L1.

Table 2. Languages reported by study sample (N = 53)

L1	N	L2		L3	N	L4	N	L5	
German	44	German	9	English	3	Dutch	11	Dutch	3
English	8	English	42	French	18	French	8	French	2
Dutch	1	Bulgarian	1	Spanish	11	Spanish	6	Latin	1
		Croatian	1	Dutch	6	Other ²	4	Turkish	1
				Latin	2	None	24	None	46
				Turkish	2				
				Other ¹	6				
				None	5				

¹others are: Macedonian, Portuguese, Russian, Thai, Vietnamese, Swahili

²other are: Croatian, Latin, Russian, Tagalog

Language experience factors

A summary of demographic and multilingual language experience and background variables is given in Table 3. There was substantial variation in the number of spoken languages and the self-indicated percentage of exposure to these languages. This variety is captured in the language entropy value as an index of language diversity, which showed quite some variability in the current sample. None of the participants were found to be on the extreme left end of the entropy continuum, where there is exposure to only one of the spoken languages.

Differences between German and English were significant for self-rated proficiency ($t = 7.77$, $p < .001$, German>English), objective proficiency ($t = 7.51$, $p < .001$, German>English), exposure to media ($t = -14.29$, $p < .001$, English>German), social networks ($t = 12.07$, $p < .001$, German>English), and language attitude ($t = -3.52$, $p < .001$, English>German), meaning that the language experience of German in our sample notably differed from their English language experience. Pearson correlations

were calculated to provide additional context about the current study sample (Fig 2). A higher language entropy value was moderately related to a lower tendency to switch between languages ($r = -.36$), and to less contextual language switching ($r = -.28$), but was not found to be related to unintended switches ($r = .04$).

Fig 2. Correlation matrix for all multilingual language experience and for attentional blink task performance factors. * indicates significant correlation (at significance level .05). The p-values are corrected for multiple inference using Holm's method.

Table 3. Demographic and language experience variables

Variable (unit / min and max answer)	Mean	SD	Min	Max
Age (years)	20.58	2.06	18	29
Education (years)	12.67	1.42	10	18
German AoA (years)	0.83	1.67	0	10
English AoA (years)	7.87	1.94	1	12
Number of spoken languages	2.96	0.83	2	5
L1 exposure (%)	54.19	17.80	15	94
L2 exposure (%)	37.15	15.94	5	85
L3 exposure (%)	6.73	11.88	0	50
L4 exposure (%)	3.16	4.62	0	15
L5 exposure (%)	4.28	5.07	0	12
Entropy (0-2.3)	1.16	0.33	0.37	1.82
Switching total (1-50)	27.55	5.55	17	43
Contextual switching (1-15)	8.77	2.52	4	14
Unintended switching (1-15)	5.72	2.21	3	12
Language switching (1-20)	13.05	2.00	9	19
German proficiency self-rated (1-10)	9.62	0.56	7.5	10
English proficiency self-rated (1-10)	8.52	0.87	5.75	10
German proficiency LexTALE (%)	86.64	6.08	73.25	97.5
English proficiency LexTALE (%)	75.26	9.21	52.5	95
German exposure media (1-10)	2.72	2.04	0	9
English exposure media (1-10)	8.00	1.75	2.5	10

German social network (1-10)	7.96	2.12	0	10
English social network (1-10)	3.31	1.88	0	9
German attitude (1-10)	4.33	0.79	2	5
English attitude (1-10)	4.76	0.42	2.2	5

L1 = most dominant language, L2 = second most dominant language, L3 = third most dominant

language, L4 = fourth most dominant language, L5 = fifth most dominant language, AoA = Age of Acquisition

