Less is more:

Depleting cognitive resources enhances language learning abilities in adults

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Word count: 6786

Pre-registered at https://osf.io/de5na

Data and materials at https://osf.io/fegb2

Abstract

It is still an unresolved question why adults do not learn languages as effortlessly as children do. We tested the hypothesis that the higher cognitive control abilities in adults interfere with implicit learning mechanisms relevant for language acquisition. Across two days, Dutch-speaking adults were asked to rapidly recite novel syllable strings in which, unannounced to the participants, the allowed position of a phoneme depended on another adjacent phoneme. Their cognitive control system was either depleted or not depleted prior to learning, after performing an individually tailored dual-working memory task under high or low cognitive load. A third group did not perform any cognitive task prior to training. Speech error analyses revealed stronger (and faster) learning of the novel phoneme combination constraints in the cognitively depleted group compared with the other two groups. This indicates that late-developing cognitive control abilities, and in particular attentional control, constitute an important antagonist of implicit learning behavior relevant for language acquisition. These findings offer novel insights into developmental changes in implicit learning mechanisms and how to alter them temporarily in order to improve language skills in adults.

Key words*:* cognitive depletion, implicit learning, language acquisition, phonotactic constraints, speech errors

The ability to acquire language is essential and unique to humanity. However, language acquisition becomes more difficult with age (Lenneberg, 1967; Newport, 1990). Children seem to acquire first and/or second language(s) relatively easily, particularly for sequential properties such as phonology or grammar, when compared to adults (Newport, Bavelier, & Neville, 2001). The reason why remains unclear (Kennedy & Norman, 2005; Thiessen, Girard, & Erickson, 2016). Adults outperform children on almost every other measure of cognitive ability (Craik & Bialystok, 2006). Yet, they fail learning language with the apparent ease that children do. This is also referred to as the sensitive period hypothesis: there seems to be a maturational window in which young learners are maximally prepared to acquire language (Thiessen et al., 2016). In the present study, we aim to present evidence for the hypothesis that adult's higher cognitive control abilities, especially those that rely on a late-developing prefrontal system such as attentional control, interfere with implicit, statistical learning mechanisms that are important for language acquisition in children. Our rationale relies on a generalization of evidence from the field of skill learning to the field of language acquisition.

Human learning is supported by two memory systems that maturate at different rates across the life span (Poldrack et al., 2001; Ullman, 2004). The declarative memory system is characterized by voluntary processes that rely on cognitive-control abilities such as attention and working memory, supporting explicit learning (e.g., of facts and episodes) (Ullman, 2004). This system is mediated by late-developing prefrontal and medial-temporal lobe structures (see also, Poldrack & Packard, 2003). Procedural memory on the other hand is part of implicit memory, mediated by early-developed striatal structures (Poldrack & Packard, 2003), as well as the cerebellum and parts of the frontal cortex (e.g., Broca's area) (De Vries et al., 2010; Pascual-Leone, Wassermann, Grafman, & Hallett, 1996; Uddén et al., 2008; Ullman, 2004, 2006). Learning in the procedural system takes place without the intention to do so and allowing the implicit acquisition of regularities in the environment, such as for instance transitional probabilities of successive syllables in spoken words (Cleeremans, Destrebecqz, & Boyer, 1998; Squire & Dede, 2015). We will refer to this as implicit or statistical learning. Each of these two memory systems has its own characteristics and a differential reliance on either of them may explain developmental differences and/or difficulties with learning (Krishnan, Watkins, & Bishop, 2016; Smalle, Page, Duyck, Edwards, & Szmalec, 2018).

Although the declarative and procedural memory system are known to support human learning in mostly cooperative ways, they may also compete with each other (Poldrack et al., 2001; Poldrack & Packard, 2003). For example, the declarative and procedural memory systems are known to interfere mutually during offline memory consolidation (Brown & Robertson, 2007). As for the procedural system, surprising evidence from the human skill learning literature shows enhanced implicit learning in conditions where declarative memory resources are limited due to, for instance, hypnosis, transcranial magnetic disruption of prefrontal activity, intake of benzodiazepines, alcohol consumption, and/or distraction tasks (Ambrus et al., 2020; Foerde, Knowlton, & Poldrack, 2006; Frank, O'Reilly, & Curran, 2006; Galea, Albert, Ditye, & Miall, 2010; Nemeth, Janacsek, Polner, & Kovacs, 2013; Virag et al., 2015). Moreover, prior developmental work suggests that children are better implicit skill learners than adults due to an underdeveloped cognitive control system associated with the declarative memory system (Janacsek, Fiser, & Nemeth, 2012; Juhasz, Nemeth, & Janacsek, 2019). Cognitive control processes come online at around 12 and are useful for more targeted explicit learning but this comes at a cost for pure implicit skill learning abilities (Nemeth, Janacsek, & Fiser, 2013).

Recently, Borragán and colleagues showed that mental or *cognitive fatigue*, which is defined as the decrease in sustained attentional control abilities not caused by sleepiness

(Borragan, Slama, Bartolomei, & Peigneux, 2017), can facilitate performance on an implicit serial-reaction time (SRT) task (Borragán, Slama, Destrebecqz, & Peigneux, 2016). Performance on the SRT task is a commonly used parameter for measuring implicit statistical learning within the perceptual motor domain (Robertson, 2007; Song, Howard, & Howard, 2008). In an SRT task, participants are asked to repeatedly respond to a fixed set of stimuli in which a particular visual cue (e.g., location on the screen) signals to the participant that a particular response (i.e., button press) has to be made. Unknown to the participant, transitional probabilities exist between the position of the cues so that the required responses become increasingly predictable. This becomes reflected in a decrease of response times for sequence trials compared with random trials; taken as evidence for implicit learning of a novel perceptual-motor skill (Robertson, 2007). Borragán and colleagues introduced their participants to an individually tailored dual working-memory task, called the TloadDback task, prior to training on this SRT task (Borragán et al., 2016). In the TloadDback task, participants are asked to perform two simultaneously-ongoing tasks (i.e., parity number decision and 1-back letter memory) at either their maximum processing speed capacity or at half of their maximum speed capacity, which is pretested within subjects during a separate session. Due to the constrained time to process two ongoing cognitive demands, a maximum speed condition will tax the individual's cognitive resources more heavily, so that limited attention remains for processing incoming information (Borragan et al., 2017). This leads to overall weaker cognitive performance (e.g., decreased dual-task accuracy) as well as long-lasting changes in spontaneous beta and alpha power oscillations in frontal cognitive-control regions that are associated with feelings of cognitive exhaustion (Käthner, Wriessnegger, Müller-Putz, Kübler, & Halder, 2014; Shigihara et al., 2013). As a consequence, performing the TloadDback task at maximum speed capacity (i.e., under high cognitive load) results in cognitive depletion and an increased state of mental or cognitive fatigue, highly associated with temporary impairments in cognitive control, in high-level information processing and in sustained attention on subsequent tasks (Borragan et al., 2017). Cognitive depletion can then be demonstrated as a decrease in actual dual task performance (i.e., decreased accuracy on the TloadDback task) and a decrease in alertness on a subsequent psychomotor vigilance task (see Supplementary Data of Borragan et al., 2017). It can also be demonstrated rather subjectively as an increased feeling of mental fatigue on a pre versus post-task rating scale for fatigue (Borragan et al., 2017; Borragán et al., 2016). Interestingly, the authors observed facilitated performance, rather that impairment, on the SRT task after performing the TloadDback task under high cognitive load (i.e., at maximum speed) compared with performing the task under low cognitive load (i.e., at half of maximum speed). This indicates that cognitive depletion facilitates implicit perceptual-motor sequence learning. Their findings strongly suggests that higher cognitive-control abilities, particularly attentional control that supports the declarative memory system, compete with implicit learning mechanisms involved in human skill acquisition.

