

Research Article

Maximum Speech Performance and Executive Control in Young Adult Speakers

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Purpose: This study investigated whether maximum speech performance, more specifically, the ability to rapidly alternate between similar syllables during speech production, is associated with executive control abilities in a nonclinical young adult population.

Method: Seventy-eight young adult participants completed two speech tasks, both operationalized as maximum performance tasks, to index their articulatory control: a diadochokinetic (DDK) task with nonword and real-word syllable sequences and a tongue-twister task. Additionally, participants completed three cognitive tasks, each covering one element of executive control (a Flanker interference task to index inhibitory control, a letter–number switching task to index cognitive switching, and an operation span

task to index updating of working memory). Linear mixed-effects models were fitted to investigate how well maximum speech performance measures can be predicted by elements of executive control.

Results: Participants' cognitive switching ability was associated with their accuracy in both the DDK and tongue-twister speech tasks. Additionally, nonword DDK accuracy was more strongly associated with executive control than real-word DDK accuracy (which has to be interpreted with caution). None of the executive control abilities related to the maximum rates at which participants performed the two speech tasks.

Conclusion: These results underscore the association between maximum speech performance and executive control (cognitive switching in particular).

Adult speakers have years of experience speaking, yet they often stumble over sentences such as “she sells sea-shells on the sea shore,” where constant alternation between /s/ and /ʃ/ at word onsets is needed. What kind of control abilities is required from speakers to successfully produce the alternations in such “tongue-twisting” sentences? Recent clinical studies have suggested that articulatory control abilities may relate to executive control abilities (e.g., Dromey & Benson, 2003; Nijland et al., 2015). Some psycholinguistic studies, on the other hand, have argued that stages of speech production following lexical selection, such as articulation (covering phonetic encoding, motor programming, and articulatory execution), do not require processing resources (e.g., Ferreira & Pashler, 2002). Our study will take an individual differences approach to investigate whether executive control abilities predict the ability to rapidly alternate between similar syllables during speech production. We investigated individual differences in maximum speech performance in a

nonclinical population of young adult speakers. The choice for this population enabled us to include a relatively large group of participants, as individual differences research should preferably be carried out with large samples. Moreover, even in relatively homogeneous student populations, language performance has been demonstrated to be variable enough to show relationships between cognitive control and lexical access (e.g., Piai & Roelofs, 2013).

Studies on Articulatory Control

The terms *articulatory control* and *speech motor control* are often used interchangeably to refer to the “systems and strategies that regulate the production of speech, including the planning and preparation of movements and the execution of movement plans to result in muscle contractions and structural displacements” (Kent, 2000, p. 391). Articulatory control in clinical settings is often quantified by various maximum performance speech tasks in the assessment of motor speech disorders (Kent et al., 1987). Among those maximum performance speech tasks, rapid repetition rate or the diadochokinetic (DDK) rate task has been one of the most commonly used tasks. It is relatively simple to conduct and administer, and speakers' performance on this task has been claimed to be a stable

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index of oral motor skills (Bernthal et al., 2009; Duffy, 2013; Fletcher, 1972; Kent et al., 1987).

In a DDK task, participants are typically asked to accurately and rapidly repeat the same nonsense syllables (e.g., pa, pa, pa) or to alternate between different nonsense syllables (e.g., pa, ta, ka; Duffy, 2013; Fletcher, 1972; Yang et al., 2011). Previous research has investigated differences in maximum performance for repetition of nonsense sequences compared to repetition of real words. As speakers have more experience speaking real words and hence have access to stored motor programs for words, but not for nonwords, they can be expected to reach faster rates for real-word repetition than nonword repetition. Indeed, for Hebrew, school-age children (Icht & Ben-David, 2015) and healthy older adults (Ben-David & Icht, 2017) achieved faster repetition rates in producing the real (familiar) Hebrew word *bodeket* relative to the trisyllabic nonword “pataka” (note, however, that lexical status is confounded with voicing of plosives here, which may also influence rate differences in the two stimulus types). Additionally, for languages with lexical stress, real words, but not nonwords, have fixed stress patterns that may lead to reduction of unstressed syllables. This would also lead to potentially faster rates for real-word than nonword repetitions.

This effect of lexical status also brings up the much-debated question of how representative DDK maximum performance based on nonword repetitions is for patients' speech performance (Maas, 2017). Ziegler and colleagues (cf. also Staiger et al., 2017) have argued that motor requirements for “nonspeech” (i.e., DDK) behavior may differ from those for natural speech. Ziegler (2002), for instance, found that patient groups who had comparable sentence production rates differed significantly in their (nonword) DDK rates. Moreover, whereas one pathology (apraxia of speech) might affect sentence production more than DDK, another pathology (cerebellar dysarthria) would affect DDK performance more than sentence production. Possibly, speech tasks differ in their involvement of executive control. Performance on tasks involving articulation of less familiar (nonsensical) sequences may be more variable and more vulnerable to differences (within and between speakers) than production of familiar phrases or words. Repetition of unfamiliar (such as DDK) sequences may therefore be expected to involve more executive control than repetition of familiar sequences.

Kent (2004) illustrated that speech, as a motor behavior, is influenced by cognition and that speaking should be viewed as a “cognitive-motor accomplishment” (Kent, 2004, p. 3). Thus, in order to successfully complete the stages of speech production, a certain amount of executive control may be required from speakers. Executive control (or executive functions) is known as a set of general-purpose control mechanisms that regulate our thoughts and actions (Gilbert & Burgess, 2008; Logan, 1985). Executive control is proposed to have three main underlying components, namely, inhibitory control, cognitive switching, and updating of working memory (Miyake et al., 2000). More specifically, inhibitory control is the ability to suppress activation of

unwanted information in order to resolve conflict. Cognitive switching is defined as the ability to rapidly switch back and forth between mental sets or operations. Lastly, updating of working memory refers to the ability of maintaining or actively refreshing the contents of working memory while processing incoming information (Miyake et al., 2000).

In a review article, Kent (2000) suggested motor speech disorders should be investigated in relation to (phonological and) cognitive systems. The question of whether articulatory control may be related to executive control has been investigated in different clinical populations. In children with childhood apraxia of speech (CAS), a relationship between memory abilities and speech production has been observed (Nijland et al., 2015). Significant correlations were found between scores on two cognitive factors (extracted from a set of complex sensorimotor and sequential memory tasks) and speech scores (based on maximum repetition rates of nonspeech stimuli such as the trisyllabic, “pataka”-type, maximum repetition task) of children with CAS (Nijland et al., 2015). Similar associations between cognitive and speech performance were found in a study testing adults with dyslexia and adults with a probable history of CAS (Peter et al., 2018). Peter et al. (2018) used a battery of speech tasks (nonword repetition, multisyllabic real-word repetition, and nonword decoding), testing for patients' sensory encoding, memory, retrieval, and motor planning/programming abilities. Their results showed that the two disordered groups performed significantly worse on all three speech tasks compared to adults from the control group, again suggesting links between sensory encoding, (short-term) memory, and speech motor programming (Peter et al., 2018).

Perhaps more direct evidence for a relationship between cognition and speech motor performance has been found among nonclinical populations in studies where cognitive load was manipulated experimentally. For instance, using kinematic measures of lip movement, Dromey and Benson (2003) found healthy young adults' speech production to be more variable in a sentence repetition task when repetition was paired with cognitive or linguistic distractors (i.e., a higher cognitive load), relative to simple repetition. Similar results were obtained in follow-up studies, for instance, Bailey and Dromey (2015) on effects of dual tasking on speech motor performance of younger, middle-age, and older adults and MacPherson (2019) on increased cognitive load effects, as induced by Stroop interference, on speech motor performance in healthy younger and older adult speakers.

Results of these studies on clinical and nonclinical populations therefore suggest a relationship between cognitive and articulatory control. Nevertheless, several psycholinguistic studies, to be reviewed below, have argued that the involvement of executive control in “late” stages of speech production, such as phonological encoding and articulation, is minimal.

Psycholinguistic Studies

There is now ample evidence for a relationship between executive control and formulation and lemma selection

stages (or the “early” stages) of speech production, such as in language control in bilinguals (e.g., Costa et al., 2006; Rodriguez-Fornells et al., 2006), in noun phrase production (e.g., Sikora et al., 2016), and in word-level lemma selection (e.g., Piai & Roelofs, 2013; Shao et al., 2012). The relationship between executive control and “late” stages of speech production, such as phonological encoding and articulation, however, remains less straightforward. Garrod and Pickering (2007) argued that the processes of syllable or phoneme selection and articulation are largely automatic comparing to, for instance, the process of lexical selection. Their claim was supported by experimental evidence by Ferreira and Pashler (2002), who used a dual-task paradigm to test participants’ performance on a picture-naming and a concurrent manual tone discrimination task. Ferreira and Pashler manipulated the availability of processing resources for lemma selection, phonological word form selection, and phoneme selection by introducing a secondary task. They found that both lemma retrieval and morphological encoding delayed the latencies of the secondary tone discrimination task, while phonological encoding did not show such interference. Their argumentation, based on these results, was that phoneme selection did not require central processing resources (Ferreira & Pashler, 2002).