Attentional blink performance

Regarding performance on the attentional blink task, accuracies in identifying the first and second target for all conditions are shown in Fig 3 (see Supporting Information S1 Table 1 for all accuracy percentages for each condition). Overall, participants showed a typical pattern of performance on the AB task: accuracy for identifying the first target (T1) was high for all lags, while accuracy for identifying the second target (T2|T1) at Lag 3 was clearly lower than at Lag 8. In relation to the correct rejection of targets in trials with no targets, there was a 98% ($SD = 5.29$) accuracy for correctly reporting that there was no T1, and 91% ($SD = 11.73$) accuracy for correctly reporting that there was no T2. The average AB magnitude, indicative of a decrease in T2|T1 performance relative to average T1 performance, was approximately 41% ($SD = 19.86$), reflecting a substantial AB [45]. However, there was considerable variability in AB magnitude, which ranged from 1% to approximately 89%. Pearson correlation coefficients showed that average T1 accuracy and AB magnitude correlated negatively ($r = -.48$; Fig 2).

Fig 3. Target accuracy on the Attentional Blink task. Mean percentages for correct report of T1 and T2|T1 (T2 given correct report of T1) as a function of lag (no-target trials, single-target trials, Lag 3 and Lag 8). T1 for no-target trials and T2|T1 for no-target and single-target trials represent correct rejections. Error bars reflect one standard error of the mean.

Language experience factors and attentional blink performance

The regression analyses showed that language entropy significantly predicted average T1 accuracy ($F(1,51) = 4.32, p = .046, R^2 = .08$, adjusted $R^2 = .06$; Table 4), but not AB magnitude ($F(1,51) = 2.96, p = .09, R^2 = .05$, adjusted $R^2 = .04$; Table 4). Both models explained a moderate amount of variance in the data [73]. However, neither model reached significance when tested against a Bonferroni-adjusted alpha level of .035 (.05/2, taking into account the intercorrelation between the two dependent variables [T1 accuracy and AB magnitude] of -.48;

<https://www.quantitativeskills.com/sisa/calculations/bonfer.htm>). When tested one-tailed, in accordance with the hypothesis of better target accuracy in relation to multilingualism, the effect on T1 accuracy was found to be significant at an alpha level of .035, but AB magnitude was not. When AB magnitude was calculated relative to T2/T1 performance at Lag 8 rather than average T1 performance, AB magnitude was also not significantly predicted by language entropy ($F(1,51) = 1.99, p = .17, R^2 = .04$, adjusted $R^2 = .02$). The Q-Q plot for the model showed acceptable symmetry to run a linear model.

Subsequently, to explore which multilingual language experience factors (language entropy, unintended switching, contextual switching, language switching, German and English objective LeXTALE proficiency, German and English overall self-reported proficiency, German and English AoA, German and English media exposure, social exposure and attitude) were predictors of AB magnitude, backward regression analyses was conducted. Attentional Blink magnitude was most strongly, but not significantly, predicted by language entropy and self-rated language proficiency in English ($F(1,50) = 3.28, p = .05, R^2 = .12$, adjusted $R^2 = .08$). The regression model with all 16 variables included showed that 30% of the variance was explained by the model ($R^2 = .30$, adjusted $R^2 = .00$). Again, in this regression model, language entropy ($p = .06$) and L2 self-rated proficiency ($p = .05$) predicted AB magnitude the best.

Table 4. Results of the regression analyses for performance on the Attentional Blink task.

Test	Predictor	β	Std. error	t	p	Adjusted R^2
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T1 Accuracy	Language Entropy	3.766	1.844	2.042	.046	.058
AB	Language Entropy	-14.124	8.209	-1.721	.091	.039
magnitude						
AB	Language Entropy	-5.662	3.049	-1.857	.069	.080
magnitude	English proficiency self-rated	-14.930	8.030	-1.859	.069	

Prefrontal cortex activation during the attentional blink task

The effect of task condition (no-target, single-target, Lag 3 blink, Lag 3 no-blink, and Lag 8) on prefrontal cortex (PFC) activation was measured by means of fNIRS. Activation maps of the different conditions are presented in Fig 4. Contrast analyses showed differences between the task conditions (see Table 5). Compared to the no-target task condition, all other conditions yielded larger levels of activity, indicated by an increase in oxygenated hemoglobin levels, for multiple channels mainly covering the left hemisphere. Lag 3 blink trials only showed higher levels of activity compared to single-target trials in multiple left hemisphere channels, whereas Lag 3 no-blink trials yielded higher levels of activity compared to no-target, single-target and Lag 8 trials in channels covering both the left and right hemisphere. No significant differences ($q < .05$) in oxygenated hemoglobin levels were found when comparing Lag 3 blink to no-blink trials.