Although the hypothesis of competing cognitive and procedural memory mechanisms during learning is gaining some attention within the field of language learning (e.g., Cochran, McDonald, & Parault, 1999; Finn, Lee, Kraus, & Hudson Kam, 2014; Smalle, Panouilleres, Szmalec, & Möttönen, 2017), direct experimental evidence remains limited (Thiessen et al., 2016). Recently, one of our own studies showed that a temporary disruption by Theta-Burst Stimulation of the left Dorsolateral Prefrontal Cortex (DLPFC), an area that is strongly associated with the higher cognitive (control) system, improved performance on a novel-word memorization task (Smalle, Panouilleres, et al., 2017). In this study, adult participants were asked to immediately recall sequences of syllables that occasionally repeat in the same order every n^{th} trial. The sequence repetition was not announced to the participants. We observed that memory for the repeated syllable sequences, but not for the unrepeated syllable sequences, increased following the disruption. This suggests that late-developing prefrontal abilities can induce changes in efficiently picking up sequential language information in implicit memory (Thompson-Schill, Ramscar, & Chrysikou, 2009), a finding that is largely in line with previously reported evidence from the skill learning literature.

Language acquisition involves many different memory and learning processes, such as extracting statistical information on how sounds and words combine, word-segmentation abilities, and retention of word-to-referent mappings (Krishnan et al., 2016). A first step in acquiring language is gaining implicit knowledge about the phonological structure in one's spoken language system, i.e. learning the probabilistic constraints on how speech sounds combine. This is also referred to as *phonotactic* knowledge (e.g., English words never start with /ŋ/ at onset). We implicitly extract this knowledge from surrounding speech during infant language exposure (e.g., Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993), and the ability continues well into (late) adulthood with second language exposure (e.g., Onishi, Chambers, & Fisher, 2002). Indeed, accumulating evidence shows that both children and adults of different ages can rapidly pick up *new* phonotactic constraints in their spoken language (Anderson & Dell, 2018). This has been shown by looking at *speech errors*, which mirror implicitly gained knowledge of the phonotactic constraints in the spoken language. Speech always conforms to the phonotactic constraints of a language (Fromkin, 1971); and therefore, these constraints are rarely violated when speech errors are made. For instance, native English speakers will never erroneously slip the sound /ŋ/ to an onset word position because English words never start with /ŋ/. Since speakers do not intend to err, spontaneous speech errors reflect an unobtrusive, *implicit* measure for a speaker's acquired phonotactic knowledge (e.g., Warker, Dell, Whalen, & Gereg, 2008). In 2000, Dell and his team asked participants to recite written sequences of syllables (e.g. *hes feng nek tem*) at a fast pace in time with a metronome, to elicit spontaneous speech errors involving consonant movements (e.g. *hef seng)* (Dell, Reed, Adams, & Meyer, 2000). They registered how often consonants erroneously moved to the opposite syllable position as presented (i.e., from onset to coda or from coda to onset) *versus* the same syllable position (i.e., from onset to another onset or from coda to another coda). Importantly, in the paradigm, some consonants are constrained to one particular syllable position (i.e., onset or coda) conform the spoken language (e.g., in English, /ŋ/ always appears at coda while /h/ always appears at onset); and thus if such a consonant moves it should always be to the same, legal position (i.e., 100% of the errors should be "same-position"). Other consonant positions appear unrestricted, also consistent with the spoken language (e.g., In English, /f/, /m/, /n/, and /s/, /k/, /t/ appear both at onset and coda). For these unrestricted consonants, the percentage of errors that are "same-position" provides a baseline measure of the extent to which a participant's speech errors can preserve the syllable position within a trial. This is also called the syllable-position effect (Dell et al., 2000). Same-position slips for unrestricted consonants are between 25%-40% more frequent than would be predicted by chance. Thus, even though a consonant such as /f/ can be both onset and coda across the experiment, /f/ is more likely to slip to the same syllable position rather than to the opposite syllable position within the exposed sequence trial. Interestingly, two of the normally unrestricted consonants appear restricted within the setting of the experiment (e.g., /k/ always appears at onset while /t/ always appears at coda, or vice versa, in the experiment while they normally appear unrestricted in the spoken language). The key question is whether the percentage of same-position errors for the experimentally restricted consonants rises significantly above the unrestricted baseline rate (i.e., the percentage same-position slips for the unrestricted consonants). This would be evidence that novel phonotactic constraints have been acquired; the novel constraints significantly influence production (errors) in the longer term (i.e., across trials) that cannot be explained by correctly labeling the syllable position within the recited sequence (i.e., the syllable position effect). In other words, the difference between unrestricted and experimentally restricted same-position percentages is described as the phonotactic learning score (with positive values suggesting that phonotactic learning has taken place).

Dell and colleagues observed that participant's speech errors mirror new constraints after only limited exposure (< 96 trials). Moreover, they showed that this occurs irrespective of participant's awareness of the constraints, thus indicating rapid *implicit* learning of novel phonotactic constraints (Dell et al., 2000). The finding has, from then, been widely replicated; also with more complex, second-order constraints in which consonant positions depend on the medial vowel of the syllables (e.g., /k/ appears at onset and /t/ as coda when the vowel is /iː/ while the inverse is true when the vowel is /a/) (for a review, see Anderson & Dell, 2018). Interestingly for the current study, second-order constraint learning occurs slower, typically from a second day of training, after sleep, and is much weaker in adults than in children (Anderson & Dell, 2018; Smalle, Muylle, Szmalec, & Duyck, 2017). Moreover, children learn already on a first day of training (see, Smalle, Muylle, et al., 2017). This indicates that children are more efficient adapters to implicit changes in their existing phonotactic system than adults, which supports a sensitive period for at least some aspects of language acquisition such as phonology and grammar learning (Newport et al., 2001) .

In the present study, we aim to elicit enhanced second-order phonotactic constraint learning performance in adults, similar to what we see in children (cf. Smalle, Muylle et al., 2017), by putting the adults in a situation of limited cognitive control abilities. Cognitive depletion was experimentally manipulated prior to language training by presenting the TloadDback task at the participant's maximum speed level capacity (i.e., under high cognitive load) or at half of maximum speed (i.e., under low cognitive load) (Borragan et al., 2017; Borragán et al., 2016). We additionally exposed a third group of participants to the speech error task without letting them perform any cognitive load task prior to training. We added this extra control group because Borragán et al. (2017) showed that performing the TloadDback task under *low* cognitive load conditions can lead to feelings of boredom and sleepiness independently of cognitive fatigue (Borragan et al., 2017). This could result in overall decreased performance on (any) subsequent task, and may thus complicate the interpretation of our results on the speech error task. Overall, we predicted enhanced phonotactic constraint learning for the cognitively depleted group (i.e., the group who performed the dual task under high cognitive load) compared with the two other groups (i.e., the group who performed the dual task under low cognitive load and the extra control group who performed no dual task). The main focus of the study concerned the first training session (i.e., Day 1), because this is the time course during which child advantages are observed (Smalle, Muylle, et al., 2017). The second training session was added to confirm that all participants adopted the novel constraints in their production system following a night of sleep, as is typically seen in young adults (Anderson & Dell, 2018). If our predictions turn out to be correct, this would support the hypothesis that limited cognitive resources boost implicit learning mechanisms relevant for early language acquisition. The study design and predictions were preregistered in an Open Science Framework repository prior to data-collection: https://osf.io/de5na). The data transcription files and scripts for analyses are made available on https://osf.io/fegb2/.