Roelofs (2008) followed up on these results and examined dual-task interference using a slightly different paradigm than Ferreira and Pashler (2002). Roelofs found that phonological encoding on picture naming did spill over to performance on an unrelated manual task. This result thus suggests that some form of executive control may be required for phonological encoding as well. Additionally, in a more recent experimental study also using a dual-task paradigm, Jongman et al. (2015) tested whether sustained attention (related to executive control) is consistently needed throughout the different stages of speech production. Their evidence suggests that individual differences in sustained attention were mainly related to the processes of phonetic encoding and initiation of articulation (Jongman et al., 2015).

Evidence for selection and resisting interference from competitors at the level of phonological and phonetic encoding comes from studies using the tongue-twister paradigm (Wilshire, 1999). For instance, using tongue-twister-like utterances, McMillan and Corley (2010) manipulated the phonemic similarity of onset consonants and compared speakers’ production of word sets with and without phonemic competition (e.g., *kef def def kef* vs. *kef kef kef kef*). Their results showed that articulation of onset phonemes in tongue-twister-like word sets is influenced by competing phonemes, such that even if speakers do not produce full-blown errors, their productions are less target-like and more variable in the context of competing phonemes (*kef def def kef*) than when produced in a context without competing phonemes (*kef kef kef kef*). Furthermore, their results also showed that the more similar the competing phoneme to the target phoneme (/t/ being more of a competitor for /k/ than is /d/), the greater the effect of articulatory interference (McMillan & Corley, 2010). These results suggest

higher level executive control may be needed during the “late” stages of tongue-twister production to resist interference in order to select the correct target phoneme. In summary, despite the mixed findings listed above, some psycholinguistic studies are in line with the speech kinematics evidence by Bailey and Dromey (2015) and Dromey and Benson (2003), that executive control may be involved during the “late” stages of speech production (phonological encoding and articulation), thereby challenging the claims that the “late” stages of speech production are largely automatic (Ferreira & Pashler, 2002; Garrod & Pickering, 2007).

This Study

We now return to our initial question of what control abilities are required for speakers to successfully produce “tongue-twisting” sentences that contain constant alternations between similar syllables, whereby we focus on the three elements of executive control (inhibition, shifting, and updating of working memory) in the Miyake model (Miyake & Friedman, 2012). Note that there are multiple models of cognitive abilities, working memory, or attentional abilities (e.g., Baddeley & Della Salla, 1996; Posner & Peterson, 1990) and that different models have distinguished different elements. For this study, we chose to investigate the link between speech performance and the three executive control elements defined in the Miyake model.

The interference induced by phoneme similarity in the McMillan and Corley (2010) study suggests that phonologically similar phonemes are jointly activated due to shared features and that similar phonemes compete for selection. As resolving competition at lexical selection has been linked to executive control (Piai & Roelofs, 2013), we hypothesize that higher level executive control may be needed during phonological encoding or the “late” stages of tongue-twister production to resist interference and to select the correct target phoneme. More specifically, in order to accurately and fluently produce tongue-twister phrases or sentences, inhibitory control may be involved in the suppression of coactivated but incorrect competing phonemes and/or phoneme clusters. Additionally, speakers producing tongue-twister phrases typically need to switch between two or more similar competing onset phonemes, between similar onset clusters, or between singleton onset phonemes and onset clusters. As such, we hypothesize that production of alternating sequences, such as tongue twisters, may require cognitive switching. Furthermore, in line with evidence that speech performance is associated with sequential memory functioning in children with CAS (Nijland et al., 2015), we investigate whether updating ability relates to tongue-twister performance as speakers need to constantly update the planning and programming of the required speech movements during production.

Similar to the tongue-twister paradigm, the maximum performance speech task that we discussed earlier, the DDK task, also contains several elements that may require executive control. For instance, in order to repetitively produce the DDK sequence “pataka,” the amount of shared phonetic

features in the syllable-initial consonants may require speakers to suppress the coactivated but incorrect phoneme (cf. McMillan & Corley, 2010). Additionally, fast alternation between the similar syllable-onset phonemes requires that speakers constantly switch between them. Lastly, the involvement of updating ability could be reflected in having to constantly update the planning and programming of familiar or unfamiliar sequences during speech production.

Note that our tongue-twister and DDK speech tasks are maximum performance tasks in which maximum speed is stressed. Therefore, we also investigate whether maximum performance on the two speech tasks (i.e., accuracy and rate) relates to the general ability of information-processing speed.

Clearly, the two maximum performance speech tasks of tongue twisters and DDK have typically been used in separate research fields for different purposes. The tongue-twister paradigm has mainly been used in psycholinguistic studies as a means to elicit speech errors or blends, while the DDK task has typically been used in a clinical setting as an index of speech motor control. According to Levelt's model of speech production (Levelt, 1989; Levelt et al., 1999), tongue-twister errors and blends may occur at the level of phonological selection and/or at the level of phonetic encoding. DDK performance has been suggested to index speech motor ability, and hence, DDK performance concerns an even later stage than the phonological encoding stage involved in tongue twisters. However, despite their differences, both tasks may capture elements of speakers' articulatory control. In a recent study in which we administered both tasks as maximum performance tasks, we found a significant correlation between maximum performance on tongue-twister and DDK repetition (Shen & Janse, 2019). This finding suggests that these two tasks tap into a task-independent articulatory control component.

The current study was thus set up to investigate the potential link(s) between maximum speech performance and executive control abilities. More specifically, we examined whether cognitive measures of inhibitory control ability, cognitive switching ability, working memory capacity, and baseline processing speed predict articulatory control as measured by DDK and tongue-twister (rate and accuracy) performance in a healthy young adult population. Finding out whether the late stages of speech production (phonological and phonetic encoding and execution) relate to cognitive control is important for (psycholinguistic or speech-motor) theories on speech production. Knowing about possible relationships between a clinical speech measure like DDK and executive control is also important for clinical practice, as it may have implications for DDK administration with patient populations suffering from cognitive impairment or comorbidities.

Method

Participants

A total number of 78 participants (age: $M = 23$ years, $SD = 3$; 61 women) were recruited online through the

Radboud Research Participation System (note that all of them were enrolled in bachelor's or master's programs or had already graduated). Participants were all native Dutch speakers with normal or corrected-to-normal vision and had no reported history of speech, hearing, or reading disabilities nor past diagnosis of speech pathology or brain injury. Our study protocol was evaluated and approved by the Ethics Assessment Committee Humanities at Radboud University. Participants had all given informed consent for their data to be analyzed anonymously, and they either received course credits or gift vouchers as compensation for their time.

General Procedure

Participants were tested individually in the Centre for Language Studies Lab at Radboud University. They completed a battery of five tasks during the experimental session; three of which were cognitive tasks (a flanker interference task, a letter-number switching task, and an operation span task), and two were maximum performance speech tasks (a DDK task and a tongue-twister task). The whole session lasted for 60–75 min. During the experimental session, participants first completed the three cognitive tasks and then performed the two speech tasks. For the three cognitive tasks, Presentation software (Version 18.0, Neurobehavioral Systems, Inc.) was used to present the visual stimuli and to record participants' responses. For the two speech tasks, PowerPoint slides were used to present speech stimuli. One audio recording was made per participant using a Sennheiser ME 64 cardioid capsule microphone on an adjustable table stand. The speech was recorded through a preamplifier (Audi Ton) onto a steady-state 2 wave/mp3 recorder (Roland R-05). All tasks were completed in a sound-attenuating recording booth. All visual stimuli from the cognitive and speech tasks were presented on a Ben Q XL 2420T 24-in. full HD monitor placed on a table in front of the participant. Participants were encouraged to sit comfortably to have a good view of the computer screen.

The experimenter (first author) monitored participants' performance in both the cognitive and speech tasks from outside the recording booth during practice trials. Whenever participants were confused or misunderstood the task requirements during the practice phase, the experimenter would verbally communicate with the participant and restart the practice to make sure all participants had sufficient understanding of the task(s). The progress of the cognitive tasks and the presentation of stimulus slides for the speech tasks were controlled by the experimenter on the stimulus computer (Dell Precision T3600).

Cognitive Tasks

The three cognitive tasks used in this study were each meant to tap into one aspect of executive control: a flanker task was used to index inhibitory control, a letter-number task was used to index switching ability, and an operation

span task was used to index working memory capacity. The three tasks are described in more detail below.