Relation between PFC activation during the AB task and language entropy

To explore effects of language entropy on activation in the PFC during AB task performance, language entropy was added to the mixed effects model as a fixed effect. On the left hemisphere, language entropy was related to a significant increase in oxygenated hemoglobin (oxy-Hb) levels in source-detector combination 2-1 ($\beta = 34.73$, $t(99) = 4.14$, $q = .003$), and in source-detector combination 3-2 ($\beta = 25.16$, $t(99) = 3.78$, $q = .009$). There also was a significant increase in oxy-Hb on the right hemisphere for source-detector combination 5-5 ($\beta = 31.51$, $t(99) = 3.99$, $q = .005$), and in source-detector combination 8-5 ($\beta = 25.33$, $t(99) = 3.39$, $q = .018$). These associations between activation during the attentional blink task and language entropy are shown in Fig 5.

Fig 4. Changes in cerebral activation during attentional blink task. Group-level analysis of oxygenated hemoglobin changes for the four task conditions in all channels; color bar represents the t-statistic value with red/blue indicating a statistical increase/decrease in oxygenated hemoglobin concentration during the task relative to the baseline period; all images are thresholded at $p < .05$, FDR corrected; locations of the fNIRS sensors were overlaid on the Colin27 atlas template for display purposes. 2D probe geometry is shown on the right.

Table 5. Significant differences between task conditions for changes in oxygenated hemoglobin (oxy-Hb)

hemisphere	source	detector	contrast	beta	se	tstat	dfe	p	q
L	3	3	No-target vs single-target	7.47	2.13	3.50	95	.001	.016
L	4	3	No-target vs single-target	6.60	1.84	3.59	95	.001	.016
L	1	1	No-target vs Lag 8	7.44	2.14	3.48	95	.001	.007
L	3	2	No-target vs Lag 8	4.56	1.04	4.40	95	.000	.000
L	3	3	No-target vs Lag 8	12.00	2.14	5.62	95	.000	.000
L	3	4	No-target vs Lag 8	3.71	1.04	3.55	95	.001	.007
L	4	3	No-target vs Lag 8	8.22	1.86	4.43	95	.000	.000
L	1	1	No-target vs Lag 3 no-blink	26.46	4.24	6.25	95	.000	.000
L	1	3	No-target vs Lag 3 no-blink	43.13	6.93	6.22	95	.000	.000
L	2	2	No-target vs Lag 3 no-blink	15.86	4.72	3.36	95	.001	.006
L	3	1	No-target vs Lag 3 no-blink	26.96	5.74	4.69	95	.000	.000
L	3	2	No-target vs Lag 3 no-blink	6.33	2.09	3.03	95	.003	.012
L	3	3	No-target vs Lag 3 no-blink	24.41	4.21	5.79	95	.000	.000
L	3	4	No-target vs Lag 3 no-blink	9.25	2.07	4.46	95	.000	.000
L	4	3	No-target vs Lag 3 no-blink	10.62	3.52	3.01	95	.003	.012
R	5	7	No-target vs Lag 3 no-blink	14.66	5.99	2.45	95	.016	.045
R	6	5	No-target vs Lag 3 no-blink	11.46	4.40	2.60	95	.011	.034
R	6	8	No-target vs Lag 3 no-blink	18.39	4.32	4.26	95	.000	.000
R	8	7	No-target vs Lag 3 no-blink	8.55	2.86	2.99	95	.004	.012
L	1	1	No-target vs Lag 3 blink	30.95	5.75	5.38	95	.000	.000
L	1	3	No-target vs Lag 3 blink	47.90	9.68	4.95	95	.000	.000