1 Method

1.1 Participants

Thirty-six psychology students from Ghent University (Belgium) participated for course credits (average age = 19 years, range = 17-22 years, 29 females, 28 right-handed). We drew upon our prior developmental study to estimate the effect size for power calculations using G*power. The effect size *d* for our main behavioural measure of language learning (i.e., the phonotactic constraint learning score on Day 1) was 2.06 and for detecting an enhanced learning effect in children 1.14. As such, we estimated that at least a sample size of n = 11 is required to detect reliable phonotactic learning differences on the first day[1]. We thus decided to test 12 participants per group, similar to our previous work with this paradigm and other related work (e.g., Warker, 2013). Given the manipulation of cognitive depletion, participants who reported poor sleep quality during the month preceding the experiment (i.e., Pittsburgh Sleep Quality Index or PSQI > 9; Buysse, Reynolds, Monk, Berman, & Kupfer, 1989) were a priori excluded and replaced by new participants (8 in total), as pre-registered. The final groups had a comparable distribution in terms of gender (i.e., 10 females in both the high and no load group and 9 females in the low load group, respectively) and handedness (i.e., 10 right-handed participants in the high load group and 8 right-handed participants in the low and no cognitive load group, respectively). All participants were born and living in the Flemish part of Belgium and were native speakers of the spoken language at study (i.e., Dutch). They reported no history of neurological and/or developmental (language) disorders (e.g., dyslexia, dyscalculia) and all participants (except for

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[1] The following input parameters were used: tails = 1, effect size = 2.06 (1.14), α err prob = 0.05; Power (1-β err prob) = 0.80; Allocation ratio N2/N1 = 1. The following output parameters were obtained: Noncentrality parameter δ = 4.03 (2.61); Critical t = 2.42 (1.73); Df = 2.82 (19.01); Sample size = 4 (Sample size group 1 = 11; Sample size group 2 = 11); Actual power = 0.90 (0.81). In parentheses are the parameters for the estimated group effect. Non-parametric tests were used.

one, see footnote 2)[2] showed a neutral to moderate circadian chronotype (i.e., score between 31 and 69 on the morningness-eveningness questionnaire) (Horne & Östberg, 1976). Informed consent was obtained prior to the experiment and debriefing took place afterwards. The experiment was approved by the ethics committee of the Psychological Sciences Research Institute (IPSY) at the Université catholique de Louvain (reference: Projet2017-27).

1.2 Tasks and procedures

The experimental procedure is illustrated in Figure 1. On Day 0, all participants filled in the background questionnaires. The cognitive load participants were also pre-tested on the Time load Dual-back Task (Figure 1, dashed lines) in order to determine their maximum speed capacity on the task. On Day 1, the Time load Dual-back Task was presented under either high or low cognitive load conditions (details, see below). Participants were (randomly) assigned to one of these two experimental conditions. This was based on alternating the number of participants entering the study. A visual numeric rating scale for fatigue (1: I feel no fatigue to 10: I feel the worst possible fatigue) was presented immediately before and immediately after the dual task. Subsequently, participants were trained on the phonotactic constraint task. On Day 2, the exact same procedure was repeated. The extra control participants, who did not perform the TloadDback task prior to training, were immediately presented with the phonotactic constraint paradigm after filling in the background questionnaires and self-assessing their base level of fatigue on the visual rating scale. The experimental sessions for these control participants took place one month later than for the other participants.

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[2] One female participant had a score of 72 indicating borderline morning type. We left her included because her testing time (12 p.m.) did not interfere with her circadian rhythm (see pre-registration https://osf.io/de5na).

1.2.1 Time load Dual-back Task

The script of the dual working memory task is freely available on osf.io/ay6er (Borragan et al., 2017). For each participant, the minimal time needed for accurately processing two ongoing task demands, namely *n*-back letter detection and parity number decision, was defined with a pre-test on Day 0. Completion of this pre-test took approximately 35 minutes. During the dual task, digits (1, 2, 3, 4, 6, 7, 8 and 9) and letters (A, C, T, L, N, E, U and P) were presented in alternation on the screen. Participants were instructed to press the space bar with their left hand every time the displayed letter is the same as the last-seen letter, and to indicate with their right hand whether the subsequently displayed digit is odd (pressing "1" on the numeric keypad) or even (pressing "2"). Different levels of cognitive depletion were induced by presenting the two tasks at different paces based on the participant's pre-tested maximum processing speed. This is defined as the fastest stimulus time duration (STD) allowing an accuracy of at least 85%. STD was matched across the high and low cognitive load condition groups: i.e., $\text{STD}_{max} = 0.907_{M} \pm 0.188_{SD}$ vs. $\text{STD}_{max} = 0.873_{M} \pm 0.123_{SD}$, $t < 1$, respectively. Under the High Cognitive Load condition (HCL), the task was performed at the participant's maximum STD while under the Low Cognitive Load condition (LCL), the pace was slowed down with half of this speed (STD = max. STD + ½ max. STD). This results in different cognitive demands, with higher sustained attentional-control requirement for the former condition leading to a state of 'cognitive depletion' or 'cognitive fatigue' (Borragan et al., 2017; Borragán et al., 2016). The script was run in Matlab2016b/Psychtoolbox, on a Dell laptop (refresh rate 60Hz). The letters were centrally presented in Arial font size 120 on a 15.6-inch computer screen. The space key was covered with a red sticker and the "1" and "2" keys were covered with a green and blue sticker, respectively.

The dual task under high or low cognitive load conditions took approximately 16 minutes to complete.

1.2.2 Phonotactic constraint task

The exact same materials and procedure were used as in the developmental study of Smalle, Muylle, et al. (2017). The only difference was that, here, we presented only two instead of four training sessions (i.e., across two consecutive days), because this was the time course (particularly Day 1) we were interested in. Participants received one set of 96 sequences on each training day. Each sequence contained four novel word forms of the structure CVC (e.g., *kieng nief siet hiem*). In total, eight different consonants were used that appeared once per sequence. These consonants belonged to three different constraint groups: language-wide, experiment-wide, and unrestricted. The language-wide consonants (i.e., /h/ and /ŋ/) were always presented at respectively onset or coda position in accordance with the Dutch spoken language; the unrestricted consonants (i.e., /m/, /n/, /f/, /s/) appeared at both positions across the entire experiment, also similar to the Dutch spoken language. Two consonants that are typically unrestricted in the Dutch spoken language (i.e., /t/, /k/) appeared restricted within the setting of the experiment (restricted or experiment-wide) depending on one of two medial (common) Dutch vowels (i.e., /i/ or /ø:/). For each group, half of the participants were exposed to the constraint that /t/ is an onset and /k/ is a coda if the vowel is /i:/ while /k/ is an onset and /t/ is coda if the vowel is /ø:/, also referred to as the *tiek-keut* condition. The other half of the participants were exposed to the reverse *kiet-teuk* constraint. The vowels were presented alternatingly between sequence trials so that half of the trials contained one vowel and half of the trials the other vowel. For each participant, two lists of 96 sequences were randomly generated by use of a computer program that was made available to us by Jill A. Warker (e.g., Warker & Dell, 2015). Letter combinations that resulted in existing words were avoided. All sequences were displayed in 80-point bold Courier New white font on a black background. The sequence appeared in one line on the screen and was read aloud by a male voice on the computer. For this, each CVC syllable or word-form was recorded separately by a native male speaker and noise cancelled. During sequence presentation, the syllables were presented via the computer at a rate of 1 syllable/sec. This took place in a silent soundproof room provided at Ghent University.