Flanker Task

Task Description

The flanker task, developed by Eriksen and Eriksen (1974), measures inhibition of dominant (flanking) stimuli. During the task, participants were presented with a sequence of five symbols, and they were asked to pay attention to the direction in which the middle symbol (an arrow head “<” or “>”) was pointing. They had to respond to the target (middle) stimulus by pressing a response button with their left thumb or index finger when the stimulus was pointing left (“<”) or with their right thumb or index finger when it was pointing right (“>”). The two target response buttons on the six-button button box were labeled with “<” on the left-hand side and “>” on the right to clarify the association between the target stimulus and the response buttons.

The target stimulus appeared in three conditions, namely, the congruent condition (target stimulus pointing in the same direction as the flanker stimuli, <<<<< or >>>>>), the incongruent condition (target stimulus pointing in the opposite direction of the flanker stimuli, <<><< or >><>>), and the neutral condition (target stimulus embedded in the middle of neutral stimuli, –<– or –>–). In total, 72 trials were presented with an equally distributed number of repetitions across the three conditions (24 trials per condition; of which 12 targets were pointing left and 12 were pointing right). The order of the 72 test trials was randomized for each participant.

On-screen instructions in Dutch were given at the beginning of the task, followed by 12 practice trials to familiarize participants with the task. On each trial, a fixation cross was presented for 750 ms, followed by a target stimulus for 500 ms. A 1,000-ms blank screen was presented immediately after the target stimulus for participants to respond (timing choices were piloted with a small sample of different younger adults to verify that the task was doable yet challenging). Participants were encouraged to respond as quickly and as accurately as possible, and any response exceeding the response duration was logged as a “miss.” After 12 practice trials, a wait screen was presented, asking whether the participant had understood the task correctly and was ready to begin. Once a ready signal was received from the participant, the experimenter proceeded the task on the main computer outside the recording booth.

Analysis

Participants’ response times (RTs) and response accuracy were measured. We only calculated individual RT means for those participants who had actually paid attention to the stimulus on screen, as evident from accuracy levels well above chance. Data of seven participants had to be excluded because they failed to meet our minimum accuracy requirement, that is, having an accuracy level of at least 2/3 correct responses overall (i.e., minimally 48 correct

out of 72) and 2/3 correct responses in each individual condition (i.e., 16 correct out of the 24 trials per condition). Overall accuracy of the remaining 72 participants ranged between 86% and 100%. RT data of the remaining 72 participants (correct trials only) were analyzed using RStudio (Version 1.1.463), the R packages languageR (Version 1.4.1; Baayen, 2013), and lme4 (Version 1.1-19; Bates et al., 2015). Data points that were more than 3 *SDs* of the individual’s overall mean were removed (47 data points in total or < 1%). Mean RT was 362 ms (*SD* = 73) for the congruent condition and 451 ms (*SD* = 73) for the incongruent condition. To examine whether there is a potential trade-off between speed and accuracy on this task, we correlated individual accuracy and overall RT. Speed and accuracy were not correlated ($r = .18, p > 0.1$).

RTs (from valid responses only) were log-transformed (to make the distribution more normal) and entered as a numerical dependent variable into a linear mixed-effects model. Condition (congruent, incongruent, or neutral, with the congruent condition mapped on the intercept) of the flanker trials was entered as the fixed effect of interest, with direction (pointing direction of the target arrow) and trial being included as fixed control predictors. By including the latter two variables in the statistical model, we can account for variance that is otherwise left unexplained (participants generally speeding up over trials and participants being generally faster on arrows pointing to the right than pointing to the left). Participant was included as random effect (Baayen et al., 2008), with condition being a random by-participant slope to capture individual variability among participants in the size of the condition effect. Across participants, RTs were longer going from the congruent to the incongruent condition (reflecting the general condition effect). The by-participant slopes reflected the modeled individual adjustment to this general slowing effect. To make the interpretation of these slopes more straightforward, we reversed the individual slopes (negative values made positive and vice versa). In this way, participants with an originally negative value of this by-participant condition adjustment (i.e., those who were less slowed, relative to the averaged condition effect, changing from congruent to incongruent flanker trials) now got a positive value, indicating better inhibitory control. Conversely, participants who originally had a positive value, indicating that they were slowed more than average, now got a negative value, indicating worse inhibitory control.

Letter–Number Task

Task Description

The task-switching paradigm, first introduced by Jersild (1927) and then popularized by Rogers and Monsell (1995), has mainly been used to measure the “switching cost” incurred during switching back and forth between different trials or sets of trials. During this letter–number task, participants were presented with letter–number combinations (e.g., C8). They were instructed to pay attention to the quality of the number being even or odd (2, 4, 6, and

8 for even; 3, 5, 7, and 9 for odd) or to the case of the letter being upper or lower (a, d, f, and h for lower case; B, C, E, and G for upper case) in the letter–number combinations. The task consisted of three blocks.

During the entire task, the experiment-monitor screen was divided into four equal quadrants by a graphic cross. In Block 1, letter–number combinations only showed up in the top two quadrants, with stimulus location changing following a left-to-right manner from trial to trial. Participants were asked to only pay attention to the *number* in the letter–number combination and judge whether the number was *even* or *odd* by pressing the buttons labeled with the Dutch word *Even* (even) or *Oneven* (odd) on the button box. In Block 2, only the bottom two quadrants of the computer screen were used. Stimulus location also followed a left-to-right manner from trial to trial. Participants were instructed to only pay attention to the *letter* in the letter–number combination and judge whether the letter case was *capital* or *small* by pressing the buttons labeled with “Hoofd” (capital) or “Klein” (small). Note that only two buttons on the button box were used for this task with top halves of the buttons labeled with “Even” and “Oneven” and lower halves with “Hoofd” and “Klein.” This was to ensure stimulus–response mapping: left index finger/thumb for even and capital stimuli and right index finger/thumb for odd or small stimuli (Rogers & Monsell, 1995).

The first two blocks were single-task blocks in which participants had to either pay attention to the number being even or odd (block one) or to the letter being in lower or upper case (Block 2). The third block was a mixed-task block, in which the position of the letter–number combination on the screen (i.e., the quadrant the combination appeared in) determined what aspect of the letter–number combinations participants had to pay attention to. In total, there were 192 trials; Blocks 1 and 2 both consisted of 48 trials, and Block 3 consisted of 96 trials.

In Block 3, the mixed-task block, the whole screen was used for presentation of letter–number combinations. Stimulus location changed following a clockwise manner from trial to trial (starting in the upper left quadrant, then upper right, followed by lower right, then lower left). Participants were required to judge the *number* of the letter–number combination as being odd or even if the letter–number stimuli were presented in the *upper* left and right quadrants and to judge the *letter* of the letter–number combination as being upper or lower case if the stimuli were presented in the *lower* quadrants. Each letter–number stimulus was presented until the participant pressed one of the response buttons, up to a maximum of 5,000 ms. The third block thus consisted of no-switch trials where participants had to pay attention to the aspect they also paid attention to on the previous trial (i.e., the no-switch trials appearing in the upper right quadrant and the lower left quadrant) and switch trials where participants needed to switch from responding to the one dimension to the other dimension (i.e., the switch trials appearing in the lower right quadrant and the upper left quadrant). Blocks 1 and 2 were practice blocks, while Block 3 was the experiment block of interest.

Participants were instructed to respond as quickly and as accurately as possible, and any response exceeding maximum trial duration was logged as a “miss.” Instructions in Dutch were displayed on screen prior to each block of trials. Upon reading the instructions of each block, participants were asked whether they had any questions understanding the task. Once everything was clear, the experimenter proceeded the task on the main computer outside the recording booth. After each block, participants were presented with visual on-screen feedback on their accuracy score for that block. This block-based feedback enabled the experimenter to evaluate whether participants had sufficient understanding of the task requirements during the first two (practice) blocks before they moved on to the third (test) block.

Analysis

Participants’ RTs and response accuracy in the third (mixed-task) block were measured. One participant’s data were excluded due to technical failure. Data of all remaining 77 participants met the minimum accuracy requirement, that is, each participant having at least two thirds of correct responses in the third block (64 correct out of 96 trials). Accuracy rates in the third block ranged between 88% and 100%. Data of these 77 participants were analyzed using RStudio (in the same way as described above for the flanker data analysis). Similar to the flanker task, 106 outliers (104 data points were more than 3 *SDs* of the individual’s mean RTs in Block 3, and two data points were lower than the 200 ms threshold) of the RT data were removed (< 1.5%). Mean RT was 794 ms (*SD* = 454) for the no-switch trials and 1,353 ms (*SD* = 621) for the switch trials. We correlated individuals’ response speed and accuracy on this task to test for potential trade-offs. Individual RT and accuracy were not significantly correlated ($r = -.11, p > 0.1$).