L	3	1	No-target vs Lag 3 blink	28.28	8.06	3.51	95	.001	.006
L	3	2	No-target vs Lag 3 blink	10.75	2.98	3.60	95	.001	.006
L	3	3	No-target vs Lag 3 blink	26.92	5.93	4.54	95	.000	.000
L	3	4	No-target vs Lag 3 blink	8.79	2.99	2.94	95	.004	.030
L	1	1	Single-target vs Lag 3 no-blink	22.36	4.23	5.29	95	.000	.000
L	1	3	Single-target vs Lag 3 no-blink	36.94	6.93	5.33	95	.000	.000
L	2	2	Single-target vs Lag 3 no-blink	15.51	4.73	3.28	95	.001	.008
L	3	1	Single-target vs Lag 3 no-blink	23.55	5.75	4.10	95	.000	.001
L	3	3	Single-target vs Lag 3 no-blink	16.94	4.22	4.02	95	.000	.001
L	3	4	Single-target vs Lag 3 no-blink	8.03	2.07	3.87	95	.000	.001
R	6	8	Single-target vs Lag 3 no-blink	16.53	4.28	3.87	95	.000	.001
L	1	1	Single-target vs Lag 3 blink	26.85	5.76	4.66	95	.000	.000
L	1	3	Single-target vs Lag 3 blink	41.71	9.68	4.31	95	.000	.001
L	3	1	Single-target vs Lag 3 blink	24.87	8.05	3.09	95	.003	.025
L	3	2	Single-target vs Lag 3 blink	9.17	3.00	3.06	95	.003	.025
L	3	3	Single-target vs Lag 3 blink	19.46	5.93	3.28	95	.001	.021
L	1	1	Lag 8 vs Lag 3 no-blink	19.02	4.23	4.50	95	.000	.000
L	1	3	Lag 8 vs Lag 3 no-blink	34.66	6.93	5.00	95	.000	.000
L	2	2	Lag 8 vs Lag 3 no-blink	13.52	4.72	2.86	95	.005	.023
L	3	1	Lag 8 vs Lag 3 no-blink	19.98	5.74	3.48	95	.001	.011
L	3	3	Lag 8 vs Lag 3 no-blink	12.41	4.22	2.94	95	.004	.020
L	3	4	Lag 8 vs Lag 3 no-blink	5.55	2.08	2.67	95	.009	.033
R	5	7	Lag 8 vs Lag 3 no-blink	14.99	5.98	2.51	95	.014	.045
R	6	8	Lag 8 vs Lag 3 no-blink	13.93	4.25	3.28	95	.001	.013
R	7	5	Lag 8 vs Lag 3 no-blink	16.09	5.37	3.00	95	.003	.019
R	7	8	Lag 8 vs Lag 3 no-blink	5.80	1.88	3.08	95	.003	.019
R	8	7	Lag 8 vs Lag 3 no-blink	8.00	2.86	2.80	95	.006	.025
L	1	1	Lag 3 vs Lag 3 blink	23.50	5.76	4.08	95	.000	.002
L	1	3	Lag 3 vs Lag 3 blink	39.43	9.69	4.07	95	.000	.002

Table 6. Effect of language entropy on oxygenated hemoglobin (oxy-Hb)

hemisphere	source	detector	beta	se	tstat	dfe	p	q
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L	2	1	34.73	8.40	4.14	99	.000	.003
L	3	2	25.16	6.66	3.78	99	.000	.009
R	5	5	31.51	7.90	3.99	99	.000	.005
R	8	5	25.33	7.47	3.39	99	.001	.018

Fig 5. Association between activation (oxy-Hb) during the attentional blink task and language entropy. Scatterplot showing association between mean attentional blink related activation over all task conditions and language entropy, for (a) source detector combination 2-1 on the left hemisphere ($r = .55, p = .012$); (b) source detector combination 3-2 on the left hemisphere ($r = .49, p = .029$); (c) source detector combination 5-5 on the right hemisphere ($r = .45, p = .047$); (d) source detector combination 8-5 on the right hemisphere ($r = .35, p = .127$).