Participants were not informed about the constraints. A practice block of four trials was presented on Day 1 to familiarize the participant with the task. During the task, participants heard the sequence once (together with the visual presentation on the screen) and were asked to recite the sequences in time with a metronome. They first recited the sequence slowly at a rate of 1 syllable/sec (in time with the metronome) and subsequently repeated this sequence 3 times without pause at a faster rate of 2.53 syllables/sec (in time with the metronome). The sequence remained on the screen until reciting was finished and participants pressed the space bar to continue with the next sequence. The trial procedure is visualized in Figure 2. In total, one set of 96 sequences was completed per day. Each session was digitally recorded using a computer-built recorder.

2 Results

2.1 Time load Dual-back Task

2.1.1 Dual-task accuracy

For each participant, a weighted composite score was calculated across the total number of trials, as a manipulation check for the attempted cognitive depletion (see, Borragan et al., 2017; Borragán et al., 2016). Accuracy for letters and digits represented 65% and 35% of the total score (Borragan et al., 2017). Performance of the two cognitive load groups across days can be seen in Figure 3. As expected and intended, the LCL group performed significantly higher than the HCL group, who performed around the minimal 85% accuracy level as defined during the pretest: Day 1, HCL: $83.7_{M} \pm 2.46_{SEM}$ vs. LCL: $94.7_{M} \pm 0.71_{SEM}$, $t_{22} = -4.31$, $p_{one\text{-}tailed} < .001$; Day 2, HCL: $87.2_{M} \pm 1.39_{SEM}$ vs. LCL: $94.1_{M} \pm 0.92_{SEM}$, $t_{22} = -4.14$, $p_{one\text{-}tailed} < .001$.

2.1.2 Numerical Rating Score

The pre –and post TloadDback task rating scores for feelings of fatigue are presented in Figure 4. The extra control group (i.e., no cognitive load) immediately started with phonotactic constraint training and thus did not perform the dual task before language exposure. They rated their subjective feeling of fatigue once at the start of the experiment (Figure 4, left). This did not differ from the baseline score of the high cognitive load (HCL) participants (i.e., Day 1: $t < 1$; Day 2: $t_{22} = 1.6$, $p_{two\text{-}tailed} = .11$) or the low cognitive load (LCL) participants (Day 1: $t_{22} = 1.5$, $p_{two\text{-}tailed} = .14$; Day 2: $t < 1$). However, the low cognitive load participants rated themselves overall higher on the pre-rating scale than the high cognitive load participants (i.e., Day 1: $t_{22} = 3.05$, $p_{two\text{-}tailed} = .006$; Day 2:, $t_{22} = 2.33$, $p_{two\text{-}tailed} = .03$).

As an additional manipulation check for the manipulated cognitive depletion (see, Borragan et al., 2017; Borragán et al., 2016), we computed difference scores between the numerical rating score (NRS) for the feeling of 'fatigue' that was given before versus immediately after the TloadDback task (i.e., [NRSpost-NRSpre]). We divided this difference score by the rating score that was given before the TloadDback task (i.e. NRSpre). This allows us to compare induced cognitive fatigue across individuals with different baselines in self-assessed feeling of fatigue. The higher the index, the more fatigue is induced as a result of the cognitive task, referred to as 'cognitive fatigue'. Performance of the two groups across days can be seen in Figure 4 (right). The HCL group reported higher cognitive fatigue compared with the LCL group, but this appeared only significant on the first day: Day 1: HCL: $.77_M \pm .18_{SEM}$ vs. LCL: $.30_M \pm .76_{SEM}$, $t_{22} = 2.36$, $p_{one\text{-}tailed} = .028$; Day 2, HCL: $.68_M \pm .17_{SEM}$ vs. LCL: $.50_M \pm .13_{SEM}$, $t < 1$.

2.2 Phonotactic constraint learning

Speech errors involving consonant movements were transcribed from the recordings and coded as ‘same-position’ (i.e., from onset to another onset or from coda to another coda) or ‘other-position’ (i.e., from onset to coda or from coda to onset). The erroneous consonant movements were coded according to the constraint type (i.e., language-wide, experiment-wide, or unrestricted). The errors involving experiment-wide consonants were always coded with respect to the medial vowel within the sequence trial and the restriction that the participant was experiencing (i.e., *tiek-keut* or *kiet-teuk* condition). For instance, if the target sequence in a trial was *kieng nief siet hiem* and a participant (who is experiencing the *kiet-teuk* restriction) recited this sequence as **h**ieng **t**ief **n**ie**s** **k**iem, then five consonant movements would be coded (in bold): One same-position error for the language-wide constraint (i.e., /h/ switched from onset to another onset), one other-position error for the experiment-wide constraint (i.e., /t/ switched from coda to onset), one same-position error for the unrestricted constraint (i.e., /s/ switched from onset to coda), and one same-position error for the experiment-wide constraint (i.e., /k/ switched from onset to another onset) (see also, Smalle, Muylle et al., 2017). For cutoff errors (e.g., s … keut), the first uttered consonant was coded. Substitutions (i.e., consonants that were replaced by other consonants different than those within the sequence, e.g., /g/ instead of /k/), omissions or indistinguishable phonemes, and word-level slips were not included in the error corpus. Transcription was done independently by two native Dutch speakers (i.e., first and second author, respectively) and completely blind to the conditions of the participants. For the 82.944 syllables doubly transcribed, both coders agreed on the presence and nature of 2124 errors and on the absence of errors on 79.954 syllables, i.e. a 99.0% agreement rate. For those syllables in which the first coder found an error (2990 errors), the conditionalized agreement rate was 71.0%. These values are highly comparable with those found in similar recent studies (Anderson, Holmes, Dell, & Middleton, 2019; Kittredge & Dell, 2016; Smalle, Muylle, et al., 2017), and thus the coding of the first coder was not changed. The results for the transcriptions of the second coder are reported in a supplementary file 1 on osf.io/fegb2; These did not differ from the main group findings reported here.