Similar to the flanker task, RTs (from correct responses only) were log-transformed (to make the distribution more normal) and entered as a numerical dependent variable into a linear mixed-effects model. Condition (the target trial being a switch or no-switch trial, with the no-switch condition being mapped on the intercept) of the letter–number trials was entered as the fixed effect of interest, with trial being included as fixed control predictor. Participant was included as random effect, with condition as a random by-participant slope to capture individual variability among participants in the size of the condition effect. The general condition effect showed that participants’ RTs generally increased going from a no-switch to a switch trial. The by-participant slopes reflected the modeled individual adjustment to this general switching effect, such that the lower the value, the less they were slowed, changing from no-switch to switch letter–number trials (relative to the averaged condition effect), indicating a smaller switching cost. Similar to the analysis of flanker responses above, we also reversed the individual slopes here (negative values made positive and vice versa). Thus, those with original lower values for this individual condition adjustment (i.e.,

those with lower negative values) were slowed less than average, changing from no-switch to switch trials, now got a positive value, indicating better switching ability.

Operation Span Task

Task Description

The operation span task (Turner & Engle, 1989), as one of the complex span tasks, is taken to assess the capacity to efficiently update working memory. The task requires participants to store and regularly update memory representations while performing another cognitively demanding task. For example, in the original version of the task, participants have to solve simple mathematical problems while memorizing word lists of varying length. The adapted version of the operation span task used in this study (from Shao et al., 2012) required participants to judge the accuracy of simple mathematical problems while remembering randomly ordered letter lists of varying length. The main reasons for using letters rather than words, as used in Shao et al. (2012), are twofold. First, we intended to increase the difficulty of the task by replacing meaningful words with meaningless, randomly sequenced letters, such that the letter lists did not resemble any familiar Dutch or English acronyms. Second, we aimed to test “purer” executive control by avoiding interference from language ability as much as possible.

For the task, 65 mathematical operations each followed by one letter (letters were selected from the alphabet) were used as trials. These 65 trials were divided over 17 lists, ranging from two to six trials per list. Two lists of two and three trials, respectively, were used as practice lists. Detailed instructions were given on screen before the practice lists. During the task, a fixation cross was presented for 800 ms at the start of each trial. After a blank screen of 100 ms, a mathematical operation followed by a letter was presented in the center of the screen, for example, $(4 \times 2) - 3 = 2$ D. Participants were instructed to read both the operation and the letter out loud in the order presented and then press one of the buttons labeled “Ja” (yes) or “Nee” (no) on the button box to judge whether or not the operation was correct while trying to remember the letter. At the end of each list of trials, a recall cue: “Nu graag typen!” (Type now please!) was presented. Upon presentation of this cue, participants were asked to recall all the letters seen since the beginning of the list and to type them in the same order as they had been presented using a keyboard. They were also encouraged to mark the position of any missing letters using “.” if they could not recall the letters themselves. The experimenter monitored participants’ performance during the practice trials. Participants were reminded to read the mathematical operation and the letter following it out loud if they forgot to do so.

Analysis

Participants’ response accuracy for the mathematical operations and their scores for the letter sequence recall were measured. Results from two participants were excluded

because of poor performance on the math problems (less than 85% correct, following Unsworth et al., 2005). Updating span (recall score) was calculated as the sum of the letters that were recalled correctly in the correct position (Unsworth et al., 2005). The higher the recall score, the better the working memory capacity. The range of a possible score is between 0 and 60. Participants’ mean task performance (number of letters correctly recalled) was 38 ($SD = 11$), and their actual scores ranged between 18 and 60 (i.e., between 30% and 100%).

Processing Speed

In order to obtain an index of individual participants’ processing speed, rather than introducing a new task, we made use of the “control” trials from the two cognitive tasks where speed was a built-in task requirement (i.e., the flanker and letter–number tasks). We used a principal component analysis to derive one single speed construct underlying the baseline speed measures from the two tasks. More specifically, this single-speed construct was derived from the individual random intercepts in the two speeded tasks (for the congruent condition mapped on the intercept in the flanker task and for the no-switch trials mapped on the intercept in the letter–number task). Factor loadings on the processing speed construct (unrotated factor solution) were 0.83 for both speed measures. Because this measure is based on the two baseline speed measures from the two cognitive tasks (where those who are faster have shorter RTs and hence negative by-participant intercepts), the values of this speed construct were also reversed (i.e., higher values of this speed construct indicates faster processing speed) for a more straightforward interpretation (higher values reflecting “better” performance).

Speech Tasks

The two speech tasks, a DDK task and a tongue-twister task, were set up as maximum performance speech tasks to capture participants’ articulatory control ability. In order to provide a more complete picture of speakers’ articulatory control ability, Yaruss and Logan (2002) proposed to focus not just on maximum (DDK) rate to quantify (children’s) speaking abilities but to also investigate other aspects of DDK performance, such as accuracy. Therefore, we quantified speakers’ maximum performance through both rate and accuracy.

DDK Task

Task Description

A DDK task often contains repetitions of mono- or trisyllabic nonsense words like “pa” and “pataka” (Bernthal et al., 2009). Due to the focus of the current study on carrying out alternations, we opted for the sequential motion rate variant of the DDK task, that is, using alternating trisyllabic sequences as task stimuli (e.g., “pataka”). We made adjustments to the canonical oral DDK task to link to the debate of whether nonword oral DDK is representative

for speakers' actual speaking capability (Ben-David & Icht, 2017; Icht & Ben-David, 2015; Maas, 2017; Ziegler, 2002). We therefore specifically included two nonword DDK stimuli, the standard "pataka" /pataka/ and the reverse-order "katapa" /katapa/, and two real-word DDK stimuli, namely, the two Dutch words that are closest to the nonword sequences: "pakketten" /pa'ketə(n)/ (packages) and "kapotte" /ka'pɔtə/ (broken). This allowed us to test whether either type of DDK performance is more strongly associated with executive control. Note that, even though the selected real words were close to the nonsense words in terms of alternating consonants, they also differed from them in multiple respects. For instance, no stress pattern was available for the nonword stimuli, whereas both real words had lexical stress on the second syllable. Moreover, vowels were full /a/ vowels in the nonsense sequences but were different vowels (different in length and place of articulation and in terms of acoustic reduction due to lexical stress) in the real words.

During the DDK task, each stimulus was always presented in the center of a full-screen PowerPoint slide. Multiple repetitions of the (nonsense) words were presented in a row, for instance, "patakapatakapataka...", to elicit repetitive production of the stimulus. Participants were instructed to repeatedly produce the presented stimulus as accurately and as rapidly as possible. A prerecorded example was played prior to the practice trials to familiarize the participants with the task. A brief line of text reminding them about accuracy and speed of repetition was constantly on display at the top of each slide. A 2-s pause (preparation time) followed by a 75-ms beep tone was used to mark the start of articulation, and each stimulus was to be repeated for around 10 s. Additionally, the mono- and disyllabic nonsense stimuli ("pa," "ta," "ka," "pata," "taka") were presented to participants as practice trials before the experimental trials, such that participants had received extensive task familiarization, including familiarization of production of alternating sequences before they moved to the test phase. All DDK trials were presented to the participants in the same fixed order (i.e., practice trials followed by nonword and then by real-word sequences). Note that this implies that we cannot rule out that the fixed order may have contributed to performance differences between nonword and word sequences, to which we will come back in the Discussion section below.

Analysis

Maximum performance in terms of rate and accuracy was analyzed acoustically in Praat (Boersma & Weenink, 2017). DDK articulation rate (syllables/s) and accuracy (fraction correct) were calculated using the first 7-s time window of the DDK utterance. This 7-s time window was selected because, even though articulation errors and disfluencies already occurred in a 3-s time window for most participants, the number and frequency of errors and disfluencies generally increased in longer time windows. Thus, in order to capture accuracy and articulation rate in

a more reliable way, we opted for a relatively long time window (7 s).

Individual DDK accuracy (fraction correct) was calculated as number of accurate and fluent repetitions divided by number of all repetitions in the 7-s time window (or as close to 7 s as possible for the repetition counts to be an integer). A repetition was only counted as correct if it did not contain any form of obvious articulation errors (e.g., if a speaker produced "patapka" or "katakpa") or disfluencies (e.g., silent pauses longer than 200 ms) within the sequence (Yaruss & Logan, 2002). Individual DDK articulation rate (syllables/s) was calculated by multiplying the total number of accurate and fluent (non)word repetitions produced by each participant in the same 7-s time window by three (syllables) and divided this number of total syllables by the actual production time (total duration minus erroneous and disfluent repetitions, as well as in-breaths and pauses longer than 200 ms between repetitions).