Discussion and conclusion

Multilingual language use and experiences differ per multilingual individual. Certain experience factors involved in multilingualism have been claimed to lead to cognitive benefits, perhaps especially to benefits in selective attention. The aim of the current study was to understand whether individual differences in language experience and language use are related to individual differences in temporal selective attention as measured in an attentional blink task. Individual differences in multilingualism could form an explanation for reported inconsistencies related to the acclaimed attentional benefits of speaking multiple languages. Additionally, brain activity during performance of the attentional blink task was measured to understand whether and how multilingualism affects prefrontal cortex functioning during selective attention, resulting in an integrative investigation that combined behavioral and neurophysiological measures.

As typically found in AB studies (cf. [39]), identification performance of the first target was observed to be high, whereas there was a marked decrement in identification performance for the second target when it occurred in close temporal proximity of the first target. We hypothesized that

individuals with higher language diversity would be better at temporally integrating incoming information and therefore show a smaller blink. However, no significant effect of language entropy on attention was found for AB magnitude and an observed positive effect of language entropy on T1 performance did not survive multiple comparison correction. The current results partially confirm earlier studies that also failed to link continuous variation in individual language factors to the AB [56]. At the same time, they contradict earlier categorical studies that found either a detrimental [53,54] or a beneficial [32,34] effect of multilingualism on selective attention. Therefore, currently, no solid support for the hypothesis that multilingual experience relates to enhanced attentional performance can be provided.

Inconsistencies in previous and current findings may relate to the fact that the current study (like the study by Yamasaki et al. [74]) looked at individual differences in language experience while others compared monolinguals to multilinguals. Individual differences in multilingual experiences have received increasing attention, as they are suggested to account for the inconsistent findings reported in studies that compare cognitive performance of people who speak a single language vs multiple languages. However, in the current study, individual differences in language entropy did not significantly predict AB magnitude, even when considering all other multilingual language use and experience factors as predictors.

The results of our study thus do not directly indicate that there is enhanced attentional control in relation to multilingualism, but neither do they show that the effect is completely absent, especially for T1 accuracy. Higher language entropy related to higher average T1 accuracy which may be indicative of efficiency in monitoring information that is competing for selection [43,44]. Average T1 accuracy and AB magnitude were furthermore negatively correlated, indicating that those with higher T1 accuracy and higher language entropy show smaller ABs, which was also the case trend-wise. This could indicate that language diversity relates to an overall better efficiency in monitoring information that is competing for selection. This conclusion is in line with Yamasaki and colleagues' [74] findings showing that multilinguals who use multiple languages in a balanced way show better attentional filtering.

Whether the influence of multilingual experiences does apply to other tasks measuring other (spatial) components of selective attention is therefore still an open question. Literature often refers to three different selective attention systems: alerting, orienting, and executive attention [75,76]. The alerting system maintains alertness and a responsive state. The orienting system regulates the ability to focus and sustain attention on relevant stimuli. The executive system allows conflict resolution and stimulus selection. Recent studies have found that the bilingual context can modulate selective attention in the alerting and executive control networks, but not the orienting network [34,77]. As the AB task is a temporal measure of attention orienting, this could explain why in the current study no significant effects on attention were found. In this light, our results would support the suggestion that multilingual language-use factors do not influence processes related to the initial orientation of attention. Nevertheless, the observed positive relation between entropy and T1 accuracy (though not surviving multiple comparison correction) leaves room for the possibility that multilingual experience factors do influence some form of alertness or more conscious control processes that happen at a later stage of attention, supporting earlier work [34,77]. The specificity of this suggestion however deserves further study.