Our key measure is whether the rate at which errors maintain their syllable position (i.e., proportion of same-position error) is higher for experimentally restricted consonants than for unrestricted consonants, which would indicate novel phonotactic learning. We predict that this learning effect occurs only late in training, i.e. from training day 2, in the cognitively non-depleted groups, as is typically seen in young adults (Anderson & Dell, 2018). In contrast, for the cognitively depleted adults (i.e., the high load group), we expect to see early learning effects, more specifically on training day 1, as is seen in children (Smalle et al., 2017). First, a logistic regression analysis was fit to the speech error data within each group. The dependent variable is whether each error preserves the syllable position of the target consonant (1) or not (0). Day (1 versus 2), Restrictedness (experiment-wide versus unrestricted) and the interaction between Day and Restrictedness were included as fixed factors. We further included participants as random intercept and a slope for Restrictedness. To further investigate group differences early in training, similar to what we see in previous developmental work (Smalle et al., 2017), a logistic regression model including an interaction factor for Restrictedness and Group was fit to the speech error data on Day 1. Position (same-position = 1 or different-position = 0) was again defined as dependent variable. Because of convergence issues, only a random intercept for Subject was included here (Bates, Kliegl, Vasishth, & Baayen, 2015). All *p* values were calculated using

Wald-z. Effect-coding was used for all factors. The analyses were performed using the lme4 package (Bates, Mächler, Bolker, & Walker, 2014) in R (R Development Core Team, 2011). Planned comparisons were performed using the phia package (De Rosario-Martinez, Fox, Team, & De Rosario-Martinez, 2015).

2.2.1 Control Group

As predicted, the language-wide constraints were never violated: Errors involving /h/ or /ŋ/ consonants always adhered to the restricted position (i.e., 100% same-position, SE = 0 based on a total of 174 errors). There was significant learning of the novel constraints, i.e., effect of Restrictedness: $\beta = 0.48$, $z = 3.33$, $X^2(1) = 11.1$, $p < .001$. The effect appeared reliably on Day 2 only (i.e., Day 1: $X^2(1) = 1.37$, $p = .24$; Day 2: $X^2(1) = 12.1$, $p = .001$; Restrictedness x Day: $\beta = 0.30$, $z = 2.42$, $X^2(1) = 5.86$, $p = .015$.

2.2.1 Low Cognitive Load Group

The language-wide constraints were never violated (i.e., 100% same-position for errors involving /h/ or /ŋ/consonants, based on a total of 233 errors). There was again significant learning of the novel constraints, i.e. effect of Restrictedness: $\beta = 0.46$, $z = 3.55$, $X^2(1) = 12.6$, $p < .001$. While there was no significant learning yet on Day 1 (i.e., $X^2(1) = 3.54$, $p = .06$, see Table 2), learning appeared reliably on Day 2 (i.e., $X^2(1) = 11.8$, $p = .001$; Restrictedness x Day: $\beta = 0.20$, $z = 1.87$, $X^2(1) = 3.48$, $p = .062$).

< INSERT TABLE 2 HERE >

2.2.3 High Cognitive Load Group

The language-wide constraints were never violated (based on a total of 134 errors). There was again learning of the novel constraints, i.e., effect of Restrictedness: $\beta = 0.91$, $z = 4.30$, $X^2(1)$

= 18.5, $p < .001$). Learning appeared reliably already on Day 1 (i.e., $X^2(1) = 15.5$, $p < .001$) and remained reliable on Day 2 (i.e., $X^2(1) = 8.3$, $p = .004$; Restrictedness x Day: $\beta = 0.03$, $z < 1$, $X^2(1) < 1$, $p = .867$).

< INSERT TABLE 1 HERE >

2.2.4 Group comparison

Individual data on overall number of errors, i.e. consonant movements, for the participants across the three groups are provided in a supplementary file 2 on osf.io/fegb2 (see also Table 1). Although the high cognitive load group committed numerically less errors than the other two groups, there were no significant differences across groups (i.e., HCL vs. LCL, Day 1: student's $t < 1$; Day 2: $t(22) = -1.98$, $p = .06$; HCL vs. control: Day 1: $t(22) = -1.002$, $p = .33$; Day 2: $t < 1$). We added number of speech errors as a covariate to the main group analysis.

The logistic regression analysis across groups revealed a significant interaction between Restrictedness and Group (i.e., $X^2(2) = 9.3$, $p = .0095$). Planned comparisons showed a significant difference in learning between the HCL group and the LCL group (i.e., $X^2(1) = 6.4$, $p = .022$) and between the HCL group and the control group (i.e., $X^2(1) = 8.9$, $p = .0085$); but not between the LCL group and the control group (i.e., $X^2(1) = 0.46$, $p = .50$). More specifically, the HCL group showed *higher* same-position percentages for the experimentally restricted condition (i.e., compared with LCL group: $X^2(1) = 8.1$, $p = .026$; compared with the control group: $X^2(1) = 6.04$, $p = .07$), while not for the unrestricted condition (i.e., all $X^2(1) < 1$).

3 Discussion

The present study investigated the interfering effect of adult's cognitive control abilities on implicit language learning. It corroborates recent findings from the skill learning literature that shows enhanced statistical learning abilities in conditions where the higher cognitive system is suppressed (e.g., Borragán et al., 2016; Galea et al., 2010; Nemeth, Janacsek, Polner, et al., 2013). Overall, our results were as predicted. The group with depleted cognitive control resources (i.e., under high cognitive load) showed the strongest and earliest learning effects on the phonotactic constraint task, similar to what we observed in a previous child-adult comparison on the speech error-task (Smalle, Muylle, et al., 2017). In fact, just like what is seen in the children, only the cognitively depleted group showed learning on the first training session. This supports the idea that late-developing cognitive functions, and in particular attentional control, is an important antagonist on the effective outcomes of language learning.

Overall, our findings support the widely supported though poorly understood sensitive period hypothesis, by attributing developmental changes in language acquisition to maturational changes in attention and memory capacities (cf. less-is-more hypothesis, Newport, 1990). Thiessen and colleagues quite recently renewed interest in the less-is-more hypothesis as a preferred explanation for the sensitive period debate (Thiessen et al., 2016). Rather than arguing that children have access to a set of implicit learning processes that appear unavailable to adults (cf. the mechanism-change or discontinuity hypothesis), one should consider maturational changes in the cognitive architecture underlying human learning as a valuable explanation for age-related sensitivities in language acquisition (Thiessen et al., 2016). Attention and memory capacities change dramatically as a function of age, and adults are much better than children at effortful controlling their focus of attention (Craik & Bialystok, 2006). This may be largely disadvantageous for language acquisition: adults are more likely to explicitly search for input that matches their expectations (or pre-existing knowledge), preferring explicit learning over implicit learning (Batterink, Paller, & Reber, 2019; Batterink, Reber, Neville, & Paller, 2015). This makes them less sensitive to hidden statistical structures in the environment (see for instance, Fletcher et al., 2005; Janacsek et al., 2012; Thompson-Schill et al., 2009, for similar arguments in the perceptual motor domain). Moreover, higher attentional control may cause adults to miss out on seemingly irrelevant idiosyncratic information in the linguistic input. For instance, in Dutch, as well as in English, vowels are largely unrelated to whether particular consonants are onsets or codas and so hidden units that detect and code for vowel-consonant dependencies in phonotactic learning are inhibited (Dell et al., 2019). When this type of information becomes relevant (for instance, within the setting of an experiment), time is needed to disinhibit the weights of these units again. We know from the literature that children have rather noisy encoding systems, meaning that they encounter many alternative sources of information to a learning situation without inhibiting one over the other (Thiessen et al., 2016). This is particularly useful for finding consistency across probabilistic or inconsistent input, such as with (ir)regular plural forms, speech and/or novel word mappings (see Thiessen et al., 2016, for a review). Here, we observe that cognitive depletion, a mental state that is highly associated with difficulties suppressing irrelevant information and focusing attention (Faber, Maurits, & Lorist, 2012), enhances outcomes on a phonotactic constraint learning task. This is consistent with the above presented alternative view on the sensitive age hypothesis. It also confirms an earlier finding from the language learning literature showing that adults learning an unfamiliar sign language tend to generalize more successfully under distraction (Cochran et al., 1999). The findings are moreover highly in line with very recent work from our lab that shows enhanced speech segmentation abilities (i.e. implicit statistical learning) in adults where the higher cognitive system is depleted, either by using Transcranial Magnetic Stimulation (TMS) to the left dorsolateral prefrontal cortex (DLPFC) or by using the presently used TloadDback task (Smalle, Daikoku et al., in preparation). Together, our findings corroborate the idea that a continuously available learning mechanism (i.e., implicit statistical learning) can give rise to discontinuous language outcomes due to changes in the cognitive system (Thiessen et al., 2016). This is further supported by recent work in the aging literature that shows that older adults are still able to pick up novel linguistic constraints despite (or thanks to) an overall decline in cognitive functioning (Palmer, Hutson, & Mattys, 2018; Muylle, Smalle & Harstuiker, under review).