Tongue-Twister Task

Task Description

Following Wilshire's (1999) tongue-twister paradigm, we selected four Dutch tongue-twister sentences containing a combination of repetition and alternation of word-initial consonants or consonant clusters (e.g., **poes** **kotst** **postzak**, and **frits** **vindt** **visfrietjes**). Below are the four tongue-twister sentences that were used as test stimuli with their literal English translations in parentheses (note that the boldface used in the tongue-twister sentences below is only for illustration purpose; the actual stimuli in the task did not have boldface on the similar/contrasting phonemes):

- De **poes** **kotst** in de **postzak** (*The cat puked in the mail bag*)
- **Frits** **vindt** **visfrietjes** **vreselijk** **vies** (*Frits finds fish-fries terribly gross*)
- Ik **bak** een **plak** **bakbloedworst** (*I fry a slice of blood-sausage*)
- **Papa** **pakt** de **blauwe** **platte** **bakpan** (*Daddy grabs the blue flat frying pan*)

Prior to the above-listed task stimuli, two additional tongue-twister sentences were presented as practice stimuli:

- **Slimme** **Sjaantje** **sloeg** de **slome** **slager** (*Smart Sjaantje hit the slow butcher*)
- **Bakker** **Bas** **bakt** de **bolle** **broodjes** **bruin** (*Baker Bas bakes the round buns brown*)

Participants were instructed to repeat the tongue-twister sentences as accurately and as rapidly as possible. Similar to the DDK task, each tongue-twister stimulus was also always presented in the center of a full-screen PowerPoint slide, with a brief line of text reminding participants about accuracy and speed of repetition at the top of each slide. A picture related to one object per tongue-twister sentence (e.g., a blue frying pan) was shown below

the printed stimulus on the same slide, and then the picture disappeared after about 2 s of preparation time. Participants were instructed to start repeating the tongue twisters minimally 5 times as soon as the picture disappeared (note that the picture disappearing only served as a cue to start speaking, whereas the sentence remained on the screen).

Analysis

Participants' maximum performance in terms of accuracy and rate was analyzed acoustically in Praat (Boersma & Weenink, 2017). Similar to the accuracy measures in the DDK task, individual tongue-twister accuracy (fraction correct) was calculated as the number of accurate and fluent repetitions divided by the first five repetitions (five being the number of repetitions speakers minimally produced). A repetition was counted as accurate and fluent if it did not contain any form of perceivable error or disfluency (including silent pauses longer than 200 ms). Tongue-twister articulation rate (syllables/s) was calculated by averaging the articulation rate of the accurate and fluent repetitions of the four tongue-twister stimulus sentences (except for two participants whose overall rate was based on three tongue-twister sentences because they each had an accuracy of "0" in the remaining sentence; in other words, all five repetitions of one of the tongue-twister sentences contained errors). The rate of each accurate and fluent stimulus was measured by dividing the number of syllables in a tongue-twister sentence by the articulation time used for that repetition.

Relating Executive Control to Maximum Speech Performance

Analysis

In order to investigate how well measures of articulatory control can be predicted by elements of executive control, we analyzed our maximum speech performance data with linear mixed-effect regression models (as is the norm in psycholinguistic research). This choice enables us to account for random participant variance and any effects of our fixed predictors (such as cognitive ability indices and lexical status) on speech task performance. Several linear mixed-effects models were fitted for DDK performance (for DDK accuracy and rate separately) and for tongue-twister performance (again one model for accuracy and one for rate). Accuracy and rate were pooled per DDK or tongue-twister item (DDK items being the two-real-word and two-nonword stimuli and tongue-twister items being the four-stimulus sentences), and these pooled item scores (fractions or pooled rates) were analyzed as dependent variables.

In the two DDK models, DDK accuracy or rate was entered as numerical dependent variable, with the executive control scores as fixed effects of interest. These included the extracted individual scores of inhibitory control (derived from the by-participant slopes in flanker task; scores scaled and centered), switching ability (derived from the

by-participant slopes in letter-number task; scores scaled and centered), working memory capacity (derived from the operation span task; scores scaled and centered), and processing speed (from the derived speed construct; scores scaled and centered). Lexicality was also included as a factor in the DDK models (real-word vs. nonword stimuli) because we expected participants' DDK performance to differ across real words and nonwords and because we wanted to investigate potential interactions between lexicality and cognitive abilities. Additionally, participant was included as a random effect in both DDK models, and we also allowed a random by-participant slope for the lexicality effect, acknowledging that speakers may be differentially affected by the difference between real words and nonwords. DDK item could not be entered as a fixed variable, as this would leave no variance to the model given the item-pooled dependent measure. These full models were then stripped in a step-wise manner to arrive at the most parsimonious model (taking out insignificant interactions, first, and then insignificant effects, starting with the ones with the lowest t values). Model comparisons were applied after each removal of the least significant predictor to verify that exclusion of each predictor term did not lead to a significantly different model fit.

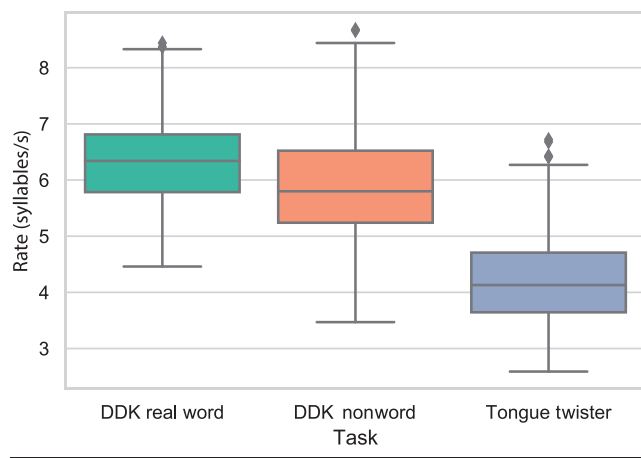
Two tongue-twister models were set up as well (one for accuracy and one for rate) with pooled tongue-twister accuracy or rate as numerical dependent variable. Tongue-twister performance was also analyzed as a function of the same four cognitive measures used in the two DDK models. Tongue-twister number (four in total) was included as a fixed control predictor (with the first sentence mapped on the intercept), and participant was included as random effect into the model. Similar to the DDK models, the full models were also stripped in a step-wise manner, with model comparisons applied after each removal of the least significant predictor, to arrive at the most parsimonious model.

Results

Descriptive performance in the two speech tasks in terms of rate (syllables/s) and accuracy (fraction correct) from 78 participants is illustrated in Figures 1 and 2 below. Rate and accuracy measures averaged over task stimuli were entered as dependent variables in two linear mixed-effect models for rate and accuracy, respectively. Task (three levels: DDK real word, DDK nonword, and tongue twister) was entered as the fixed effect of interest, with participant as a random effect. As shown in Figures 1 and 2, maximum performance in the tongue twister task is significantly worse than in DDK nonword repetition ($t = -25.17$, $p < .001$ and $t = -18.24$, $p < .001$ for rate and accuracy, respectively). Within the DDK task, real-word DDK performance is significantly better than nonword DDK performance for both rate ($t = 5.45$, $p < .001$) and accuracy ($t = 2.71$, $p < .01$).

Our DDK nonword data can be compared to previously established norms for a Dutch nonclinical speaker

Figure 1. The distribution of maximum performance rate in DDK nonword, DDK real-word, and tongue-twister tasks. DDK = diadochokinetic.



population (Knuijt et al., 2017). Median maximum repetition rate for “pataka” in young adults aged 18–29 years in their study was 7.0 syllables/s (range: 4.1–9.0), whereas median performance in our sample was 6.1 (range: 3.8–8.7) for “pataka” (and median of 5.6 for “katapa,” for which no reference value was available). Differences between samples may be due to differences in the way rate was calculated (in relation to errors and pauses).

We checked for potential speed–accuracy trade-offs in these speech tasks by examining whether rate and accuracy were correlated. Correlations between speech rate and accuracy were not significant for DDK real word ($r = -.020$, $p > .05$), DDK nonword ($r = -.056$, $p > 0.1$), and tongue twister ($r = -.084$, $p > 0.1$).

Before moving on to addressing the research question, we checked intercorrelations between cognitive predictors. Table 1 presents the correlation matrix for our measures

Figure 2. The distribution of maximum performance accuracy in DDK nonword, DDK real-word, and tongue-twister tasks. DDK = diadochokinetic.