Importantly, while current behavioral findings provide neither evidence in favor nor against the claim that multilingualism relates to a cognitive advantage in the realm of selective attention, this is different for the neural findings. There does appear to be an effect on brain activity, even in the absence of formal behavioral effects, a trend that has been observed before [27,28,78]. Higher language entropy values related to higher oxy-Hb levels in left lateral PVC, and higher levels of oxy-Hb in the right DLPFC. These results support our hypothesis and are in line with earlier studies showing greater left lateral prefrontal activation for multilinguals [57–59]. Intriguingly, the neural effect of language entropy did not differ per AB task condition. This suggests that language diversity may not influence the specific AB process but may instead have a positive effect on general alertness and attention, reflective of the subthreshold positive effect on T1 accuracy. The diversity and intensity with which one is exposed to and uses multiple languages thus seems, at least at a neural level, related to attentional control. This suggests that the way multilingual individuals use their languages is of

great importance in determining demands on attentional control, which is in line with current perspectives of multilingualism [79–81].

Notably, an important caveat of the current study is the sample that was used which resulted in relatively low linguistic diversity. By selecting participants from a pool of students in the English track of the psychology undergraduate degree program of the University of Groningen in the Netherlands, the current sample was limited to participants who mostly spoke L1 German and L2 English, because the majority of students from the international track came from Germany. Only 19 out of 53 participants indicated to use Dutch in their daily lives, while living in the Netherlands. Furthermore, variation in dialect use was not taken into account, potentially underestimating language diversity. Given the current sample, it is most likely that different languages are spoken in different contexts: German mostly in social contexts and English mostly in the context of education. Dutch, then, may be restricted to everyday encounters and perhaps extending to some social circles. The entropy index in the current study might therefore not be an accurate representation: instead of indicating language diversity within a certain social context (i.e. home/work/school, etc.), language entropy in the current study reflected the diversity and balance of use of different languages across different contexts. It is precisely the variable control demands of different communicative contexts, determined by the diversity within an interactional context, and habits of language use (e.g. switching) that were found to determine attentional engagement and state [82]. This prompts not only the need for a characterization of individual differences in language use and experience, and of the language diversity in different interactional contexts and their attentional demands, but also of language use within the different contexts.

Language entropy as a multifaceted measure may still be too simplistic to encompass the complexity of a multilingual experience. Doing justice to language use in different contexts is difficult to encompass in a single measure. What is more, past studies have amply acknowledged that language use dynamics are not static. Languages are used with varying intensities throughout life. This dynamic experience, in which language use but also proficiency and other factors play a role and interact, is difficult to capture in one measure. Indeed, a single index to capture the multilingual experience could improve clarity and comparability across studies detailing the cognitive effects to ensue from

multilingual experiences [13], but may not do sufficient justice to the diversity of any multilingual experience. To be able to conclude that language diversity has no effect on selective attention, however, the absence of such effect has yet to be confirmed in a larger sample, capturing language diversity for different contexts in addition to general language diversity.

To conclude, studying differences in individual multilingual experiences in relation to selective attention can advance our understanding of the nature of any multilingual cognitive advantage. Based on the results of the present study, we cannot conclude that language diversity influences selective attention processes in the AB task at the behavioral level in healthy and highly educated young adults. Other factors related to language use and language experience also failed to predict differences in selective attention. This does not mean that language diversity and the multilingual experience in general could not influence other attentional processes, measured with other tasks, or mental flexibility and alertness in general. Moreover, at the neural level, we did find significantly greater prefrontal activation for individuals scoring high on language entropy, thus underscoring the importance of looking at multilingualism effects holistically, integrating behavioral and neurophysiological measures. Future research would do well to explore the relationship between other aspects of attention, language diversity and other multilingual experience and use factors in greater detail, also including language use within and across different contexts.

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Supporting information

S1 Table. Summary statistics for the attentional blink task.

S1 File. Questionnaire LEAP-Q. Adapted version of the German LEAP-Q that was administered to the participants.