3.1 Further considerations

Is an offline consolidation period needed for learning novel phonotactic constraints? Previous work with typical adults showed that conditional, or second-order, patterns such as "/t/ is an onset and /k/ is a coda *if* the vowel is /i:/ while /k/ is an onset and /t/ is coda *if* the vowel is /ø:/" are learned *more slowly* than first-order constraints (e.g. /t/ is an onset and /k/ is a coda all the time) (Anderson & Dell, 2018). In fact, in adults, speech errors only begin to reflect second-order constraints during a second training session on the following day, implying the need for an offline consolidation period (Anderson & Dell, 2018; Bian & Dell, 2019; Craik & Bialystok, 2006; Dell, Kelley, Bian, & Holmes, 2019; Warker & Dell, 2006). Even adding an extra training session on the first day, for instance by doubling the amount of trials (Warker, 2013), is not sufficient for learning to emerge; unless a daytime nap is involved (Gaskell et al., 2014). This suggests that sleep is necessary for the acquisition of novel, second-order constraints. However, there are circumstances in which second-order patterns are quickly learned, such as in young participants (Anderson & Dell, 2018; Smalle, Muylle, et al., 2017). This indicates that the need for consolidation is primarily a property of the *mature* language system (Dell et al., 2019). Dell and colleagues recently proposed a hidden unit account to explain these (and other) circumstances for rapid learning, by arguing that this arises from variations in the availability of the hidden units that can detect conditional vowel-consonant conjunctions (Dell et al., 2019). As these conjunctions are largely irrelevant for syllabification in English, as well as in Dutch, they become *backgrounded* in the mature system while this is not yet true for an immature system. Hence, an offline consolidation period is needed for adults to offset and change the weights between units again. Here, we argue that mature cognitive-control abilities presumably play an important (mediating) role in this process. By reducing attentional control, either by sleep or by cognitive depletion, the suppression of the seemingly irrelevant hidden units is released again. As a result, adults become more susceptible to the (backgrounded) connection weights, similar to children, and early learning is revealed. This is highly consistent with our main finding that the high cognitive load adults, but not the low cognitive load adults, show (strong) learning already on the first day of training, similar to what we see in children. Note that there was evidence for offline consolidation (i.e., interaction between Day and Restrictedness) in the non-depleted groups (but see Supplementary Analyses for Coder 2), suggesting that sleep presumably plays a necessary role in conditions where cognitive-control resources are available. Future research should determine whether cognitive depletion supersedes sleep in protecting rapid, implicit language learning, or, alternatively, whether cognitive depletion and sleep offer unique contributions to adult language acquisition.

Ambrus et al. (2020) recently found that a TMS-induced suppression of the left DLPFC enhanced implicit learning of non-adjacent dependencies in the SRT task (cf., perceptual-motor domain), but that this effect only appeared after 24 hours (including sleep). Chen, Roig, and Wright (2020), in contrast, found that a brief bout of cardiovascular exercise (known to protect procedural memory from interference induced by declarative learning) enhanced the learning of adjacent dependencies after 6 hours of wakefulness. These findings suggest that the need for sleep-dependent consolidation (and the effect of cognitive depletion) depends on the nature of the to-be-learned pattern (i.e., adjacent or non-adjacent). Second-order phonotactic constraints in which mutually constraining elements are *adjacent* (e.g. the position of a consonant depends on an adjacent medial vowel), as tested here, are common in most Indo-European languages (Warker et al., 2008). In contrast, *nonadjacent* phonotactic constraints are much less common but they do occur in some languages (e.g., vowel harmony in Finnish), and hence should be “learnable” (Koo & Cole, 2006; see, Warker et al., 2008). Warker et al. (2008) tested whether *non-adjacent* second-order phonotactic constraints can be learned by English-speaking adults (see also, Warker & Dell, 2006). In their Experiment 1, the position of a consonant (onset or coda) depended on the identity of a nonadjacent medial consonant (e.g., if the middle consonant of consonant-vowel-consonant-vowel-consonant-vowel is /v/, /g/ is an onset and /k/ is a coda, but if it is /b/, /k/ is an onset and /g/ is a coda; e.g. *hevek geveng fevem leves* versus *mebef keben hebeng sebeg*). Overall, the results demonstrated that adults were able to learn these non-adjacent dependencies too (albeit to a somewhat weaker extent than adjacent contingencies) (Warker & Dell, 2006; Warker et al., 2008). Interestingly, the learning effect was only visible from the second day of training similar to the time course that is seen for adjacent constraints. This illustrates that sleep-dependent consolidation is needed for second-order phonotactic learning in adults, *independently* of the nature of the linguistic constraint (i.e., adjacent or non-adjacent), in contrast to what is seen in the motor domain (Ambrus et al., 2020; Chen et al., 2020). The participants in Warker et al. (2008) were unable to learn phonotactic-like constraints that hinged on speech rate (cf. Experiment 2, Warker et al., 2008), further suggesting that any type of phonotactic constraint learning is possible as long as the constraint is linguistically “learnable”. Phonotactic rules that depend on extra-linguistic features, such as speech rate or a speaker’s voice, do not exist in the natural language production system and so the required hidden units are non-existent (Dell et al., 2019). The question relevant for the present study remains how quickly children learn linguistically "learnable" *non-adjacent* constraints compared with adults, and, importantly, whether the early time course in children can be simulated in adults under cognitive depletion. This would be an interesting follow-up study to the present work.

We noticed that there were group differences in the self-assessed baseline level of fatigue (i.e., NRSpre, i.e., 1: I feel no fatigue to 10: I feel the worst possible fatigue). The low cognitive load participants rated themselves overall higher on the visual scale than the high cognitive load group. Importantly, the main group results do not change when accounting for these baseline differences (i.e., NRS_pre: $X^2(1) < 1$, Group x Restrictedness: $X^2(2) = 9.28$, $p < .01$). Moreover, we have no strong reasons to assume that these differences could have confounded our main results: First of all, the phonotactic learning score (i.e., effect of Restrictedness) did not interact with baseline fatigue scores across all groups (i.e., Restrictedness x NRS_pre: $\beta = 0.024$, $SE = 0.066$, $Z < 1$, $X^2(1) < 1$). Secondly, there were no baseline differences between the control group and the high cognitive load group while learning differed significantly between these two groups.