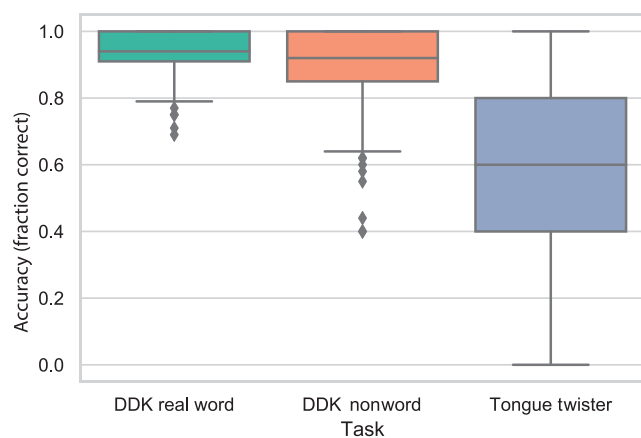


Table 1. Correlation matrix of the cognitive measures.

Measure	Flanker inhibitory control	Letter–number switching	Operation span (updating)
Letter–number switching	.019		
Operation span (updating)	–.112	.323**	
Processing speed	.507***	–.138	–.198

Note. Pearson correlation coefficients.
** $p < .01$. *** $p < .001$.

of inhibitory control (i.e., flanker task), switching ability (i.e., letter–number task), updating ability (i.e., operation span), and processing speed (based on two speeded measures).

The correlational data presented in Table 1 indicate that switching ability (as indexed by the letter–number task performance) was positively linked to updating ability (as indexed by operation span performance), $r = .323$, $p < .01$, such that those who are better at switching also have better updating ability. Processing speed is positively related to inhibitory control (as indexed by flanker task performance), such that those who have faster processing speed are also better at inhibiting irrelevant information ($r = .507$, $p < .001$). Additionally, updating ability (operation span) did not correlate with inhibitory control ability (flanker performance).

Table 2 and Figure 3 below summarize the association between executive control (from the most parsimonious model) and DDK accuracy and rate. Note that performance on nonword DDK sequences was mapped on the intercept.

Table 2 shows that DDK accuracy is significantly modulated by lexical status of the DDK stimulus, such that accuracy was higher for real-word than nonword sequences (but keep in mind that lexical and nonlexical stimuli also differed on, e.g., stress pattern and order of administration). Furthermore, DDK accuracy was significantly predicted by letter–number switching ($b = 0.213$, $SE = 0.076$, $t = 2.790$), such that participants who were more accurate at switching between the two aspects of the letter–number combination were better able to produce DDK sequences. Additionally, there is an interaction between the lexality of the DDK stimuli and (letter–number) switching ($b = -.0227$, $SE = 0.083$, $t = -2.742$), indicating that those with better letter–number switching were influenced less by the lexality of the DDK stimuli. In other words, for participants with good switching ability, the difference between their DDK word and nonword repetition accuracy was smaller than for those with poorer switching ability.

Similar to DDK accuracy, participants’ DDK rate performance differed between real-word sequences and nonword sequences, with better (i.e., faster) performance for the real-word than nonword sequences. However, DDK rate was not predicted by any of the executive control

Table 2. The coefficient estimates, standard errors, and significance levels of factors involved in diadochokinetic accuracy and rate.

Predictors	Dependent variable					
	Accuracy			Rate		
	Estimates	SE	<i>p</i>	Estimates	SE	<i>p</i>
Intercept	0.888	0.010	< .001	5.909	0.105	< .001
Lexical–yes	0.052	0.011	< .001	0.423	0.064	< .001
Letter–number switching	0.213	0.076	.005			
Lexical–Yes × Letter–Number Switching	–0.227	0.083	.006			

Note. Effects and interaction that remain significant given an extraconservative alpha level ($\alpha = .0125$) are shown in boldface.

measures in our study.¹ Table 3 and Figure 4 summarize the analysis testing for an association between executive control (from the most parsimonious model) and tongue-twister accuracy and rate.

As can be seen in Table 3, tongue-twister accuracy differed across the different sentences. Additionally, comparable to DDK accuracy, tongue-twister accuracy was significantly predicted by letter–number switching ($b = 0.357$, $SE = 0.126$, $t = 2.841$), such that those with better switching ability were also more accurate at rapid tongue-twister production. Note that we verified that our results about the link between DDK accuracy or Tongue Twister accuracy on the one hand and switching on the other also hold if we apply lmer models to the accuracy proportions converted to logits.

Tongue-twister rate, like tongue-twister accuracy, also differed across tongue-twister sentences. As was observed for DDK rate, tongue-twister rate is not predicted by any of the measures of executive control here.² As we repeatedly tested for a possible link between aspects of executive control and speech performance (i.e., in four analyses), one can argue that a more conservative alpha level would be appropriate. If we adopt a more conservative alpha level (dividing the critical alpha level by four; $p < .0125$), the relationship between switching ability and DDK accuracy (as well as the lexuality

effect and the Switching × Lexicality interaction) and the relationship between switching ability and tongue-twister accuracy remain significant (cf. Tables 2 and 3).

In summary, participants' cognitive switching ability related to their accuracy in both DDK and tongue-twister tasks. However, performance on the cognitive tasks was not related to participants' maximum rates in the speech tasks.

Discussion

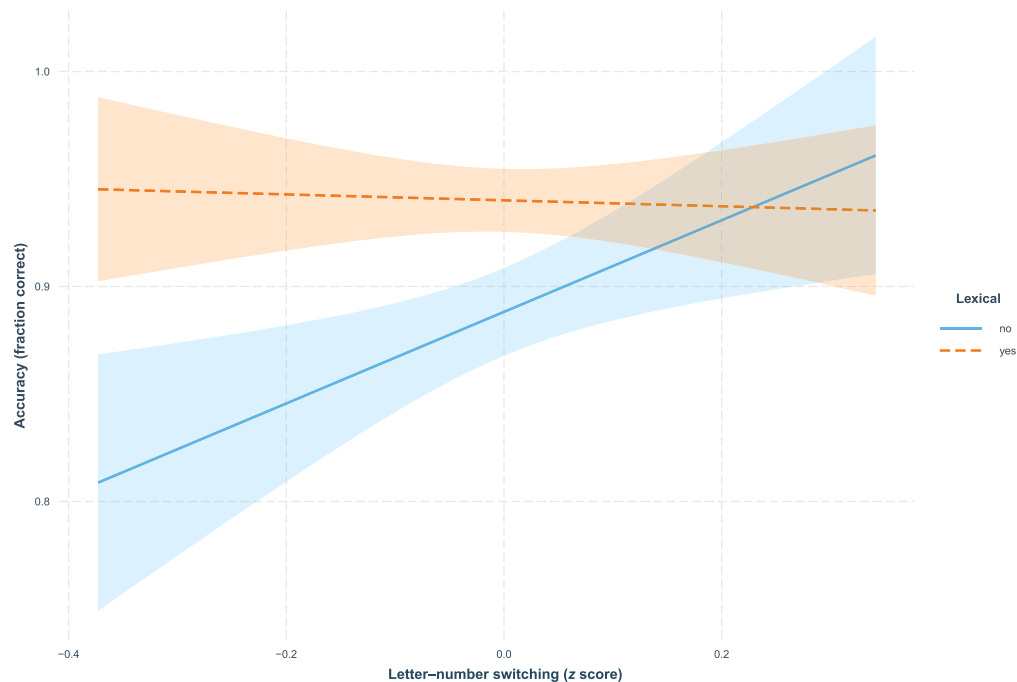
In this study, we investigated the potential link between maximum speech performance and executive control abilities in a sample of 78 young healthy adults without any language, speech, or hearing impairment. Using two maximum speech performance tasks (i.e., a clinical DDK task and a tongue-twister task), we tapped participants' articulatory control abilities through acoustic (rate) and behavioral (accuracy) data. Both speech tasks require rapid alternation between similar onset consonants or consonant clusters, as we used the sequential version of DDK (repetition of nonword sequences “pataka” and “katapa” and real Dutch words “pakketten” *packages* and “kapotte” *broken*). Additionally, participants' executive control abilities were assessed by means of three cognitive tasks, that is, a flanker task as an index of inhibitory control, a letter–number task as an index of switching ability, and an operation span task as an index of updating ability.

In general, participants' maximum performance varied for the different types of speech stimuli. More specifically, participants were more accurate and achieved faster speech rates in producing DDK sequences than tongue-twister sentences, possibly due to higher processing load involved in producing the longer “tongue-twisting” sentences and higher articulatory complexity (involving more complex syllable structures). Within the DDK task, in line with the results obtained from children and healthy older adults (Ben-David & Icht, 2017; Icht & Ben-David, 2015), our young adult speakers performed better in real-word conditions than in nonword conditions. That is, they were able to repetitively produce real words more accurately and faster than nonwords. We will come back to potential

¹To verify that our results were not driven by our data selection procedures, we reexamined the data including the previously excluded seven participants (with low accuracy on the flanker task). Additionally, for this reexamination, we based each participant's flanker cost on all valid (i.e., correct) responses, not excluding outlier RTs. Likewise, in this reexamination, each individual's letter–number performance was calculated on all valid data points (not excluding outlier RTs). The overall pattern of DDK results stayed exactly the same (significance and direction of lexuality and switching effects and their interaction).

²As was done for DDK, we reexamined the tongue-twister data to verify that our results were not driven by our data selection procedures. For this reexamination, we included all participants' valid data (as described for the data reexamination above). The effects observed for tongue-twister accuracy stayed exactly the same. For tongue-twister rate, we now found an effect of processing speed (in addition to the tongue-twister sentence effect), such that those with higher processing speed also produced faster tongue-twister rates.

Figure 3. Model plot of DDK accuracy in relation to switching ability and lexicity (of the DDK sequences). DDK = diadochokinetic.



confounds of lexical status with other factors below. More importantly, cognitive switching ability related to both DDK and tongue-twister maximum accuracy, such that individuals with better switching ability were also better able to accurately produce tongue-twister sentences and DDK sequences at a fast rate. This indicates that cognitive switching relates to the rapid production of consecutive alternating speech movements.

Apart from the general effect of cognitive switching on DDK accuracy, an interaction was found between the lexicity of the DDK sequences and cognitive switching ability, such that for participants with better cognitive switching ability, the performance difference between DDK real-word and nonword conditions was smaller, compared to those with poorer switching ability. In other words, those with poorer cognitive switching ability may have benefited

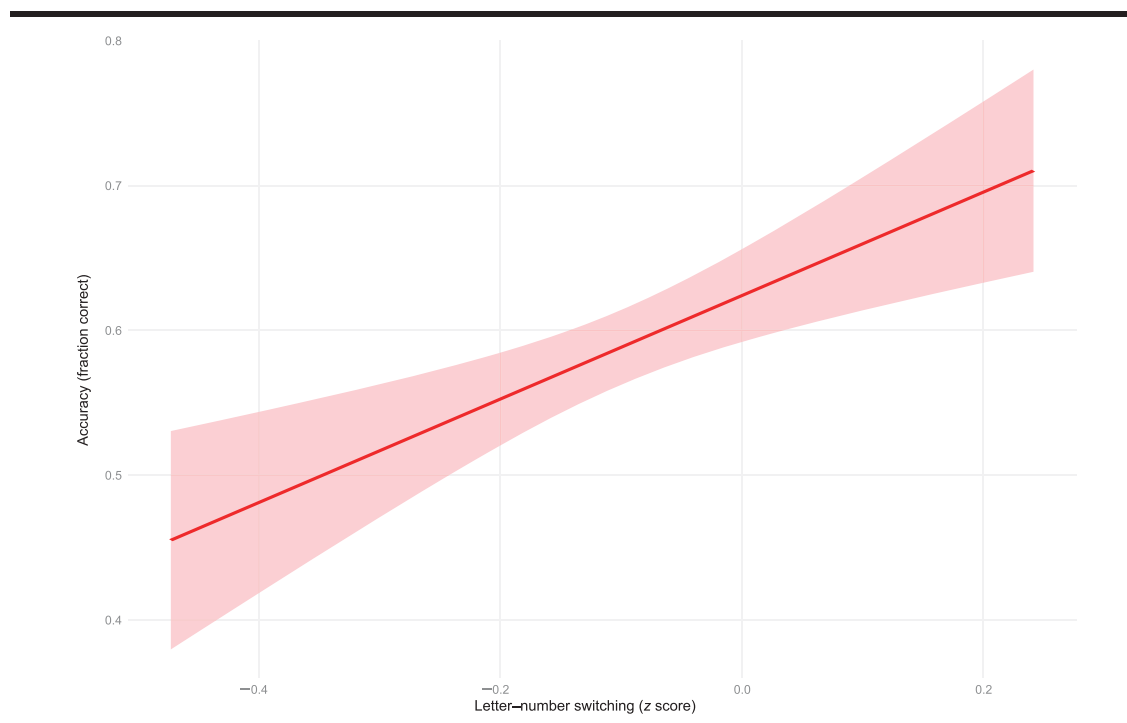
more, relatively, from producing *familiar* sequences such as real words as compared to the relatively *unfamiliar* and novel nonword sequences. As our results describe relationships from which no causality can be derived, follow-up research with experimental manipulation of cognitive switching load would be required to confirm this. Furthermore, note again that these real-word and nonword stimuli differed not only in speakers' familiarity with the required motor programs but also in their intrinsic prosodic patterns (as also argued in Ziegler, 2002) and in their order of administration in the experimental protocol. For instance, the two real Dutch words both contain one full short vowel (receiving primary stress), one schwa, and one unstressed vowel that could be reduced to a schwa, whereas nonword sequences like "pataka" or "katapa" do not have a known stress pattern and contain three long full vowels. Whereas most speakers

Table 3. The coefficient estimates, standard errors, and significance levels of factors involved in tongue-twister accuracy and rate.

Predictors	Dependent variable					
	Accuracy			Rate		
	Estimates	SE	p	Estimates	SE	p
Intercept	0.675	0.025	< .001	4.178	0.063	< .001
Tongue-twister_number 2	−0.096	0.030	.001	−0.114	0.053	.033
Tongue-twister_number 3	−0.177	0.030	< .001	−0.653	0.053	< .001
Tongue-twister_number 4	−0.075	0.030	.012	0.910	0.053	< .001
Letter-number switching	0.357	0.126	.005			

Note. Effects that remain significant given an extraconservative alpha level ($\alpha = .0125$) are shown in boldface.

Figure 4. Model plot of tongue-twister accuracy in relation to letter–number switching ability. DDK = diadochokinetic.



put primary stress on the initial syllable (“pátaka” and “kátapa”), we also observed some interspeaker variation in (the consistency of) stress placement and reduction of unstressed syllables to schwa. Uncertainty about the item’s stress pattern and about reduction of syllables may contribute to nonword production being more difficult than real-word production.

Furthermore, all participants produced the nonword DDK sequences before the real-word sequences. Even though participants had had extensive DDK practice before moving on to the critical nonword and real-word sequences, having already produced the nonalternating sequences and alternating disyllabic stimuli (pata and taka) as practice stimuli, we cannot distinguish lexical status effects from order effects on the basis of our design. These confounds may have contributed to the nonword and real-word stimuli differing in the amount of executive control required to repetitively produce the sequences.

Our results challenge the idea that “late stages” of speech-language production are largely automatic (Ferreira & Pashler, 2002; Garrod & Pickering, 2007). Rather, at least when speech production is made as challenging as we did here, executive control seems to relate to speech production, just like it has been shown to relate to language control in bilinguals (e.g., Costa et al., 2006; Rodríguez-Fornells et al., 2006), in noun–phrase production (e.g., Sikora et al., 2016), or in lemma selection (e.g., Piai & Roelofs, 2013; Shao et al., 2012). Our tongue-twister data agree with evidence (McMillan & Corley, 2010) that phoneme production is more error-prone and less target-like in

the context of competing phonemes (*kef def def kef*) than when produced in a context without competing phonemes (*kef kef kef kef*). Correct and fluent production of sequences of alternating syllables thus seems to relate to executive control to rapidly alternate between target phonemes. Data by McMillan and Corley (2010) also suggested that the more similar the competing phoneme to the target phoneme (/t/ being more of a competitor for /k/ than is /d/), the greater the competition effect (McMillan & Corley, 2010). Our DDK stimuli involved switching between highly similar voiceless stops, and accurate DDK performance was indeed also related to switching ability. Our results therefore provide evidence that switching is associated with resolving competition and selection at later stages than lemma selection in speech production (i.e., during phonological and phonetic stages).

Our finding that cognitive switching relates to the production of consecutive alternating speech movements echoes with findings in which cognitive load was manipulated experimentally, such as the findings that cognitive or linguistic load impacted on articulation stability for unimpaired speakers (Dromey & Benson, 2003). Similar findings of cognitive load effects on articulation have also been found among children with specific language impairment (Saletta et al., 2018), as well as for healthy younger and older adults (MacPherson, 2019; Sadagopan & Smith, 2013). In MacPherson’s (2019) study, healthy younger and older adults’ articulatory control was measured through reading aloud sentences that formed Stroop and non-Stroop conditions. MacPherson found that articulatory motor stability was

affected by Stroop interference, and that older adults' speech motor performance was more detrimentally affected in the Stroop condition than that of younger adults. The findings from these studies align with our findings. In our findings, those with poorer executive control were less accurate in rapidly producing alternating sequences, which can be seen as speech motor breakdown. In the MacPherson (2019) study, participants with supposedly poorer executive control due to their older age were more impacted by cognitive stress on their speech motor performance compared to those with supposedly better executive control.