3.2 Conclusion

We conclude that adults seem to benefit from a cognitive depleted system when learning linguistic input. This supports a well-known, but poorly empirically supported, theoretical view that the adult deterioration in language acquisition abilities might be due to age-related changes in the maturing cognitive system. Late-developing cognitive abilities, and in particular attentional control may interfere with basal, implicit learning processes important for language acquisition. This is highly in line with evidence from the perceptual and motor learning literature. As such, human skill acquisition, including language, presumably relies on a set of continuously available domain-general (implicit) learning processes that interact dynamically with the cognitive system across the human life span.

Context of Research

In 2005, on the occasion of its 125th anniversary, the journal Science put forward the question ‘why children appear better language learners than adults’ as a fundamental but unresolved issue in human science (Kennedy & Norman, 2005). More than ten years later, the question remains. Language learning is complex and involves unconsciously picking up statistical regularities from continuous streams of speech sounds, such as word boundaries or rules on phoneme order. Our research findings over the past 5 years, which combine various language learning paradigms, converge towards the idea that higher cognitive abilities interfere with implicit learning processes in adults (Smalle et al., 2016; Smalle, Muylle et al., 2017; Smalle, Panouillères et al., 2017; Smalle et al., 2018; Smalle, Daikoku et al., in preparation). New evidence suggests that the ability to synchronize speech movements with auditory speech rhythms is associated with the ability to learn language (Assaneo et al., 2019). Motor mechanisms that control speech movements are crucially involved in understanding speech (e.g., Smalle et al., 2015), but the exact role that they play in language learning remains unknown. We test the hypothesis that auditory-motor speech processes contribute to implicit language learning, while implicit learning receives competition from the higher cognitive system with age (cf., current work). Our long-term goal is to elucidate the agonist and antagonist mechanisms sub-serving language acquisition, to help developing a dynamic neurocognitive model for the acquisition of language and advance our understanding of why some individuals, like children, are better language learners than others.

Declaration of conflict of interest

None

Research Data

Pre-registered predictions on https://osf.io/de5na. The transcribed datasets, scripts for analyses, and supplementary files are available via osf.io/fegb2.

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Table 1. Percentage of same-position errors of unrestricted and restricted consonants in the (extra) control group, the low cognitive load group (LCL) and the high cognitive load group (HCL).

		Unrestricted	SE	Restricted	SE	*contrast*
Control	Day 1	82.2	1.6	86.8	2.5	*ns*
	Day 2	74.4	2.3	93.1	2.5	**
	***N* Errors**	**522**		**291**		
LCL	Day 1	73.6	2.4	83.8	2.6	*ns*
	Day 2	72.5	2.8	90.9	2.6	**
	***N* Errors**	**596**		**318**		
HCL	Day 1	76.5	2.7	94.5	1.8	***
	Day 2	74.3	3.7	94.7	3.0	**
	***N* Errors**	**391**		**221**		

***$p < .001$, **$p < .01$

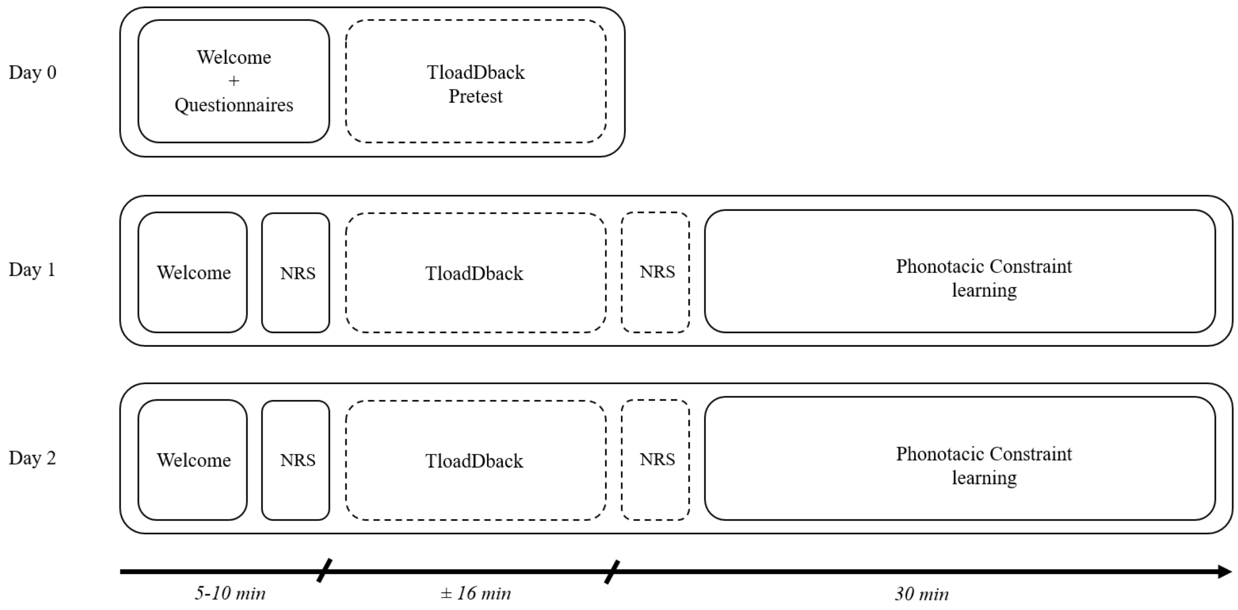

Figure 1. Experimental Procedure. Please note that the extra group of control participants were not exposed to the tasks that are presented in dashed lines.