The findings in this study are novel in the sense that we showed evidence of speakers' articulatory control abilities as reflected by maximum speech performance to be related to their executive control abilities, backing up the statement that "speech, or any motor behavior, is best viewed as a cognitive-motor accomplishment" (Kent, 2004, p. 3). However, note that our approach to articulatory control was maximum performance in terms of rate and accuracy, instead of speech motor stability as in work by, for example, Dromey and colleagues. Thus, further examination of underlying speech motor control through kinematic measures is required to investigate how cognitive ability may relate to articulatory stability. Additionally, our results also broadened the perspective on the relationship between articulatory and executive control by providing data from a young non-clinical rather than a clinical sample (e.g., Nijland et al., 2015; Peter et al., 2018; Shriberg et al., 2012).

In comparison to performance on the DDK task, rapidly producing tongue-twister sentences were shown to be more challenging for our speaker sample, as reflected by the lower and more variable rate and accuracy in performance. As described in Shen and Janse (2019), there may be multiple (methodological) reasons for the difference in performance between the DDK and the tongue-twister tasks. First, compared to DDK sequences, tongue-twister sentences are proper sentences and consequently involve more grammatical and semantic processing. Moving from word or nonword repetition to sentence repetition therefore demands a higher linguistic processing load. Second, some words in the tongue-twister sentences contain consonant clusters in both syllable-onset and -offset positions (e.g., /b/ for onset and /tst/ for offset, respectively) and more varied phonetic contrasts (e.g., the place of articulation and voicing of the alternating stop consonants /p/, /b/ and consonant clusters /pl/, /bl/), whereas both nonword and real-word DDK sequences contain rather simple consonant-vowel structures and less complex phonetic contrasts in their syllable-onset consonants (i.e., only the place of articulation differed in singleton onset consonants /p/, /t/, and /k/). However, despite their differences in linguistic content and linguistic processing load involved, performance in both speech tasks related to (elements of) executive control in that speakers had to switch between similar competing phonemes and had to keep track of where they were in their production of the sequence.

As laid out in the introduction, even though cognitive switching was thought to be most relevant to our specific

speech tasks, all three elements of executive control were expected to relate to speech performance to a certain degree. Updating was expected to relate to rapid production of alternating sequences because planning and programming of speech movements need to be constantly updated. Inhibitory control was expected to relate to the suppression of coactivated but incorrect competing phonemes and/or phoneme clusters in the speech stimuli. Our results could indicate that cognitive switching is involved in speech production (in the way speech production was operationalized here) and that inhibitory control and updating are not or to a lesser degree. However, alternative explanations cannot be ruled out. The updating and inhibitory control measures used here could potentially be noisier than the switching measure, in that they were less successful in capturing the target ability. For instance, inhibitory control data of seven participants had to be excluded due to their low accuracy in the flanker task, whereas no one failed to meet to the minimum accuracy requirement in the letter-number task that measured switching. Arguably, the level of difficulty of the letter-number task should be higher than that of the flanker task given the complexity of the letter-number task. However, due to a difference in task design, participants did more practice trials in the letter-number task (two blocks of 48 trials) than in the flanker task (one block of 12 trials). Additionally, they received feedback on their performance (i.e., number of errors made) after each block in the letter-number task, while no feedback was ever given during the entirety of the flanker task. The feedback in the letter-number task might have motivated participants to pay more attention to the task, resulting in better task performance. We cannot rule out the possibility that we might have gotten a "purer" measurement of participants' switching ability than their inhibitory control ability, and this could have contributed to observing an effect of switching but not of inhibitory control on performance in the speech tasks.

The existence of various sources of "noise" in different tasks brings up the issue of the validity of using a single task to measure (a given aspect of) executive control. As Miyake and colleagues described in their studies on measuring the construct of executive control, "task impurity" was listed as one of the problems when using single tasks to measure aspects of executive control (Miyake & Friedman, 2012; Miyake et al., 2000). *Task impurity* refers to unwanted systematic variance that exists in different cognitive tasks, for example, additional processing of the number being odd or even in the letter-number task. To minimize this task impurity problem, Miyake and colleagues proposed a "latent variable approach," which is to use multiple tasks that capture the target ability and to extract the commonality across the tasks (a latent variable) as the measure of the targeted executive control (Miyake & Friedman, 2012; Miyake et al., 2000). This latent variable approach, that is, using multiple tasks to measure a construct, requires larger participant sample sizes than used in this study but may be an approach to pursue in future research.

Another possible reason why updating and inhibitory control did not predict speech performance could be our

analysis method of having all predictors in our initial model. Although updating ability was not found to be significantly involved in the speech performance, it was actually approaching significance ($p = .08$) in the model of DDK accuracy (in addition to the observed interaction between switching and lexicality). Moreover, when updating (rather than switching), lexicality, and their interaction were included as the only fixed effects of interest in a model, both updating and the interaction between updating and lexicality became significant predictors of DDK accuracy (same direction of effects and interaction as observed for switching ability). This finding highlights the collinearity problem of having correlated predictors, even if their correlation does not exceed .3. In other words, due to the significant correlation between updating ability and switching ability, inclusion of the stronger predictor (switching in this case) overruled the potential contribution of the weaker predictor (updating). This observation echoes with Miyake and colleagues' arguments on the unity and diversity of executive control measured with simple laboratory tasks: Different elements of executive control are correlated yet separable.

As noted in the introduction, updating of the working memory has been shown to be involved in the "early stage," that is, the formulation stage of the speech production. Our results suggested that aspects of executive control may also relate to the articulatory planning and execution of speech. The significant association between switching ability (and the marginal association between updating ability) and the production of the two maximum performance speech tasks that tax the late speech production processes, therefore, challenges the idea that "late stages" of speech-language production are largely automatic (Ferreira & Pashler, 2002; Garrod & Pickering, 2007), at least when speech production is made as challenging as we did here.

Lastly, the four selected tongue-twister sentences tested here turned out to vary in difficulty level, as evidenced by rate and accuracy analyses. The more challenging tongue-twister sentences were (a) "Frits vindt visfrietjes vreselijk vies" (nine syllables) and (b) "Ik bak een plak bakbloedworst" (seven syllables), while the relatively easy ones were (c) "De poes kotst in de postzak" (seven syllables) and (d) "Papa pakt de blauwe platte bakpan" (10 syllables). The syllable counts already indicate that the difficulty difference is unlikely to be due to sentence length. For a sentence to be a real tongue twister, it should have both repetition and alternation of sounds, leading to facilitation of the repeated consonant and hence interference for any switches in sound (Monaco et al., 2017). The number of repeats and alternations is low in the easy Sentence c, but also in the difficult Sentence b, and is not low in the easy Sentence d. The difference in difficulty level may perhaps rather relate to the fact that the more challenging sentences contain trisyllabic (compound) words whereas the rather easy ones are mainly composed of bisyllabic simple words. Alternatively, the difficulty difference may relate to easier switching between alternating singleton consonants than alternating singleton consonant onsets and consonant cluster onsets. Only better controlled sentence sets would allow

systematic evaluation to determine whether alternating between place of articulation is easier or more difficult to produce than alternating between simple and complex onsets.

Clinical Implications

When testing articulatory control using the maximum performance DDK task, clinicians can consider administering both nonword and real-word stimuli. Our data suggest that, at least for the young healthy adult speakers tested here, the link to executive control (particularly switching) may be stronger for the production of nonsensical DDK sequences than for real-word sequences. However, follow-up research is required to establish whether these results generalize to other populations (including clinical populations of different ages) and to better controlled designs and stimuli (as lexical status in our design was confounded with other factors, see a more detailed explanation above). If our results are found to hold more generally, this stronger link with cognitive switching for nonword compared to real word DDK could be a reason to opt for either type of DDK stimuli, depending on the patient (group) or purpose of the speech assessment. Either way, it may be good practice to use both nonword and real-word stimuli in a DDK task to get a more complete picture of participants' speech motor/articulatory control skills. Our results also suggest that DDK may be a challenging task for clinical populations with cognitive impairment. Our analyses also showed that accuracy for DDK performance was more informative than maximum rate itself. This also held for tongue-twister performance, but this observation of accuracy being more informative than rate may have been specific for our young and unimpaired sample.

Conclusions

On the basis of our individual differences approach, we conclude that executive control (cognitive switching in particular) relates to speech motor control as quantified with maximum speech performance measures. This finding extends the body of evidence on the link between cognition and language production to late stages of production, such as articulation.

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