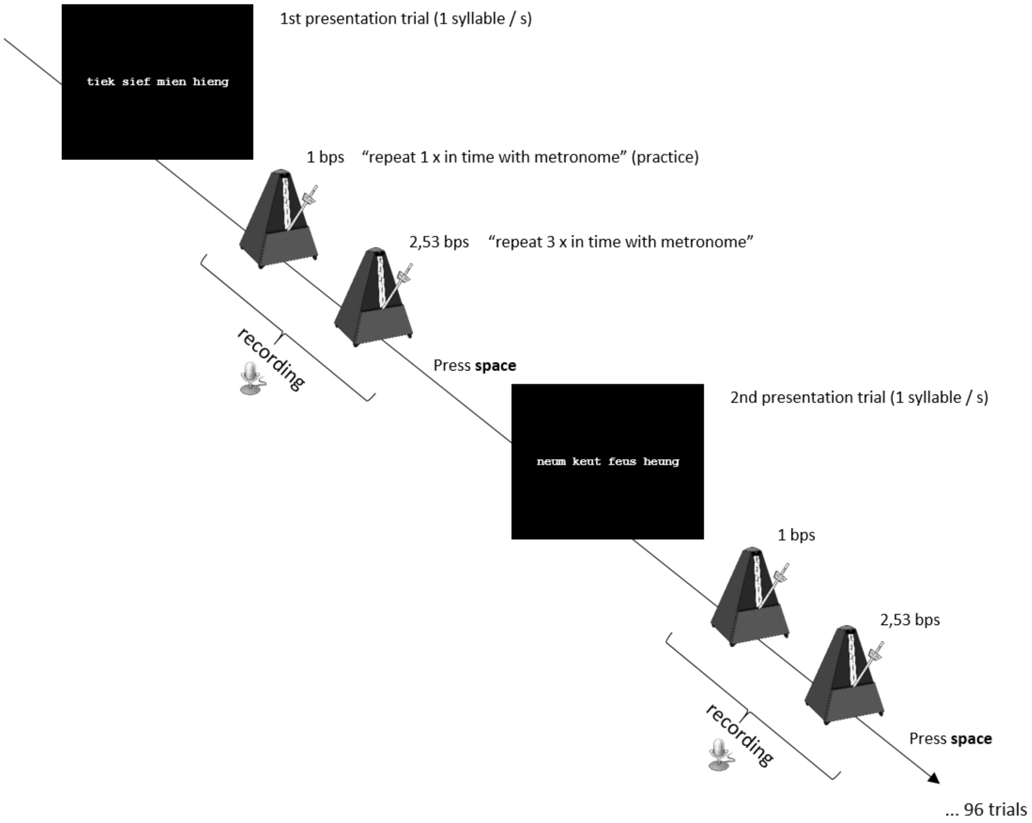

Figure 2. Trial procedure for the speech error task (cf. phonotactic constraint learning). Participants received one set of 96 sequence trials on each training day. Each sequence contained four novel word forms of the structure consonant-vowel-consonant, which the participants repeated in time with a metronome to induce tongue twisters and particularly consonant movements. In total, eight different consonants were used that appeared once per sequence. The vowels were presented alternatingly between sequence trials. Participants were not informed about the underlying (language-wide, experiment-wide and unrestricted) vowel-consonant dependencies (i.e., the phonotactic constraints).

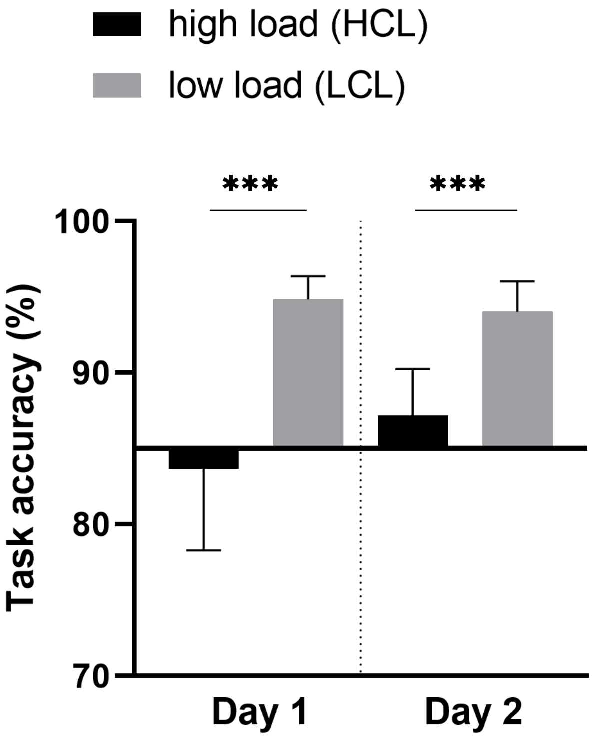

Figure 3. TloadDback task performance under high and low cognitive load conditions (HCL, LCL) across both sessions. Please note that the HCL group performs around the minimal 85% accuracy level that was defined during the pretest. Error bars denote 95% confidence intervals. ****p* < .001

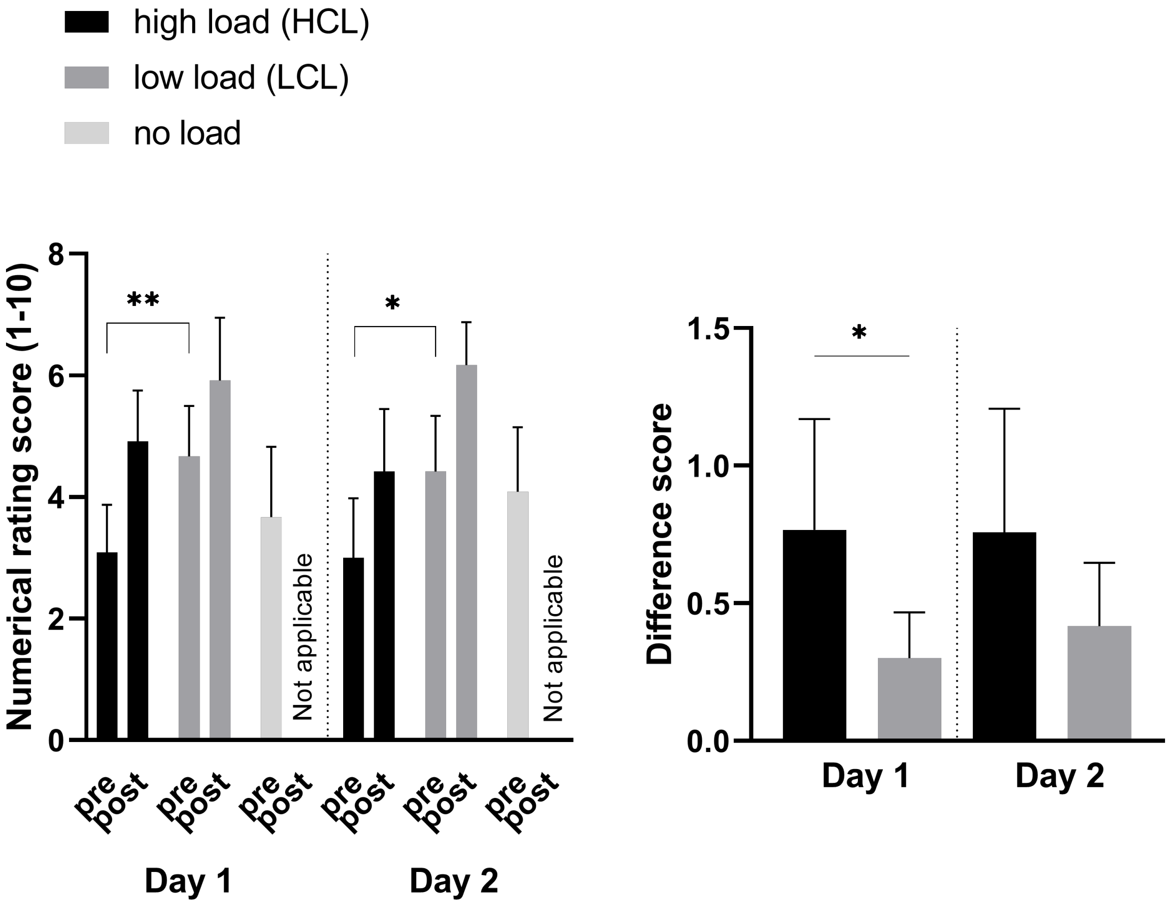

Figure 4. Left: Participant's numerical rating for their subjective feeling of 'fatigue' (1: I feel no fatigue to 10: I feel the worst possible fatigue). This was assessed at the start of the experiment (i.e., pre) and immediately after performing the TloadDback task (i.e. post) to check for cognitive fatigue induction (Right). This is defined as the difference between the numerical rating score given before (i.e. pre) versus after (i.e. post) performing the TloadDback task and divided by the participant's baseline rating of fatigue (only for the cognitive load participants, see Figure 1). Error bars denote 95% confidence intervals. * $p < .05$, ** $p < .01$